# XI International Symposium on Electrohydrodynamics (ISEHD2025)

# **Book of Proceedings**

June 10-13, 2025

Sevilla, Spain



# Contents

Table	of Contents	3
Conte	nts	3
Procee	edings by Session	7
Full P	roceedings	13
4	Energy And Exergy Analysis Of EHD Drying	13
5	Viscoelastic Effect On Electrically Induced Dynamics In A Suspended	
	Droplet: A Mathematical Approach	19
7	Numerical Modeling Of A Nanosecond DBD Discharge In An Icing Envi-	
	ronment	23
8	Decomposition Of Acetic Acid By Pulsed Plasma Generated In N2-O2	~ -
0		27
9	The Impact Of The Polarization Layer On Electrohydrodynamic Drying	20
10		29
10	visualization Of Liquid-vapor interface Oscillation in Parallel Plate Elec- trodes By Wayy Dielectrophonosis	22
11	Numerical Investigation On The Effect Of Non Autonomous Charge Inject	55
11	tion In EHD-Assisted Charging Of A Latent Heat Thermal Storage System	35
12	Optoelectronic Control Of Active Janus Particles: Trajectory Reconfigu-	00
12	ration And Mobility Reversals	39
13	PWP Measurement Of Charge Distribution In A Liquid Under DC Field	41
14	Enhanced Nano-Droplet Generation By Counter Ionic Liquid Electrospray	
	Configuration For Efficient CO2 Absorption	45
15	Impact Of An External Static Electric Field During The Foaming Process:	
	Equipment Design And First Results	49
16	Fundamental Characteristics Of Ionic Liquid Electrospray With Pump-	
	Free Porous Emitter For Enhanced CO2 Absorption	53
18	Hybrid Heat Exchanger And Wet Electrostatic Precipitation For Collect-	
	ing Water And Saving Energy	57
19	Modeling Steady Electrothermal Convection Using Physics-Informed Neu-	
	ral Networks	61
20	Numerical Simulation For Decomposition Of Organic Compounds In Wa-	
	ter By Plasma Generated Above Solution Under Consideration Of EHD-	
01	Induced Liquid Flow	65
21	Estimation of electrospray droplet diameters using Current-Voltage char-	<u> </u>
	acteristics with and without liquid flow	07

24	Surface Potential Analysis Of SiO2 Wafers After Two-Fluid Spray Using	
	Pure Water	71
25	The Role Of Charge Transfer In Mass Transfer In EHD Drying	75
26	Effect Of Electric Field On Moisture Transport In Porous Media During	
	Electrohydrodynamic Drying	79
27	Evaluation Of Effect Of Electrode Shape On Electrohydrodynamic Heat	
	Transfer Enhancement In Phase Change Materials	83
28	Adiabatic Bubble Growth And Detachment Under AC Electric Fields	87
29	Numerical Modeling Of Dust Particle Motion In A Corona Discharge-	0.
20	Based Ionic Wind Cleaning System For Solar Panels	91
30	Magneto-Electro-Osmotic Micro-Stirring: A Pathway To Enhanced Molec-	01
00	ular Transport	95
32	Heat Transfer Enhancement Driven By Thermo-Electro-Hydrodynamics	
	(TEHD): Influence Of The Marangoni Effect	99
33	Numerical Modelling Of EHD Liquid-Vapour Flow Redistribution In Co-	
	Axial Heat Exchangers	103
34	Observation And Simulation Of ElectroHydroDynamical Effects For Mass	
	Transfer Study In Surface-Based Biosensing Applications	107
35	Efficiency Of Static And Alternating Electric Fields For EHD Drying	111
36	Characteristics Of Liquid Phase Continuous Arc Discharge Plasma	115
37	Visualization Of Dust Removal Characteristics For Electrodynamic Dust	
	Shields With Parallel Electrodes Under Martian Atmosphere	119
38	The Mechanism Of Ionic Self-Phoresis	123
39	Large Eddy Simulation Of Turbulent Electro-Convection In Dielectric	
	Liquids	127
41	Numerical Simulation Of AC Electrified Jets In A Flow-Focusing Device	131
42	Problem Of Recombination Coefficient Specified By The Langevin For-	
	mula When Describing EHD Flows	135
43	Numerical Analysis Of Three-Dimensional Electroconvection Of Dielectric	
	Liquids In A Cubical Cavity	139
44	Experimental Investigation Of Relation Between Surface Charging And	
	Ionic Wind In Facing Plasma Actuator	143
45	Design And Performance Of Swirling Flow-Based Electrostatic	
	Precipitator	147
46	Molecular Dynamics Simulation On The Collision Of Ionic Liquid Nan-	
	odroplets With Surfaces In An Electrospray Environment	149
47	Oscillatory Behavior Of Electrospray Under Periodic Electric Fields	153
48	Experimental Investigation Of The Influence Of Electrode Spacing On	
	The Intensity Of Electric Wind	157
49	Investigation Of Underwater Discharge Phenomena And Shock Wave Reg-	
	ulation	161
50	Influence on Ionic Liquid Electrospray Emission Processes in Hybrid	
	Emitters under Rapid Electric Field Variation	163
51	Hydrophilic Treatment Of Graphite By Using Controlled Plasma-Induced	1.0-
	Liquid Flow	167
52	Numerical Simulation Of Electrodeformation Of A Droplet Immersed In	
<b>F</b> 6	Oil Under The Influence Of An Alternating High-Frequency Electric Field	171
53	Energy analysis of 2D electro-thermo-hydrodynamic turbulent convection	175

55	$\label{eq:Visualization} Visualization Of Electrohydrodynamic Convection Cells In A Phase Change$	
	Material Using Schlirien Imagery	179
56	Coupling Characteristics Of Shock Waves Induced By Nanosecond Pulse Tri-Electrode Dual-Spark SDBD And Plasma Diagnostics	183
57	Enhanced Hydrogen Production Through Plasma Methane Decomposition With Soot	187
59	Charged Phenomenon Of High-Speed Nanodroplet Impact On The Copper Plate	191
60	Hydrodynamic and electrostatic contributions to tracer-particle dynamics	
	near a patch, which actively releases ion-pairs, located on a planar wall .	195
63	Concentration Polarization Electroosmosis: Theory And Microfluidic Ap-	100
65	Vigualization Of Singlet Dalta Orangen Dradwood Dr. Atmospheric Dragoung	199
00	Plasma Iot	203
66	Universal Time-Scale Parameter For Describing The Coalescence Of Con-	203
00	ductive Droplets Under Pulsed Electric Fields	207
67	The Complex Structure Of Electrohydrodynamic Flows Arising In A Two-	201
	Phase Liquid With Weakly Conducting Dispersion Medium And Unequal	
	Ions Mobilities	211
68	Effect Of Charge On The Coalescence Of A Water Droplet Suspended In	
	Oil And A Water Layer	215
69	Aerosol Jet Printed Surface Dielectric Barrier Discharge (AJP-SDBD)	
	Plasma Actuators: Fabrication And Electromechanical Characteristics	219
71	Electrohydrodynamic Water Flow Produced By A DC Discharge Ignited	
70	Above Its Surface	223
72	Electrical Discharge Characteristics In A Dielectric Liquid Flow In A	207
72	Traveling Wave Fleetrophoresis Of Miero Particles	227
75 75	Improving Collection Efficiency And Energy Saving In A High Electric	201
10	Field Type Electrostatic Precipitator With High Gas Velocity For Diesel	235
77	Numerical Study On Dynamics Of Falling Drop Over Hydrophobic Sub-	200
•••	strate Under The Influence Of Electric Field	239
80	Molecular Dynamics Simulation Of Electrical Conduction In	
	Room-Temperature Ionic Liquids Under Strong Electric Field	245
81	Plasma Jet Impacting The Surface Of A Liquid: Electrical Analysis And	
	Electrohydrodynamic Flows	249
82	Time Evolution Of The Electrohydrodynamic Water Flow Produced By	
	A Dielectric Barrier Discharge Ignited Above Its Surface	253
83	Effect Of Voltage Slope On Electrohydrodynamic Force Generation In	057
0.4	Pulsed Corona Discharges	257
84	Cas liquid Interface: Investigation Through Halogon Congration	961
85	The Method Of Determining Ion Mobilities In A Liquid Dielectric In A	201
00	Wire-Cylinder Electrode System Based On Current Characteristics	265
87	Experimental Investigation Of Electrocoalescer Unit Prototype For Nu-	200
- •	merical Models Verification	269
89	The Effect Of Polarity Change On An Asymmetric Cylinder-To-Cylinder	
	EHD Device	273

90	Application Of The Arbitrary Lagrangian–Eulerian Approach To Simulate	
	Two-Phase Electrohydrodynamics Of Low-Conducting Droplets In Low-	
	Conducting Dispersion Medium	277
91	Impact Of Seeding Particle Properties On PIV Accuracy In Electrohydro-	
	dynamic Systems	281
92	Finite Taylor Cone: The Impact Of The Electrospray	285
93	Electrokinetic Effects in Cone-Jet Electrospraying: Ion Size and Solvent	
	dependence	287
94	Effective control method of high Reynolds number flow around airfoil	
	using plasma actuator	291
95	Experimental study of particle removal by dielectric barrier discharge	295
96	Characteristics of single-phase gliding arc equipment with twisted elec-	
	trodes and radial gas injection	299
97	Fully 3D Numerical Computations of the Unipolar Injection between	
	an Hyperbolic Blade and a Plane Electrode	303
98	Numerical Investigation of Flow Reversal in Electrohydrodynamic Con-	
	duction: An Analysis of Blade-Plane Configuration	307
99	Numerical Study of Electro-Thermo-Hydrodynamic Conduction in Dielec-	
	tric Liquids: Impact of Temperature-Dependent Properties and Dielectric	
	Forces on Rayleigh-Bénard Instability.	311
106	Numerical Simulation of Electrohydrodynamic Deformation of a Leaky	
	Dielectric Droplet employing Arbitrary Eulerian Lagrangian (ALE) Ap-	
	proach using COMSOL Multiphysics	315

# Proceedings by Session

## Drying (S01)

4: Energy And Exergy Analysis Of EHD I	Drying P14
26: Effect Of Electric Field On Moisture T	Fransport In Porous Media
During Electrohydrodynamic Drying	

## Electroconvection (S02)

19: Modeling Steady Electrothermal Convection Using Physics-Informed	
Neural Networks	P61
30: Magneto-Electro-Osmotic Micro-Stirring: A Pathway To Enhanced Molecular	
Transport	P95
39: Large Eddy Simulation Of Turbulent Electro-Convection In Dielectric Liquids F	<b>`</b> 127
80: Molecular Dynamics Simulation Of Electrical Conduction In	
Room-Temperature Ionic Liquids Under Strong Electric Field	<b>'</b> 245
89: The Effect Of Polarity Change On An Asymmetric Cylinder-To-Cylinder	
EHD Device	<b>'</b> 273
91: Impact Of Seeding Particle Properties On PIV Accuracy In	
Electrohydrodynamic Systems F	<b>'</b> 281
97: Fully 3D Numerical Computations of the Unipolar Injection between	
an Hyperbolic Blade and a Plane ElectrodeF	<b>'</b> 303
98: Numerical Investigation of Flow Reversal in Electrohydrodynamic Conduction:	
An Analysis of Blade-Plane ConfigurationP	<b>'</b> 307

# Electro-Thermo-EHD (S03)

11: Numerical Investigation On The Effect Of Non-Autonomous Charge	
Injection In EHD-Assisted Charging Of A Latent Heat Thermal Storage System	P35
27: Evaluation Of Effect Of Electrode Shape On Electrohydrodynamic Heat	
Transfer Enhancement In Phase Change Materials	P83
32: Heat Transfer Enhancement Driven By Thermo-Electro-Hydrodynamics	
(TEHD): Influence Of The Marangoni Effect	P99
43: Numerical Analysis Of Three-Dimensional Electroconvection Of Dielectric	
Liquids In A Cubical Cavity	. P139

53: Energy analysis of 2D electro-thermo-hydrodynamic	
turbulent convection	P175
55: Visualization Of Electrohydrodynamic Convection Cells In A Phase Change	
Material Using Schlirien Imagery	.P179
99: Numerical Study of Electro-Thermo-Hydrodynamic Conduction in Dielectric	
Liquids: Impact of Temperature-Dependent Properties and Dielectric Forces on	
Rayleigh-Bénard Instability.	P311

## Multiphase (S04)

5: Viscoelastic Effect On Electrically Induced Dynamics In A Suspended	
Droplet: A Mathematical Approach	P19
10: Visualization Of Liquid-Vapor Interface Oscillation In Parallel Plate	
Electrodes By Wavy Dielectrophoresis	P33
24: Surface Potential Analysis Of SiO2 Wafers After Two-Fluid Spray	
Using Pure Water	P71
33: Numerical Modelling Of EHD Liquid-Vapour Flow Redistribution In	
Co-Axial Heat Exchangers	P103
41: Numerical Simulation Of AC Electrified Jets In A Flow-Focusing Device	P131
66: Universal Time-Scale Parameter For Describing The Coalescence Of	
Conductive Droplets Under Pulsed Electric Fields	P207
67: The Complex Structure Of Electrohydrodynamic Flows Arising In A	
Two-Phase Liquid With Weakly Conducting Dispersion Medium And Unequal	
Ions Mobilities	P211

### Droplets and Bubbles (S05)

15: Impact Of An External Static Electric Field During The Foaming Process:	
Equipment Design And First ResultsP4	9
28: Adiabatic Bubble Growth And Detachment Under AC Electric Fields	7
59: Charged Phenomenon Of High-Speed Nanodroplet Impact On The Copper	
Plate	1
68: Effect Of Charge On The Coalescence Of A Water Droplet Suspended In	
Oil And A Water LayerP21	5
77: Numerical Study On Dynamics Of Falling Drop Over Hydrophobic Substrate	
Under The Influence Of Electric FieldP23	9

### Electrospray (S06)

14: Enhanced Nano-Droplet Generation By Counter Ionic Liquid Electrospray	
Configuration For Efficient CO2 Absorption	P45
16: Fundamental Characteristics Of Ionic Liquid Electrospray With Pump-Free	
Porous Emitter For Enhanced CO2 Absorption	P53

46: Molecular Dynamics Simulation On The Collision Of Ionic Liquid	
Nanodroplets With Surfaces In An Electrospray Environment	P149
47: Oscillatory Behavior Of Electrospray Under Periodic Electric Fields	P153
50: Influence on Ionic Liquid Electrospray Emission Processes in Hybrid Emitters	
under Rapid Electric Field Variation	P163
92: Finite Taylor Cone: The Impact Of The Electrospray	$\mathbf{P285}$
93: Electrokinetic Effects in Cone-Jet Electrospraying: Ion Size and Solvent	
dependence	P287

### Particles and Electrokinetics (S07)

12: Optoelectronic Control Of Active Janus Particles: Trajectory Reconfiguration	
And Mobility Reversals	P39
34: Observation And Simulation Of ElectroHydroDynamical Effects For Mass	
Transfer Study In Surface-Based Biosensing Applications	P107
37: Visualization Of Dust Removal Characteristics For Electrodynamic Dust	
Shields With Parallel Electrodes Under Martian Atmosphere	P119
38: The Mechanism Of Ionic Self-Phoresis H	P123
60: Hydrodynamic and electrostatic contributions to tracer-particle dynamics	
near a patch, which actively releases ion-pairs, located on a planar wall H	P195
63: Concentration Polarization Electroosmosis: Theory And Microfluidic	
Applications	P199

### Liquid properties (S08)

13: PWP Measurement Of Charge Distribution In A Liquid Under DC Field	P41
85: The Method Of Determining Ion Mobilities In A Liquid Dielectric In A	
Wire-Cylinder Electrode System Based On Current Characteristics	$\dots P265$

### EHD in Electrical Discharges in Liquids (S09)

P65
. P115
.P161
. P223
. P227
.P249

### Plasmas (S10)

7: Numerical Modeling Of A Nanosecond DBD Discharge In An Icing Environment P23
8: Decomposition Of Acetic Acid By Pulsed Plasma Generated In N2-O2 Mixed Gas P27
56: Coupling Characteristics Of Shock Waves Induced By Nanosecond Pulse
Tri-Electrode Dual-Spark SDBD And Plasma Diagnostics
65: Visualization Of Singlet Delta Oxygen Produced By Atmospheric Pressure
Plasma Jet
69: Aerosol Jet Printed Surface Dielectric Barrier Discharge (AJP-SDBD) Plasma
Actuators: Fabrication And Electromechanical Characteristics
84: Influence Of Co-Existing Ions On Plasma-Induced Chemical Reactions At
Gas-liquid Interface: Investigation Through Halogen Generation

### EHD in Gas Discharges (S11)

29: Numerical Modeling Of Dust Particle Motion In A Corona Discharge-Based	
Ionic Wind Cleaning System For Solar Panels	P91
83: Effect Of Voltage Slope On Electrohydrodynamic Force Generation In Pulsed	
Corona Discharges	P257
94: Effective control method of high Reynolds number flow around airfoil using	
plasma actuator I	P291

### Electrostratic Precipitation (S12)

18: Hybrid Heat Exchanger And Wet Electrostatic Precipitation For Collecting
Water And Saving Energy
75: Improving Collection Efficiency And Energy Saving In A High Electric
Field Type Electrostatic Precipitator With High Gas Velocity For Diesel $\ldots\ldots$ P235

### Poster session (P01)

9: The Impact Of The Polarization Layer On Electrohydrodynamic Drying
Efficiency
21: Estimation of electrospray droplet diameters using Current-Voltage
characteristics "with and without" liquid flowP67
25: The Role Of Charge Transfer In Mass Transfer In EHD DryingP75
35: Efficiency Of Static And Alternating Electric Fields For EHD DryingP111
42: Problem Of Recombination Coefficient Specified By The Langevin Formula
When Describing EHD Flows
44: Experimental Investigation Of Relation Between Surface Charging And Ionic
Wind In Facing Plasma ActuatorP143
45: Design And Performance Of Swirling Flow-Based Electrostatic Precipitator $\ .$ . P147
48: Experimental Investigation Of The Influence Of Electrode Spacing On The
Intensity Of Electric WindP157

51: Hydrophilic Treatment Of Graphite By Using Controlled Plasma-Induced
Liquid Flow P167
52: Numerical Simulation Of Electrodeformation Of A Droplet Immersed In Oil
Under The Influence Of An Alternating High-Frequency Electric Field
57: Enhanced Hydrogen Production Through Plasma Methane Decomposition
With SootP187
73: Traveling-Wave Electrophoresis Of Micro-Particles
82: Time Evolution Of The Electrohydrodynamic Water Flow Produced By A
Dielectric Barrier Discharge Ignited Above Its Surface
87: Experimental Investigation Of Electrocoalescer Unit Prototype For
Numerical Models Verification
90: Application Of The Arbitrary Lagrangian–Eulerian Approach To Simulate
Two-Phase Electrohydrodynamics Of Low-Conducting Droplets In
Low-Conducting Dispersion Medium
95: Experimental study of particle removal by dielectric barrier discharge P295
96: Characteristics of single-phase gliding arc equipment with twisted
electrodes and radial gas injection
106: Numerical Simulation of Electrohydrodynamic Deformation of a Leaky
Dielectric Droplet employing Arbitrary Eulerian Lagrangian (ALE) Approach
using COMSOL Multiphysics

# **Full Proceedings**

### Exergy and energy analysis of EHD drying technology

Alex I. Martynenko

Department of Engineering, Faculty of Agriculture, Dalhousie University, Truro, Canada Corresponding author: alex.martynenko@dal.ca

*Abstract*- Electrohydrodynamic drying is a novel non-thermal drying technology with extremely low energy consumption. A thermodynamic study, followed by energy and exergy analysis, has been accomplished to understand the reason for energy-efficient drying. The thermodynamic study showed that drying efficiency depends on the air temperature. The efficiency of the process was measured as a specific energy and exergy consumption in kJ per kg of evaporated water. Energy and exergy analysis showed the advantages of EHD compared to other sustainable drying technologies, based on renewable energy sources.

Keywords- Energy, exergy, efficiency, sustainability

#### I. INTRODUCTION

Research and development of novel drying technologies require careful analysis of multiple factors, determining the acceptance by industry and the area of applications. It includes but is not limited to the operation mode (batch, continuous), temperature and pressure of drying medium, mode of heat and mass transfer (convective, conductive, radiative), state of the material (stationary, moved, or agitated), dehydration rate, size, capital cost, carbon footprint, etc. [1]. More recently, the requirements for clean and sustainable technologies have been introduced [2]. The sustainability of drying technology can be evaluated based on a thorough energy and exergy analysis, and the environmental impact on climate change due to thermal and GHG emissions [3].

There is increased interest in electrotechnologies as a clean energy source for drying. They include microwave applications combined with hot air, vacuum, and freezedrying [4], infrared drying [5], radiofrequency (RF) drying [6], and electrohydrodynamic (EHD) drying [7]. All these electrotechnologies, except EHD, are converting electric energy into heat. In contrast, EHD drying directly applies electric energy for water extraction without heat losses. It operates under ambient conditions without heat losses, which makes drying sustainable [8]. Specific energy consumption of EHD drying usually ranges from 600 to 800 kJ/kg, decreasing in some cases to 100 kJ/kg [9], which is much smaller than the enthalpy for water evaporation. So far, the existing literature does not explain such low energy consumption.

To understand the cause of high energy efficiency, this paper provides a brief description and a thermodynamic study of EHD drying technology, followed by energy and exergy analyses. Energy analysis was carried out according to the first law of thermodynamics, while exergy analysis was based on the second law of thermodynamics. Specific energy and exergy consumption were used to compare EHD with other drying technologies.

#### II. METHODOLOGY

A modified lab-scale EHD dryer is shown in Figure 1. The discharge electrode (1) was made of 72 stainless steel (SS) pins, arranged in a  $9\times8$  rectangular grid with a 2 cm spacing on a fiberglass board of  $240\times170\times2$  mm (Vector Electronics Inc., Canada). Pins were connected to a high-voltage DC power supply (2) (Universal Voltronics, USA). The collecting electrode (3) was a stainless-steel pan with dimensions  $340\times180$  mm, filled with water. EHD flow was created by applying a 16 kV voltage at a 4 cm gap, providing an electric field strength of 4 kV/cm. The FLUKE-110 ammeter (FLUKE, Everett, USA) measured the electric current in the ground wire.



Fig 1. Experimental setup for thermodynamic measurements of EHD-induced water evaporation

The relative humidity (RH) was measured using a wet and dry bulb hygrometer (model B6030, Baker Instruments, NY, USA). Air temperature was measured using a T-type thermocouple with an accuracy of 0.1 °C. The evaporation rate was evaluated from the weight change of a pan using a digital scale HCB 1002 (Adam Equipment, Kingston, England) with an accuracy of 0.01 g. Ionic wind velocity was measured by a hot wire anemometer 405i (Testo Instruments, Canada). The water surface temperature was measured with a thermal camera T640 (FLIR Systems, North Billerica, USA) with the uncooled FPA bolometer with a resolution of  $640 \times 480$ pixels in a spectral range of 7.5–13 µm. Camera settings for emissivity were constant at 0.95 for all experiments. The experiments with water evaporation from the free surface were conducted in the range of air temperatures from 5 to 35  $^{\circ}$ C and compared with natural evaporation (control).

The discharge power P (W) was calculated as a product of the current and voltage of the power supply:

$$P = VI \tag{2}$$

Specific energy consumption (SEC) was calculated as the ratio of the power *P* provided to the drying equipment to the evaporation rate  $\dot{m}_w$  [9]:

$$SEC = \frac{\Sigma E}{\Sigma m_w} = \frac{P}{\dot{m}_w}$$
(3)

Energetic efficiency was calculated from the specific energy consumption in kJ per kg of evaporated water.

#### **III. RESULTS**

#### A. Experimental Study

Our experiments at different temperatures showed that an applied electric field of 4 kV/cm resulted in a similar electric current of 100  $\mu$ A and an ionic wind velocity of 1.0 m/s in all experimental settings. It led us to the conclusion that air temperature did not impact discharge power. At the same time, air temperature influenced specific energy consumption (SEC). It was maximal at low temperatures, decreasing at higher temperatures (Figure 2).



Fig 2. Specific energy consumption of EHD drying as a function of air temperature.

An increase in air temperature from 5 to 35  $^{\circ}$ C decreased SEC from 860 to 120 kJ/kg. At lower temperatures, the evaporation rate was limited by the heat available in the air, and the effect of EHD on the evaporation rate is negligible. It should be noted that these values are much smaller than the thermodynamic threshold for water evaporation (2450 kJ/kg).

Since SEC is a function of discharge power and evaporation rate (Equation 3), but the discharge power was constant, it follows that the decrease in SEC at elevated temperatures could be attributed to an increase in evaporation rate. This assumption was tested by direct evaporation rate measurements (Figure 3).



Fig 3. Effect of air temperature on the evaporation rate for natural (empty circles) and EHD-induced (filled circles) drying

Air temperature facilitated the evaporation rate in both natural and EHD-induced convection. This result was expected due to the higher temperature gradient and increased heat transfer. However, the EHD-induced evaporation rate increased faster than the control, which could be explained by the additional effect of EHD on the heat transfer resistance.

Parallel measurements of wet bulb  $T_{wb}$  and water surface  $T_w$  temperatures revealed the difference between natural and EHD-induced drying. In the control experiments (without EHD), water temperature coincided with wet bulb temperature. In the EHD-induced drying, the surface temperature of the water  $T_w$  dropped below the wet bulb temperature  $T_{wb}$ . The most remarkable difference between these two temperatures was observed at low air temperatures (-7.8 degrees), decreasing with air temperature to -1.0...-1.5 degrees. It follows that the EHD flow lowers water temperature below the point expected from classical thermodynamics. This observation concurs with an earlier report [10].

The difference between wet bulb and water surface temperatures allowed evaluation of EHD-induced entropy changes. The decrease in water surface entropy in the range of tested temperatures could be calculated from Equation 4:

$$\Delta S = c_p ln \frac{T_w}{T_{wb}} \tag{4}$$

At the air temperature of 5 °C, a small electric current caused a decrease in the water surface entropy by 0.118 kJ/(kg·K), resulting in a larger temperature gradient and better conditions for heat transfer from air to the water surface. However, at the air temperature of 35 °C, the effect of electric current on the surface entropy was smaller- about 0.057 kJ/(kg·K), probably because of direct heating of the water surface. Smaller entropy changes resulted in a smaller temperature gradient and decreased heat transfer. It means that the optimal air temperature for water evaporation is somewhere between 5 and 35 °C.

This experimental study revealed two previously unknown phenomena: (1) the effect of air temperature on the efficiency of EHD drying; (2) EHD-induced depression of water surface temperature below the wet bulb temperature. These discoveries created the background for further energy and exergy analysis.

#### B. Energy Analysis

Historically, energy efficiency is calculated based on the *first law of thermodynamics*, reflecting the energy conservation principle. It is expressed as the ratio of the energy required to evaporate water  $\dot{Q}_{evap}$  to the total power provided to the drying equipment *P* [11]:

$$\eta_E = \frac{\dot{Q}_{evap}}{P} \tag{5}$$

This index ranges from 0 to 1, showing how close the process is to ideal thermodynamic conditions. However, it is not suitable for EHD drying, where the electric energy consumption *P* is smaller than the thermal energy of evaporation  $\dot{Q}_{evap}$ . This implies  $\eta_E > 1$ , pointing out that energy efficiency should be calculated similarly to a heat pump, which saves more thermal energy than it consumes. The heat pump efficiency is evaluated with the *coefficient of performance* (COP), usually ranging from 2.3 to 3.5:

$$COP_{heat} = 1 + \frac{\dot{Q}_{evap}}{P} \tag{6}$$

Similarly to the heat pump dryer, the COP of the EHD dryer is larger than two. Considering that EHD drying at ambient conditions (temperature 20 °C) provided water evaporation of 0.1 g/(m<sup>2</sup>s) at 35 W/m<sup>2</sup> electric energy, calculated COP<sub>*EHD*</sub> = 8. From lab-scale experiments, it follows that the maximum evaporation rate can reach 0.4 g/(m<sup>2</sup>s) at the same power density, so COP<sub>*EHD*</sub> max = 29..30. The drying performance of EHD could be evaluated with *Specific Moisture Extraction Rate* (SMER) (kg water/kWh), which is defined as follows:

$$SMER = \frac{Mass of water extracted}{Electric energy consumed}$$
(7)

It is important to note that SMER is the reciprocal number of SEC (kWh/kg<sup>-1</sup> water). Excluding the removed sensible heat, the relationship between SMER and the coefficient of performance  $COP_{heat}$  is:

$$SMER = 3600 \frac{COP_{heat} - 1}{h_{lv}}$$
(8)

The SMER of a well-designed EHD dryer is 40 kg water·kWh-1, with an average value of 10 kg water·kWh-1, which is significantly better than that of the most efficient heat pump dryers [12]. The efficiency of an EHD dryer decreases with the increase in relative humidity [9] and air velocity [13].

Although the energy indices, such as SEC, COP, and SMER, give the proper measure for the system, energy analysis does not consider energy exchange with the environment. The fact that in EHD drying the SEC  $< h_{lv}$ , indicates that other (than electric) energy sources should be considered.

The thermal energy supplied from ambient air to the water could be calculated from Newton's law:

$$\dot{Q_a} = h_T A (T_a - T_w) \tag{9}$$

where  $h_T$  stands for the coefficient of convective heat transfer. It should be noticed that in conditions of natural convection (control), the thermal energy of the air could not be easily transferred to the water because of the high heat transfer resistance of the thermal boundary layer. At the same time, EHD produced highly efficient airflow, decreasing heat transfer resistance. The numerical simulation predicted a significant effect of EHD flow on the coefficient of convective heat transfer [14]. It was experimentally proved that EHD flow increased the heat transfer coefficient from 5-10 Wm<sup>-2</sup>K<sup>-1</sup> (natural convection in gases) to 60-65 Wm<sup>-2</sup>K<sup>-1</sup> [15].

If the energy for water evaporation  $\dot{Q}_{evap}$  is partially supplied by the air  $\dot{Q}_a$  and partially by electricity *P*, the energy balance equation could be presented as:

$$\dot{Q}_a + P = \dot{Q}_{evap} \tag{10}$$

which means that energy for water evaporation is proportional to electric discharge energy and heat energy utilized from the air. The evaporation rate is proportional to the overall energy input and could be calculated from equation (10):

$$\dot{m}_w = \frac{\dot{Q}_a + P}{h_{lv}} \tag{11}$$

The major challenge in scaling EHD technology is removing water vapor from the drying volume. In this case, the enthalpy of the outlet air  $h_{a,out}$  will exceed the enthalpy of the inlet air  $h_{a,in}$ . The effect of air exchange  $\dot{m}_a$  on the energy balance could be accounted for by modification of equation (10):

$$\dot{Q}_a + P = \dot{Q}_{evap} + \dot{m}_a \left( h_{a,out} - h_{a,in} \right)$$
(12)

If energy loss due to vapor diffusion is negligibly small, EHD drying could be considered a completely lossless drying technology. However, this assumption required thorough testing. The next section presents an introduction to the thermodynamic efficiency of energy use, based on the second law of thermodynamics or *exergy analysis*.

#### C. Exergy Analysis

The concept of exergy analysis is extremely useful for open steady-state systems with renewable energy sources. It was successfully applied to the optimization of renewable energy systems [16], including solar [17] and heat pump dryers [18]. The starting point of exergy analysis is the exergy balance equation, which accounts for specific exergies at the input/output and internal heat/mass transfer:

$$\left(1 - \frac{T_w}{T_a}\right) \dot{Q}_a + \dot{E}x_{in} + \sum_{in} \dot{m}_a Ex_{in}$$

$$= \dot{W} + \sum_{out} \dot{m}_a Ex_{out} + \dot{E}x_{dest}$$
(13)

In this equation, the first term represents the exergy related to the heat transfer into the water from the air at a certain temperature  $T_a$ ;  $Ex_{in}$  indicates the electric exergy

flow (W),  $\dot{W}$  represents the energy used for water evaporation (W), Ex indicates the specific exergy of the air at the input or output of the system (kJ/kg), and  $Ex_{dest}$ is the exergy destroyed in the form of energy losses (W).

Internal exergy loss due to irreversibility  $\delta Ex$  could be calculated as [19]:

$$\delta Ex = Q \frac{T_a - T_w}{T_a T_w} T_a \tag{14}$$

Considering the extreme case of 35 °C air temperature, the maximum exergy loss is calculated as 4.9% of the overall exergy supply or 119 kJ per kg of evaporated water. A small part of exergy lost because of vapor diffusion in the surrounding air,  $Ex_{au}$ , could be calculated, knowing the air exchange in the drying system.

The *exergy efficiency* of water evaporation is defined as the fraction of input exergy used for evaporation [19]:

$$\psi_{drying} = \frac{\dot{W}}{\dot{W}_{max}} = 1 - \delta Ex \approx 95\%$$
(15)

EHD drying operates at ambient temperature and does not create any heat losses. Minimizing air exchange to values sufficient to maintain desirable relative humidity, we could achieve exergy efficiency up to 90-95%. In contrast, the exergy efficiency of a thermal convective dryer does not exceed 14%. Increasing the temperature of drying air leads to a higher rate of heat loss, thereby decreasing energy and exergy efficiencies. Table 1 compares EHD drying with other drying technologies, using renewable energy sources [20].

Table 1: Comparison of EHD drying to other sustainable drying technologies

	EHD	Solar	Heat pump	Geothermal
SEC, kJ/kg	600-800	820-950	900-1600	1200-2000
Exergetic efficiency,%	90-95	33-55	15-21	21-42

#### Conclusions

Our study confirmed the EHD effect on the decrease of water entropy at the gas-liquid interface. Energy analysis suggested SEC and COP as key performance indicators of EHD drying. Exergy analysis revealed that a major part of the energy for water evaporation comes from ambient air. Since EHD does not use or generate any heat, it is considered a completely lossless, highly sustainable drying technology, using renewable energy.

#### REFERENCES

- A.S. Mujumdar, Principles, Classification, and Selection of Dryers. *In: Handbook of Industrial Drying*, 4<sup>th</sup> ed. Chapter 1, p. 4-29, 2015.
- [2] United Nations. *The 2030 Agenda for Sustainable Development*, 2015.
- [3] I. Dincer. On energetic, exergy and environmental aspects of drying systems. *Int Journal of Energy Research* 26, 717-727, 2002.
- [4] M. Zielinska, E. Ropelewska, H-W Xiao, A.S. Mujumdar, C.L. Law. Review of recent applications

and research progress in hybrid and combined microwave-assisted drying of food products: Quality properties. *Critical Reviews in Food Science and Nutrition* 60, 2212-2264, 2020.

- [5] P. Sakare, N. Prasad, N. Thombare, R. Singh, S.C. Sharma. Infrared drying of food materials. *Food Engineering Reviews 12*, 381-398, 2020.
- [6] X. Zhou, S. Wang. Recent developments in radiofrequency drying of food and agricultural products: A review. *Drying Technology* 37, 271-286, 2019.
- [7] A. Martynenko, T. Kudra. Electrohydrodynamic Drying. In Advanced Drying Technologies for Foods; Mujumdar, A.S., Xiao, H-W., Eds.; CRC Press: Boca Raton, FL, 2020.
- [8] T. Kudra, A. Martynenko. Electrohydrodynamic drying: The opportunity for sustainable development. *Drying Technology* 41, 2606-2619.
- [9] A. Martynenko, I. Bashkir, T. Kudra. The energy efficiency of electrohydrodynamic (EHD) drying. *Trends in Food Science & Technology 118*, 744-764, 2021.
- [10]A. Martynenko, NN Misra. Thermal phenomena in electrohydrodynamic (EHD) drying. *Innovative Food Science & Emerging Technologies* 74, 102859, 2021.
- [11]T. Kudra. Energy aspects in drying. Drying Technology, v. 22(5), 917-932, 2004.
- [12]A.B.T. Loemba, B. Kichonge, T. Kivevele. Comprehensive assessment of heat pump dryers for drying agricultural products. *Energy Science & Engineering 11*, 2985-3014, 2022.
- [13]A. Martynenko, W. Zheng. Electrohydrodynamic drying of apple slices: Energy and quality aspects. *Journal of Food Engineering 168*, 215-222, 2016.
- [14]T. Defraeye, A. Martynenko. Electrohydrodynamic drying of food: New insights from conjugate modelling. *Journal of Cleaner Production 198*, 269-284, 2018.
- [15]B.L. Owsenek, J.S. Yagoobi, R.H. Page. Experimental investigation of corona wind heat transfer enhancement with a heated horizontal flat plate. *Journal of Heat Transfer 117*, 309-315, 1995.
- [16]S.R. Park, A.K. Pandey, V.V. Tyagi, S.K. Tyagi. Energy and exergy analysis of typical renewable energy systems. *Renewable and Sustainable Energy Reviews*, 30, 105-123, 2014.
- [17]S. Tiwari, G.N. Tiwari. Energy and exergy analysis of a mixed-mode greenhouse-type solar dryer, integrated with partially covered N-PVT air collector. *Energy*, 128, 183-195, 2017.
- [18]W. Catton, G. Carrington, Z. Sun. Exergy analysis of an isothermal heat pump dryer. *Energy*, 36, 4616-4624, 2011.
- [19] J. Szargut. Exergy method: technical and ecological applications. Southampton: WIT Press, 2005.
- [20] I. Dincer, M.A. Rosen. Exergy analysis of drying processes and systems. In: *Exergy: Energy, Environment and Sustainable Development*. 2<sup>nd</sup> ed, 167-191, 2013.

### Viscoelastic Effect on Electrically Induced Dynamics in a Suspended Droplet: A Mathematical Approach

Pulak Gupta<sup>1\*</sup>, Purbarun Dhar<sup>2</sup>, Devranjan Samanta<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering, Indian Institute of Technology Ropar, Punjab–140001, India <sup>2</sup>Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, West Bengal–721302, India \*Corresponding author: pulak.20mez0007@iitrpr.ac.in

Abstract- The electrohydrodynamic (EHD) deformation of viscoelastic (VE) droplets in microfluidic applications remains largely unexplored compared to Newtonian (N) fluids, necessitating this mathematical analysis. This model predicts the EHD behavior of a confined, suspended droplet based on known properties while maintaining physical consistency. A leaky dielectric VE droplet in a VE medium under a DC electric field is analyzed within the Stokes flow regime, constrained to low electric field intensity, small deformation, and Weissenberg number (Wi)  $\leq 1$ . The electrical and hydrodynamic behaviors are governed by Laplace and Cauchy Momentum Equations, respectively, with the latter incorporating the Upper Convected Maxwell (UCM) model. The influence of the weight parameter ( $\delta$ ) and confinement ratio ( $\alpha$ ) is assessed across Newtonian (N) and non-Newtonian (NN) fluid combinations. Model predictions align with experimental findings, indicating minimal deformation in N-NN systems and maximal in N-N cases, with NN fluids exhibiting greater streamline divergence than N fluids. These insights aid microfluidic device design for industrial applications.

Keywords- Electrohydrodynamics (EHD), Upper convected Maxwell (UCM) Model, Weight Parameter ( $\delta$ ), Deformation Parameter (D).

#### I. INTRODUCTION

In recent decades, significant efforts have been devoted to understanding the EHD of droplets suspended in another fluid, driven by both fundamental curiosity and practical relevance. These studies provide insights into various natural and engineered phenomena, ranging from fluid interactions in dynamic environments to processes influenced by electric fields, aiding advancements across multiple disciplines [1, 2].

This work explores the EHD of droplets in N and NN viscoelastic (VE) media, deriving an approximate analytical solution that captures interfacial and rheological interactions governing deformation and flow fields. Classic electro-hydrostatics theory [3] predicts prolate spheroid deformation for perfect dielectric or highly conductive droplets, while later studies introduced the leaky dielectric model, which accounts for interfacial charge accumulation and tangential electric stresses that drive fluid motion. Experimental findings [4], however, revealed discrepancies with theoretical predictions, prompting refinements through higher-order corrections and charge transport models. Despite these efforts, a fully comprehensive analytical model remains elusive.

Beyond N droplets, limited studies have addressed NN EHD interactions. Experiments demonstrated reduced deformation under equivalent electrical stresses, highlighting the influence of rheology, stress relaxation, and elasticity [4]. Theoretical challenges stem from the nonlinear stressstrain relationship and additional rheological complexities. This study advances the field by incorporating a VE rheological equation into the governing EHD model, obtaining deformation and flow expressions while accounting for confinement effects. Using the UCM model [5], we analyze configurations where (i) a N fluid surrounds a NN droplet,

(ii) a NN fluid surrounds a N droplet, and (iii) both phases are NN. Our analytical predictions align well with experimental results for small deformations, offering valuable insights into EHD-driven droplet behavior in diverse applications.

#### II. PHYSICAL SYSTEM



Figure 1: The schematic depicts a spherical droplet, confined within a rigid spherical container, with an applied electric field along the z-axis in spherical coordinates.

Figure 1 depicts a spherical, VE, leaky dielectric droplet (radius  $R_1$ ) suspended in an immiscible, VE, leaky dielectric medium, confined within a concentric spherical container (radius  $R_2$ ) with negligible wall-induced effects. The system, neutrally buoyant and initially concentric, is described in axisymmetric spherical coordinates (r,  $\theta$ ,  $\phi$ ), where  $\phi$ -dependence is absent under symmetric conditions. However, a sufficiently strong electric field disrupts concentricity, introducing non-axisymmetric flow and  $\phi$ -dependence.

A weak, divergence-free, irrotational electric field applied along the z-axis ensures a negligible induced magnetic field, maintaining the study's validity for small deformations. In leaky dielectric fluids, charge accumulates at the interface while the bulk remains effectively charge-free due to a negligible charge relaxation time, yielding an electric Reynolds number  $Re_E \ll 1$ .

To analyze interfacial dynamics, we employ property ratios of the droplet relative to the surrounding medium, including electrical conductivity (R), permittivity (S), and zero-shear viscosity ( $\lambda$ ). The governing equations are nondimensionalized using characteristic scales for length, velocity, time, pressure, electric potential, surface charge density, and stress, facilitating mathematical tractability and physical insight [1, 2].

All the mathematical equations related to the present study have been compiled in the Supplementary Information (SI).

#### III. METHODOLOGY

# A. Electrical Phenomena: Governing Equations with Associated Boundary and Interfacial Conditions

The governing equations for EHD stem from Gauss' and Ampere's laws, linking electric fields, charge distribution, and current density. Poisson's equation relates the electric potential to charge distribution, while fluid motion obeys mass and momentum conservation. For NN VE fluids, the UCM model, coupled with the Navier-Stokes equation, facilitates analyzing droplet deformation under electric fields.

In leaky dielectric systems, the bulk fluid remains charge-free, decoupling electric and hydrodynamic equations, with interfacial momentum jumps addressing property mismatches. The electric field, assumed irrotational and divergence-free, satisfies Laplace's equation, subject to boundary and interfacial conditions ensuring charge conservation. Confinement effects, governed by droplet-tocontainer size, shape the electric potential, solved via separation of variables and Legendre functions.

The derived electric field expressions introduce a confinement correction factor, modifying field strength and distribution. Interfacial charge density, obtained through jump conditions, ensures charge conservation. The applied field induces normal and tangential stresses at the interface, governed by the Maxwell stress tensor, where stress discontinuities drive deformation, contingent on the electrical property mismatch between the droplet and surrounding fluid.

# B. Hydrodynamic Phenomena: Governing Equations with Associated Boundary and Interfacial Conditions

The motion of an incompressible fluid under an external electric field follows the Cauchy momentum equation, where the electrical body force arises from the Maxwell stress tensor's divergence. This force includes Coulomb interactions, polarization effects, and electrostriction, though

in leaky dielectric fluids, interfacial charge accumulation eliminates bulk Coulomb and polarization forces, leading to EHD effects. Assuming constant electrical properties, electrostriction is negligible.

In steady-state analysis, non-dimensionalization simplifies the governing equation, particularly under creeping flow, where viscous forces dominate. The equation applies to both droplet and surrounding fluid, subject to boundary and interfacial conditions ensuring velocity continuity, no normal penetration, and stress balance to prevent interfacial fracture. Droplet deformation, quantified by interfacial curvature and the deformation parameter, D, depends on the field-induced aspect ratio. For small deformations ( $|D| \ll 1$ ), this framework elucidates EHD-driven interfacial dynamics.

To incorporate rheological effects, the stress distribution follows the UCM model [5], where stress evolution depends on relaxation time, viscosity, and mobility. Under steady, symmetric conditions, the non-dimensionalized UCM model expresses stress in terms of the rate of deformation tensor and Weissenberg number (Wi). At low field strengths ( $Wi \leq 1$ ), elastic forces remain subordinate to viscous effects, allowing perturbative simplifications that decompose stress into N and NN contributions.

For N flows at low Reynolds numbers ( $Re \ll 1$ ), the momentum equation reduces to a balance of pressure gradient and viscous forces, yielding the biharmonic stream function. The interfacial conditions define the stream function in spherical coordinates, leading to expressions governing velocity fields and interfacial dynamics. Stress jumps across the interface, determined via the stream function, depend on viscosity ratios and boundary conditions, ensuring force equilibrium.

The governing equations reveal that hydrodynamic stress components inherently follow a  $sin\theta cos\theta$  dependency. A similarity solution analysis confirms that the non-Newtonian tangential stress must also be a function of  $sin\theta cos\theta$ . Enforcing interfacial conditions on the assumed stream function form imposes constraints, determining its final expression. By systematically comparing trigonometric coefficients, the governing exponent parameters are resolved, yielding explicit stress and pressure jump formulations in terms of Weissenberg numbers for both droplet and medium.

#### C. Solution for the droplet deformation parameter (D)

The interfacial condition on tangential stress jump expresses the total tangential hydrodynamic stress jump as a balance between N and NN contributions. To quantify this,  $\delta$  is introduced, representing the fraction of N stress in the total stress jump. The stress components are then defined accordingly, showing how N and NN stresses adjust while maintaining overall balance.

The N and NN parameters are derived in terms of  $\delta$ , with  $\delta = 0.0$  corresponding to purely NN stress and  $\delta =$ 1.0 to purely N stress. The Non-Newtonian Index (NNI) determines whether an electric field can induce flow in a NN droplet.

The interfacial condition on the normal stress jump leads to an expression for D, which accounts for both N and NN influences. The deformation parameter depends on capillary number, EHD effects, and stress contributions, with separate terms representing N and NN components.

#### IV. RESULTS

#### A. Validation of the Mathematical Model Against Existing Experimental Studies

Figure 2a and Figure 2b illustrate the steady-state deformation (D) of a droplet in an unconfined domain under varying capillary numbers  $(Ca_E)$ , for different dropletmedium combinations: EN, and NE, where E, and N denote purely elastic, and Newtonian fluids, respectively. The model's accuracy is validated against experimental data from Ha and Yang [4], which investigated the R > S system. According to Taylor [3], in such a system, a Newtonian droplet in a Newtonian medium deforms into a prolate spheroid along the electric field due to dipole alignment, leading to a positive D.



Figure 2: D as a function of electric capillary number  $(Ca_E)$  for an unconfined droplet under a uniform electric field: (a) Elastic droplet in a Newtonian medium (EN) with  $Wi_1 = 1.0, Wi_2 = 0.0$ , and (b) Newtonian droplet in an elastic medium (NE) with  $Wi_1 = 0.0, Wi_2 = 1.0$ . Fluid properties are taken from Ha and Yang.

For small deformations (D < 0.1), our mathematical model (black lines) closely aligns with experimental observations [31]. Figure 2a (EN case) examines a purely elastic droplet (PAM solution in NaCl) suspended in a Newtonian medium (silicone oil, viscosity 0.98 Pa·s) under a uniform electric field. Here, shear-thinning effects dictate viscosity variations. The model remains reliable up to  $(Ca_E \sim 0.18)$ , beyond which deviations arise due to the limitations of the small deformation approximation. Notably, viscoelastic droplets exhibit greater deformation than purely elastic ones under identical conditions, as inherent elasticity resists deformation, stabilizing the droplet.

At low Wi, viscous forces dominate, imparting fluidlike behavior, while at higher Wi, elasticity prevails, imparting solid-like characteristics, which stabilize the droplet and hinder deformation under weak electric fields. Our analysis restricts  $Wi \leq 1.0$  to maintain viscous dominance and ensure effective deformation under applied fields.

For non-Newtonian systems, droplet stability is governed by the normal stress coefficient ratio between the droplet and the medium. A higher ratio enhances droplet stability, whereas increased elasticity in the surrounding medium reduces this ratio, making the droplet more susceptible to deformation. Figure 2b (NE case) demonstrates that an elastic surrounding medium stabilizes a Newtonian droplet, further reinforcing the role of elasticity in modulating droplet deformation.

#### B. Variation of D with $\delta$ at different $\alpha$ for different combinations of droplet and surrounding medium (i.e. $Wi_1$ and $Wi_2$ )

The figure illustrates the variation of D with  $\delta$  for different rheological combinations of the droplet and the surrounding medium. The black, blue, and red curves represent cases where only the droplet, only the surrounding medium, and both phases, respectively, exhibit non-Newtonian behavior.



Figure 3: D as a function of  $\delta$  for different combinations of droplet and surrounding medium at (a)  $\alpha = 0.0$ , (b)  $\alpha = 0.3$ , (c)  $\alpha = 0.6$ , and (d)  $\alpha = 0.9$ .

Deformation increases with  $\delta$ , as a higher  $\delta$  implies an augmented Newtonian stress jump, thereby enhancing deformation. Non-Newtonian fluids, due to their inherent elasticity, stabilize the interface, reducing deformation. At  $\delta = 1.0$ , all cases converge, indicating a nullified non-Newtonian stress jump, similar to the Newtonian case at  $\delta = 0.0$ .

The highest deformation is observed when only the droplet is non-Newtonian, whereas the lowest occurs when only the surrounding medium exhibits non-Newtonian behavior. When both phases are non-Newtonian, deformation remains intermediate. Increasing  $\alpha$  (transitioning from an unconfined to a confined state) modifies this trend: for a non-Newtonian surrounding medium, deformation decreases, whereas for the other cases, it increases. With a further increase in  $\alpha$  from 0.3 to 0.6, deformation decreases in all cases. However, at  $\alpha = 0.6$ , deformation decreases with  $\delta$  when the droplet is non-Newtonian and the surrounding medium is Newtonian.

With a subsequent increase in  $\alpha$  from 0.6 to 0.9, defor-

mation increases only when the droplet is non-Newtonian and decreases for other cases. At  $\alpha = 0.9$ , confinement leads to shape reversal (from prolate to oblate) at low  $\delta$  when the surrounding medium is non-Newtonian, regardless of the droplet phase.

These trends arise from the interplay of electrical stress jumps (due to polarization and Coulombic forces), Newtonian normal hydrodynamic stress jumps (influenced by  $\alpha$ and thermo-physical properties), and non-Newtonian normal hydrodynamic stress jumps (affected by Wi and  $\delta$ ). Shape reversal occurs when the non-Newtonian stress jump dominates the combined effects of Newtonian and electrical stress jumps, which otherwise counteract each other, suppressing deformation without inducing shape reversal.

C. Comparative Analysis of Streamline Patterns: Newtonian vs. Non-Newtonian Droplets at Varying Confinement Ratios



Figure 4: Comparative analysis of streamlines for case where both the droplet and the surrounding medium are Newtonian at (a)  $\alpha = 0.2$ , (b)  $\alpha = 0.4$ , (c)  $\alpha = 0.8$  versus when both are non-Newtonian at (d)  $\alpha = 0.2$ , (e)  $\alpha = 0.4$ , (f)  $\alpha = 0.8$ .

This section examines the streamline patterns within the droplet and surrounding medium under varying confinement ratios ( $\alpha$ ) and fluid rheologies. Figure 4 illustrates these patterns for Newtonian (N-N) and non-Newtonian (NN-NN) cases at different  $\alpha$  values. The analysis adheres to small deformation ( $|D| \ll 1$ ) and low Weissenberg number ( $Wi \leq 1$ ) constraints, ensuring symmetry in streamline patterns, which results from the omission of higher-order Wi terms that could otherwise introduce asymmetry.

For Newtonian systems, streamlines form closed loops, with circulation in the droplet and medium occurring in opposite directions. In contrast, non-Newtonian effects alter these patterns, inducing symmetry about either a horizontal or vertical axis, leading to co-directional circulations in adjacent quadrants. Confinement ( $\alpha$ ) further influences the streamline topology: while Newtonian media maintain closed contours, non-Newtonian fluids exhibit a transition from closed to open contours as  $\alpha$  increases, signaling a shift in flow dynamics. This transition underscores the role of confinement in modifying stress distribution, which is more pronounced in the surrounding medium than

in the droplet. Notably, streamline contours within non-Newtonian droplets remain closed across all  $\alpha$  values, highlighting the interplay between confinement and fluid rheology in determining flow behavior.

#### V. CONCLUSION

The study analytically investigates the steady-state deformation and flow field of a confined non-Newtonian droplet in a surrounding non-Newtonian liquid pool under a weak DC electric field. Using the UCM model in the Cauchy momentum equation, it incorporates non-Newtonian effects to derive deformation and streamline expressions. Within the small deformation regime  $(Wi \leq 1)$ and Stokes flow, confinement is addressed via  $\delta$ . The interfacial stress jump, decomposed into Newtonian and non-Newtonian components, governs deformation through  $\alpha$ ,  $\delta$ , and thermophysical properties. Validation against experimental data confirms accuracy in an unconfined domain. A formulated non-Newtonian index  $(\eta_N)$  predicts flow feasibility based on system properties and confinement, revealing distinct streamline patterns-four contours in Newtonian cases versus two in non-Newtonian cases. Shape reversal in N-NN and NN-NN configurations and enhanced deformation in NN-N systems under strong confinement are also observed. These findings advance understanding of electrohydrodynamics (EHD) in confined non-Newtonian droplets, with implications for microfluidic applications in biological and industrial systems.

#### ACKNOWLEDGMENTS

The authors sincerely appreciate the research support and the technical assistance from IIT Ropar.

#### REFERENCES

- [1] P. Gupta, P. Dhar, and D. Samanta, Deformation transients of confined droplets within interacting electric and magnetic field environment, *Physics of Fluids*, vol. 35, 2023.
- [2] P. Gupta, P. Dhar, and D. Samanta, Electromagnetohydrodynamics (emhd) of a confined liquid droplet suspended in another liquid pool, *International Communications in Heat and Mass Transfer*, 2024.
- [3] Geoffrey Taylor. Studies in electrohydrodynamics. I. The circulation produced in a drop by an electric field, *Proc. R. Soc.London Ser. A. Math. Phys. Sci.*, 1966.
- [4] Jong Wook Ha and Seung Man Yang. Deformation and breakup of Newtonian and non- Newtonian conducting drops in an electric field, *Journal of Fluid Mechanics*, 2000.
- [5] B. I.M. ten Bosch. On a variational principle for the Upper Convected Maxwell model, *Journal of Non-Newtonian Fluid Mechanics*, 2022.

### Numerical modeling of a nanosecond DBD discharge in an icing environment

M. Bibal<sup>1\*</sup>, G. Dufour<sup>1</sup>, G. Hagelaar<sup>2</sup>, K. Kourtzanidis<sup>3</sup>, L. Reboul<sup>4</sup>

<sup>1</sup>The French Aerospace Lab (ONERA), 2 av. Edouard Belin, 31055 Toulouse Cedex 4

<sup>2</sup>LAPLACE, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France

<sup>2</sup>Chemical Process Energy Resources Institute (CPERI), Centre for Research Technology Hellas (CERTH), 6th km

Charilaou-Thermi, Thermi, 57001 Thessaloniki, Greece

<sup>4</sup>The French Aerospace Lab (ONERA), 6 Chem. de la Vauve aux Granges, 91120 Palaiseau

\*Corresponding author: marie.bibal@onera.fr

*Abstract-* Ice accretion on aircraft surfaces is a critical issue when flying in cold weather conditions, posing significant safety risks. One of the emerging deicing technologies proposed to address this challenge involves the use of surface dielectric barrier discharge (DBD) plasma actuators. A DBD system consists of two electrodes separated by a dielectric layer: one electrode is exposed to the surrounding air, while the other is embedded within the dielectric material. In this work, we explore through numerical modeling the possibility of using the thermal effects produced by these devices for deicing and anti-icing purposes. We investigate several key parameters, including the joule heating generated by the plasma discharge in the gas, the average position where energy is deposited, and the average duration of energy transfer. Under dry air conditions, we perform numerous simulations using various chemical kinetic models to quantify the errors associated with the reduced model. This study highlights the significant role that photoionization plays in streamer dynamics, demonstrating that its integration into the chemical model is essential. Additionally, the influence of boundary conditions on the simulation domain is examined. The results indicate that a reduced domain can be utilized to decrease the simulation time without affecting plasma discharge and energy deposition. A humid air chemistry model is developed based on the water vapor description found in the literature. The influence of varying percentages of water vapor in the air on the heat deposited by the DBD was then investigate. We also conduct simulations with ice/water, modeled as a dielectric material. We observe that the streamer can propagate along the surface of the ice/water and deposit energy at this interface.

Keywords- gas discharge physics, low-temperature plasmas, streamer, icing, DBD nanosecond.

#### I. INTRODUCTION

The accumulation of ice in flight conditions reduces aerodynamic performance by increasing drag and reducing lift. It can even lead to aircraft stall. Aircraft manufacturers are therefore required to demonstrate the airworthiness of their aircraft within the framework of increasingly stringent certification regulations. The use of dielectric barrier discharges for anti-icing or de-icing is an innovative and recent idea [1], stemming from research on plasma actuators studied for flow control in aeronautics. It seems to be a promising solution for preventing the formation and accumulation of ice. Two types of DBD plasma actuators exist: (1) alternating current driven (AC-DBD) and (2) high voltage repetitive nanosecond pulse driven (ns-DBD). Despite having a similar setup, AC-DBD and ns-DBD function in distinct ways. AC-DBD creates an airflow along the surface, while ns-DBD generates a sudden thermal effect that triggers a localized compression wave. Initial research has primarily investigated AC-DBD plasma actuation [2, 3]. More recently, preliminary studies [5, 4] have explored the potential of ns-DBD plasma actuators for aircraft icing mitigation by leveraging their ultra-fast heating mechanisms.

In this paper, we investigate the use of nanosecond dielectric barrier discharge plasma actuators for deicing and anti-icing applications through numerical modeling. The first section describes the physical model used to

simulate plasma discharge. Then, we present the general configuration of the system employed in the simulations. Next, we analyze the influence of photoionization on discharge dynamics and energy deposition. In the section that follows, we extend the study to humid air simulations to assess the impact of water vapor on plasma behavior. We then present simulations incorporating ice, detailing the ice modeling approach and analyzing the interaction between the plasma discharge and the ice surface. Finally, we examine energy dissipation mechanisms, focusing on the fraction of Joule heating that effectively contributes to gas heating.

#### A. Plasma Model

This section describes in detail the physical and numerical basis of the model in the plasma solver "Plasmasim" [10, 11], developed at Laplace.

The modeling of dielectric barrier discharges is based on solving a system of fluid equations, including continuity and drift-diffusion equations, for each plasma species (electrons, ions, and excited neutrals). These equations are coupled with Poisson's equation to account for the deformation of the applied electric field due to plasma charges. The number of species considered separately depends on the gas type and the desired level of detail. Since the neutral gas remains weakly ionized and evolves on a much slower timescale than the plasma, it is treated as a fixed background in plasma simulations. For each species j, the particle density is solved from the continuity equation and the species number flux  $\Gamma_j$  is given by the momentum balance which is approximated by the drift diffusion equation:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (\Gamma_j) = S_j \quad \text{with} \quad \Gamma_j = sign(q_j) n_j \mu_j E - D_j \nabla n_j$$
(1)

where  $n_j$  is the density number of species j,  $q_j$  is the species charge,  $\mu_j$  and  $D_j$  are the species mobility and diffusion coefficient respectively,  $S_j$  is the net rate of production of species j due to chemical reactions, given by  $S_j = \sum_k N_{j,k} R_k$ . Here,  $N_{j,k}$  is the net number of particles of species j created or lost in one reaction event of type k and  $R_k$  is the reaction rate. The reaction rate is proportinal to the densities of the reacting particles.

The electric field is derived from the electric potential, obtained via the Poisson equation:

$$\nabla \cdot (\varepsilon E) = \rho = \sum_{j} q_{j} n_{j} \quad ; \quad E = -\nabla \phi$$

where  $\varepsilon$  is the dielectric permittivity,  $\rho$  is the volumic charge induced by the charged species and  $\phi$ , is the electrical potential. It is assumed that the boundary conditions allowing the Poisson equation to be solved are either of Dirichlet type (anode and cathode) or of Neumann type (exterior boundaries).

Finally, since we use the local energy approximation (LEA) model, we introduce an additional equation for the average electron energy:

$$\frac{\partial n_e \bar{\varepsilon}_e}{\partial t} + \nabla \cdot \left(\frac{5}{3} n_e w_e \bar{\varepsilon}_e - \frac{5}{3} n_e D_e \nabla \bar{\varepsilon}_e\right) = -q n_e w_e \cdot E + C$$
(2)

where the term C groups together the effects of collisions

#### II. NUMERICAL SETUP

In this study, the numerical simulations are performed within a computational domain of 30 mm  $\times$  3 mm. A uniform square mesh is applied in the *x*-direction, while a nonuniform mesh is used in the *y*-direction, with local refinement just above the dielectric surface. A standard nanosecond dielectric barrier discharge configuration is considered. The electrode system used in the simulation is schematically shown in Figure 1.



Figure 1: (a) Configuration of a nanosecond dbd, (b) voltage versus time at the anode

The exposed electrodes have a length of 2 mm and a thickness of 50  $\mu$ m and the encapsulated electrode is im-

posed as a boundary condition, meaning it has no thickness and a length of 28 mm. The dielectric layer, which separates the electrodes, has a thickness of 0.3 mm. The voltage applied to the anode follows a voltage ramp, as shown in Figure 1(b).

#### III. RESULTS

## A. Effect of chemical kinetic models on NS-DBD plasma discharge

The numerical simulations of nanosecond dielectric barrier discharge plasma depend on the choice of chemical kinetic models. To evaluate their influence on the discharge, four chemical kinetic models are considered: the chemistry developed by Zhu [7], which includes 13 species and 38 reactions; the chemistry proposed by Pancheshnyi [6] with 10 species and 15 reactions ; a reduced model proposed by J. Leboeuf [8] with only 4 species and 4 reactions; and finally, a reduced model that incorporates photoionization.

In order to assess the effects of these different chemical kinetic models, several key parameters were evaluated using the solver. These parameters provide insight into how the energy is deposited within the plasma and how the discharge evolves over time. The following parameters were analyzed:

1. The deposited energy integrated over y along the dielectric:

$$U = \int_{y} \left( \int_{0}^{\tau} P(t) dt \right) dy \tag{3}$$

2. Mean time and position of energy deposition:

$$\bar{t} = \frac{\int_y \left(\int_0^\tau P(t)t\,dt\right)\,dy}{\int_y \left(\int_0^\tau P(t)dt\right)\,dy}; \quad \bar{y} = \frac{\int_y \left(y_j \int_0^\tau P(t)dt\right)\,dy}{\int_y \left(\int_0^\tau P(t)dt\right)\,dy} \tag{4}$$

 Standard deviation of position and time of energy deposition

$$\sigma_t = \sqrt{\bar{t^2} - (\bar{t})^2}; \sigma_y = \sqrt{\bar{y^2} - (\bar{y})^2}$$
(5)



Figure 2: Spatial distribution of energy deposited along the dielectric for the different chemical kinetic models (legend: "4R" [8] refers to the 4R chemical kinetic model, while "4R photo" represents the same model with added photoionization. "Zhu" [7] and "Pancheshnyi" [6] correspond to the chemical kinetic models proposed by Zhu and Pancheshnyi, respectively.)

Figures 2 and 3 respectively illustrate the temporal evolution of the discharge current and the spatial distribution of deposited energy along the dielectric for the different chemical kinetic models. It can be observed that the 4R model, which is the only one that does not account for photoionization, exhibits a significantly different current profile compared to the others. Notably, it presents a peak around 175 J/m<sup>3</sup>, which is more than twice the amplitude of the peaks observed in the other models. This higher current peak directly influences the deposited energy.



Figure 3: Comparison of the time current according to different chemical kinetics

Moreover, without photoionization, the streamer remains very narrow, extending only about 10  $\mu$ m, whereas with photoionization, its thickness increases to the order of 1 mm. This significantly impacts the energy deposition height. Without photoionization, energy is deposited much closer to the dielectric within a narrow region (5  $\mu$ m), while in other cases, deposition occurs over several tens of micrometers (30-60  $\mu$ m).

#### B. Effect of Water Vapor Fraction on Plasma Discharge



Figure 4: Comparison of the time current according to different molar fractions of  $H_2O$ 

For this study, a chemical kinetic model incorporating water vapor was developed, building upon Zhu's model [9]. To investigate the influence of water vapor content on discharge dynamics, a series of simulations have been conducted with varying water vapor fractions. this includes extreme (unrealistic) cases such as one with 10% water vapor, which corresponds to a relative humidity of 433%, in

order to visualize its impact on the discharge. The results show that the water vapor fraction has a negligible impact on both the discharge dynamics and energy deposition. Notably, the influence becomes discernible only for unrealistically high water vapor levels. To illustrate this, Figure 4 presents the discharge current as a function of time for the different simulations, demonstrating that the water vapor fraction has minimal effect. for the sake of concisness, the complete set of results is omitted here. Overall, these findings indicate that including water vapor in the chemical kinetics is not crucial for accurately modeling the streamer discharge and estimating energy deposition, its magnitude, and the time at which energy is deposited

#### C. Numerical simulation in the presence of ice

In this section, numerical simulations are conducted to investigate the impact of ice on plasma discharge behavior. To account for the presence of ice, a dielectric layer representing ice is introduced into the simulation domain Since the response time of ice is approximately  $2 \times 10^{-5}$  s, while the simulation timescale is only 30 ns, the ice does not have sufficient time to polarize in response to the variations of the electric field. Due to this significant timescale difference, it can be effectively modeled using a constant permittivity of  $\varepsilon_i = 3$ .







Figure 6: a) Potential field and b) Electron density field at time t=10 ns.

The initial setup remains unchanged, with the addition of an thin laye of ice, as illustrated in Figure 5. A layer of ice, with a thickness of 10  $\mu m$ , is added and partially

covers the electrode and the dielectric. Between the dielectric and the ice, there is a thin layer of air. Figure 6 shows the potential and the electronic density of the discharge. In the presence of ice, the discharge initially develops within the air gap between the dielectric and the ice. The electric field ionizes the air in this gap, creating a streamer. However, the discharge does not immediately propagate above the ice. Once the gap is fully ionized and the discharge has developed, the electric field becomes strong enough to bridge the gap and extend over the ice surface. At this point, the discharge moves above the ice, ionizing the air above it.

#### D. Analysis of dissipated energy

In this study, the goal is to evaluate the fraction of energy dissipated by plasma discharges that actually contributes to heating the gas. During the discharge, electrical energy is transferred to the plasma through the acceleration of the charged particles. The energy that is thus consumed by the particle species p is

$$W_p = \int_{time} \iiint_{vol} q_p \Gamma_p \cdot E d^3 V dt \tag{6}$$

where q is the particle charge,  $\Gamma$  is the particle flux, and E is the electric field

It was found that 98.23% of the energy is absorbed by the electrons, while 1.77% is absorbed by the ions. The energy absorbed by the ions contributes directly to the heating of the gas. Subsequently, we studied the electron-molecule collision reactions involving  $N_2$  and  $O_2$  molecules. The energy that is used for a reaction r is:

$$W_r = \iiint_{vol} \bar{\varepsilon} R_r d^3 V dt \tag{7}$$

where  $\bar{\varepsilon}$  is the threshold energy,  $R_r$  is the reaction rate.

High-energy electrons can excite these molecules through inelastic collisions, resulting in energy transfers that, under certain conditions, contribute to the heating of the gas. Electron collisions can lead to the excitation of electronic levels, as well as vibrational and rotational states of the molecules. These excitations can then be converted into heat through relaxation processes, including vibrational and rotational relaxation, where the energy from the excited states is converted to translational motion of the gas molecules, increasing the temperature of the gas.

Through calculations, it has been determined that the minimum amount of energy transferred to the gas corresponds to approximately 60% of the total Joule heating effect. This indicates that, from the total energy dissipated by the Joule effect in the discharge, around 60% is effectively utilized for heating the gas, while the remainder may be involved in other processes such as ionization

#### IV. CONCLUSION

We have modeled a ns-DBD. Through an analysis of chemical kinetics, the importance of considering photoion-

ization in streamer discharges was highlighted. The analyzed parameters revealed that energy deposition is significant and occurs almost instantaneously, localized within just a few micrometers. Subsequently, we used Zhu's humid air chemical kinetics to simulate plasma discharges in an icing environment. We observe that a very high water vapor fraction was required to start seeing an effect on energy deposition. Ultimately, considering water vapor in plasma discharge simulations does not significantly alter the discharge dynamics. Finally, we investigated which part of the energy contributes to heating the gas. According to our estimates, at least 60% of the Joule effect contributes to gas heating. Based on these findings, it will be possible to integrate a source term into ONERA's de-icing code, IGLOO2D to evaluate the ice accreation.

#### ACKNOWLEDGMENTS

The authors would like to thank the French National Research Agency (ANR) for its financial support through the ASTRID program, project PLASMICE, under grant number ANR-22-ASTR-0004.

#### REFERENCES

- [1] Meng X, Cai J, Tian Y, Han X and Zhang D. *In 47th AIAA*, p.4019, 2016
- [2] Zhou W, Liu Y, Hu H, et al. AIAA J, 56 1097–104, 2018.
- [3] Cai J, Tian Y, Meng X, Han X, Zhang D and Hu H. *Exp. Fluids*. 58 102, 2018.
- [4] Kolbakir C, Liu Y, Hu H, Starikovskiy A and Miles R. *AIAA J*, 2018.
- [5] Liu Y, Kolbakir C, Hu H, Starikovskiy A and Miles R. *Plasma Sources Sci. Technol.*, 2018.
- [6] Pancheshnyi S, Nudnova M and Starikovskii. *Phys. Rev. E*,71 016407, 2005.
- [7] Zhu Y, Shcherbanev S, Baron B and Starikovskaia S. *Plasma Sources Sci. Technol.*,26 125004, 2017.
- [8] J.P. Boeuf, L. Pitchford. J. Appl. Phys., 97, 2005.
- [9] Zhu Y, Wu Y, Wei B, Xu H, Jia M, Song H and Li Y. J. *Appl. Phys.*,53 145205, 2020.
- [10] Hagelaar, GJM and Fubiani, Gwenael and Boeuf, Jean-Pierre. *Plasma Sources Sci. Technol.*,20 015001, 2011.
- [11] Gregório, J and Aubert, X and Hagelaar, GJM and Puech, V and Pitchford, Leanne C. *Plasma Sources Sci. Technol.*,23 015005, 2013.

### Decomposition of Acetic Acid Using Pulsed Plasma Generated in N2-O2 Gas Mixture

T. Miichi<sup>\*</sup>, M. Okamoto

Department of Electrical and Electronic Systems Engineering, Osaka Institute of Technology, Japan \*Corresponding author: tomoaki.miichi@oit.ac.jp

Abstract-This study examined the decomposition behavior of acetic acid using pulsed plasma generated in a nitrogen–oxygen ( $N_2$ – $O_2$ ) gas mixture. The liquid to be treated during the experiment was an aqueous solution of acetic acid, used as a model persistent organic compound. Pulsed plasma was generated by varying the  $N_2$ – $O_2$  mixing ratio. Plasma was produced on the surface of the acetic acid solution, and treatment was conducted for 30 min. The initial concentration of acetic acid was approximately 25 mg/L, corresponding to a total organic carbon (TOC) concentration of approximately 10 mg/L. The highest decomposition rate of acetic acid was observed at an  $N_2$ – $O_2$  ratio of 25:75. At this ratio, the TOC decomposition rate was 45%. These results suggest that the gas mixture ratio influences the formation of hydroxyl radicals. Investigations into the reaction mechanisms at the gas–liquid interface are underway.

Keywords-pulsed plasma, N<sub>2</sub>-O<sub>2</sub> gas mixture, OH radicals, water treatment.

#### I. INTRODUCTION

In recent years, water treatment using discharged plasma has garnered increasing research attention [1, 2]. One key advantage of this plasma-based water treatment is the production of hydroxyl (OH) radicals—reactive species with short lifespans—within the water medium or near its surface during the plasma process. Although OH radicals are powerful oxidizing agents, their short lifespans typically limit their effectiveness in water treatment applications. However, in plasma systems, the proximity of OH radicals to the water medium enables their effective utilization for treatment.

We used pulsed plasma generated in a nitrogen– oxygen (N<sub>2</sub>–O<sub>2</sub>) gas mixture to decompose acetic acid in solution. Acetic acid was selected as a model compound representing persistent organics. The distance between each needle electrode tip and the water surface was set to 5 mm, and plasma was generated from all electrodes toward the water surface. In the plasma generation region, both short-lived (e.g., OH, NO<sub>2</sub>, and NO) and long-lived (e.g., O<sub>3</sub>, H<sub>2</sub>O<sub>2</sub>, NO<sub>3</sub><sup>-</sup>, and NO<sub>2</sub><sup>-</sup>) chemical species were produced. Lukes et al. used phenol and *E. coli* to investigate the associated aqueous-phase chemistry and clarify the role of air discharge plasma in producing chemical and biocidal effects on these organisms in water [3].

In this study, we investigated the reaction mechanisms of chemical species generated during plasma-based water treatment. To this end, pulsed plasma was produced by varying the  $N_2$ - $O_2$  gas ratio. Subsequently, acetic acid decomposition and the measurement of long-lived species concentrations were conducted.

#### II. EXPERIMENTAL APPARATUS AND METHOD

Fig. 1 presents a schematic of the reactor used in our experiment. This discharge reactor was equipped with a high-voltage electrode at the top and a ground electrode at the bottom. Stainless-steel needles were used as high-voltage electrodes, while a stainless-steel plate served as the ground electrode. Each needle electrode had an outer

diameter of 1 mm, and a total of 91 electrodes were installed. When 20 mL of water was added, the distance between the water surface and the needle electrode tips was 4 mm.

Fig. 2 presents a schematic of the electrical circuit. When a high-voltage DC was applied to the reactor and gap switch, electrical breakdown first occurred at the gap switch. This was followed by the application of a steep voltage pulse to the reactor, which generated plasma. The repetition frequency of the discharge was approximately 1.2 kHz. The liquid to be treated during the experiment was an aqueous solution of acetic acid, used as a model persistent organic compound. This solution was prepared by dissolving acetic acid in ion-exchanged water to a final concentration of 25 mg/L. The corresponding total organic carbon (TOC) concentration was approximately 10 mg/L. During processing, an N<sub>2</sub>–O<sub>2</sub> gas mixture was supplied to the reactor at a flow rate of 100 mL/min. The N2-O2 mixture ratios used were 10:90, 25:75, 50:50, and 75:25. The voltages applied to the reactor and gap switch were measured using a voltage probe (EP-100K, Pulse Electronic Engineering). The discharge current was calculated based on the voltage across a 1  $k\Omega$  resistor. The TOC concentration of the aqueous acetic acid solution during treatment was measured using a TOC analyzer (TOC-2300, HIRANUMA). Gaseous ozone concentrations were measured using a detector tube (182SA, Komyo Rikagaku Kogyo). The concentrations of H<sub>2</sub>O<sub>2</sub> and HNO<sub>2</sub> generated in the solution were measured using both a pack test (WAK-H<sub>2</sub>O<sub>2</sub> and WAK-NO<sub>2</sub>, Kyoritsu Riken Co., Ltd) and a digital pack test (DPM2-H<sub>2</sub>O<sub>2</sub> and DPM2-NO<sub>2</sub>, Kyoritsu Riken Co., Ltd).



Fig. 1. Schematic of the reactor. Fig. 2. Electrical circuit.

#### **III. RESULTS**

Fig. 3 presents the decomposition rate of acetic acid, based on changes in the TOC concentration. Across all cases, the discharge time was set to 30 min. As illustrated, the decomposition rate varied with the  $N_{2}$ - $O_{2}$  gas mixture ratio.



Fig. 4 and Fig. 5 illustrate the changes in  $H_2O_2$  and  $HNO_2$  concentrations in the solution over time. Notably, the rate of increase in their concentrations differed depending on the gas mixture ratio. Specifically, when the  $N_2:O_2$  ratio was 25:75—the condition under which acetic acid was most effectively decomposed—the concentrations of  $H_2O_2$  and  $HNO_2$  were lower than those observed under other gas mixture ratios.



Fig. 4 H<sub>2</sub>O<sub>2</sub> concentration as a function of time.



Fig. 5 HNO<sub>2</sub> concentration as a function of time.

Fig. 6 illustrates the change in gaseous ozone concentration in the reactor over time. As depicted, the ozone concentration was relatively high at  $N_2$ - $O_2$  mixture ratios of 25:75 and 50:50. Dissolved ozone was below the detection limit at all mixing ratios.



Fig. 6 Gaseous ozone concentration as a function of time.

Notably, the decomposition of acetic acid did not solely improve with increasing ozone concentrations. Instead, it was also likely influenced by OH radicals produced through reactions among various chemical species in the liquid phase. As reported by P. Lukes et al.,  $H_2O_2$  and  $HNO_2$  react to form peroxynitrite, which subsequently decomposes to generate OH radicals. A similar reaction may have occurred under the present conditions.

#### V. CONCLUSION

In this study, plasma generated in an  $N_2$ – $O_2$  gas mixture was used to decompose acetic acid in an aqueous solution. An analysis of the decomposition rate of acetic acid and the formation trends of chemical species such as  $H_2O_2$  revealed that the most pronounced decomposition occurred at an  $N_2$ – $O_2$  ratio of 25:75. Investigations into the decomposition mechanism of acetic acid are underway, and corresponding details will be shared during the presentation.

#### REFERENCES

- B. R. Locke, M. Sato, P. Sunka, M. R. Hoffmann, and J.-S. Chang, Electrohydraulic discharge and nonthermal plasma for water treatment, *Ind. Eng. Chem. Res.*, 45, 882–905, 2006.
- [2] P. Bruggeman and C. Leys, Non-thermal plasmas in and in contact with liquids, J. Phys. D: Appl. Phys., 42, 053001, 2009.
- [3] P. Lukes, E. Dolezalova, I. Sisrova, and M. Clupek, Aqueous-phase chemistry and bactericidal effects from an air discharge plasma in contact with water: evidence for the formation of peroxynitrite through a pseudo-second-order post-discharge reaction of H<sub>2</sub>O<sub>2</sub> and HNO<sub>2</sub>, *Plasma Sources Sci. Technol.*, 23, 015019, 2014.

### The impact of the polarization layer on electrohydrodynamic drying efficiency

Alex Martynenko<sup>1\*</sup>, Pejman Naderi<sup>1</sup>

<sup>1</sup>Department of Engineering, Dalhousie University, Nova Scotia, Canada \*Corresponding author: alex.martynenko@dal.ca

*Abstract-* This study investigates the influence of a wet dielectric layer on electric behavior in an Electrohydrodynamic (EHD) drying setup. Using a pins-to-plate electrode configuration, experiments compared setups with and without a wet tissue layer. The wet layer increased the system's capacitance, enhancing charge storage, while most of the voltage drop remained across the air gap. These findings offer insights into how material polarization affects electric field distribution and energy dynamics in EHD drying.

Keywords- electrohydrodynamic, polarization, discharge, capacitance, drying

#### I. INTRODUCTION

Electrohydrodynamic (EHD) drying is an emerging technique that enhances moisture removal from materials by applying a high-voltage electric field. Unlike conventional thermal drying, EHD relies on ion-induced air movement, which improves drying efficiency at lower temperatures, making it especially suitable for heatsensitive materials [1]. A critical factor influencing EHD performance is the dielectric environment between electrodes, as it affects electric field distribution and charge movement.

In practical applications, drying often involves moist materials with non-uniform compositions. These can create a polarization layer, a region within the material where dipole alignment under an electric field alters the system's dielectric properties [2]. Such layers may impact the electric force distribution, charge accumulation, and drying rate. However, the exact role of the polarization layer in EHD drying remains poorly understood.

#### II. METHODOLOGY

This study investigates the influence of polarization layer and electrode geometry on electrostatic interactions by comparing various discharge electrode configurations and introducing wet tissue layers. Through force measurements and capacitance analysis, the capacitance of each setup (air only, wet tissues, and different electrode types) is determined. This approach provides insights into how dielectric layering and emitter design affect the performance and optimization of EHD drying systems. The experimental setup includes a high-voltage DC power supply (Universal Voltronics, Atlanta, IL, USA), a discharge electrode system composed of either a flat plate or various pin arrays with different emitter densities (Table 1), and a stainless-steel ground electrode  $(23 \times 16 \text{ cm})$  positioned 4 cm away. The discharge electrodes are fixed and electrically insulated from the frame, while the ground electrode rests on a precision digital balance (Adam Equipment, HCB1002), supported by plastic rods and plexiglass to mitigate electric field interference (Fig. 1). The digital balance enables reliable and simple measurement of the electrostatic force between electrodes without disturbing the electric field [3].

The voltage was incrementally increased from 0 kV in 1 kV steps, up to a level just below ionization inception for pin electrodes, or before electrical arcing occurred for plate electrodes. At each step, the electric current and the change in mass were recorded. Each experiment was repeated three times, and the average of the mass readings was used for analysis. Two configurations were tested: (1) an air gap only, and (2) an air gap partially replaced by a layer of wet tissues.

When using wet tissues, water evaporation from the surface also contributes to the observed weight changes during the experiment. To account for this, the residual mass remaining on the digital balance after turning off the voltage was recorded. The evaporation-induced weight loss was separated from the electrostatic force measurements by adjusting the recorded values based on the final residual mass reading. Ambient relative humidity was 46.5%, and the moisture ratio for wet tissues was 4.8 g/g.

Electrode	Cell size, cm	Grid, rows	Number of pins	Emitters' density, pins/m <sup>2</sup>
#1	1×1	11×13	143	7536
#2	2×2	6×7	42	2213
#3	3×3	4×6	24	1265
#4	6×6	2×3	6	316

Table 1. Characteristics of pin electrodes.



In both cases, the attractive force between the electrodes was interpreted as an electrostatic interaction and the electric charge Q on each electrode was calculated using the relation:

$$Q = \sqrt{2\varepsilon_0 AF} \tag{1}$$

where  $\varepsilon_0$  is the vacuum permittivity, *A* is the area of the electrode, and *F* is the electrostatic force calculated from the mass change.

The capacitance was determined by plotting Q versus applied voltage V, where the slope of the line yields the capacitance. For the second configuration, which includes both air and wet tissues as dielectric layers, the total capacitance was used alongside the known air-only capacitance to isolate the capacitance of the wet tissue layer. The voltage drop across each dielectric was

subsequently calculated using the capacitive voltage division rule. This approach enables a comparative assessment of dielectric behavior in the presence and absence of a moisture layer.

#### **III. RESULTS**

The capacitance and electrostatic force were compared between a plate-to-plate configuration and various pin-to-plate electrode configurations, all at a fixed 4.0 cm gap. The plate-to-plate setup exhibited the highest capacitance (11.97 pF) due to its continuous surface area, while the capacitance decreased progressively for pin arrays with larger cell sizes: 8.97 pF for the 1×1 cm array, 7.86 pF for  $2\times2$  cm, 6.93 pF for  $3\times3$  cm, and 4.69 pF for  $6\times6$  cm configurations. This decrease in capacitance is attributed to the reduced effective emitter area and increased field localization around the pins.

The effect of pin density on the electric field distribution and electrostatic attraction is illustrated by the simulated equipotential lines. In the case of  $2\times2$  cm pin spacing, the electric field is stronger and more uniformly distributed across the electrode surface, leading to a larger cumulative attraction force on the counter electrode. In contrast, for the  $4\times4$  cm spacing, the electric field is more isolated around each pin, resulting in a weaker overall electrostatic force (Fig. 3).

The effect of introducing wet tissue layers between the discharge and counter electrodes is shown in Fig 4. As the thickness of the wet tissue increases from 3 mm to 9 mm, the attractive force (reflected as mass change) becomes more negative at each voltage step, indicating a stronger electrostatic attraction. Correspondingly, the calculated charge also increases with the presence of wet tissues, as seen in the charge–voltage plot. The slope of



Fig. 2. Mass change and accumulated charge as a function of applied voltage for plate-to-plate and various pin-to-plate electrode configurations. Capacitance and attractive force decrease with lower pin density.



Fig. 3. Simulated equipotential lines for pin arrays with  $2\times 2$  cm (left) and  $4\times 4$  cm (right) spacing, showing stronger and more distributed electric fields with higher pin density.

the fitted lines reveals that the system capacitance slightly increases with greater tissue thickness, from 11.9 pF (no tissues) to 12.6 pF (3 mm tissues) and 12.9 pF (9 mm tissues), demonstrating the contribution of the wet material to the overall dielectric properties of the gap.

Unlike the previous cases where only electrostatic forces were present, Figures 5(a) and 5(b) show results under conditions where ionization also occurs. In Figure 5(a), as the applied voltage increases, the attractive force between the electrodes strengthens until ionization begins. This transition is marked by a rapid rise in current and a noticeable shift in mass measurements. At this point, the onset of ionic wind generates a downward force on the digital scale, resulting in a positive weight change. In both scenarios, the start of ionization coincides with a sharp increase in current, which becomes audible as a pulsing



Fig. 4. Mass change and accumulated charge as a function of voltage for no tissue, 3 mm wet tissue, and 9 mm wet tissue cases, showing increased attraction force and capacitance with thicker wet layers.

discharge near 14 kV. By 16 kV, the sound becomes continuous and much louder, indicating sustained ionization.

Figure 5(b) illustrates the mass change and current behavior after ionization starts. Although evaporation from the wet tissues is present even before ionization, the onset of ionic wind accelerates the evaporation rate. The resulting mass loss partially offsets the positive force exerted by the ionic wind, causing the weight change to remain negative throughout the experiment despite the downward airflow.

#### IV. DISCUSSION

From the slope of each line, the system capacitance was determined. For the air-only configuration, the capacitance was 11.97 pF. Introducing a 0.3 cm layer of wet tissue, which reduced the air gap to 3.7 cm, increased the overall capacitance to  $12.6 \, pF$ . Adjusting for the shortened air gap, the calculated capacitance of the air portion alone would be approximately  $12.9 \, pF$ . Based on the series capacitance model, the equivalent capacitance of the 3 mm wet tissue layer was estimated to be  $551 \, pF$ , indicating a strong dielectric contribution from the moist material. For thicker wet tissues (9 mm), the capacitance was calculated to be  $80 \, pF$ . The corresponding voltage drops across the wet tissues were 2.3% and 16.2% respectively, confirming that most of the applied voltage is still concentrated across the air gap.



Fig. 5. Mass and current measurements in case of (a) air gap only, and (b) air and wet tissues in the gap.

The observed increase in overall capacitance when introducing a wet tissue layer is consistent with basic electrostatic principles. The presence of a dielectric material with a higher permittivity than air increases the ability of the system to store charge at the same voltage. Although the tissue layer is thin compared to the air gap, its high moisture content enhances polarization, contributing disproportionately to the total capacitance. This layered configuration leads to a redistribution of the electric field, where most of the voltage still drops across the air, while the wet tissues hold more charge.

From a practical standpoint, this behavior has important implications for EHD drying. A higher system capacitance implies stronger surface polarization effects, which can influence moisture movement at the interface. However, the fact that the wet layer experiences minimal voltage drop means the electric stress within the material remains low, potentially preserving structural integrity while still enhancing drying through interfacial mechanisms.

Preliminary experiments with the drying of wet material, using different electrodes, are presented in Fig.6



Fig. 6. Drying flux, generated by discharge electrodes with  $1 \times 1$  cm and  $2 \times 2$  cm spacing.

It follows that different spacing between emitters results in different inception voltages. Inception voltage was smaller for a 2x2 discharge electrode, increasing to 7 kV for 1x1 pin electrode. This could be related to the different charges on the surface of the wet material. Pin density of 1x1 discharge electrode is closer to the plate-toplate system, which requires a larger electric field intensity to initiate discharge.

#### V. CONCLUSION

This study showed that even a thin wet layer can significantly alter the electrical behavior of an EHD system by increasing its capacitance and influencing field distribution. The fact that most of the voltage drops across the air gap while the wet material contributes heavily to capacitance highlights the strong polarization at the air– material interface. This interfacial polarization may play a role in moisture transport and drying enhancement. Understanding and controlling this effect could help design more efficient EHD drying systems by maximizing interfacial interactions while minimizing internal electric stress on the material.

#### REFERENCES

- A. Martynenko, T. Kudra. Electrically-induced transport phenomena in EHD drying – A review, *Journal of Trends in Food Science & Technology*, 54, 63–73, 2016.
- [2] K. Iranshahi, D. I. Onwude, A. Martynenko, T. Defraeye. Dehydration mechanisms in electrohydrodynamic drying of plant-based foods. *Journal of Food and Bioproducts processing*, 131, 202–2016, 2022.
- [3] P. Naderi, A. Martynenko. Measurement of Ionic Wind Speed Using Dynamic Pressure Analysis. *Available at SSRN 5113582*.

### Visualization of liquid-vapor interface oscillation in parallel plate electrodes by wavy dielectrophoresis

M. Nishikawara<sup>1\*</sup>, H. Maejima<sup>1</sup> <sup>1</sup>Department of Energy Engineering, Nagoya University, Japan \*Corresponding author: nishikawara@nagoya-u.jp

Abstract- In liquid-vapor (L-V) phase change phenomena, the velocity of the L-V interface motion is an important factor governing the phenomena. In this study, we experimentally investigated how much L-V interface velocity can be obtained by wave dielectrophoresis. Time-varying high voltages are applied to an insulating liquid between parallel plate electrodes to induce dielectrophoresis at the L-V interface, and the L-V interface behavior is visualized using a backlight method. The results showed that the appearance of the interface oscillation varied greatly depending on the frequency of the voltage: The interface oscillated up and down while maintaining a horizontal shape, and the interface oscillated with standing waves. The amplitude of the interface was found to be larger for the standing wave oscillation.

Keywords- Fast Oscillation, Resonance, Two-Phase Flow, Wavy Dielectrophoresis.

#### I. INTRODUCTION

Applying high voltage to an insulating refrigerant promotes flow and heat transfer due to Coulomb forces and dielectrophoretic (DEP) forces. O'Connor and Yagoobi enhanced heat transfer in liquid film flow boiling by pulsating DEP generated with a slit electrode [1].

When a high voltage is applied between vertical parallel plate electrodes immersed in an insulating refrigerant, the liquid level between the electrodes rises against gravity due to the DEP force [2]. In the case of DC, it is known that the height of the rise is proportional to the square of the applied electric field. However, the speed of movement of the liquid-vapor (L-V) interface when a time-varying electric field is applied is unknown. In phase change heat transfer, the L-V interface velocity is one of the most important parameters governing the phenomenon [3, 4]. Therefore, in this study, we investigate the use of dielectrophoresis to increase the L-V interface velocity. In this paper, we measured the behavior of the L-V interface oscillation driven by wavy DEP forces.

#### II. METHODOLOGY

The electrode is an indium tin oxide (ITO) thin film deposited on a glass substrate. The size is  $100 \text{ mm} \times 100 \text{ mm}$ . Two electrodes were placed in a plastic container in a vertical upright position and the electrode gap was kept uniform at 2 mm (Fig. 1). The experiment was conducted in a vacuum test chamber. The container was filled with a constant amount of refrigerant. The electric field is applied parallel to the L-V interface. The time-varying DEP force acts on the L-V interface in the direction opposite to gravity.

The interface oscillation was filmed by the backlight method using an LED light and a high-speed camera. The area of the recorded images was 19 mm  $\times$  51 mm. The recorded images were processed by binarization to obtain the position data of the interface at each time. The applied voltage and current were measured synchronously with



Fig. 1. Experimental setup for visualization of liquid-vapor interface oscillations in parallel plate electrodes.

the camera.

The applied voltage is an offset sine wave and the peak voltage is  $V_{pp} = 6$  kV. The frequency of the applied voltage, *f* was varied between 1 Hz and 100 Hz. The working fluid is HFE7100.

#### III. RESULTS AND DISCUSSION

At f = 1 Hz, the interface reached its maximum height in half a period (t = 4/8 T) while remaining horizontal and returned to its initial position in one period (t = 8/8 T), as shown in Fig. 2a. The initial position is equal to the height at no voltage load. The amplitude, which is the difference between the highest and lowest level was 12 mm (Fig. 3). With increasing frequency up to 5 Hz, the highest level and the amplitude of the interface oscillation were decreased. At f = 10 Hz, the interface behavior changed significantly. The interface shape appeared as a standing wave, as shown in Fig. 2b. This is called the DEP resonance mode in this study, while the interface oscillation at lower frequency is the horizontal oscillation mode. In the DEP resonance mode, the period of the interface oscillation was twice that of the voltage,



Fig. 2. Time sequence of liquid-vapor interface oscillations at 1 Hz and 15 Hz of voltage frequency. T is the period of the voltage.



Fig. 3. Maximum amplitudes, which are the difference between the highest and lowest levels, as a function of voltage frequency. The open and closed circles show the DEP resonance mode and the horizontal oscillation mode, respectively.

therefore, it is shown as 2*T* in Fig. 2b. After reaching its maximum height at t = 2/8 2*T*, the interface becomes nearly horizontal at t = 4/8 2*T*. Then, at t = 6/8 2*T*, the maximum height is reached at the location of the trough at t = 2/8 2*T*, and the interface becomes nearly horizontal again at t = 8/8 2*T*. The DEP resonance mode appeared at 10 Hz to 35 Hz, 50 Hz, 85 Hz to 100 Hz (Fig. 3). The amplitudes were decreased with increasing frequency. However, the amplitudes increased when the oscillation mode changed to the DEP resonance.

#### IV. CONCLUSION

The visualization reveals the behavior of the L-V interface oscillation driven by time-wave

dielectrophoretic forces generated by parallel-plate electrodes. Depending on the frequency of the applied voltage, the interface oscillation modes of the horizontal oscillation and the DEP resonance appeared. The amplitude increased in the DEP resonance mode.

#### ACKNOWLEDGMENT

This work was supported by the PI grant of Toyohashi university of technology, JSPS KAKENHI grant number JP25K01170 and CCI holdings Co., Ltd.

#### REFERENCES

- N. O'Connor, J. Yagoobi, The Effect of Pulsating Dielectrophoresis on Liquid Film Flow Boiling, in Proceedings of the 22nd IEEE International Conference on Dielectric Liquids, No. 203, 2023.
- [2] B. Blaineau, S. Dutour, T. Callegari, P. Lavieille, M. Miscevic, S. Blanco, B. Schlegel, Y. Bertin, A.M. Benselama, Experimental Investigation of a Dielectric Liquid-Vapor Interface between Two Vertical Planar Electrodes: Influence of the DC Electric Field and Temperature, *Experimental Thermal and Fluid Science*, 105:144–152, 2019.
- [3] M. S. El-Genk and H. Bostanci, Saturation Boiling of HFE-7100 from a Copper Surface, Simulating a Microelectronic Chip, *International Journal of Heat* and Mass Transfer, 46:1841–1854, 2003.
- [4] I. I. da Silva, B. A. de Andrade, L. L. Manetti, J. D. de Oliveira, and E. M. Cardoso, Saturation Boiling of HFE-7100 on Copper Surfaces: Bubble Departure Diameter and Bubble Frequency, in *Proceedings of* 18th Brazilian Congress of Thermal Sciences and Engineering, ENC-2020-0204, 2020.

### Numerical investigation on the effect of non-autonomous charge injection in EHD-assisted charging of a latent heat thermal storage system

Amirabbas Ghorbanpour Arani, Ethan Chariandy, James S. Cotton<sup>\*</sup> Department of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada \*Corresponding author: Cottonjs@mcmaster.ca

Abstract- The present study aims to investigate the effect of different charge injection functions on electrohydrodynamically driven flows, focusing on three specific injection models: autonomous, the Schottky, and the Heaviside step function of injections. Previous research predominantly relied on the autonomous charge injection, which oversimplifies the boundary condition and neglects the influence of the electric field, resulting in a space charge density distribution on the boundary and within the medium that does not accurately mimic the realistic charge injection phenomena. This study utilizes the lattice Boltzmann method (LBM) to simulate the behavior of paraffin wax, a phase change material (PCM), in a latent heat thermal storage system (LHTSS) under both autonomous and non-autonomous charge injection. Initially, the solid PCM begins melting due to thermal conduction from the hot top wall, after which electro-convection generated by charge injection enhances heat transfer rate. The solver was verified against two benchmarks, including analytical solutions of the electrical equations at the hydrostatic state and the Stefan problem. The current-voltage curve presented by Hassan and Cotton was used in this study. The electrode in the simulation is under 6 kV and charges are collected by two flat electrodes at the top and bottom of the computational domain. Liquid fraction over time, heat transfer coefficient, and velocity at the center were plotted for each charge injection function. The results for the Schottky and Heaviside step functions of injections are very close but differ from autonomous injection significantly despite identical current for all cases.

Keywords- Non-Autonomous Charge Injection, Lattice Boltzmann Method, Electro-Convection, Latent Heat Thermal Storage System

#### I. INTRODUCTION

New technologies are developed to deal with growing problems like pollution, energy shortages, and rising energy costs. Therefore, finding ways to store energy has become very important. One promising method is LHTSSs, in which they can absorb a large amount of energy compared to traditional methods. LHTSSs use PCMs, which can hold a lot of heat due to their high latent heat and specific heat capacity. However, they cannot conduct heat very well [1]. The inherently low thermal conductivity of PCMs poses a significant challenge, necessitating a method to induce convective flow and improve heat transfer rates. Among various techniques to improve the heat transfer rate of PCMs, electro hydrodynamics (EHD) has recently gained significant attention [2].

EHD refers to the interaction between a fluid flow and an electric field. One of the key outcomes of this interplay is charge injection, a process where electric charges are introduced into a dielectric material when the applied voltage between two electrodes passes the saturation voltage [3]. These charges are repelled from the emitter and create electro-convection, which is a form of forced convection. These electric charges create a body force, which is expressed as:

$$f_{EHD} = qE - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla(\rho E^2 \left(\frac{\partial\varepsilon}{\partial\rho}\right)_T)$$
(1)

In which q, E,  $\epsilon$ ,  $\rho$ , T denote space charge density, electric field, permittivity, and temperature, respectively.

To close the set of governing equations, a proper boundary condition is needed for the Nernst-Plank equation. One of the main problems in solving the Nernst-Plank equation numerically is uncertainty about the amount of space charge density at the emitter. Although experimental studies provide the total amount of current passed through the medium, the exact amount of space charge density all over the medium has not been presented by an experimental setup so far [2].

Many studies implemented autonomous charge injection [4], [5], [6] at the boundary. Since the charge injection depends on the local electric field, a few studies proposed alternatives to the autonomous charge injection. Gazarvan et al. [2] proposed a Heaviside step injection function consisting of a linear component and a quadratic component. The linear component describes the injection based on the electrochemical reaction between the electrode and the dielectric material, while the quadratic component relates to the high voltage potential. Felici and Gosse [7] followed the Schottky effect for charge injection. This effect assumes that there are ions before applying the electric field. In this approach, the electrode applies image force to the ions, which are only injected into the medium if their energy exceeds their work function. In numerous investigations, this injection rule has been employed as the pioneer non-autonomous space charge density at the electrode surface [8], [9].

Numerical modeling is the best choice for capturing the space charge density and flow behavior all over the storage cell in a case in which space charge density at the electrode surface varies with the electric field. LBM has recently become quite popular in order to better comprehend a wide range of phenomena, including heat and mass transfer applications, single-phase and twophase flows, single and multicomponent flows, and nonNewtonian flows. The LBM offers several significant benefits, such as integrated parallelization, support for complex geometry, and ease of usage [10], [11], [12], [13].

In this study, a unified LBM is utilized to compare the results of autonomous injection, the Schottky injection, and Heaviside step functions. Thus, in this study, we investigate how different injection functions with an identical current affect the charging of an LHTSS.

#### II. PHYSICAL PROBLEM

The computational domain is a rectangular enclosure with height 2H and width H. A circular electrode of radius R is placed at the center of the domain, injecting charges into the system. To increase melting speed, the top wall is kept at a hot temperature T<sub>h</sub>, while the bottom wall is maintained at a cold temperature T<sub>c</sub>. The circular electrode is under a high voltage  $\phi_1$ , while the top and bottom walls are grounded at zero voltage, as shown in Fig. 1. Initially, the storage cell is full of solid paraffin wax. Then, melting begins because of thermal conduction. When the liquid fraction in the system reaches 20%, charge injection starts to create convective flows. Key assumptions in this setup include: The solid PCM is non-Ohmic, meaning that charges are transported by drift, diffusion, and liquid convection mechanisms. The paraffin wax is a pure material, and its electrical conductivity remains unchanged during the phase change process. All thermophysical properties of the paraffin wax, such as permittivity and thermal conductivity, are constant, except for density, which varies with temperature.

#### III. METHODOLOGY

A unified lattice Boltzmann method presented by He et al. [14] is used in this study to solve the Navier-Stokes equation, continuity equation, energy equation, Nernst-Plank equation, Gauss's law, and the definition of electric field in a microscopic level. The governing equations in a macroscopic level are given as follows.



Fig. 1- Schematic of the physical problem.

$$\partial(\rho \, u)/\partial t \ + \, \nabla \cdot (\rho \, u \, u) = \, - \nabla p \ + \, \nabla \cdot \qquad (3)$$

$$(\mu \nabla u) + q E - g[1 - \beta(\theta - \theta_1)]$$

$$\nabla \cdot (\varepsilon \, \nabla \phi) = -q \tag{4}$$

$$E = -\nabla\phi \tag{5}$$

$$\frac{\partial q}{\partial t} + \nabla \cdot (K Eq + u q) = \nabla \cdot (D \nabla q)$$
<sup>(6)</sup>

$$\frac{\partial(\rho H)}{\partial t} + \nabla \cdot (\rho c_{\rm p} u \theta) = \nabla \cdot (k \nabla \theta) \tag{7}$$

In which u, t, g,  $\beta$ ,  $\mu$ , P,  $\phi$ , K, D, H, cp, k,  $\theta$  denote velocity, time, gravity, thermal expansion coefficient, pressure, electric potential, ionic mobility, diffusion coefficient, total enthalpy, specific heat capacity, thermal conductivity, and temperature, respectively.

#### III. RESULTS

#### A. Code Verification

The code was verified against two benchmark cases, including the Stefan problem and hydrostatic solution of electrical equations, as shown in Fig. 2 and Fig. 3. The LBM results are in good agreement with analytical solutions, demonstrating the reliability of the algorithm.

#### B. Quantitative analysis

The liquid fraction of the PCM, heat transfer coefficient, and velocity field are crucial metrics for understanding how different charge injection methods influence the system's phase transition dynamics. This section compares the melting performance under three conditions: Heaviside-step function of injection, Schottky injection, and autonomous injection.



Fig. 2- Liquid fraction over time for different Stefan numbers.



Fig. 3- Space charge density, electric field, and electric potential variation along the gap between two plates.
Pure conduction is the main mechanism of melting in the absence of electro-convection and thermo-convection. In this stage, heat transfer is limited to molecular diffusion from the top wall. The liquid fraction over time is shown in Fig. 4 for different cases. The slope of the curve, which shows melting speed, is high in the beginning because of low thermal resistance. Then it decreases gradually until it reaches a steady state. However, for charge injection cases, there is a huge jump at the liquid fraction of 0.2 because electrodes inject charges at that moment. However, as the liquid portion gets closer to the electrode wall, the initial quick melting speed slows down. The curves' slope lowers as the wall attempts to stabilize the fluid. The curves' slope rises once more as the solid-liquid interface passes the electrode. This phenomenon happens for all charge injection cases. Fig. 4 shows that autonomous injection's liquid fraction has a high deviation from non-autonomous injection's liquid fraction when the electric field changes on the electrode surface.

The heat transfer coefficient on the top wall for different injection functions is plotted in Fig. 5. The maximum amount of the heat transfer coefficient happens opposite to the electrode, and the minimum amount happens between electrodes, which is consistent with what was reported by Nakhla et al. [15]. The heat transfer coefficients associated with Schottky and Heaviside injections are very close to each other. However, the autonomous injection creates a very low peak with a deviation of 16% compared to the Heaviside injection, demonstrating that the autonomous injection creates heat transfer coefficients that are far from the real situation.



Fig. 4- Liquid fraction over time for different conditions.



Fig. 5- Heat transfer coefficient on the top wall for different charge injection functions.



Fig. 6- Velocity profile in the y direction in the center of LHTSS.

The vertical velocity component at the center of the computational domain is analyzed to highlight the dynamic changes induced by different injection functions. As shown in Fig. 6, V-velocity is divided into three parts. V-velocity is fully developed at the upper part of the storage cell, where the maximum deviation of the autonomous injection's velocity is 42%. However, Heaviside and Schottky injections give a very similar trend. At the middle level of the storage system, where the electrode is located, the V-velocity is zero for all cases. At the lower level of the storage cell, the velocity is fully developed while the peak velocity is lower than the upper level of the storage cell because there is a small amount of the solid PCM left nearby the cold boundary. There is still a huge deviation between autonomous and nonautonomous charge injection functions at the lower level of the storage system.

#### IV. CONCLUSION

This study aims to compare the effect of autonomous and non-autonomous charge injection functions at the electrode within an LHTSS. To this end, a unified LBM was employed to simulate the melting of paraffin wax under the effects of Coulomb force. The accuracy of the LBM code was validated by comparing it to the analytical solution of the Stefan problem and electrical equation at the hydrostatic state. The total current used in this study is obtained from the experimental current-voltage curve presented by Hassan and Cotton [16]. Also, the proposed Heaviside step function of injection by Hassan and Cotton was used in this study. Paraffin wax was melted via conduction until a liquid fraction of 0.2 was achieved, at which point charge injection using three different functions was initiated by applying a 6 kV voltage difference between the emitter and collectors. These charges created electro-convective rolls, which redistributed the temperature within the LHTSS to augment the heat transfer rate. The results in this study show that autonomous charge injection creates a huge error compared to the real situation. Also, it was shown that instead of defining a non-autonomous charge

injection function for each geometry and physical configuration, Schottky injection can be used, which gives results similar to Heaviside's results. Expanding upon these findings, future research could focus on modeling the large mushy zone, ambipolar charge injection, and solid extraction phenomena to further enhance numerical modeling of this problem.

#### ACKNOWLEDGMENT

The first author would like to thank Dr. Michael Thompson, associate dean of graduate studies at McMaster University. Also, the authors would like to thank the Digital Research Alliance of Canada for providing the resources, which played a pivotal role in conducting the simulations and numerical investigations reported in this study.

#### REFERENCES

- [1] F. Agyenim, N. Hewitt, P. Eames, and M. Smyth, "A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)," *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 615–628, Feb. 2010, doi: 10.1016/j.rser.2009.10.015.
- [2] A. Gazaryan, A. Sitnikov, V. Chirkov, and Y. Stishkov, "A Method for Estimation of Functional Dependence of Injection Charge Formation on Electric Field Strength," *IEEE Trans. Ind. Appl.*, vol. 53, no. 4, pp. 3977–3981, Jul. 2017, doi: 10.1109/TIA.2017.2680398.
- [3] A. V. Gazaryan, S. A. Vasilkov, and V. A. Chirkov, "Simple in fabrication and high-performance electrohydrodynamic pump," *Phys. Fluids*, vol. 34, no. 12, p. 123604, Dec. 2022, doi: 10.1063/5.0124657.
- [4] K. Luo, J. Wu, H.-L. Yi, and H.-P. Tan, "Numerical investigation of heat transfer enhancement in electro-thermo-convection in a square enclosure with an inner circular cylinder," *Int. J. Heat Mass Transf.*, vol. 113, pp. 1070–1085, Oct. 2017, doi: 10.1016/j.ijheatmasstransfer.2017.06.003.
- [5] K. Luo, A. T. Pérez, J. Wu, H.-L. Yi, and H.-P. Tan, "Efficient lattice Boltzmann method for electrohydrodynamic solid-liquid phase change," *Phys. Rev. E*, vol. 100, no. 1, p. 013306, Jul. 2019, doi: 10.1103/PhysRevE.100.013306.
- [6] T.-F. (李天富) Li, K. (罗康) Luo, and H.-L. (易红亮) Yi, "Suppression of Rayleigh-Bénard secondary instability in dielectric fluids by unipolar charge injection," *Phys. Fluids*, vol. 31, no. 6, p. 064106, Jun. 2019, doi: 10.1063/1.5100124.
- [7] N. Felici and J. P. Gosse, "Injection d'ions par des électrodes métalliques dans les hydrocarbures liquides de résistivité élevée," *Rev. Phys. Appliquée*, vol. 14, no. 5, pp. 629–633, May 1979, doi: 10.1051/rphysap:01979001405062900.
- [8] K. Luo, T. Li, J. Wu, H.-L. Yi, and H.-P. Tan, "Electro-thermoconvective flow of a dielectric liquid due to nonautonomous injection of charge by an elliptical electrode," *Int. J. Heat Mass Transf.*, vol. 127, pp. 373–384, Dec. 2018, doi: 10.1016/j.ijheatmasstransfer.2018.07.015.
- [9] F. Pontiga, A. Castellanos, and B. Malraison, "Some considerations on the instabilities of nonpolar liquids subjected to charge injection," *Phys. Fluids*, vol. 7, no. 6, pp. 1348–1356, Jun. 1995, doi: 10.1063/1.868522.
- [10] A. Ghorbanpour Arani, R. Haghani-Hassan-Abadi, M. Majidi, and M. H. Rahimian, "Drag Coefficient of a Rising Bubble in a Shear-Thinning Fluid Using the Power-Law Scheme Coupled with a Cahn-Hilliard Equation with a Variable Mobility: A Lattice Boltzmann Study and Comparison with Experiment," Sep. 26, 2022, Social Science Research Network, Rochester, NY: 4229588. doi: 10.2139/ssrn.4229588.
- [11] A. Ghorbanpour-Arani, M.-H. Rahimian, and R. Haghani-Hassan-Abadi, "Numerical simulation of dissolved air flotation using a

lattice Boltzmann method," *Phys. Rev. E*, vol. 101, no. 2, p. 023105, Feb. 2020, doi: 10.1103/PhysRevE.101.023105.

- [12] M. Majidi, M. A. Bijarchi, A. G. Arani, M. H. Rahimian, and M. B. Shafii, "Magnetic field-induced control of a compound ferrofluid droplet deformation and breakup in shear flow using a hybrid lattice Boltzmann-finite difference method," *Int. J. Multiph. Flow*, vol. 146, p. 103846, Jan. 2022, doi: 10.1016/j.ijmultiphaseflow.2021.103846.
- [13] T. R. Mitchell, M. Majidi, M. H. Rahimian, and C. R. Leonardi, "Computational modeling of three-dimensional thermocapillary flow of recalcitrant bubbles using a coupled lattice Boltzmannfinite difference method," *Phys. Fluids*, vol. 33, no. 3, p. 032108, Mar. 2021, doi: 10.1063/5.0038171.
- [14] K. He, Y. Zhao, and L. Wang, "Numerical investigation on electrohydrodynamic enhancement of solid–liquid phase change in three-dimensional cavities," *Int. J. Multiph. Flow*, vol. 168, p. 104562, Nov. 2023, doi: 10.1016/j.ijmultiphaseflow.2023.104562.
- [15] D. Nakhla and J. S. Cotton, "Effect of electrohydrodynamic (EHD) forces on charging of a vertical latent heat thermal storage module filled with octadecane," *Int. J. Heat Mass Transf.*, vol. 167, p. 120828, Mar. 2021, doi: 10.1016/j.ijheatmasstransfer.2020.120828.
- [16] A. Hassan and J. S. Cotton, "Investigation of the role of electrohydrodynamic forces on the heat transfer enhancement and solid extraction during melting of paraffin wax under constant temperature boundary conditions," *Int. J. Heat Mass Transf.*, vol. 204, p. 123831, May 2023, doi: 10.1016/j.ijheatmasstransfer.2022.123831.

# **Optoelectronic Control of Active Janus Particles: Trajectory Reconfiguration and Mobility Reversals**

S. S. Das<sup>1</sup>, P. García-Sánchez<sup>2</sup>, A. Ramos<sup>2</sup>, G. Yossifon<sup>1,3</sup>

<sup>1</sup>School of Mechanical Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel

<sup>2</sup>Departamento de Electrónica y Electromagnetismo, Facultad de Física, Universidad de Sevilla, Avenida Reina

Mercedes s/n, Sevilla 41012, Spain

<sup>3</sup>Department of Biomedical Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel

\*Corresponding author: gyossifon@tauex.tau.ac.il

Abstract- Self-propelling active particles represent a dynamic and interdisciplinary research frontier with promising biomedical and environmental applications. However, their autonomous motion makes it challenging to control their trajectories. This study employs optically patterned electrodes on a photoconductive substrate, utilizing a digital micromirror device (DMD), to dynamically regulate the movement regions of self-propelling particles, specifically metallo-dielectric Janus particles (JPs). Unlike previous studies where passive micromotors were manipulated by a translocating optical pattern, this system uses the optically patterned electrode to delineate the area within which JPs move autonomously. Notably, JPs avoid crossing the edges of the optical region, allowing for the constraint of their movement area and dynamic shaping of their trajectories. Recently, we observed a second intriguing mobility reversal in optoelectronically-driven JPs. This reversal appears to be linked to asymmetry in the photoconductivity of the underlying substrate, localized beneath the JP, due to the self-shading effect of the metallic hemisphere when illuminated from above. Multiple control tests, including bottom-side illumination, and numerical simulations support this proposed mechanism.

# Keywords- Active particles, Janus particle, Optoelectronics, mobility reversal

## I. INTRODUCTION

Active particles that convert external energy into motion form a dynamic research field with applications in drug delivery, environmental cleanup, microsurgery, and self-repair. Unlike passive particles moved by external gradients, active particles—such as metallodielectric Janus particles (JPs)—self-propel by asymmetrically dissipating energy, enabling autonomous motion even in uniform environments. JPs can move under uniform AC electric fields via induced-charge electro-phoresis (ICEP) or self-dielectrophoresis (sDEP), with frequency modulation tuning their motion and interactions.

Despite progress, precise trajectory control remains challenging. We recently demonstrated optoelectronic (OE) control of JP trajectories using light-patterned virtual electrodes on a photoconductive a-Si:H substrate. Using a DMD, we dynamically confined and guided JPs, exploiting electrohydrodynamics (EHD) flows at low frequencies and dielectrophoretic forces at high frequencies [1]. This approach enables reconfigurable, parallel JP steering with a single field and supports applications in cargo delivery, electroporation, biosensing, and mechanical probing.

In this work, we examine a previously overlooked second mobility reversal at frequencies beyond the ICEP– sDEP transition. We show that top illumination intensity and its interplay with bottom illumination strongly influence JP mobility, expanding the OE platform's control capabilities across broader optical and electrical conditions.

#### II. METHODOLOGY

JP Fabrication: PS and SiO<sub>2</sub> microparticles (~27  $\mu$ m) were cleaned, plasma-treated, and coated with metal

(Cr/Ni/Au) or indium tin oxide (ITO). JPs were detached via sonication in 2% Tween 20 and suspended in 10  $\mu$ M KCl + 0.1% Tween 20 (5  $\mu$ S/cm).

OE Device: An OE chamber was built using ITOcoated slides and a 120  $\mu$ m spacer. The bottom slide had a ~1 $\mu$ m hydrogenated amorphous silicon (a-Si:H) layer deposited by plasma-enhanced chemical vapor deposition (PECVD) (see Fig.1a). A photoresistor test structure with Ti/Au contacts was used to assess photoconductivity.

Experimental Setup: A DMD-based 625 nm LED projected light patterns onto the substrate via a Nikon microscope. A custom bottom illumination setup enabled combined top–bottom lighting. AC signals (10–20 Vpp, 1 kHz–10 MHz) were applied via ITO electrodes.

Imaging & Analysis: JP motion was recorded at 5 fps and tracked using a Python script (CSRT, OpenCV). Velocities were averaged and verified against ImageJ.

Numerical simulations: We used COMSOL (v5.3) to simulate electric forces on a JP above an illuminated a-Si:H electrode. The JP was assumed stationary and vertically aligned. The a-Si:H under the metal side was treated as insulating, while illuminated regions remained conductive. Induced electro-double layers (EDLs) were modeled as boundary conditions on the JP's metallic coated hemisphere and the powered electrode. Electrical forces were computed from the field solution, and particle velocities were estimated by balancing with viscous drag. We also simulated induced-charge electroosmotic (ICEO) flow to assess hydrodynamic forces.

#### III. RESULTS & DISCUSSION

Beyond the known mobility reversal from ICEP to sDEP with increasing frequency, we observed a second reversal at >100 kHz, where the JP again moves dielectric



Fig. 1. (a) Schematic of the optoelectronic setup with a JP moving on an a-Si:H substrate under an applied electric field. The JP's metallic (Au) and dielectric (PS) sides are shown. (b) The second mobility reversal observed in the OE setup, unlike the standard ITO-coated glass slides setup. (c) 3D simulations of forces on the JP as a function of frequency, including total force (electrostatic + electro-hydrodynamic, with hydrodynamic force scaled by 0.05), for varying a-Si:H substrate conductivity, with and without shading.

side forward (Fig.1b). This new mode, termed selfshading optoelectronic modulated electrokinetic propulsion (ss-OMEP), arises from asymmetric light transmission—metal-coated hemispheres block more light, creating uneven photoconductivity beneath the JP (see schematic in Fig.1a). This phenomenon was absent in standard ITO devices, confirming the role of self-shading in the observed behavior.

We tested bottom illumination in conjunction with top illumination to investigate the second mobility reversal. Bottom-only illumination showed no reversal, but combining weak bottom illumination with strong top illumination did. Increasing bottom illumination intensity reduced asymmetric shading and eventually eliminated the second reversal.

Numerical simulations complementing the experimental results show the electrostatic and electrohydrodynamic forces on the JP as a function of angular frequency, a-Si:H conductivity, and induced electric double layers. The electrostatic force reveals a second mobility reversal, which disappears when shading is absent beneath the JP's metallic hemisphere (Fig.1c). The electro-hydrodynamic force is always positive, indicating ICEP with the dielectric side forward. Shading enhances both high-frequency ss-OMEP and low-frequency ICEP mobility, driven by asymmetry in the substrate's photoconductivity. Total force simulations predict two reversals, aligning with experiments when shading is considered. Additional experiments with SiO2-Au JPs confirmed the second mobility reversal, which disappeared with strong bottom illumination, supporting the role of shading in this effect.

## V. CONCLUSION

To conclude, we investigated a second mobility reversal in Janus particles (JPs), caused by self-shading under top illumination, which breaks the substrate's photoconductivity symmetry. Experiments varying top-tobottom illumination ratios and using JPs with differing optical transmission confirmed this effect. We also showed that increasing illumination intensity suppresses sDEP motion, leaving only ICEP or the newly identified ss-OMEP mode. Simulations supported these findings. This self-shading mechanism offers a new optical control lever for JP mobility, enabling advanced trajectory control, self-assembly, and differentiation of JPs based on asymmetric optical and electrical properties.

# ACKNOWLEDGMENT

G.Y. acknowledges support from the Israel Science (ISF) (1934/20).P.G.S. Foundation and A.R. acknowledge the financial support from MCIN/AEI/10.13039/501100011033/FEDER, UE (Grant No. PID2022- 138890NB-I00). We thank the Center for Nanoscience and Nanotechnology, Hebrew University of Jerusalem for assisting us in fabricating the photoconductive substrates.

- S. S. Das, G. Yossifon, Optoelectronic Trajectory Reconfiguration and Directed Self-Assembly of Self-Propelling Electrically Powered Active Particles, arXiv: 2302.04784, *Advanced Science*, 2206183 (2023).
- [2] S. S. Das, P. García-Sánchez, A. Ramos, G. Yossifon, Understanding the Origin of a Second Mobility Reversal in Optoelectrically Powered Metallo-Dielectric Janus Particles, *Journal of Colloid and Interface Science 686 (2025) 118–125.*

# **PWP** measurement of charge distribution in a liquid under DC field

V. Berry<sup>1</sup>, P. Leblanc<sup>1</sup>, S. Hole<sup>2</sup>, T. Paillat<sup>1\*</sup>

<sup>1</sup>Institut PPRIME, Université de Poitiers, CNRS, ENSMA, Poitiers, France

<sup>2</sup> Laboratoire de Physique et d'Etude des Matériaux, Sorbonne Université, ESPCI Paris PSL, CNRS, France

\*Corresponding author: thierry.paillat@univ-poitiers.fr

*Abstract-* Regardless of the liquid used, it exhibits a non-zero electrical conductivity, indicating the presence of electric charges. Although their distribution is often assumed to be homogeneous, it is actually influenced by the presence of an interface (electric double layer) or an external electric field. The local accumulation of electric charges can significantly affect the reliability of equipment such as power components. There are few experimental methods available to measure the distribution of electric charges in liquids accurately and sensitively. For several years, the PPRIME Institute has been working, notably with the Pressure Wave Propagation (PWP) method, to adapt space charge measurement techniques from solids to liquids. These measurements have been used to observe the spatial and temporal reorganization of electric charges when a dielectric liquid is subjected to an external DC electric field.

Keywords- Charge distribution, Pressure Wave Propagation method, solid/liquid interface.

#### I. INTRODUCTION

Like solids, dielectric liquids such as mineral oils and synthetic or natural esters play a crucial role in equipment like transformers, circuit breakers, and HVDC cables. The distribution of electric charges within these liquids is often assumed, as a first approximation, to be homogeneous. However, the presence of a solid/liquid interface associated with the electric double layer, or the application of an external electric field, can locally disrupt this distribution. This may lead to an intensification of electric field lines, the occurrence of partial discharges, or more energetic discharges, which can weaken or even destroy the equipment.

It is therefore essential to characterize and measure the distribution of electric charges in these liquids to ensure the reliability and longevity of electrical systems. Aside from the use of the Kerr effect for specific liquids [1], few experimental methods are able to accurately mapping charge distribution in liquids.

Over the past fifteen years, space charge measurement techniques, initially developed for solids using specific stimuli, have been adapted for liquids [2,3]. These adaptations account for the unique properties of liquids, including their significantly higher ionic and electronic mobility, as well as convective phenomena that can influence charge distribution. Among these techniques, the pressure wave propagation method (PWP) currently using a piezoelectric actuator appears to be the most advanced [4]. It has notably been used to study the polarization of solid/liquid interfaces under the effect of the electric double layer (EDL). It seems effective for both conductive and insulating liquids with an electrical conductivity greater than  $10^{-9}$  S/m. The purpose of this document is to apply the PWP measurement to dielectric liquids subjected to a constant electric field.

#### II. PWP MEASUREMENT DESCRIPTION

A. The Pressure Wave Propagation method (PWP) applied to the EDL

The Pressure Wave Propagation (PWP) method involves generating a planar pressure wave that propagates through a liquid sample placed between two electrodes (Fig. 1). This wave disrupts the electrostatic equilibrium of charges within the sample, particularly at the electric double layer (EDL) present at both electrode/liquid interfaces.



Fig.1. Principe of the PWP method in short-circuit configuration applied to the EDL [4].

The measurement of the short-circuit current between the two electrodes  $I_{pwp}(t)$  (1) provides temporal information on the variations of the electric field (E<sub>L</sub>) and, consequently, on the charges, through Gauss's equation induced by the pressure wave p(x,t):

$$I_{PWP}(t) = C_0 \int \left(1 - \frac{a}{\epsilon}\right) E_L(x) \chi \frac{\partial p(x,t)}{\partial t} dx \qquad (1)$$

where  $\varepsilon$  is the permittivity of the sample, a the electrostrictive coefficient,  $\chi$  compressibility coefficient and C<sub>0</sub> is the capacitance of the sample.

#### *B. The PWP cell description applied to the EDL*

The cell (Fig. 2) consists of an electronic control card ① that imposes a sudden voltage fall on a piezoelectric transducer ②. This leads to the generation of a negative unipolar pressure pulse, whose amplitude (maximum 5 MPa) is controlled by the voltage of the electronic board (V<sub>ex</sub>) and whose duration is 40 ns at half-height. This pressure pulse propagates through an aluminum ③ component that serves as a dual purpose: it acts both as the ground electrode and as the waveguide, while also

introducing a 4.77  $\mu$ s delay between the noise of the excitation phase and the useful electrical response of the sample. The wave then continues to propagate through the liquid ④ until it reaches a brass measuring electrode ⑤, which is connected to an oscilloscope via a 100-dB voltage amplifier. The measured voltage (V<sub>pwp</sub>) is directly correlated with the I<sub>pwp</sub> current through the input impedance of the device (Z<sub>in</sub>).

In this configuration, two electric double layers (EDL) are disturbed by the pressure wave, leading to the appearance of two successive features in the signal. Chronologically, the first is induced at the interface between the aluminum electrode and the liquid, while the second results from the interface between the liquid and the brass electrode. The time interval between these two signals depends on the inter-electrode spacing, which is adjustable using a micrometric screw with a precision of  $10 \,\mu\text{m}$ .

To apply a DC voltage to the liquid between the two electrodes, the brass electrode is connected to a DC voltage generator ( $V_{DC}$ ) via a resistor ( $R_{DC}$ ). Measuring the voltage across  $R_{DC}$  allows for determining the current injected into the cell ( $I_{DC}$ ). A capacitance (C) is also introduced between the brass electrode and the measurement amplifier to filter out the DC component of the  $V_{pwp}$  signal.



Fig.2. Measurement PWP cell (1: Electronic board, 2: Piezoelectric actuator, 3: Wave guide, 4: Liquid, 5: Electrode).

The measured signal results from the average of 500 consecutive acquisitions without DC field, and 10 under DC field at the frequency of 100 Hz. Since the pressure stimulus is negative, the  $I_{pwp}$  current is inverted in all figures to facilitate signal analysis and establish a direct correlation between the signal and the electrical charge signature of the sample. Furthermore, flow electrification measurements [5] have shown that the electric double layer at the aluminum/oil and brass/oil interfaces exhibits negative polarization in the metal and positive polarization in the liquid.

Figure 3 presents a typical  $I_{PWP}$  signal for an interelectrode spacing of 150  $\mu$ m with oil including OLOA 218A without external electric field. The electrical conductivity of the liquid and its relative permittivity are respectively 1.19·10<sup>-9</sup> Sm<sup>-1</sup> and 2.51.

The  $I_{pwp}$  signal consists of two sets of peaks associated with dipoles induced by the two interfaces. The first set, starting at 4.7 µs and including "Peak 1" and "Peak 2," corresponds to charge distribution and polarization at the aluminum/oil interface. The second set, appearing around 4.86 µs and including "Peak 3" and "Peak 4," is associated with charge distribution at the oil/brass interface. These two dipoles have opposite orientations, induced by the direction of stimulus propagation at the interfaces: for the first, it propagates first through the solid before and in the liquid; for the second, it first moves through the liquid before reaching the solid. For a negative pressure wave, Peaks 1 and 4, associated to the negative EDL charges in the solids, are positive, while Peaks 2 and 3 associated with positive EDL charges in the liquid, are negative. The appearance time of the second set of transients is governed by the inter-electrode distance and the speed of sound propagation in the liquid (1308 ms<sup>-1</sup>).

The two dipoles exhibit different amplitudes due to the nature of the interfaces, the varying electric double layers (EDL), as well as the properties of the stimulus. The wave propagation is influenced by reflection and transmission phenomena related to the acoustic properties of the materials, which affect both the amplitude and the shape of the measured signal. However, regardless to the initial excitation amplitude, the measured signal remains directly proportional to it [6].



Fig.3. -I<sub>PWP</sub>(t) distribution for aluminum/oil and oil/brass interfaces which are  $150 \ \mu m$  apart without external potential.

#### III. PWP MEASUREMENT UNDER DC FIELD

#### A. The PWP measurement under negative DC field

Measurements are made continuously when the DC voltage is switched on in order to follow the evolution of charges in the liquid. In figures 4 and 5, a negative voltage is applied to the brass electrode at t=14 s. The charge distribution at the interfaces gradually reorganizes, reaching a new equilibrium after a few seconds. At the second interface (oil/brass), this process is marked by a significant increase in the absolute values of I<sub>PWP</sub> (peaks 3 and 4). In contrast, at the first interface, an initial increase occurs within the first milliseconds, followed by a polarity reversal: peak 1, initially negative, turns positive, while peak 2 undergoes the opposite transition (Fig. 4 and 5). The magnitude of the signal is directly proportional to the intensity of the pressure wave stimuli.

The resulting electric field is oriented toward the brass electrode. As a consequence, Coulomb forces drive the movement of positive charges in the liquid, including those from the electrical double layer and ionic impurities in the bulk, toward the brass electrode. Meanwhile, anions (negatively charged impurities in the liquid bulk) migrate toward the aluminum electrode. This process leads to the formation of two dipoles at the interfaces, both aligned with the polarity imposed by the DC field. At equilibrium,  $I_{pwp}$  reflects this behavior through two sequentially occurring sets of peaks, where a negative peak (indicating positive polarization) is followed by a positive peak (indicating negative polarization).



Fig.4. -I<sub>PWP</sub>(t) evolution for aluminum/oil and oil/brass interfaces under a -1.5V potential at different times (l=150 $\mu$ m). -I<sub>PWP</sub> (nA)



Fig.5. Mapping of the  $-I_{PWP}(t)$  amplitude over the time for aluminum/oil and oil/brass interfaces under a -1.5V potential different times (l=150 $\mu$ m).

#### B. The PWP measurement under positive DC field

The same acquisition procedure is applied for positive voltage application. A similar but opposite behavior is observed (Fig. 6 and 7). Current peaks 1 and 2, associated with the first interface (aluminum/oil), gradually increase in absolute value, while for the second interface (oil/brass), peaks 3 and 4 also increase before undergoing a polarity reversal. The inversion of the electric field drives the migration of positive charges in the liquid toward the aluminum electrode, while negative charges are drawn to the brass electrode. As with the negative voltage case, this results in the formation of two dipoles at the interfaces, but with reversed polarities compared to negative DC polarity.

#### IV. ANALYSIS AND DISCUSSION







Fig.7. Mapping of the  $-I_{PWP}(t)$  amplitude over the time for aluminum/oil and oil/brass interfaces under a 1.5V potential at different times (1=150 $\mu$ m).

The organization of the electric charge distribution described earlier results from the combination of two phenomena: the polarization of the interfaces induced by the EDL and the polarization imposed by the external applied electric field. Assuming that the effects of this field are symmetrical, the charge distribution arising from each of these phenomena can be separated by combining two measurements performed at the same potential but with opposite polarities. Thus, the half-difference of the measurements eliminates the intrinsic charges of the EDL. retaining only the effects of the external electric field. Conversely, the half-sum removes the effects of the electric field, preserving only the EDL charges. Figure 8 is focusing on calculated current due to the EDL. Whether in the presence or absence of an external electric field (t = 5.01 s), the current signal from the EDL maintains the same shape at both interfaces. It corresponds to a dipole with a negative polarity in the solid and positive one in the liquid. The application of the electric field strengthens the signal intensity and, with works of P. Leblanc [7].

The effects of polarization are illustrated in Figure 9. The formation of a dipole is observed at each interface which polarity with the applied electric field regardless of the nature of the material (solid or liquid).



Fig.8. Temporal evolution of the half-sum of the measurements, determined from measurements taken at potentials of  $V_{DC} = \pm 1.5$  V at different time.

The time integration of the signal at equilibrium is correlated with the charge accumulated at both interfaces (Fig. 10). Figure 10 clearly highlights the two electric field regions at the electrodes, which exhibit different amplitudes. In this planar capacitor geometry, with no charge transfer at the interfaces, the electric field levels on both sides should be similar. However, the amplitude differences arise solely from the combined effects of wave propagation and the transmission of the excitation pressure wave across the two consecutive interfaces. These behaviors are consistently observed regardless of the applied  $V_{DC}$ , and the data at both interfaces appear directly proportional to it (Fig. 11). The area of each peak in the figure 10 also follows this behavior. The comparison of these experimental results with the theoretical charge expected for a planar capacitor could provide a robust calibration method for the precise quantification of the charges distribution at each interface. Calibration of the measurement for a solid sample is similar and defined in works of L. Zheng [8].



Fig.9. Temporal evolution of the half-difference of the measurements, determined from measurements taken at potentials of  $V_{DC} = \pm 1.5$  V at different time.

#### ACKNOWLEDGMENT

This work is supported by the French Government program "Investissement d'Avenir" LABEX INTERACTIF, (ANR-11 LABX-0017-01) and EUR IntREE, (ANR-18-EURE-0010).



Fig.10. Temporal evolution of the integration of the half-difference of the measurements, determined from measurements taken at potentials of  $V_{DC} = \pm 1.5$  V at different time.



Fig.11. Data of accumulated charge at the two interfaces vs  $V_{\text{DC}}$ 

#### REFERENCES

[1] Washabaugh, A.P., Zahn, M., A chemical reaction-based boundary condition for flow electrification. *IEEE Trans. Dielect. Electr. Insul.* vol. 4, pp. 688–709, 1997

[2] Sidambarompoulé, X. *et al.*, Experimental validation of the use of thermal stimuli for space charge measurements in dielectric liquids: Application to electrical double layers. *Journal of Electrostatics* vol. 131, pp. 103965, 2024.

[3] Paillat, T., Berquez, L., Leblanc, P., New Advancements in Measuring the Distribution of Electric Charges within Liquids using PEA, in: 2024 *IEEE 5th ICD*, IEEE, Toulouse, France, pp. 1–4.

[4] Berry, V., Leblanc, P., Holé, S., Paillat, T., Space charge measurement at solid/liquid interface by PWP method. *Journal of Electrostatics* vol. 128, pp. 103894., 2024

[5] Leblanc, P., Paillat, T., Cabaleiro, J.M., Touchard, G., Flow electrification investigation under the effect of the flow parameters. *International Journal of Plasma Environmental Science and Technology* vol. 11, pp. 156–160, 2018.

[6] Berry, V., Zheng, L., Leblanc, P., Holé, S., Paillat, T., Numerical investigation of electric charge measurement by PWP method at solid and liquid interfaces. *Journal of Electrostatics* vol. 132, pp. 103991, 2024.

[7] Leblanc, P., Paillat, T., Morin, G., Perrier, C., Behavior of the charge accumulation at the pressboard/oil interface under DC external electric field stress. *IEEE Trans. Dielect. Electr. Insul.* vol. 22, pp. 2537–2542, 2015.

[8] Zheng, L., Holé, S., Influence of interface voltage on charge build-up under high voltage. *Phys. Scr.* vol. 99, pp. 125921, 2024.

# Enhanced Nano-Droplet Generation by Counter Ionic Liquid Electrospray Configuration for Efficient CO<sub>2</sub> Absorption

Y. Kaneko<sup>1</sup>, Y. Onodera<sup>2</sup>, T. Makino<sup>3</sup>, M. Kanakubo<sup>3</sup>, and H. Takana<sup>1\*</sup>

<sup>1</sup>Institute of Fluid Science, Tohoku University, Sendai, Japan

<sup>2</sup>Graduate School of Mechanical and Aerospace engineering, Tohoku University, Sendai, Japan

<sup>3</sup>National Institute of Advanced Industrial Science and Technology, Sendai, Japan

\*Corresponding author: takana@tohoku.ac.jp

Abstract- Ionic liquid (IL) has great ability of  $CO_2$  absorption. Electrospray atomization of IL generates nanosize droplets with increased specific surface area, thus enhancing the  $CO_2$  absorption performance. To achieve further improvement in  $CO_2$  absorption efficiency, this study proposes counter-electrospray as an innovative electrospray configuration, in which two nozzles are placed facing each other so that the IL sprays from both nozzles interfere each other. Spray visualization shows that the counter-electrospray configuration generates radially wider spray compared to that with a single-electrospray configuration due to Coulomb repulsion between positively charged droplets. In addition, the enhanced atomization of IL is also confirmed through droplet size distribution measurements. It was elucidated that the counter electrospray of IL clearly improves the  $CO_2$ absorption amount and efficiency in a flow reactor.

Keywords- ionic liquid, counter electrospray, atomization, carbon dioxide absorption.

# I. INTRODUCTION

Ionic liquids (IL) are ambient temperature molten salts consisting of cation and anion [1]. IL possess many unique characteristics, such as non-volatility, nonflammability, thermal and chemical stability [2]. IL with specific combinations of cation and anions exhibits superior selective  $CO_2$  absorption properties, making IL promising candidates as novel  $CO_2$  absorbent. Because  $CO_2$  chemical absorption occurs at the interface between the IL and  $CO_2$  gas, increasing the specific surface area of IL is essential for enhancing absorption efficiency. Although atomization is one of the effective methods to increase the specific area of liquids, the relatively high viscosity of IL makes their atomization difficult.

Electrospray is one of the liquid atomization techniques capable of producing fine droplets even for highly viscous liquids [3]. In previous studies, the electrospray atomization of IL has been proposed as a promising method for enhancing  $CO_2$  absorption efficiency [4, 5]. Typically, electrospray systems consist of a single nozzle and counter electrode. IL supplied through the nozzle is atomized into nano-sized droplets by applying a high voltage between the nozzle and counter electrode.

For further improvement of CO<sub>2</sub> absorption efficiency in this system, this study proposes an innovative nozzle configuration with two nozzles facing each other. In this configuration, interference between sprays from each nozzle may occur due to the interaction between charged droplets with the same polarity, which affects both atomization and CO<sub>2</sub> absorption characteristics. The effect of IL flow rate and the nozzle configuration on electrospray characteristics and  $CO_2$ absorption characteristics are clarified through electrospray



Fig. 1 Counter electrospray system consisting of nozzles and ring-shaped counter electrode.

visualization, droplet diameter measurement, and evaluation of  $CO_2$  absorption performance in flow reactor.

# II. METHODOLOGY

Figure 1 shows the electrospray system consisting of nozzles and a common counter electrode. IL is supplied into capillary nozzles by syringe pumps. The inner and outer diameter of the nozzles are 0.1 and 0.375 mm, respectively. The distance between the nozzle tip and ring-shaped counter electrode is set as 6.0 mm. DC high voltage of -7.0 kV is applied to the counter electrode with nozzles grounded, resulting in the emission of positively charged droplets from both nozzles. In a counter electrospray configuration, an additional nozzle is arranged on the other side of the counter electrode. In all experiments, the electrospray system is placed so that the nozzles coincide with the center axis.



Fig. 2 Experimental setup for (a) electrospray visualization, (b) droplet diameter distribution measurement using U-shaped acrylic support, and (c)  $CO_2$  absorption experiment in a flow reactor.

The IL used in this study is 1-ethyl-3methylimidazolium acetate ([emim][Ac], 95.0% purity, Sigma-Aldrich) with a viscosity and conductivity of 125 mP s and 0.4 S/m, respectively at 298 K [6].

The electrospray setup for the visualization and droplet diameter measurements is shown in Fig. 2. The nozzle(s) and counter electrode are installed in a U-shaped acrylic support. Nd-YAG laser light sheet with the wavelength of 532 nm is irradiated so that the light sheet passes through the nozzle axis. The scattered light of IL droplets are captured using a high-speed camera at the frame rate of 4000 fps. The IL droplet diameter distribution is measured using a scanning mobility particle sizer spectrometer (SMPS model 3938, Tokyo Dylec Corp.). A sampling tube with an inner diameter of 4 mm is placed 10 mm below the center of counter electrode. The aerosols of IL droplets are sampled at 1.5 L/min for 60 seconds.

As shown in Fig. 2 (c), the  $CO_2$  absorption measurement is conducted in a flow reactor, which consists of an acrylic cylindrical chamber with the inner diameter of 40 mm and the height of 90 mm. The electrospray system (Fig. 1) is mounted on polyvinyl chloride lids used to seal both ends of the chamber. A



Fig. 3 Sequential photographs of (a) single and (b) counter electrospray at an IL flow rate of 1.0 mL/h per nozzle



Fig. 4 Overlayed picture of electrospray of (a) single and (b) counter electrospray with IL flow rate of 1.0 mL/h per nozzle.

mixture of  $N_2$  and  $CO_2$  gases with a  $CO_2$  concentration of 1% is introduced into the chamber at the flow rate of 30 cm<sup>3</sup>/min through the inlet on the left lid at the lower part of the chamber. The gas mixture flows out of the outlet on the opposite lid. The  $CO_2$  concentration at the outlet is monitored using a non-dispersive infrared  $CO_2$  sensor (VAISALA GMP252). Prior to the spraying, the chamber is purged with the 1%  $CO_2$ . Note that  $CO_2$  absorption measurement is conducted under the controlled temperature in a thermostatic chamber because the physical properties vary and  $CO_2$  absorption performance of IL are affected by the ambient temperature.

#### III. RESULTS AND DISCUSSION

#### A. Visualization of ionic liquid electrospray

Figure 3 shows the sequential photographs of (a) single and (b) counter electrospray at the IL flow rates of 1.0 mL/h per nozzle. The applied electric field induces



Fig. 5 Droplet diameter distribution normalized by a total number of detected droplets.

polarization of the IL in the nozzles, accumulating the positive charge density at the nozzle tips. When the electrostatic force becomes larger than the surface tension, a Taylor cone forms, followed by the formation of an IL ligament that subsequently breaks up into droplets. Then, the spray event stops when the amount of IL consumed by spraying exceeds the amount of supplied IL. These electrospray events occur intermittently. In the counterelectrospray configuration shown in Fig. 3 (b), spraying does not necessarily occur simultaneously from either nozzle.

Figure 4 (a) shows an overlaid photograph of the single-nozzle electrospray over a period of 0.5 s. The spray from the nozzle radially spreads toward the counter electrode. On the other hand, in the counter-electrospray configuration (Fig. 4 (b)), the sprays spread more widely near the nozzle tips. This may be attributed to the electric field caused by the existence of the additional counter nozzle's potential. The sprays interact with each other near the counter electrode. Because the droplets generated from both nozzles are charged with the same polarity, Coulomb repulsion causes wider spreading of droplets.

#### B. Droplet diameter distribution measurement

Figure 5 plots the droplet diameter distribution normalized by the total number of droplets, ranging from 8 to 100 nm. By comparing the results of single and counter electrosprays under the same IL flow rate per nozzle, the proportion of droplets larger than 20 nm in the counter electrospray is smaller than that in the single electrospray. This implies the possibility of further atomization of droplets due to Coulomb repulsion with breakup (secondary breakup) when positively charged droplets interact each other in the counter electrospray.

To evaluate the enhanced atomization effect, the Sauter mean diameter (SMD),  $d_{32}$ , defined as Eq. (1), is plotted in Fig. 6.

$$d_{32} = \frac{\sum d_i^3 N_i}{\sum d_i^2 N_i},$$
 (1)



Fig. 6 Sauter mean diameter of electrospray as a function of an ionic liquid flow rate per nozzle.

where  $N_i$  is the number of droplets with the diameter of  $d_i$ . The SMD of the single-nozzle electrospray increases with increasing the IL flow rate, while that of the counter electrospray is independent of the IL flow rate. In the counter electrospray, further atomization by secondary breakup of the primary larger droplet is more likely to occur due to spray interference in the counter-electrospray configuration. Figure 6 clearly demonstrates the electrospray interference effect of further atomization above IL flow rate of 0.5 mL/h.

#### C. CO<sub>2</sub> absorption characteristics

Figure 7 shows the time evolution of CO<sub>2</sub> concentration in the flow reactor,  $\phi(t)$ . After the application of high voltage at  $t = 0 \min$ , the CO<sub>2</sub> concentration decreases with time due to the CO<sub>2</sub> absorption by IL droplets generated by electrospray, eventually reaching a steady state at t = 60 min. In both electrospray configurations, the CO<sub>2</sub> concentration at t = 60 min decreases with increasing the total IL flow rate. In addition, both the amount of absorbed CO<sub>2</sub> and the decay rate of CO<sub>2</sub> concentration in the counter electrospray are superior to those in the single electrospray under the same total IL flow rate. Figure 8 shows the CO<sub>2</sub> absorption rate,  $(\phi(0) - \phi(60))/\phi(0)$ , as a function of IL flow rate per nozzle. Under the same IL flow rate per nozzle, the counter electrospray achieves higher CO<sub>2</sub> absorption rate than the single electrospray does. This enhancement is attributed not only to the larger supplied amount of IL, but also to the wider spreading spraying and further atomization resulting in an increase in specific surface area, as shown in Figs. 4 and 6.

Finally, a loading rate  $\alpha$  is calculated to discuss the CO<sub>2</sub> absorption efficiency. The loading rate is defined as the ratio of CO<sub>2</sub> absorption molar amount to the supplied molar amount of IL. Equation (2) is the definition of the loading rate in this study.

$$\alpha = \frac{(\phi(0) - \phi(60))Q_{\rm CO_2}/V_{\rm m}}{Q_{\rm IL}\rho_{\rm IL}/M_{\rm IL}},$$
(2)



Fig. 7 Time evolution of CO<sub>2</sub> concentration.

where  $Q_{CO_2}$  is the gas flow rate,  $V_m = 22.4$  L/mol is the molar volume,  $Q_{IL}$  is the total IL flow rate,  $\rho_{\rm IL} = 1027 \text{ kg/m}^3$  and  $M_{\rm IL} = 170 \text{ g/mol}$  is the density and molecular weight of IL ([emim][Ac]), respectively. Figure 9 shows the loading rate as a function of the total IL flow rate. In both configurations, the loading rate decreases with the total IL flow rate. Considering that the SMD of the counter electrospray is independent of the total IL flow rate, the decrease in the loading rate could be caused by µm order sized droplets, which are outside the range of the scanning mobility particle sizer spectrometer. Although such undetected droplets may also affect the results of single electrospray, the deterioration in CO<sub>2</sub> absorption efficiency by single electrospray is mainly caused by the decrease in the specific surface area as shown in Fig. 6. Under the same total IL flow rate, the loading rate of the counter electrospray is higher than that of single one. These results suggest that, under the same total IL flow rate, it is preferable for more efficient CO<sub>2</sub> absorption to spray IL from two facing nozzles rather than spraying from a single nozzle.

#### IV. CONCLUSION

For the efficient  $CO_2$  absorption by IL electrospray, the effect of IL flow rate and the nozzle configuration on the electrospray characteristics and  $\text{CO}_2$  absorption are clarified for the two types of IL electrosprays: one with a single nozzle and the other with counter nozzles in which the nozzles are arranged to face each other. Through the visualization of the spray, it is found that the counter electrospray generates more widely spreading spray in a radial direction compared to that of single-electrospray configuration. In addition, there is an interference of sprays near the counter electrode, resulting in the further atomization of charged IL droplets. Through the CO2 absorption experiment, the interference of sprays from twin-nozzles clearly enhances the CO<sub>2</sub> absorption efficiency. From these results, it can be concluded that, compared to the single-electrospray configuration, more efficient CO<sub>2</sub> absorption by IL electrospray is achieved by introducing an additional counter-nozzle configuration under the same IL flow rate.



Fig. 8  $CO_2$  absorption rate as a function of IL flow rate per nozzle.



Fig. 9 CO<sub>2</sub> loading rate as a function of total IL flow rate.

- T. Makino and M. Kanakubo. CO<sub>2</sub> Absorption Property of Ionic Liquid and CO<sub>2</sub> Permselectivity for Ionic Liquid Membrane, *Journal of the Japan Petroleum Institute*, 59:109–117, 2016.
- [2] K. Dong, X. Liu, H. Dong, X. Zhang, and S. Zhang. Multiscale Studies on Ionic Liquids, *Chemical Reviews*, 117:6636–6695.
- [3] A. M. Gañán-Calvo, J. M. López-Herrera, M. A. Herrada, A. Ramos, and J. Montanero. Review on the physics of electrospray: From electrokinetics to the operating conditions of single and coaxial Taylor cone-jets, and AC electrospray, *Journal of Aerosol Science*, 125:32–56, 2018.
- [4] H. Takana, K. Yamamoto, T. Makino, and M. Kanakubo. Improvement of CO2 absorption by ionic liquid electrospray, *Europhysics Letters*, 131:34002, 2020.
- [5] H. Takana, N. Hara, T. Makino, and M. Kanakubo. Effect of environmental temperature on CO<sub>2</sub> selective absorption characteristics by ionic liquid electrospray in flow system, *Journal of Electrostatics*, 114:103634, 2021.
- [6] A. Pinkert, K. Ang, K. Marsh, and S. Pang. Density viscosity and electrical conductivity of protic alkanolammonium ionic liquids, *Physical Chemistry Chemical Physics*, 13:5136–5143, 2011.

# Impact Of An External Static Electric Field During The Foaming Process: Equipment Design And First Results

M. Havet<sup>1\*</sup>, A. Garcia<sup>1</sup>, S. Swyngedau Chevallier<sup>1</sup>, T. Dessev<sup>2</sup>, A. Le Bail<sup>1</sup> <sup>1</sup>Oniris, Nantes Université, CNRS, GEPEA, UMR 6144, F-44000 Nantes, France <sup>2</sup>Food and Health Department Nofima, 1433 Aas, Norway \*Corresponding author: michel.havet@oniris-nantes.fr

Abstract- This study focuses on a set-up, called ElectroFoamVision, designed to evaluate the stability of a foam, generated by gas phase incorporation into a liquid medium placed within a chamber, with a glass column that incorporates stainless steel flat parallel electrodes (30x200 mm, gap 5cm). Experiments were performed on Whey Protein Isolate (WPI) and Chickpea aqueous solutions. Experiments revealed a remarkable shift in the foam's stability according to the applied electric field. Under the influence of an external electric field during the foaming period, the liquid remains in the foam state for a longer period. This was attributed to a reduction in the size of gas bubbles escaping from the frit, thus diminishing surface tension. These results are promising for the conception of an innovative food foam equipment able to produce a high-quality foam.

Keywords- Foam, Bubbles, Stability, Electric field.

# I. INTRODUCTION

Foams play a significant role in the food industry, revolutionizing the texture, appearance, functionality and sensory experience of various food products [1]. Food foams are intricate systems of gas bubbles dispersed in a liquid. Their stability, i.e maintaining their structural integrity over time, remains a challenge for various applications. The primary hurdle arises from the natural tendency of foams to collapse, coalesce, or break, leading to a loss of their porous texture and functionality. By nature, foams are highly thermodynamically unstable systems and evolve irreversibly. An important mechanism is the drainage of liquid from the foam structure due to gravity [2]. This inevitable drainage takes place through the Plateau borders and by capillary action from the lamellae to the Plateau borders. Thus, over time, the foam dries out as the volume of liquid in the foam tends to decrease. Free drainage is the spontaneous evolution of the liquid fraction under the influence of gravity, starting from an initial state different from the equilibrium. Over time, the irreversible flow of liquid downward dries out the foam. The position of the interface between the foam and the drained liquid rises with time. In many applications, it is required to control the lifetime of a foam by limiting the drainage or triggering the collapse at a specific location or a given time. Applying an external electric field at the edge of the foam induces some liquid flows and, depending on the flow magnitude, it controls either gravity driven drainage, the foam stability, or the foam collapse at a specific location [3]. A work has been carried out to study electro-osmosis, a method to cancel and even reverse the drainage [3, 4]. The principle is as follows: due to ionic surfactants covering the liquid-gas interface, liquid is locally charged near this surface and can therefore be set in motion by an external electric field. By controlling the applied field and the resulting flow of liquid, the foam can be maintained in a superstable state and even rejuvenated in some way on demand.

This experimental study aims to unravel the dynamics of foam formation and stability under the influence of a static electric field. Our investigative tools include a new apparatus, called ElectroFoamVision, and advanced analysis algorithms, allowing real-time assessments of foam volume and behavior. Utilizing solutions of animal derived Whey Protein Isolate (WPI) and plant derived Chickpea protein (CKP), we explore the influence of electric fields during the foaming process.

#### II. METHODOLOGY

# A. Experimental set-up

The ElectroFoamVision (Fig. 1 and 2) is purposefully developed to evaluate the attributes of foam, encompassing its generation and stability. This involves introducing gases such as Air, N2, O2, CO2, etc... into the liquid medium to generate the foam. The experimental setup entails placing the liquid sample within a designated chamber. This chamber was augmented with a glass column that incorporates flat parallel electrodes, spaced 5 cm apart; this rectangular chamber with flat electrodes is a completely original setup compared to existing FoamScan systems. Using a high voltage source (Ottersweier, Germany), an electric field can be applied to the foam either during foaming or after foaming or eventually both, using the two parallel electrodes (30 x 200 mm / 1 mm thick / stainless steel). Foam is generated in the sample chamber through sparging, leading it to ascend into the glass column. Within this column, the evolving foam is continually monitored via a video camera. The visual data captured by the camera is subsequently extracted and processed on ImageJ (NIH), an open source Java-based image processing program. A specific algorithm for interface tracking was developed. This information serves as the basis for real-time calculations and visual representations of the foam's volume.



Fig. 1. Sketch of ElectroFoamVision, focus on the column



Fig. 2. Sketch of the experimental set-up (High voltage source not represented).

By systematically capturing and analysing the foam's development and behavior, ElectroFoamVision allows for a comprehensive understanding of its properties. This apparatus facilitates insights into foam generation mechanisms, its ability to retain structural integrity, and its real-time volumetric changes. The integration of video imaging technology enhances the precision and detail of data collection, enabling more accurate characterization of foam behavior.

# B. Experimental procedures

The foam-type food matrices can be assimilated to liquid protein solutions in which a gas injection is performed. Experiments were performed on two foam models from Whey Protein Isolate (WPI) and Chickpea (CKP) solutions.

WPI is a protein of animal origin, an isolate's short chain proteins that are extracted from Whey Protein Concentrate, derived from milk. We prepared solutions containing 3% WPI. The total mass of WPI was incorporated in 4 times, staggered at 15min intervals, under moderate agitation (3-blade propeller, speed 100 rpm), at room temperature (20°C), to guarantee the complete dissolution of the powder.

Considering a clean label approach, a protein of plant origin was considered for the second model solution, namely an aqueous chickpea protein solution (CKP). Aquafaba has shown good food functional properties, as this plant-based liquid has the ability to function as both a foaming agent and an emulsifier under conditions of pH and NaCl concentrations that happen to be those readily encountered in food products. As a vegetable alternative to egg white or WPI, CKP aquafaba seems to be an interesting candidate for foamed products. Therefore, we decided to use a chickpea aquafaba-based solution. The aquafaba from 10 cans was collected by sieving. It was then centrifuged to ensure homogeneity of the mixture. A sample of this aquafaba was taken for determination of the protein content by the Dumas method (protein content of 3% +/- 0.2%).

50 mL solution of the model system is meticulously prepared. This solution is then introduced into the ElectroFoamVision with great care, utilizing a syringe and tubing to avoid foaming. Once the solution is in place, the next steps involve preparing for image acquisition. The experiment begins by switching on the light source and inserting a millimeter paper between the glass column and the camera. A photo is taken, which serves as a reference for metric calibration during image analysis. Each measurement was conducted with five repetitions. The gas injection rate is set to 10 mL/s, and the desired voltage value is adjusted on the high-voltage generator. When these settings are in place, the gas injection and highvoltage generator are initiated simultaneously. This marks the beginning of the foaming phase, which lasts 120 seconds. Once the 120-seconds foaming phase is completed, the gas injection is stopped, as is the highvoltage generator.

# C. Foam stability

To analyze the evolution of the foam stability, image acquisition is then automatically initiated, capturing one image per second (Fig. 3); the liquid phase at the bottom is clearer than the foam. This stage captures the destabilization phase of the foam during 15 minutes.



Fig. 3. Images captured during the drainage of a foam generated with the chickpea model solution. The red dotted line indicates the position of the foam/liquid interface.

# D. Foam quality

The quality of the food foam can be determined using two parameters: the "expansion" and "half-life." Expansion is defined as the ratio between the final volume of the food foam and the original volume of the food product. To calculate the expansion of foams generated under the influence of an electric field, some adjustments were made to the experimental procedure. The initial volume of the model solution introduced into the ElectroFoamVision remained unchanged. The foaming process with the electric field lasted for 120 s. At the end of this foaming period, the foam height was carefully recorded.

Half-life is defined as the time during which the food foam loses half of its volume. To calculate the half-life of the foam, the same initial volume of the model solution was introduced into the column. The foaming process with the electric field was initiated and continued until the foam reached a physical limit marked on the column, which corresponded to 200 mL of foam. At this point, the high voltage was promptly disconnected. The half-life measurement was then conducted, observing the time it took for the foam to collapse and recede to another physical limit marked on the column, corresponding to half of its original volume.

The ElectroFoamVision experiment presents its own challenges due to complex 3D optical effects that can interfere with accurate measurements. Determination of bubble size and distribution is inherently not possible in the set-up.

#### III. RESULTS

#### A. Foam stability

Fig. 4 illustrates the evolution of the average volume of the liquid phase within the column over time. This data is presented for various applied voltages.



Fig. 4. Liquid phase volume as a function of time, according to the applied voltage during foaming - WPI solution.

Our observations reveal distinctive trends in foam stability concerning the influence of the applied voltage. Without any applied voltage during the foaming, the volume of the liquid increases up to 16 mL after 1000 s of drainage. When applying 1 kV (corresponding to a mean electric field strength of 20 kV/m), the drainage kinetic is reduced with a final volume of 13.5 mL after 1000 s. As the voltage is increased, we notice a shift in the foam's stability, which manifests as changes in the volume of the liquid phase. A clear pattern emerges: as the electric field strength increases, the volume of the drained liquid phase significantly decreases. This observation signifies that, under the influence of an electric field during the foaming period, the liquid remains in the foam state for a more extended period, ultimately resulting in enhanced foam stability. For instance, when applying a voltage of 10 kV (mean electric field of 200 kV/m), we recorded a substantial two-fold reduction in the volume of the liquid phase at the column's base. This effect of decreased recoverable liquid phase (indicating a foam stabilization)

is more pronounced at lower voltage electric fields. However, it becomes less prominent as higher voltage levels are applied, with minimal deviation between the results obtained at 6 kV and 10 kV, for example.

Experiments performed on the chickpea solution led remarkably to similar trends. Fig. 5 represents the final volume of liquid after 1000 s. of drainage for both solutions. As we increase the applied voltage, we consistently observe a noteworthy reduction in the volume of the liquid phase. This commonality strongly reinforces the earlier conclusions regarding the electric field's role in foam stabilization.



Fig. 5. Liquid phase volume in the ElectroFoamVision at the end of the drainage for WPI and chickpea solutions.

#### B. Foam quality

As a general rule, higher-quality food foam is achieved when the expansion is maximal and the half-life is longer [5]. To determine the optimal operating conditions, we generated a map of foam expansion as a function of half-life for applied voltage from 0 to 10 kV (Fig. 6). This analysis enabled us to swiftly identify the voltage setting that produced the best combination of expansion and half-life.



Fig. 6. Map of foam expansion as function of the half-life of the collapse (Numbers after bracket correspond to the applied voltage).

The foam expansion is stable for the moderate applied voltages up to 2 kV: it is close to 4 for WPI and 3.4 for CKP. For higher applied voltages, there is a significant reduction of the foam expansion for both foams. One significant factor is the increase in foam stability induced

by the high voltage. The electric field generated by the high voltage alters the properties of the gas bubbles within the foam, leading to enhanced stability and reduced coalescence between bubbles. As a result, the bubbles are less likely to merge and form larger bubbles, which ultimately limits the expansion of the foam.

Without applied voltage, the half-life is close to 500 s. for the WPI and CKP's foams. When foaming is performed under an electric field, the half-life of the foams increases up to 1000 s at the higher applied voltage. When the applied voltage is increased, there is a notable densification of the foam structure, leading to a reduced expansion and an extended half-life.

It can be considered that the optimal condition to obtain the maximal expansion of the foam with a long half-life is reached at a low voltage setting of 1 kV (20 kV/m) for both the WPI and chickpea solutions. Results indicated that at low voltage, foams exhibited remarkable expansion but had shorter half-lives, while at high voltage, expansion was reduced, but half-lives extended.

## IV. DISCUSSION

Our observations revealed distinctive trends in foam stability according to the applied voltage. As the electric field increased, we noticed a remarkable shift in the foam's stability, which yielded changes in the volume of the drained liquid phase. This observation signifies that, under the influence of an external electric field during the foaming period, the liquid remains in the foam state longer. This was attributed to a reduction in the size of gas bubbles escaping from the frit, thus diminishing surface tension. These smaller and more uniform gas bubbles incorporated into the liquid phase exhibited heightened stability and limited the disproportionation effect of foam destabilization. Furthermore, the electric field may influence protein conformation and weak intermolecular interactions, further contributing to foam stabilization.

The densification of the foam structure can be attributed to several underlying factors. The intensified electric field induces stronger electrostatic interactions between the gas bubbles and the surrounding liquid phase, promoting closer packing and reduced bubble coalescence. As a result, the foam structure becomes more compact, leading to decreased expansion during the foaming process. Additionally, the electric field strength alters the interfacial properties of the foam, such as surface tension [6] and viscosity, which further contribute to foam densification. Moreover, the electric field may induce changes in the distribution and orientation of surfactant molecules at the gas-liquid interface, leading to enhanced foam stability and prolonged drainage time. Overall, the observed increase in foam density and extended half-life with higher electric field strength is attributed to the complex interplay between electrostatic forces, interfacial properties, and foam structure dynamics.

#### V. CONCLUSION

Experiments performed on the original set-up called ElectroFoamVision confirm that applying an electric field

during the foaming process lead to more stable foams. A low voltage is sufficient to decrease surface tension, which results in smaller and more numerous gas bubbles during the foaming process, thus enhancing the foam's quality. Moreover, the decreased surface tension contributes to foam stabilization, leading to a prolonged half-life. However, at high voltages, the effects on protein structure lead to a reduction in foaming properties. In conclusion, applying a low-level electrostatic field during foaming can potentially enhance both the foaming process and the stability of the resulting foam. These results are promising for the conception of innovative food foaming equipment able to produce a high-quality foam under an electric field while reducing the energy required to create the new interfaces.

#### ACKNOWLEDGMENT

The present work has been co-funded by ONIRIS-GEPEA and by the FEDER European funds Ref 2020/FEDER/n°PL0019794 within the international Chair "CONT-E-FOOD" on continuous food processes under electrical disturbances. Disclaimer: the content found in this contribution reflects only the author's view. The EU commission is not responsible for any use that may be made of the information it contains.

We thank Pedro Llovera-Segovia (Instituto de Tecnología Electrica - Universitat Politecnica de Valencia, Spain) for his contribution on electrostatic phenomena.

- W. Drenckhan, A. Saint-Jalmes. The Science of Foaming. Advances in Colloid and Interface Science, 222:228–59. Elsevier B.V. 2015.
- [2] A. Saint-Jalmes, D. Langevin. Time evolution of aqueous foams: drainage and coarsening. *Journal of Physics: Condensed Matter.* 14. pp 9397–9412. 2002.
- [3] O. Bonhomme, L. Peng, A.L. Biance. Thermally Enhanced Electro-Osmosis to Control Foam Stability. *Physical Review* X 10 (2). 2020.
- [4] O. Bonhomme, B. Blanc, L. Joly, C. Ybert, A.L. Biance. Electrokinetic Transport in Liquid Foams. *Advances in Colloid and Interface Science*. Elsevier B.V. 2017.
- [5] A. Garcia, T. Dessev, L. Guihard, S. Swyngedau Chevallier, M. Havet, A. Le Bail. Impact of external static electric field on surface tension of model solutions *Innovative Food Science & Emerging Technologies*. 87, pp.103406. 2023.
- [6] B.S. Murray. Stabilization of Bubbles and Foams. *Current Opinion in Colloid and Interface Science*. Volume 12, Issues 4–5. Pp 232-241. 2007

# Fundamental Characteristics of Ionic Liquid Electrospray with Pump-free Porous Emitter for Enhanced CO<sub>2</sub> Absorption

H. Takana<sup>1\*</sup>, S. Kawaharada<sup>2</sup>, T. Makino<sup>3</sup>, and M. Kanakubo<sup>3</sup> <sup>1</sup>Institute of Fluid Science, Tohoku University, Japan <sup>2</sup>Graduate School of Mechanical and Aerospace Engineering, Tohoku University, Japan <sup>3</sup>National Institute of Advanced Industrial Science and Technology (AIST), Japan \*Corresponding author: takana@tohoku.ac.jp

Abstract- Innovative ionic liquid electrospray with pump-free porous emitters was developed for CO<sub>2</sub> selective absorption. Ionic liquid is passively supplied from the reservoir by capillary force. The electrospray is initiated from the permeated ionic liquid through the porous. The electrospray is possible even using the counter electrode with a hole over the multiple porous emitters when the diameter of the hole is small enough to reach the onset electric field at the emitter tip. Finer droplets can be generated by placing small hole for each emitter, resulting in enhanced CO<sub>2</sub> absorption. The distance between the emitters should be large enough to suppress the deposition on the counter electrode due to electrostatic repulsive interaction between charged droplets.

Keywords- Ionic Liquid, Electrospray, Porous emitter, Interaction, CO2 absorption.

#### I. INTRODUCTION

For crewed long-term deep-space missions, the control of the atmospheric  $CO_2$  level in the space cabin is key in modern spacecraft environmental control and life support systems during exploration.

Recently, ionic liquids have garnered significant attention as an energy-efficient innovative liquid absorbent for CO<sub>2</sub> [1-4]. Takana et al. proposed ionic liquid electrospray to make the most use of ionic liquids' CO<sub>2</sub> absorption kinetic capability by generating nanoorder fine droplets [5,6]. It was experimentally demonstrated that the fine droplets were successfully generated by using ionic liquid electrospray. The fine droplets with a high specific surface area enhanced the surface reaction of CO<sub>2</sub>, resulting in significant decrease of the CO<sub>2</sub> concentration in both closed [5] or flow chamber [6].

In this study, the innovative ionic electrospray method using porous emitters has been proposed as the pump-free electrospray system. Using the porous material as the emitters, ionic liquid is passively supplied by capillary effect from the reservoir at the optimum flow rate for the spray. The onset voltage for electrospray with porous emitter under atmospheric pressure was clarified as its fundamental characteristics. The effect of counter electrode configuration on the generation of ultra-fine droplets and  $CO_2$  absorption characteristics was experimentally elucidated.

#### II. METHODOLOGY

Figure 1 shows the photos of the porous emitter made of the alumina with pore size of 0.5  $\mu$ m at the porosity of 30%. At the center of the 18 mm x 18 mm porous plate with the thickness of 1 mm, 7 cone-shape emitters are fabricated. Each emitter is 150  $\mu$ m in height with bottom diameter of 250  $\mu$ m. They are arranged at the interval of 450  $\mu$ m. As shown in Fig.2 (a), the counter electrode with the thickness of 0.1 mm is located 4 mm above the emitter



Fig. 1. Photos of porous emitter. (a) top view and (b) side view.



Fig. 2. Schematic illustrations of porous emitter with counter electrode. (a) 5 mm hole, (b) 1.0 mm hole, (c) 0.3 mm hole, and (d) 0.3 mm holes x 7.

plate with the hole diameter of 5.0 mm, 1.0 mm and 0.3 mm, respectively. The center of the hole coincides with the center axis of the middle emitter. The counter electrode with 7 holes with 0.3 mm in diameter for each emitter is also used in the experiment (Fig. 2(d)). Collector plate is located 2 mm above the counter electrode to measure the current carried by sprayed charged droplets. The current from the counter electrode is also measured by pico-ammeter. Here the current from the collector plate and counter electrode are referred to as spray current and emitter current, respectively. The ionic reservoir is located at the bottom of the emitter plate so that the ionic liquid



Fig. 3. Relationship between voltage and collector current for different counter electrodes.



Fig. 4. Relationship between voltage and emitter/collector current.

permeates into porous emitter by capillary effect. The ionic liquid used in this study was [Emim][Ac]. The high voltage is applied to the electrode rod in the ionic liquid with the counter electrode and collector plate grounded. The size distribution of the generated droplet was measured by scanning mobility particle sizers (SMPS3938, TSI) by sampling the droplets at 3 mm above from the counter electrode for 30 seconds at 1.0 L/min.

#### **III. RESULTS AND DISCUSSIONS**

Figure 3 shows the collector current when the applied voltage increases at 33 V/s. In the case of counter electrode with 5.0 mm hole, there is almost no current flowing up to 6 kV, meaning that the electrospray does not occur due to not reaching the onset electric field at the emitter tips. The collector current shows the highest for 0.3 mm x 7 holes, followed by 1.0 mm and 0.3 mm hole in counter electrode. Since the current for 1.0 mm hole is higher than that of 0.3 mm single hole (single emitter), it is found that electrospray is initiated from multiple emitters even using one hole over the emitters in the counter electrode. The collector current rises at approximately 3 kV in all cases, it can be concluded that the onset voltage for the spray is around 3 kV in this experimental setup. Even introducing 7 emitters (0.3 mm x 7 case), the collector current is not



Fig. 5. Cumulative percentage of droplet diameter for various applied voltages for counter electrode with 0.3 mm x 7 holes.



Fig. 6. Time evolution of absorbed carbon dioxide for various counter electrode at 5.5 kV.

necessarily 7 times higher than that of single emitter (0.3 mm case).

The emitter/collector current for the applied voltage is shown in Fig. 4 for the counter electrode with 1.0 mm hole and 0.3 mm x 7 holes. The lower collector current than emitter current implies that the part of generated droplets deposited on the counter electrode. In the case of 0.3 mm x 7 holes, the difference between the emitter and collector current is higher than that of 1.0 mm case, and this difference increases with applied voltage. The collector current at 6 kV in the case of 0.3 mm x 7 holes is about 0.1 times lower than emitter current. When the sum of the emitter and collector current corresponds to the number of generated droplets by electrospray, 89 % of the generated droplets were considered to be deposited on the counter electrode. This could be the reason why the increase in collector current for 0.3 mm x 7 holes is suppressed as discussed in Fig. 3.

Figure 5 shows the cumulative percentage of the droplet diameter for the counter electrode with 0.3 mm x 7 holes. The data for 0 kV corresponds to the atmospheric nanoparticle in the room. By applying the electric field, it is clearly shown that the finer droplets were generated by electrospray from the porous emitter. With the applied voltage, the median diameter of the droplets decreases. The median diameter for 6 kV was 15 nm.

The CO<sub>2</sub> absorption was demonstrated by electrospraying in the closed acrylic chamber. Before the electrospray, the chamber air is replaced by CO<sub>2</sub> gas (>99.5% purity). The pressure in the closed chamber decreases with electrospray absorbing CO<sub>2</sub>. Therefore, the molar number of the absorbed CO<sub>2</sub> was obtained by measuring the chamber pressure and temperature. The time evolution of absorbed CO<sub>2</sub> is shown in Fig. 6 during 60 minutes of electrospray at 5.5 kV using the counter electrode with 1.0 mm hole and 0.3 mm x 7 holes, respectively. The ionic liquid volume in the reservoir was 0.45 mL.

The absorbed CO<sub>2</sub> increases with time even without applied electric field because the ionic liquid itself absorbs  $CO_2$ . The highest  $CO_2$  absorption was obtained for the counter electrode with 0.3 mm x 7 holes. The absorbed CO<sub>2</sub> in this case reaches 0.25 mmol after 60 minutes of spraying, which is 2.7 times higher than the case without electric field. This result comes from increased specific area of the ionic liquid droplets in space through generation of ultra-fine droplets. The improvement in CO<sub>2</sub> absorption remains 19% between the cases with counter electrode with 1.0 mm hole and 0.3 mm x 7 holes. This is because more droplets deposited the counter electrode with 0.3 mm x 7 holes by electrostatic repulsive interactions between droplets as implied from Fig. 4. Further improvement is expected by increasing the emitter intervals for less electrostatic interaction between charged droplets.

# IV. CONCLUSIONS

The fundamental characteristics of ionic liquid electrospray by porous emitter as well as the CO<sub>2</sub> experimentally absorption was clarified. The configuration of the counter electrode strongly affects the spray characteristics. For multiple porous emitters, electrospray is possible even using counter electrode with one hole, however the diameter of the hole has to be small enough for the electric field at the emitter tip being over the onset electric field for the electrospray. Finer droplets are obtained by placing the holes for each porous emitter in the counter electrode, which contributes to enhancement of CO<sub>2</sub> absorption by increasing the ionic liquid specific surface area with smaller droplets. The distance between emitters should be large enough to suppress the deposition of generated droplets on the counter electrode due to the electrostatic repulsive interaction between charged droplets.

#### ACKNOWLEDGMENT

Part of this work was supported by JSPS KAKENHI Grant Numbers 16H04262 and the Collaborative Research Project of the Institute of Fluid Science, Tohoku University. Authors would like to thank Mr. Tomoki Nakajima for his technical support.

- L.A. Blanchard, D. Hancu, E.J. Beckman, and J.F. Brennecke. Green Processing Using Ionic Liquids and CO<sub>2</sub>, *Nature*, 399:28-29, 1999.
- [2] S. Babamohammadi, A. Shamiri, and M.K. Aroua. A review of CO<sub>2</sub> capture by absorption in ionic liquidbased solvents, *Reviews in Chemical Engineering*, 31: 383-412, 2015.
- [3] P.J. Carvalho, K.A. Kurnia, and J.A.P. Coutinho. Dispelling some myths about the CO2 solubility in ionic liquids, *Physical Chemistry Chemical Physics*, 18:14757-14771, 2016.
- [4] T. Makino, T. Umechy, and M. Kanakubo. CO<sub>2</sub> absorption properties and mechanisms for 1-ethyl-3methylimidazolium ether-functionalized carboxylates, *Industrial & Engineering Chemistry Research*, 55: 12949-12961, 2016.
- [5] H. Takana, K. Yamamoto, T. Makino, and M. Kanakubo. Improvement of CO<sub>2</sub> absorption by ionic liquid electrospray, *Europhysics letters (EPL)*, 131: 34002, 2020.
- [6] H. Takana, N. Hara, T. Makino, and M. Kanakubo. Effect of environmental temperature on CO<sub>2</sub> selective absorption characteristics by ionic liquid electrospray in flow system, *Journal of Electrostatics*, 114:103634, 2021.

# Hybrid Heat Exchanger And Wet Electrostatic Precipitation For Collecting Water And Saving Energy

Hui Fu<sup>1</sup>, Qinzhen Zheng<sup>2</sup>, Shuran Li<sup>3</sup>, Zhen Liu<sup>3</sup>, Keping Yan<sup>3\*</sup>
1. Huanghuai laboratory, Zhengzhou, China
2. Jiangsu Hengtong Intelligent Equipment Co.,Ltd., Suzhou, China
3. Zhejiang University, Hangzhou, China
\*e-mail: kyan@zju.edu.cn

Abstract- By cooling down the collection electrode temperature of wire-cylinder type wet electrostatic precipitator, both gas cleaning and heat saving can be simultaneously realized. Both laboratory tests and small pilot demonstrations have confirmed that the heat transfer coefficient can be enhanced by a factor of 2, and water aerosol and/or particle matter can be collected at an energy cost of around  $800 \text{kg}(\text{H}_2\text{O})/\text{kWh}$ . Considering the energy costs of per kWh and water are 0.1-0.3 CNY/kWh and 5-8CNY/t, the technique may lead to wide applications for water saving.

Keywords: Wet Electrostatic Precipitator, Ion Wind, Heat Exchanger

# 1. Technical Background

Today, two kinds of wet electrostatic precipitators (WESPs) have been widely investigated and used for particle matter (PM) collection. Traditional one is based on directly sparry water into the WESP to cool down gaseous and electrode temperature and at the same time to clean the electrodes. One drawback of such design is large amount of waste water need to be further treated. The new WESP design is based on both gaseous and electrode temperatures are reduced by the gas-liquid heat exchange processes [1,2]. Advantages of such WESP include small amounts of waste water, heat recovery via producing hot water, electrode self-cleaning due to condensed water film, improvement PM collection due to reduced gaseous velocity near the collection electrode [3,4]. Moreover, ions wind enhanced heat exchange processes have been widely reported by using corona discharge technique [5,6,7]. This paper discusses both PM collection improvement and enhancement of the heat exchange process.

# 2. Results and Discussions

Figure 1 shows schematic diagram of a single wirecylinder type wet electrostatic precipitator, the inner diameter and length are 200mm and 920mm, respectively. For heat exchange, tap water is used to cool down the outside temperature of the cylinder. The PM, gas temperature, relative humidity, and gaseous velocity are  $\leq$ 50mg/m3,  $\leq$  120°C,  $\leq$  100%, and 0.4-1.2m/s, respectively. PM grade collection efficiency, gaseous temperature drop, water collection rate and corona power consumption are used to evaluate the processes. Details were reported early [1,2]. Under similar test conditions, Figure 2 shows a photo of small pilot test set up with a gas flow rate of 10000m<sup>3</sup>/h. 19 of parallel wire-cylinder WESP are used with inner diameter of 160 mm and length of 1200 mm.



Fig.1 laboratory test setup



Fig.2 pilot test setup

## 2.1 Effects on heat exchange coefficient

Figurec3 shows typical effects of the applied voltage, gaseous velocity, relative humidity, inlet gaseous temperature, and initial PM concentration on the heat transfer coefficient. The heat transfer coefficient is defined by Newton's law of cooling as expressed as:

$$\mathbf{q} = \mathbf{k} \cdot \mathbf{A} \cdot \Delta T_m \tag{1}$$

where,

q: Heat transfer rate (W)

k: Heat transfer coefficient (W/m<sup>2</sup>K)

A: Surface area of contact (m<sup>2</sup>)

 $\Delta T_m$ : Log Mean Temperature Difference (LMTD) as defined as below.

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\Delta \frac{T_1}{\Delta T_2}\right)} \tag{2}$$

where:

 $\Delta T_1$ : Temp difference at one end of the exchanger.  $\Delta T_2$ : Temp difference at the other end.

The coefficient  $k_0$  refers to the observed data without applying voltage. The ratio  $k/k_0$  is used to evaluate the enhancement factor. When the voltage is below the corona inception value, the electrostatic field has almost no effect on the coefficient. With increasing the applied voltage, the ratio rises from 1 to 2 due to ions wind, PM collection and condensation of water film on the inside wall of the cylinder.



Fig.3 shows typical effects of applied voltage, gaseous velocity, relative humidity, and inlet gaseous temperature, initial PM concentration on the heat transfer coefficient.

#### 2.2 Water collection and PM collection

Figure 4 shows typical PM collection efficiency via the applied voltage. Previous experimental observation via Particle Image Velocity (PIV) have confirmed that due to the water film on the collection electrode, the ions wind induced vortex can be significantly limited, as a result the PM collection efficiency is improved. Outlet PM concentration can be easily down to less than 5mg/m<sup>3</sup>. Figure 5 shows water collection rate via the applied voltage. By reducing gaseous velocity and increasing the applied voltage, the water collection rate rises from about 1.5kg/h to about 3.5kg/h, which is in agreement with the enhancement of the heat exchanger coefficient as shown in Fig.2. The gaseous temperature drops with increasing the applied voltage from about 10°C to 20°C.



Fig.4 shows typical PM collection



Fig.5 shows typical water collection

With regard to the small pilot test, the same heat exchange coefficient enhancement was observed, but due to its small size, the temperature drop and water collection rate become smaller in contrast to laboratory results as shown in Fig.6 and Fig.7. And typical energy cost is shown in Fig.8.



Fig.6 Temp drop via the applied voltage



Fig.7 Water collection rate via the applied voltage

#### 3. Conclusion

Both laboratory and pilot tests confirmed that the hybrid wet electrostatic precipitator can be used not only for PM and/or aerosol collection, but also for energy recovery with very little waste water generation. It is expected to use the technique for several kinds of industries, such as coal-fired power plants for water saving, phosphorus collection and gasification for PM collection. For industrial applications, however, the ESP sizing methods must be revised according to the following observations:

- In contrast to traditional wet ESP, the gas velocity should be reduced from 2-3m/s to be less than 1m/s in order to achieve a significant temperature or a large amounts of water collection. Both positive and negative corona can be used for the industrial systems.
- 2) A factor of two heat transfer coefficient enhancement is reliable for evaluating energy saving and/or the electrode area. Electrode shape, however, should be further optimized to have a very compact system.
- 3) Both positive and negative corona can be used for the industrial systems.

## Reference:

- 1. H. Fu, W. Xu, S. Li Z. Liu and K. Yan, "Convective heat transfer enhancement by corona discharge in a wire–cylinder electrostatic precipitator with the water-cooling system", Journal of Electrostatics. 2023, 125: 103845
- H. Fu, W. Xu, Z. Liu, K. Yan, "Fog Droplet Collection by Corona Discharge in a Needle-Cylinder Electrostatic Precipitator with a Water-Cooling System", Separations, 9 (2022) 169.
- Z. Ning, L. Cheng, X. Shen, S. Li, K. Yan, "Electrode configurations inside an electrostatic precipitator and their impact on collection efficiency and flow pattern", The European Physical Journal D, 70 (2016).
- S. Li, M. Li, J. Ma, Y. Fu, Y. Tian, X. Shen, J. Li, W. Zhu, Y. Ke, H.L. Clack, K. Yan, Characterization of electrohydrodynamic flow in a plate-plate electrostatic precipitator with a wire-cylinder precharger by data-driven vortex and residence time analysis, Powder Technology, 397 (2022) 117015.
- 5. J. Wang, T. Zhu, Y. Cai, J. Zhang, J. Wang, "Review on the recent development of corona wind and its application in heat transfer enhancement", International Journal of Heat and Mass Transfer, 152 (2020) 119545.
- 6. B.L. Owsenek, J. Seyed Yagoobi, Theoretical and Experimental Study of Electrohydrodynamic Heat Transfer Enhancement Through Wire-Plate Corona Discharge, Journal of Heat Transfer, 119 (1997) 604-610.
- 7. N. Zehtabiyan Rezaie, M. Saffar Avval, K. Adamiak, Forced convection heat transfer enhancement using a coaxial wire-tube corona system, Journal of Electrostatics, 103 (2020) 103415.



Fig.8 shows typical water collection cost via the applied voltage

# Modeling Steady Electrothermal Convection Using Physics-Informed Neural Networks

Q Wang<sup>1,2</sup>, YF Guan<sup>3</sup>, P. A. Vázquez<sup>4</sup>, J Wu<sup>1\*</sup>

<sup>1</sup>School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

<sup>2</sup>Suzhou Research Institute of HIT, Suzhou 215104, China

<sup>3</sup> Department of Mechanical Engineering, Union College, Schenectady, NY, USA

Dept. of Applied Physics III, ETSI, Universidad de Sevilla, Sevilla, Spain

\*Corresponding author: jian.wu@hit.edu.cn

Abstract- This work presents a physics-informed neural network framework for solving steady-state electrothermal convection problems in electrohydrodynamics. The results show that Tanh activation coupled with dimensional governing equations yields better convergence, and integrating Ray Tune for dynamic hyperparameter optimization significantly improves training efficiency. Compared to traditional methods, the PINN offers faster predictions with comparable accuracy, though charge density estimates need refinement. Overall, the framework improves computational efficiency by up to 52%, including data preparation and training.

Keywords- Physics-Informed Neural Networks, Electrohydrodynamics, Electro-thermal Convection, Hyperparameter Optimization, Charge Injection.

#### I. INTRODUCTION

Electrohydrodynamics (EHD) studies the interaction between electric fields and dielectric media such as liquids, and crystals, integrating concepts gases, from electrodynamics, fluid mechanics, electrochemistry, and heat transfer<sup>[1]</sup>. Electrothermal convection (ETC), a key topic in EHD, poses numerical challenges due to the strong coupling among electric, thermal and flow fields, especially in complex geometries or multiscale problems where traditional methods demand fine grids and high computational cost [2]. Physics-Informed Neural Networks (PINNs) offer an efficient alternative by embedding governing PDEs into the loss function, enabling mesh-free, physics-constrained learning of solution fields. This enhances efficiency and reduces solver complexity. The core principle of PINNs is to incorporate the governing partial differential equations directly into the loss function of deep learning models. Unlike traditional numerical methods that rely heavily on fine mesh generation and iterative solvers, PINNs leverage neural networks to approximate the solution fields while inherently satisfying the physical laws. This approach not only enhances computational efficiency but also reduces the dependency on mesh resolution and solver complexity.

Currently, numerous studies have successfully applied PINNs to CFD, highlighting the practical potential of this approach. Zou et al.<sup>[3]</sup> proposed a method using PINNs to solve 2D Rayleigh-Bénard convection problems, overcoming the limitations of traditional numerical methods. Patricio Clark Di Leoni et al.<sup>[4]</sup> investigated the ability of PINNs to reconstruct turbulent RBC using only temperature data. The results show that at low Rayleigh, PINNs yielded results comparable to nudging methods, while at higher Rayleigh, PINNs outperformed nudging, achieving satisfactory reconstruction of the velocity field when high-resolution spatial and temporal temperature data were provided. Moreover, PINNs have shown exceptional performance in inverse time prediction problems, significantly enhancing the accuracy of future predictions. For instance, Lucor et al.<sup>[5]</sup> enhanced the

PINNs training process by relaxing the incompressibility condition in the PDE residuals, which improved both the convergence and the model performance.

This study focuses on developing a PINN solver capable of automatically performing hyperparameter optimization for the rapid prediction of steady-state ETC flow. A comprehensive evaluation of the accuracy and efficiency of the PINN solver is conducted, laying the foundation for future research on applying PINNs to transient predictions and electro-thermal turbulence.

#### II. METHODOLOGY

A. Configuration, governing equations, and boundary conditions

In this study, we investigate the two-dimensional electro-thermal convection process within a square cavity with slip boundaries, which represents a common physical configuration in EHD research. Fig. 1 shows a graphical representation of the physical configuration.





Under the weakly compressible Boussinesq approximation, and ignoring the influence of charge diffusion, the governing equations for ETC flow include:

$$\nabla \cdot \mathbf{u} = \mathbf{0} \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P + \mu \nabla^2 \mathbf{u} - \mathbf{g}\beta(\theta - \theta_0) + \frac{q\mathbf{E}}{\rho}$$
(2)

$$\frac{\partial \theta}{\partial t} + \nabla \cdot (\mathbf{u}\theta) = \kappa \nabla^2 \theta \tag{3}$$

$$\frac{\partial q}{\partial t} + \nabla \cdot (q\mathbf{u} + q\mathbf{E}) = 0 \tag{4}$$

$$\nabla^2 \phi = -\frac{4}{\varepsilon} , \mathbf{E} = -\nabla \phi \tag{5}$$

The characteristic length is *H*, characteristic velocity is chosen as the charge drift velocity  $U_r = \frac{K\phi_1}{H}$ , the characteristic temperature is  $(\theta_1 - \theta_0)$ . The characteristic electric potential and charge density are denoted by  $\phi_1$ and  $q_1$  respectively. The resulting nondimensional governing equations are given as follows:

$$\nabla^* \cdot \mathbf{u}^* = \mathbf{0}$$
(6)  
$$\frac{\partial \mathbf{u}^*}{\partial t^*} + (\mathbf{u}^* \cdot \nabla^*) \mathbf{u}^* = -\nabla^* P^* + \frac{M^2}{T} \nabla^2 \mathbf{u}^* - \frac{M^4 R a}{T^2 P r} \theta^*$$
(7)

$$\frac{\partial \sigma}{\partial t^*} + \nabla^* \cdot (\mathbf{u}^* \theta^*) = \frac{n}{TPr} \nabla^2 \theta \tag{8}$$

$$\frac{1}{\partial t^*} + \nabla^* \cdot (q^* \mathbf{u}^* + q^* \mathbf{E}^*) = 0$$

$$\nabla^{*2} \phi^* = -Cq^* \cdot \mathbf{E}^* = -\nabla^* \phi^*$$
(10)

 $\nabla^{*2}\phi^* = -Cq^*$ ,  $\mathbf{E}^* = -\nabla^*\phi^*$  (10) Here, the dimensionless parameter *T* is the electric Rayleigh number, representing the ratio of electric force to viscous force. Parameter C denotes the charge injection intensity, and *M* is the ratio of hydrodynamic mobility to ionic mobility. Ra is the Rayleigh number, which characterizes the convective heat transfer capability of the system. *P*r is the Prandtl number, determined by the physical properties of the fluid.

$$C = \frac{q_0 H^2}{\varepsilon(\phi_1 - \phi_0)} \qquad M = \frac{(\varepsilon/\rho)^{0.5}}{K} \qquad T = \frac{\varepsilon(\phi_1 - \phi_0)}{\mu K}$$
$$Ra = \frac{g\beta(\theta_1 - \theta_0)H^3}{k\nu} \qquad Pr = \frac{\nu}{k}$$

#### B. Multilayer Physics-Informed Neural Network

In this study, a multilayer PINN is developed to solve the ETC problem. The architecture of the PINN is schematically illustrated in Fig. 2. The network consists of an input layer, multiple hidden layers, and an output layer. The input layer receives two-dimensional Cartesian coordinates, while the output layer simultaneously predicts the relevant physical fields, including velocity components, pressure, temperature, electric potential, and charge density.





A notable feature of the ETC system is the large disparity in the magnitudes of different physical quantities.

To mitigate the risk of gradient imbalance and biased weight updates during training, all input coordinates and output variables are normalized.

$$Data_{norm} = \frac{Data - mean(Data)}{std(Data)}$$
(11)

Additionally, neural network training employs Adam optimizer, which adaptively estimates the first- and second-order moments of the gradients to assign individual learning rates to each parameter. To further enhance training efficiency and robustness, a learning rate scheduling strategy based on ReduceLROnPlateau is adopted.

#### C. Error assessment

In this study, the mean squared error (MSE) is adopted as the loss metric due to its smoothness, differentiability and its tendency to penalize larger errors more heavily, which supports stable and efficient gradient-based optimization.

$$MSE = \frac{1}{N} \sum_{i=1}^{N} \left( Data_{PINN}^{i} - Data_{exact}^{i} \right)^{2}$$
(12)  
$$Loss = Loss_{GE} + Loss_{BC} + Loss_{Data}$$
(13)

MSE offers a unified and interpretable framework for integrating multiple loss components while maintaining consistency with the physical objective of minimizing the average prediction error.

#### **III. RESULTS**

#### A. Hyperparameter optimization

Hyperparameter optimization is an important process to ensure the efficiency and accuracy of PINNs. In this study, we systematically investigate the effects of four commonly used activation functions in fluid dynamics problems, namely Tanh, SiLU, ReLU, and LeakyReLU. The governing equations used for training include both the dimensional form (Equations 1–5) and the nondimensional form (Equations 6–10).

Fig.3 illustrates the evolution of the  $L_2$  norm of the velocity in the *x*-direction with respect to the number of training iterations, under different activation functions and for both dimensional and non-dimensional forms of the governing equations. As shown, the most effective setup for solving the ETC is to employ the dimensional governing equations together with the hyperbolic tangent (Tanh) activation function.



Fig. 3 Comparison of  $L_2$  errors for x-direction velocity (u) with different activation functions at C=1, M=10, T=200, Ra=10000, Pr=0.7

The Ray Tune HPO framework is also integrated into the PINN architecture to enable automated and adaptive tuning of key hyperparameters. Ray Tune is a distributed hyperparameter tuning library in Python that offers advanced features such as automated sampling, parallel execution, and support for various search algorithms. It performs random sampling within predefined hyperparameter ranges, evaluates the resulting configurations by computing the corresponding global loss, and identifies the optimal configuration from the sampled candidates. The HPO workflow using Ray Tune is illustrated in Fig. 4.



Fig. 4 Ray Tune-Based Hyperparameter Optimization Workflow

According to the Ray Tune optimization results, the best performing model consists of 4 hidden layers with 80 neurons per layer, a learning rate of 0.00408634, and the Tanh activation function. The choice of activation function is consistent with previous findings, further validating the selection. Fig. 5 illustrates the evolution of the global MSE loss during training using the hyperparameter configuration optimized by Ray Tune. It can be observed that the hyperparameters identified through Ray Tune significantly accelerate the decrease of the MSE loss, demonstrating the necessity and effectiveness of the HPO process.



Fig. 5 Effect of Ray Tune-Based Hyperparameter Optimization on MSE Loss Evolution During Training

# B. PINN prediction

In previous tests, we established a complete PINN framework for solving ETC flows and employed Ray Tune to identify the optimal hyperparameter configuration, thereby enhancing the generalizability of the model. In the following section, this trained PINN will be applied to solve ETC problems, and its predictions will be compared against high-fidelity FVM simulation results to evaluate the accuracy of the PINN-based solution.

A representative case is considered in this study as shown in Fig. 1. The domain dimensions were set to  $L_x=3H$  and  $L_y=H$ . The bottom plate was configured as a high-temperature, high-voltage electrode, while the top plate served as a low-temperature grounded electrode. The left and right boundaries are treated as slip walls. The dimensionless parameters were kept consistent with the previous case: Ra=10000, C=1, M=10, T=200. Figs. 5 and 6 present a comparison between the PINN results and the CFD reference solution.



Charge distribution Fig. 6 Comparison of the space distribution at Ra=10000, C=1, M=10, T=200: (left) High-resolution FVM solution; (right) PINN results



Fig. 7 Comparison between PINN and high-resolution FVM solutions at *Ra*=10000, *C*=1, *M*=10, *T*=200

As shown in Figs. 6 and 7, the PINN is able to accurately reconstruct the spatial distributions of velocity, temperature fields, and electric potential. However, due to the steep gradients in the charge density distribution, the network struggles to capture highly accurate values in regions of sharp variation. Nevertheless, it still succeeds in reproducing the overall spatial pattern and trend of the charge distribution with reasonable fidelity. This issue is primarily attributed to the inability of coarse-mesh CFD training data to accurately capture the charge density distribution. Improving the accuracy of training data can alleviate this limitation to some extent; however, generating high-fidelity data requires significantly increased computational cost, which partly contradicts the original motivation of using PINNs for efficient and rapid prediction.

Finally, we evaluate the practicality of the PINN approach from the perspective of computational efficiency.

Taking the last case as an example, the fine-mesh finite volume simulation using OpenFOAM required 15 hours on a 32-core CPU. In comparison, the training of the GPU-based PINN model took approximately 7 hours and 12 minutes, while the generation of the coarse-mesh supervision data required only 35 minutes. Considering the training time, this results in an overall efficiency improvement of approximately 52%. More importantly, once trained, the PINN model can be reused to reconstruct high-resolution flow fields in under 5 seconds, representing a substantial gain in prediction speed for ETC flows. Therefore, although the predictive accuracy of PINNs may still fall short of high-fidelity CFD solvers, their ability to deliver rapid approximations makes them a highly attractive tool for real-time or iterative applications.

## V. CONCLUSION

In this study, Physics-Informed Neural Networks are applied to model steady-state electro-thermal convection in electrohydrodynamic systems. The effectiveness of different activation functions is systematically evaluated, and the Ray-Tune algorithm is used for dynamic hyperparameter optimization, significantly improving training efficiency. The trained PINN is validated on two representative EHD scenarios, demonstrating high accuracy in capturing key flow and temperature features. A comparative analysis with conventional CFD methods highlights the advantages of the PINN approach in terms of both computational efficiency and predictive performance. The main findings are as follows:

- 1. The combination of the Tanh activation function and the governing dimensional equations yields optimal performance. Ray Tune further enhances training efficiency by enabling automated hyperparameter tuning.
- 2. The PINN model effectively reconstructs the spatial distributions of velocity, electric potential, and temperature. While predictions of charge density show reduced accuracy due to coarse training data and steep spatial gradients, the overall distribution trend is well captured.
- 3. Compared to traditional CFD, the PINN method improves computational efficiency by up to 52%, even when accounting for data preparation and training time. Once trained, the model can generate high-fidelity predictions within 5 seconds, making it highly suitable for rapid simulations.

In summary, this work demonstrates the potential of integrating PINNs into EHD modeling and offers a novel framework for physics-driven and data-efficient simulation. Future research will further explore the reconstruction and prediction of transient EHD phenomena using PINNs.

# ACKNOWLEDGMENTS

Author Q. Wang supported by the Heilongjiang Province Postdoctoral General Funding (Grant No. AUGA4110006724) and Postdoctoral research start-up funds, HIT (Grant No. AUGA5710027524).

Author P.A. Vázquez acknowledges the grant PID2022-138890NB-I00 funded by

#### MCIN/AEI/10.13039/501100011033.

- [1] Jones T B. Electrohydrodynamically enhanced heat transfer in liquids—a review [J]. Advances in heat transfer, 1979, 14: 107-148.
- [2] Wang Y, Qin G, He W, et al. Spectral element method for numerical simulation of ETHD enhanced heat transfer in an enclosure with uniform and sinusoidal temperature boundary conditions [J]. International Journal of Heat and Mass Transfer, 2019, 141: 949-963..
- [3] Zhang Q, Guo X, Chen X, et al. PINN-FFHT: A physics-informed neural network for solving fluid flow and heat transfer problems without simulation data [J]. International Journal of Modern Physics C, 2022, 33(12): 2250166.
- [4] Hammoud M A E R, Alwassel H, Ghanem B, et al. Physics-informed deep neural network for backwardin-time prediction: Application to Rayleigh–Bénard convection [J]. Artificial Intelligence for the Earth Systems, 2023, 2(1): e220076.
- [5] Lucor D, Agrawal A, Sergent A. Simple computational strategies for more effective physicsinformed neural networks modeling of turbulent natural convection [J]. Journal of Computational Physics, 2022, 456: 111022.

# Numerical Simulation for Decomposition of Organic Compounds in Water by Plasma Generated above Solution under Consideration of EHD-induced Liquid Flow

Nozomi Takeuchi\*

Department of Electrical and Electronic Engineering, Institute of Science Tokyo, Japan \*Corresponding author: takeuchi@ee.eng.isct.ac.jp

Abstract- The effect of liquid flow on decomposition of organic compounds in water using a plasma generated above the solution was investigated using a two-dimensional numerical simulation of pulsed argon plasma that was generated between a needle electrode and a solution surface. The behavior of the reactive oxygen species generated by the plasma was calculated by considering electron-impact reactions, gas- and liquid-phase reactions, and mass transfer, assuming a gas-liquid equilibrium on the interface and flux continuity through the interface, under consideration of EHD-induced liquid flow. The numerical results indicated that even a weak liquid flow could drastically change the liquid-phase chemistry.

Keywords- Plasma, EHD-induced liquid flow, decomposition of organic compounds, numerical simulation.

#### I. INTRODUCTION

Gas-liquid interfacial plasma generated on the surface of a liquid or in a liquid is expected to be used as an advanced water treatment technology to decompose persistent organic compounds by highly reactive OH radicals (•OH). •OH has a short lifetime due to its high reactivity, and it is important to make generated •OH react with decomposition targets effectively. The reaction process is complex, involving a gas phase including plasma, gas-liquid interface, and liquid phase. Understanding the complex reaction process is essential for effective and efficient water treatment, but there are many factors that are difficult to measure quantitatively, such as the precise distribution of radical densities. Therefore, a numerical simulation is an effective tool for understanding the reaction processes in gas-liquid interfacial plasmas.

Recently, the formation of flow in the liquid phase by pulsed plasma generated on the water surface has been reported [1],[2]. In this study, the importance of liquid flow was evaluated by simulating the reaction of acetic acid decomposition using argon pulsed plasma generated above the acetic acid solution.

#### II. REACTION MODEL

Numerical simulations were performed using COMSOL Multiphysics<sup>®</sup>. As shown in Fig. 1, an axisymmetric 2D model was built. For details of the reaction model, please refer to [3].

The treatment solution was an aqueous acetic acid solution with a total organic carbon (TOC) concentration of 10 mg<sub>TOC</sub>/L. The gap length between the needle tip and the water surface was 1 mm. The discharge gas was argon containing 3% water vapor. A positive pulsed voltage of 3 kV peak, 200 ns pulse width, and 1 kHz repetition rate was applied to the needle electrode to simulate the argon

plasma formed between the needle tip and the water surface. The particles considered are  $e^-$ , Ar, Ar<sup>+</sup>, Ar<sup>\*</sup>, H<sub>2</sub>O, H<sub>2</sub>O<sup>+</sup>, •OH, H•, HO<sub>2</sub>•, H<sub>2</sub>O<sub>2</sub>, and CH<sub>3</sub>COOH.

In the present reaction model, the formation of  $\bullet$ OH in the liquid phase by positive ion irradiation of the water surface or ultraviolet light irradiation is neglected. Basically, the active species produced in the gas phase by the plasma are transported to the liquid phase through the gas—liquid interface. The mass transfer of reactive oxygen species through the gas—liquid interface was calculated by imposing the following two boundary conditions for each species:

$$D_{\rm gas} \frac{\partial C_{\rm gas}}{\partial z} = D_{\rm liq} \frac{\partial C_{\rm liq}}{\partial z}, \qquad (1)$$

$$C_{\rm liq} = HRT_{\rm gas}C_{\rm gas}, \qquad (2)$$

where  $D_{\text{gas}}$  and  $D_{\text{liq}}$  are the diffusion coefficients in the gas and liquid phases, respectively, and were set to  $10^{-5}$  m<sup>2</sup>/s and  $10^{-9}$  m<sup>2</sup>/s for all species.  $C_{\text{gas}}$  and  $C_{\text{liq}}$  are the densities of the species in the gas and liquid phases, respectively. *H* is Henry's constant, *R* is the gas constant, and  $T_{\text{gas}}$  is the



Fig. 1. Simulation model geometry.



Fig. 2. Assumed liquid flow induced by plasma.

gas temperature set at 300 K. The flux at the gas–liquid interface was assumed to be continuous according to (1), thus satisfying the mass conservation law. Equation (2) assumes that the gas–liquid interface is in equilibrium according to Henry's law.

To see the effect of the liquid-phase flow, calculations were performed with and without the flow shown in Fig. 2.

#### **III. RESULTS AND DISCUSSION**

Gas-phase •OH was mainly produced by the dissociation of water molecules by metastable argon atoms (Ar\*). Therefore, the •OH density was high near the water surface, where much amount of Ar\* was produced due to high electron number density and electron energy. The gas-phase •OH density increased during the 200 ns of voltage application and then decreased due to a self-quenching reaction producing  $H_2O_2$ .

A small portion of •OH produced near the water surface and  $H_2O_2$  produced by the self-quenching reaction of •OH diffuse into the liquid phase. The instantaneous reaction rates of •OH with different species in the liquid phase during one period of the applied voltage at 1 kHz are shown in Fig. 3(a) without and Fig. 3(b) with the liquid flow, respectively. In the case of no liquid flow, only diffusion transported the species. Since the diffusion coefficient in the liquid phase is very small, the concentrations of  $H_2O_2$  and  $HO_2$ • near the water surface were very high, consuming much amount of •OH in the liquid phase. Considering the liquid flow, the concentrations of  $H_2O_2$  and  $HO_2$ • became lower due to their convection, and the amount of •OH contributing to the decomposition of  $CH_3COOH$  increased by a factor of 2.5. Thus, even a very weak flow with a velocity of about 1 cm/s has a significant effect on the reaction process in the liquid phase.

#### ACKNOWLEDGMENT

This work was partially supported by JSPS KAKENHI Grant Number JP23K26088.

- [1] S. Kanazawa, H. Kawano, S. Watanabe, T. Furuki, S. Akamine, R. Ichiki, T. Ohkubo, M. Kocik, and J. Mizeraczyk. Observation of OH radicals produced by pulsed discharges on the surface of a liquid, *Plasma Sources Sci. Technol.*, 20:034010, 2011.
- [2] T. Shimizu, Y. Iwafuchi, G.E. Morfill, and T. Sato. Transport mechanism of chemical species in a pinwater atmospheric discharge driven by negative voltage, *J. Photopolym. Sci. Technol.*, 24:421–427, 2011.
- [3] N. Takeuchi, M. Ando, and K. Yasuoka. Investigation of the loss mechanisms of hydroxyl radicals in the decomposition of organic compounds using plasma generated over water, *Jpn. J. Appl. Phys.*, 54:116201, 2015.



Fig. 3. Instantaneous reaction rate of •OH in liquid phase, (a) without liquid flow, (b) with liquid flow.

# Estimation of electrospray droplet diameters using Current-Voltage characteristics "with and without" liquid flow

Rukhsar Parveen<sup>1</sup>, Hitesh Rawate<sup>1</sup>, Rochish M Thaokar<sup>1\*</sup>, Arshad Khan<sup>2</sup>, Y S Mayya<sup>1</sup>

<sup>1</sup>Department of Chemical Engineering, Indian Institute of Technology Bombay, Mumbai -400 076 <sup>2</sup>Radiological Physics & Advisory Division, Bhabha Atomic Research Centre, Mumbai -400 085 \*Corresponding author: <u>rochish@iitb.ac.in</u>

# Abstract:

Electrospray-based systems have been extensively studied for ionization mass spectrometry, nanoparticle synthesis, size reduction, drug delivery and in recent times as possible air cleaners. The initial droplet diameters of an electrospray are important parameters which govern the emergent size distributions as well as the subsequent dynamics of the electrospray-based device. We propose a first principle semi-theoretical approach, validated by comparison with scaling laws as well as previous experimental data available in literature, to estimate these diameters from the information of the measured currents. It has been known that electrospray currents are often associated with corona discharge that makes it difficult to ascribe the currents entirely to droplet charges. We examine this problem afresh by measuring currents with (spray mode) and without (dry mode) liquid, using water-ethanol mixture. The low voltage (<5 kV) current (stable cone jet regime) information crucially enables us to combine the measured currents with Rayleigh critical charge information and establish the upper bound droplet sizes. The results also have implications to the development of electrospray devices with minimal corona discharge currents.

Keywords: Electrospray, Current- Voltage Estimation, Droplet Diameter

# I. Introduction

Electrospray devices have been extensively used in ionization mass spectrometry [1], [2], nanoparticle synthesis [3], [4], drug delivery [5] etc. In recent times attempts also have been made to explore their potential as air cleaners [6], [7], [8]. The current-voltage response of an electrospray device provides fundamental characteristics of its operation[9]. The electrospray droplets carry high charges and undergo evaporation leading to successive Rayleigh break up in the course of their traversal towards the ground plate [10]. The breakup process determines the size distribution of the satellite nano-droplets. The charges carried by electrospray droplets depend upon the flow-rate and the applied potential or equivalently [11], the currents in the system. In this paper we argue that from the information on the measured currents, it is possible to establish an upper bound on the original size of the mother droplets by invoking the Rayleigh critical charge. It may be noted that electrospray droplet size measurements are difficult requiring sophisticated, expensive instrumentation such as phase-doppler anemometry. In the light of this, a semi-theoretical approach proposed here might be useful in providing a first estimate the droplet sizes at the stage of stable cone-jet mode. However as shown by previous investigators [9] there could be significant influence of corona discharge on the electrospray current, which makes it difficult to ascribe

the currents entirely to the liquid jet. To take a step forward, it is necessary to delineate the corona current. This is often done using light emission measurements [12]. In the present study, we measured the currents across the nozzle and ground plate without (dry mode) and with liquid flow. The dry mode currents are unequivocally attributed to corona discharge and this was compared with currents with the liquid. In a general context, an understanding of the current-voltage characteristics is essential for characterizing various aspects associated with the droplet dynamics and breakup in electrosprays.

In this study, we examine the dependence of estimated diameters on droplet flow rate using current-voltage data for a specific case of water-ethanol electrospray system. This system is chosen for a potential future application of nanoparticle generation of water-soluble compounds. The estimated droplet diameters are also compared with the theoretical predictions using the formula derived from scaling laws [13].

# II. Methodology

The purpose of this study is to develop a simple methodology for providing a first estimate of electro sprayed mother droplet diameters. A knowledge of the primary (mother) droplet diameter in turn provides critical insight into the characteristics of secondary (daughter) droplets formed through a cascading breakup process. Accordingly, we present the setup employed and the experimental details of the current measurement in electrospray systems.

#### **Devices and Components**

#### i. Body of spray:

Researchers have used needles, orifices, wicks etc. for electrospray formation on the basis of applications. Although, needle-based electrosprays are preferable due to robustness and ease of uses. We have used SS based blunt needles (Nordson Corporation) with 0.25 mm inner and 0.52 mm outer diameters.

## ii. Liquid Composition:

Various liquids have been used in literatures for electrospray generation. Our focus is on water-based electrospray. However, its high surface tension hinders stable electrospray formation. To overcome this, a 50% ethanol with 50% DI water mixture was used, reducing the surface tension to approximately 0.03 N/m, sufficient for generating stable electrosprays at lower voltages.

## **iii.** *Liquid delivery method:*

We used the syringe pump (NE-1000) for maintaining liquid flow. While, one can also use gravity driven flow, it is difficult to manage the flow rate in gravity driven flow and hence syringe pump is chosen.

iv. Power supply:

A DC potential was applied using a function generator (Agilent 33220A) and amplifier (Trek 20/20C-HS), with the positive potential in the liquid. A grounded plate placed 30 mm from the needle tip established the electric field.

# v. Current measurement:

A pico-ammeter (SES Instruments, DPM111) is used for measuring the current between the needle and the ground electrode.

# **Experimental Procedure:**

# i. Current-Voltage Curve:

The electrospray exhibits distinct operational modes depending on the applied potential, which can be inferred from the measured current data. For various flow rates, the corresponding electrospray current was recorded across a range of applied voltages. The resulting current-voltage characteristics are presented in Fig. 1. The current value for the stable cone-jet mode was used to estimate the charge density.

## ii. Relationship with Droplet Diameter:

If the current measured at the stage of formation of a stable electrospray is denoted by (*I*) for a liquid flow rate ( $Q_f$ ), then the volumetric charge density ( $\rho_c$ ) in the fluid is defined as,  $\rho_c = \frac{I}{Q_f}$ . We now assume that this charge density is uniform across all droplet sizes. In that case, the total charge ( $Q_d$ ) carried by a typical droplet of size *d*, is

$$Q_d = \rho_c \, \frac{\pi}{6} d^3 = \frac{\pi}{6} \frac{I}{Q_f} d^3, \qquad [1]$$

It would be true for all the droplet sizes. However, due to the presence of electric charge, the droplets will develop Rayleigh instability if the charge contained in the droplet exceeds its Rayleigh limit, given by,

$$Q_R = (8 \pi^2 \epsilon_0 \gamma d^3)^{1/2}.$$
 [2]

Where,  $\epsilon_0$  is the permittivity of free space and  $\gamma$  is the surface tension of liquid.

Since droplets cannot exist with charges higher than the Rayleigh charge  $(Q_R)$ , the crossover point is the diameter at or below which the droplets will exist. Since Rayleigh break-up process involves expelling large charge (40%) with very little (~1-4%) loss of mass [14], the size of the primary droplets will alter very little in the initial stages. This is essentially an upper limit since evaporation and break up events will eventually create a broad droplet spectrum as they traverse in the electrospray.

# III. Results & Discussion

# i. Current- Voltage Characterization

The operational modes of the electrospray system in Fig. 1, consist of measured current with increasing applied voltage under two distinct conditions of "with and without (dry mode)" liquid flow. The electrospray attains stable cone-jet mode in the potential range of 3.5 kV to 5 kV as confirmed by visual observation. Also, the data indicate that at low applied potentials (<5 kV), the currents "with liquid" are distinctly higher than those in the "dry" mode. The negligible currents observed below 6 kV in the "with liquid" case suggests the absence of corona discharge in this voltage range. Hence at the onset of the cone jet mode, the measured



Fig. 1: Current- Voltage characteristic curve for different liquid flow rates and in dry mode

currents "with liquid" may almost entirely be assumed to be due to liquid flow. This information crucially enables us to combine the measured currents with Rayleigh critical charge information and establish upper bound droplet sizes. In contrast, the currents for the cases of both "with liquid" and "without liquid" approach each other at higher potentials thereby pointing at a corona-assisted electrospray regime [9].

#### ii. Estimation of Droplet Diameters

By equating the Rayleigh charge (Eq.2) with the acquired charge  $(Q_d)$  (Eq.1) at the cross-over point, we obtain the following formula for maximum droplet diameter:

$$d_{max} \approx \left(\frac{6\sqrt{8\epsilon_0\gamma}}{\rho_c}\right)^{\frac{2}{3}}$$
 [3]

Table-1 shows the droplet diameters estimated using Eq. [3] along with the diameters predicted by scaling laws [13]. Barring the low flow rate case (0.5 mL/h), the agreement between the two approaches for other flow rates is excellent. The results indicate that droplet sizes increase with flow rates, thereby validating the scaling laws.

We further test the present approach against the experimental data of Gañán-Calvo et al. (1997) [13], who employed phase-doppler anemometry to measure droplet sizes. They reported a mean droplet diameter of about 34.6  $\mu$ m for heptane having conductivity of 4.3  $\mu$ S/m, flow rate of  $1.53 * 10^{-9}$  m<sup>3</sup>/s and a current of  $4.5 * 10^{-8}$  *A*. From Eq. [3], we obtain  $d_{max} = 39 \mu$ m, which is quite close to their directly measured diameter. This agreement lends further validation to the present approach based on current measurements.

Table-1: Droplet diameters in the cone jet spray mode obtained by the present method (Eq.[3]) and from the scaling laws (Ref.[13]) at different flow rates for 50% water-ethanol mixture

Flow rate (mL/h)	Measured Current	Estimated Droplet Diameter (μm)	
	( <b>n</b> A)	This Work Eq. [3]	Scaling Laws [13]
0.5	19.0	15.99	9.62
1	41.7	15.04	13.60
3	69.3	22.28	23.55
6	68.9	35.52	33.33

# IV. Conclusion

The measurements indicate an operational regime in which the current arises predominantly from electro sprayed droplets. However, at higher applied potentials, the observed current remains relatively similar, suggesting the possible contribution of corona-assisted droplet spray.

Also, the semi-theoretical approach presented in this paper, validated by scaling laws as well as available experimental data, offers a simple way to estimate primary droplet sizes. This assessment (without direct measurements) will be helpful in characterizing, modeling and optimizing the system for different applications. Although an upper bound diameter, rather than a mean, it is useful for assuring that one does not have to include droplets larger than this size in developing theoretical models. The sizes of satellite droplets, however, cannot be obtained this way and need to be estimated by detailed modelling of the evaporative shrinkage, Rayleigh break up processes and validated by instrumental technique.

#### ACKNOWLEDGMENT

This work was supported by the Board of Research in Nuclear Sciences through sanction number 59/14/11/2022-BRNS/34062

- Prabhu, G.R.D., Williams, E.R., Wilm, M. et al. Mass spectrometry using electrospray ionization. Nat Rev Methods Primers 3, 23 (2023). https://doi.org/10.1038/s43586-023-00203-4.
- [2] J. A. Loo, "Electrospray ionization mass spectrometry: a technology for studying noncovalent macromolecular complexes," *Int J*

*Mass Spectrom*, **200**, pp. 175–186, (2000), doi: 10.1016/S1387-3806(00)00298-0.

- [3] L. Y. Yeo, Z. Gagnon, and H. C. Chang, "AC electrospray biomaterials synthesis," *Biomaterials*, 26, no. 31, pp. 6122–6128, (2005), doi: 10.1016/J.Biomaterials.2005.03.033.
- [4] J. Tang, H. Wang, and A. Gomez, "Controlled nanoparticle synthesis via opposite-polarity electrospray pyrolysis," *J Aerosol Sci*, **113**, pp. 201–211, (2017), doi: 10.1016/J.JAEROSCI.2017.07.001.
- [5] R. T. Steipel, M. D. Gallovic, C. J. Batty, E. M. Bachelder, and K. M. Ainslie, "Electrospray for generation of drug delivery and vaccine particles applied in vitro and in vivo," *Materials Science and Engineering: C*, **105**, p. 110070, (2019), doi: 10.1016/J.MSEC.2019.110070.
- [6] Singh, S., Khan, A., Nakhwa, A. et al. Scavenging of Submicron Aerosol Particles by Cloud of Charged Droplets Generated from Electro-Hydrodynamic Atomizer (EHDA). Aerosol Sci Eng 5, 223–232 (2021). https://doi.org/10.1007/s41810-021-00096-4.
- [7] A. Jaworek, W. Balachandran, M. Lackowski, J. Kulon, and A. Krupa, "Multi-nozzle electrospray system for gas cleaning processes," *J Electrostat*, **64**, pp. 194–202, (2006), doi: 10.1016/J.ELSTAT.2005.05.006.
- [8] G. Tepper, R. Kessick, and D. Pestov, "An electrospray-based, ozone-free air purification technology," *J Appl Phys*, **102**, (2007), doi: 10.1063/1.2818364.
- [9] A. Jaworek, A. Sobczyk, T. Czech, and A. Krupa, "Corona discharge in electrospraying," *J Electrostat*, **72**, pp. 166–178, Apr. 2014, doi: 10.1016/j.elstat.2014.01.004.
- [10] M. Cloupeau and B. Prunet-Foch, "Electrohydrodynamic spraying functioning modes: a critical review," *J Aerosol Sci*, 25, pp. 1021–1036, (1994), doi: 10.1016/0021-8502(94)90199-6.
- [11] Z. Wang *et al.*, "An experimental study on the role of electrical conductivity in the steady cone-jet electrospray," *International Journal of Multiphase Flow*, **171**, p. 104696, (2024), doi: 10.1016/J.IJMultiphaseflow.2023.104696.

- [12] T. J. Wang *et al.*, "Direct observation of laser guided corona discharges," *Sci Rep*, 5, (2015), doi: 10.1038/srep18681.
- A. M. Gañán-Calvo, J. Dávila, and A. Barrero, "Current and droplet size in the electrospraying of liquids. Scaling laws," *J Aerosol Sci*, 28, pp. 249–275, (1997), doi: 10.1016/S0021-8502(96)00433-8.
- [14] Neha Gawande, Y.S Mayya, and Rochish Thaokar, "Numerical study of Rayleigh fission of a charged viscous liquid drop," *Phys Rev Fluids*, 2, 113603, (2017), doi: https://doi.org/10.1103/PhysRevFluids.2.11360 3.

# Surface Potential Analysis of SiO<sub>2</sub> Wafers After Two-fluid Spray with Pure Water

Y. Seike, K. ITO, I. Watanabe, Y. Ichino, N. Taoka, T. Mori

<sup>1</sup>Electrical and Electronics Engineering Course, Graduate School of Engineering, Aichi Institute of Technology

<sup>2</sup> la quaLab LLC.

\*Corresponding author: y\_seike@aitech.ac.jp

Abstract- This study examines the surface potential of SiO<sub>2</sub> wafers following two-fluid spray cleaning with pure water. Despite the positive charge of the sprayed droplets, the wafer surface ultimately becomes negatively charged, likely owing to triboelectric effects and the wafer's floating state. Needle electrode experiments confirm that the wafer surface aligns with the polarity of an applied high voltage, with potential saturation observed near  $\pm 60-120$  V. These results highlight the importance of controlling droplet velocity, wafer grounding, and water chemistry to optimize cleaning efficiency while minimizing electrostatic risks.

Keywords- electrostatic discharge (ESD), two-fluid spray, triboelectric charging, SiO2 wafer

## I. INTRODUCTION

In the modern era of advancing semiconductor miniaturization, eliminating microparticles and chemical residues from wafer surfaces is a critical challenge that directly impacts manufacturing yield and device quality [1]. Particularly in cutting-edge processes with circuit patterns at the nanometer scale, even minimal contamination can substantially affect device characteristics and result in defects. As a result, the development of highly efficient and safe cleaning technologies has become essential.

Two-fluid spray cleaning has attracted attention as an effective method that simultaneously delivers gas and liquid at high speeds, leveraging the impact energy of fine droplets along with chemical reactions to eliminate contaminants [2]. In contrast, conventional immersion cleaning applies chemical agents uniformly over the entire wafer surface, which hinders diffusion and control of solution concentrations. By accurately adjusting the spray parameters in two-fluid spray cleaning, it is possible to control droplet size and impingement force, facilitating the efficient removal of stubborn particles and photoresist residues. Moreover, this method allows for rapid cleaning, enhances throughput, and reduces the consumption of cleaning agents.

Conversely, using pure water as the fluid in two-fluid spray cleaning raises considerable concerns regarding electrostatic discharge (ESD) [3]. Owing to its low ion content, pure water exhibits extremely low electrical conductivity. The friction generated among the droplets, gas flow, and the nozzle or inner walls of the piping during high-speed spraying facilitates charge accumulation. Any subsequent discharge of this accumulated charge can damage the fine patterns and gate oxide films on the wafer, potentially resulting in a substantial reduction in yield. This risk is especially high in advanced nodes, where the insulating films are exceptionally thin and therefore possess lower ESD tolerance. Consequently, static control is essential for leveraging the benefits of two-fluid spray cleaning.

To address this issue, one approach is to inject trace amounts of carbon dioxide gas into pure water to create CO<sub>2</sub> water, or to add small quantities of ammonia, followed by hydrogen decomposition to produce ammonia hydrogen water. However, semiconductor manufacturing requires stringent limitations on impurities in the cleaning fluid, leading to strict regulations regarding the types and concentrations of additives. Ultimately, achieving a balance between cleaning effectiveness and ESD risk, along with a high level of integration in equipment design and process management, is crucial for ensuring high quality and yield. Therefore, although two-fluid spray cleaning provides robust cleaning performance, the implementation of integrated process control—especially for ESD mitigation—is vital in this advanced technology.

Previously, we measured the static charge of droplets sprayed during two-fluid spray cleaning using a Faraday cup. Under the specific nozzle and spray conditions used, we observed a positively charged current ranging from 50 to 200 nA [4]. Our hypothesis posited that these charged droplets transferred their charge to the wafer upon contact, thereby generating static electricity. In this report, we measured the potential on the surface of a SiO<sub>2</sub> wafer following two-fluid spraying. We discovered that the areas of the wafer affected by the droplets displayed a negative polarity, reaching a value of -5 V. Additionally, we identified the factors contributing to this phenomenon.

#### II. TWO-FLUID SPRAY FOR CLEANING SEMICONDUCTOR DEVICES

Figure 1 shows the process of two-fluid spray cleaning. The two-fluid spray nozzle used in this study is an internal mixing type, which combines gas and pure water in the nozzle before spraying. The resulting atomized droplets are directed onto the wafer, with cleaning achieved through the impact of these fine



Fig. 1. Appearance of two-fluid spray cleaning



Fig. 2. Relationship between generated current, pure water flow rate, and air flow rate

droplets. The cleaning effectiveness is influenced by the droplets' velocity, size, and the flow rate of the pure water. The main parameters for regulating these factors are the gas flow rate (compressed air in this experiment) and the flow rate of pure water supplied to the two-fluid nozzle.

We assessed the static electricity generated by capturing the sprayed droplets in a Faraday cage and measuring the current flowing between the cage and the ground. Figure 2 shows the measured current in relation to variations in the pure water flow rate and air flow rate. The black dots in the figure denote measurement points recorded at 0.5-s intervals, while the overlaid surface represents a local regression smoothed from the measured values. The measured current generally increases with an increasing air flow rate. As shown in Figure 2, the droplets exhibit positive polarity, and increasing the droplet velocity enhances the amount of generated static charge. Additionally, based on our findings and those of Kanno et al., higher droplet velocity results in stronger cleaning power [5]. Therefore, there is a trade-off between cleaning power and the amount of generated static electricity [6, 7].

# III. EXPERIMENTAL

Figures 3 and 4 show the experimental apparatus and procedure, respectively. The  $SiO_2$  wafer used in this experiment is a 4-inch p-type wafer featuring a 1,000-Å-thick oxide layer with a <1,0,0> orientation. The cleaning apparatus operates as a spin-type system, and because the

cup is composed entirely of resin, it cannot be grounded, resulting in the wafer being in a floating state. The silicon wafer is placed on a stage in the cleaning chamber, on top of a copper plate, which is grounded only during the measurement of the surface potential.

A surface potential meter (Trek Model 323) mounted on a robot arm (IAI IXP) is used to measure the potential at 45 points across the SiO<sub>2</sub> wafer surface. First, the surface potential of the grounded copper plate is assessed to ensure it reads 0 V. Next, the SiO<sub>2</sub> wafer is positioned on the copper plate, and its surface potential is measured. Following this, two-fluid spraying is performed, with the nozzle fixed at the center of the wafer. For the two-fluid spray conditions, the flow rate of pure water is set at 80 mL/min, while the compressed air flow rate is maintained at 80 NL/min. The distance between the nozzle tip and the wafer surface is kept at 30 mm. The wafer is rotated at 100 rpm, and pure water is sprayed for 60 s. Following this, the wafer undergoes spin-drying at 500 rpm for 300 s. Once it is confirmed that the wafer surface is free of water droplets, the surface potential is measured again using the surface potential meter. The difference in surface potential before and after the two-fluid spray is recorded as the change in the SiO<sub>2</sub> wafer's surface potential resulting from the spray. The pure water used for spraying is generated by filtering tap water through an activated carbon filter, an ion-exchange resin, and a final filter. During this process, its resistivity is monitored with a resistivity meter (Horiba HE-480R) and is maintained at 17.3 M $\Omega$ ·cm or higher.



Fig. 3. Appearance of the experimental apparatus

- Confirmation that the potential is zero at the installed copper plate
- Measurement of surface potential of silicon wafer
- Spraying
- Measurement of surface potential of silicon wafer
- Calculate the difference in potential

Fig. 4. Experimental procedure
#### IV. RESULTS AND DISCUSSION

Figure 5 shows the variation in surface potential on the SiO<sub>2</sub> wafer before and after the application of the twofluid spray. Figure 5(a) is a 3D representation of the voltage distribution on the wafer. Around the central region of the wafer-directly under the two-fluid spray nozzle-a maximum of approximately -5 V on the negative side is observed. (Figure 5(a) corresponds to a view looking down on the wafer, similar to Figure 3.) In Figure 4, the solid-line circle represents the area with a diameter of approximately 5 mm where the sprayed pure water droplets made direct contact; the two-fluid spray creates a conical pattern. The dotted-line circle denotes a region with a diameter of approximately 20 mm where the pure water mist, dispersed by compressed gas, came into contact with the wafer. In both circles, the wafer surface is negatively charged. A total of six wafers were sprayed under identical conditions, and each displayed a similar charge distribution. From these experiments, we concluded that when pure water is atomized and directly





Fig. 5. Surface potential after two-stream spray (pure water flow rate: 80 mL/min, air flow rate: 80 NL/min, and spray distance: 30 mm)

interacts with the SiO<sub>2</sub> wafer surface during two-fluid spraying, the surface becomes negatively charged.

As shown in Figure 2, the flying droplets of pure water during two-fluid spraying are positively charged. However, as shown in Figures 5 and 6, the surface of the SiO<sub>2</sub> wafer after spraying exhibits a negative charge. To confirm this phenomenon, we positioned a needle-shaped electrode 30 mm above the center of the wafer and measured the surface potential. After obtaining the initial surface potential of the SiO<sub>2</sub> wafer, we used a high-voltage power supply (Matsusada Precision Model HEOPS 10B2) to apply voltages ranging from -10 to +10 kV to the needle electrode for 30 s, followed by measuring the surface potential of the SiO<sub>2</sub> wafer. The same type of SiO<sub>2</sub> wafer used in the previous experiment was used for this measurement.

Figure 6 shows a representative example of the surface potential on the wafer when a voltage of 6 kV was applied to the needle electrode. Near the center of the silicon wafer, where the needle electrode is positioned, the wafer charged to approximately +60 V, with the charge gradually decreasing toward the edges. When a voltage of 10 kV was applied, the entire surface of the wafer exhibited a charge of approximately +60 V. Figure 7 shows the wafer's surface potential along the central cross-section when voltages ranging from -10 kV to +10 kV were applied. Upon the application of a positive voltage, the wafer began to charge at +4 kV, and at +10 kV, the entire surface potential reached approximately +60 V, indicating saturation. Likewise, when a negative voltage was applied, the SiO2 wafer surface started charging from -4 kV. Although the surface potential was approximately +5 V at +4 kV, it decreased to approximately -10 V at -4 kV. At -10 kV, the wafer surface achieved approximately -120 V and also reached saturation. This needle electrode experiment confirmed that the wafer surface potential consistently aligned with the polarity of the voltage applied to the needle electrode. These findings indicate that the charging of the



Fig. 6. Wafer surface potential when a 6 kV voltage is applied to the needle electrode

wafer surface during two-fluid spraying is not dictated by the polarity of the droplets themselves. Possible contributing factors include collision- or friction-induced charging, commonly known as triboelectric charging [8]. In two-fluid spraying, droplets are atomized at high speeds, and upon their impact with the wafer, triboelectric-like charging can occur. Consequently, negative charges accumulate on the wafer surface. In practice, ion separation may take place in the nozzle or during the flight of the droplets, leading to the formation of positively charged droplets while the wafer surface acquires a negative charge upon contact, creating a polarized state. Furthermore, if the wafer is in a floating (nongrounded) state, the dissipation of these charges becomes more challenging, facilitating the retention of negative charge on the wafer surface. Another important factor is that the surface of a silicon wafer coated with SiO<sub>2</sub> contains silanol (Si-OH) groups. Upon contact with water, these silanol groups can dissociate, which leads to a tendency for the surface to acquire a negative charge. In fact, Sven et al. have reported that glass and silica surfaces readily form electrical double layers when exposed to aqueous solutions, resulting in a negatively charged surface and a positively charged liquid [9].



Fig. 7. Potential in the central cross-section of a silicon wafer when a voltage of -10 to 10 kV is applied

#### V. CONCLUSION

In conclusion, this study demonstrates that  $SiO_2$  wafers develop a negative surface charge after being subjected to two-fluid spraying with pure water, even when the droplets carry a positive charge. Factors such as triboelectric effects, collision-induced charging, and the floating wafer state contribute to the observed negative potentials. In the absence of grounding, the charges remain on the wafer, leading to a net negative voltage. Needle electrode tests confirm that the surface potential of the wafer responds to the applied voltage, suggesting that  $SiO_2$  surfaces readily accumulate charge. The presence of silanol groups on the oxide layer promotes negative charging by dissociating in water. While increasing droplet velocity enhances cleaning efficiency, it also leads to a higher generation of charge.

To mitigate electrostatic risks, strategies such as grounding the wafer, adjusting water conductivity, and optimizing nozzle design to minimize friction can be used. These approaches consider the interactions among droplet polarity, surface chemistry, and triboelectric effects, providing valuable insights for achieving safer and more efficient semiconductor cleaning processes.

#### ACKNOWLEDGMENT

This research was supported by the JSPS Grant-in-Aid for Scientific Research (23K03627) and the Aichi Institute of Technology Project Collaborative Research. Further, we thank Sony Semiconductor Manufacturing Corporation and Sony Semiconductor Solutions Corporation for their support during this research.

#### REFERENCES

- Y. Yoshida, K. Akiyama, S. Zhang, D. Ueda, M. Inaba, H. Takahashi, Scalable particle removal for sub-5 nm nodes, *Solid State Phenomena*, 314, 222– 227, 2021.
- [2] X. Mei Xu, A. Pacco, M. Wada, L. Leunissen, H. Struyf, P. W. Mertens, Uniformity of particle removal by aerosol spray, *Solid State Phenomena*, 187, 149–152, 2012.
- [3] Y. Hagimoto, H. Iwamoto, Y. Honbe, T. Fukunag, H. Abe, Defects of silicon substrates caused by electrostatic discharge in single wafer cleaning process, *Solid State Phenomena*, 145–146, 185–188, 2009.
- [4] H. Suzuki, Y. Fukuoka, T. Mori, Y. Ichino, Y. Seike, Relation between electrostatic discharge generation and droplet characteristics during two-fluid spraying of deionized water, *Journal of the Institute of Electrostatics Japan*, 46(1), 38–43, 2022. in Japanese
- [5] Y. Hirota, I. Kanno, K. Fujiwara, H. Nagayasu, S. Shimose, Damage-free wafer cleaning by water and gas mixture jet, *IEEE International Symposium on Semiconductor Manufacturing*, 2005, pp. 219–222.
- [6] Y. Seike, K. Miyachi, T. Shibata, Y. Kobayashi, S. Kurokawa, T. Doi, Silicon wafer cleaning using new liquid aerosol with controlled droplet velocity and size by rotary atomizer method, *Japanese Journal of Applied Physics*, 49(6R), 066701, 2010.
- [7] Y. Seike, H. Suzuki, Y. Ichino, T. Mori, ESD prevention technology for two-fluid pure water spray cleaning with controlled electrostatic charge, *Solid State Phenomena*, 346, 244–249, 2023.
- [8] T. A.L. Burgo, F. Galembeck, G. H. Pollack, Where is water in the triboelectric series? *Journal of Electrostatics*, 80, 30–33, 2016.
- [9] S. H. Sven, D. G. Behrens, The charge of glass and silica surfaces, *Journal of Chemical Physics*, 115(14), 6716–6721, 2001.

### The Role of Charge Transport in EHD Drying

Alex Martynenko<sup>1\*</sup>, NN. Misra<sup>2</sup>

Department of Engineering, Faculty of Agriculture, Dalhousie University, Truro, Canada <sup>2</sup>Ingenium Naturae Pvt Ltd, Gujarat, India

\*Corresponding author: alex.martynenko@dal.ca

*Abstract* - The paper presents the theoretical background and experimental results on the charge transport and accumulation at the gas-liquid interface during EHD drying. This paper explores the concept of internal capacitance and charge evaluation by using current and electrostatic force measurements.

Keywords- Transport phenomena, charge, drying

#### I. INTRODUCTION

Corona discharge in the air results in air ionization and the formation of non-uniform space charge [1]. The charge transport in the air is caused by at least three phenomena: (1) ions moving from emitter to collector electrode due to the electric field, (2) charged particles due to airflow, (3) diffusion of ions [2]. As such, the electric current density j [C m<sup>-2</sup>s<sup>-1</sup>] becomes:

$$i = \rho_e bE + \rho_e u - D_i \nabla \rho_e \tag{1}$$

where  $\rho_e$  is space charge density, [C·m<sup>-3</sup>], *b* is the ionic mobility [m<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>], *u* is air velocity [ms<sup>-1</sup>] and  $D_i$  is the diffusivity of the ions (m<sup>2</sup>s<sup>-1</sup>). According to Warburg [3], the current density depends on the applied voltage and the geometry of the discharge electrode:

$$i = g\varepsilon_0 b \cdot V(V - V_0) \tag{2}$$

In this expression,  $V_o$  represents the inception voltage, and g is a constant that depends on the geometry of the electrode system, including the emitter radius, electrode gap, and other geometrical factors.

The Warburg model has been widely used in EHD research [4-6]. However, this model is accurate only for low currents in the range from 50 to 250  $\mu$ A. It was shown that for a wider range of currents, the model proposed by Stuetzer [7] is more accurate:

$$i = g\varepsilon_o b \cdot (V - V_o)^2 \tag{3}$$

where *i* – total current (A), *g* is the geometry factor (1/m),  $V_o$  is the inception voltage (V), and  $\varepsilon$ ,  $\varepsilon_o$  is the dielectric permittivity of gas and vacuum, respectively (F/m). This relationship has been experimentally verified for pin [8,9] and wire [10,11] discharge electrodes.

The expression for the geometry factor in the plane geometry<sup>1</sup> was proposed by Owsenek et al. [8]:

$$g = \frac{g_o A}{d^3} \tag{4}$$

where A is the area (m<sup>2</sup>), d is the distance between electrodes (m) and  $g_o$  is the dimensionless geometry constant, reflecting the curvature of the discharge

electrode. This equation was verified for different curvatures and emitter spacings in [12]. Combining equations (3) and (4) and introducing the capacitance of the electrode system  $C = \frac{\varepsilon \varepsilon_0 A}{d}$ , the current-voltage relationship becomes:

$$i = g_o Cb \cdot \left(\frac{v - v_o}{d}\right)^2 \tag{5}$$

The electric field between the electrodes generates a mechanical force that can pull the electrodes toward each other (or repel them, depending on polarity). This force can register as a change in apparent weight on a balance or load cell, even if no moisture is removed. Thus, the electrostatic interaction of electrodes with space charge could be measured by a weighing system [13, 14]. However, the results of these studies could not be directly applied to EHD drying with a wet material between the discharge and collector electrodes.

The specific feature of EHD drying, differentiating it from other EHD applications, is the presence of a gasliquid interface. The effect of the liquid interface on the charge flow and accumulation has never been studied. Our objective was to evaluate volumetric and interfacial charge by measuring the electrostatic force between electrodes. The charge accumulation at the interface was verified using the concept of internal capacitance. The process of charging and discharging internal capacitance was simulated with an electrical model.

#### II. METHODOLOGY

#### A. Material

Thin sheets of tissue paper (Cascades Tissue Group, Canada),  $10 \times 16$  cm in size and  $36.4 \text{ g/m}^2$  density, were chosen as the model of wet material. The 25 g sample pack of dry tissues was wetted with tap water to  $50.0\pm1.0$  g and placed centrally on the surface of the collecting electrode, being entirely exposed to the electric field from the discharge electrode. The thickness of the wet sample was 2 mm, which was negligibly small compared to the gap between electrodes.

<sup>&</sup>lt;sup>1</sup> For the coaxial geometry  $g = \frac{8\pi L}{R^2 \ln(R/r)}$ , where *L* is the length of the wire (m), *R* is the radius of the outer cylinder (m), and *r* is the thickness of the wire (m).

#### B. Experimental apparatus

The experimental setup is shown in Fig. 1, and a detailed description is provided in [15].



Figure 1. A lab-scale experimental setup for electrostatic force measurements (DC power source is not shown).

The experimental setup consisted of the electrode system and a weighing system. The multipin discharge electrode with effective area  $0.023 \text{ m}^2$  was formed from 143 sharp stainless-steel emitters, attached to a fiberglass plate  $185 \times 125 \times 1.5$  mm and electrically connected to the positive pole of the DC power source (BAL-32-5, Voltronics, USA). The collector electrode, made of an aluminum plate  $230 \times 160 \times 1.5$  mm, was centered below the discharge electrode and electrically connected to the ground. The gap between the tip of the discharge and the collector electrodes was fine-tuned in the range of 2.0 to 4.0 cm using a motorized rack and the pinion assembly.

A digital balance ADAM HCB 1002 (Adam Equipment Co, UK) with a 20 cm-high support was placed beneath the collector electrode to monitor voltage-induced weight changes. All variables (voltage, current and weight) were continuously recorded through a computer interface NI USB-6210 (National Instruments, USA).

The multifactorial experiment was designed using voltages from 0 to 23 kV and gaps from 2 to 4 cm, in the presence or absence of wet material. This design allowed us to establish the relationship between applied voltage and space charge for different scenarios. Control experiments were performed at the same settings and environmental conditions, but without an electric field.

#### C. Electrostatic force measurements

To measure electrostatic force, the discharge electrode was mechanically connected to the rigid frame, while the collector electrode was set free on the digital balance. The electrostatic force was measured as a negative weight change for applied voltages above 0 kV. A direct effect of the electric field on the balance measurements was excluded by turning the high voltage ON and OFF.

For the given configuration of discharge electrode and ions polarity, the first three parameters in Equation 5, i.e. geometry factor, capacitance and ionic mobility, are constant. It is worthwhile mentioning that ion mobility b and diffusivity D are strongly dependent on humidity. The attraction force F between two oppositely charged plate electrodes is proportional to the square of the electric field intensity E:

$$F = \frac{1}{2} \cdot \varepsilon_o A E^2 \tag{6}$$

where  $\varepsilon_o$ -the electric permittivity of vacuum (8.85×10<sup>-12</sup> F/m), *A*- effective area of electrodes, m<sup>2</sup>; *d*-gap between electrodes (m). Considering the relationship between electric field intensity and surface charge density, the electrostatic force:

$$F = \frac{1}{2} \cdot \frac{Q^2}{\varepsilon_0 A} \tag{7}$$

At the same time, assuming there exists a mechanical equilibrium, where electrostatic force results in a change in apparent weight on a balance, the electrostatic force is proportional to the weight change  $\Delta m$ :

$$F = \Delta m \cdot g \tag{8}$$

where g is standard gravity (9.81 m/s<sup>2</sup>). It should be noted that the measured  $\Delta m$  is due to electrostatic attraction, and not to be confused with a moisture loss effect.

Combining equations (7) and (8), we can get an equation for the calculation of charge:

$$Q = \sqrt{2\varepsilon_o A \cdot \Delta mg} \tag{9}$$

The capacitance was evaluated from the voltagecharge relationship as the slope of the plot.

$$C = Q/V \tag{10}$$

Measurements of electrostatic force allowed us to evaluate volumetric and surface charge in the presence of wet material.

#### D. Space charge determination

The space charge is proportional to the divergence of electric field intensity.

$$\nabla \cdot E = \frac{\rho_c}{\varepsilon_o} \tag{11}$$

For the high density of emitters (1x1 cm), we assumed conditions of a uniform electric field. The accumulation of space charge in a uniform electric field could be predicted from Poisson's equation:

$$\rho_c = \frac{\varepsilon_0 E}{d} \tag{12}$$

Interfacial charge  $\sigma$  (C/m²) could be calculated from the equation (13:

$$\sigma = \frac{Q}{A} \tag{13}$$

Space charge density  $\rho_c$  (C/m<sup>3</sup>) could be calculated from the equation (14):

$$\rho_c = \frac{Q}{A \cdot d} \tag{14}$$

The values of space charge calculated from mass measurements have been compared with space charge predicted by Poisson's equation (12) for different voltages and gaps.

#### III. RESULTS

#### Experimental study of charge transport

The first set of experiments was carried out using bare electrodes without any material between them. The experiments were done with the gaps 2.0, 2.5, 3.0, 3.5, and 4 cm, in the range of applied voltages from 0 to 23 kV. The mass measurements are presented in Fig. 2a, while the charge calculations (Equation 9) are shown in Fig. 2b.



Fig 2. Measurements and interpretation of electrostatic force at different gaps for bare electrodes without wet material.

Our experiments showed the quadratic relationship between electrostatic force and applied voltage (Fig. 2a) and the linear relationship between surface charge and applied voltage for all gaps from 2 to 4 cm. The linear approximation revealed that capacitance decreased from 4.84 pF at a 2 cm gap to 2.57 pF at a 4 cm gap. With a further increase in the gap, charge diffusion dominates, and the current becomes small, becoming insensitive to changes in the gap.

It should be noted that the measurement of electrostatic force is possible in a certain range of voltages above zero. An increased voltage would create ionic wind and mechanical pressure on the collector electrode, acting against the electrostatic force.

The presence of wet material in the discharge gap changed the charge distribution. Our experiments showed a significant effect of wet material on the mass measurements. However, the effect of electrostatic attraction between electrodes was still observable. Results of charge calculations for different voltages and gaps are shown in Fig. 3.



Fig 3. Interfacial charge accumulation in the electric field between 1x1 electrodes without (dry) or with wet material (area =  $0.012 \text{ m}^2$ )

Small deviations from the linearity for the wet material could be explained by uncontrolled changes of mass with evaporation. The difference in the capacitance between dry and wet cases was significant:  $C_{dry}$ =4.5 pF for bare electrodes vs.  $C_{wet}$ =3.46 pF with the addition of wet material.

It follows from the second set of experiments that the wet material introduces another capacitance due to charge accumulation at the gas-liquid interface (double-layer). Both gap capacitance  $C_{dry}$  and the double-layer capacitance  $C_{DL}$  are schematically presented in Fig. 4.



Fig 4. Effect of wet material capacitance on the overall capacitance

The capacitance of the double layer could be calculated from the equation:

$$C_{DL} = \frac{C_{dry} c_{wet}}{c_{dry} - c_{wet}} \tag{15}$$

From our measurements, it follows that  $C_{DL}$ =15 pF. Surface charge, calculated from Equation (13), is changing from 0.45 to 3.0  $\mu$ C/m<sup>2</sup>. Space charge density, calculated from Equation (14), varies in a range from 150  $\mu$ C/m<sup>3</sup> at a 2 cm gap to 11.25  $\mu$ C/m<sup>3</sup> at a 4 cm gap. Numerical studies show that space charge density may achieve up to 0.6 C/m<sup>3</sup> in the vicinity of the discharge electrode [16]. Another numerical study showed that the space charge decreased in proportion to the cube of the distance from the discharge electrode [2].

The internal capacitance model was experimentally verified for the scenario with corona discharge. In the experiment, the DC power was periodically switched ON and OFF. Electric current was recorded with a 0.1-second resolution. The transient process of charging/discharging internal capacitance, along with mass changes of wet material, is shown in Fig. 5.



Fig. 5. Effect of periodic application of high-voltage (0-21 kV) on the current (a) and mass (b): wet towel, 1x1 electrode, gap 4 cm, area of discharge electrode 0.012 m<sup>2</sup>.

During the first phase of charging, the current spiked to 250-350  $\mu$ A, followed by a decrease to the equilibrium value within 5-6 seconds. Similar behavior was observed during discharging, when the power source was turned off. In this phase, the excess charge accumulated at the surface of the wet material was released back to the circuit. The back current of 150 $\mu$ A decayed in 5 to 6 seconds, which allowed us to calculate the charge:

$$Q = \int_0^5 150 e^{-0.8t} dt = 180 \ \mu\text{C}$$

The surface charge, calculated for the surface area  $0.023 \text{ m}^2$  using Equation (13), is estimated as  $8.0 \text{ mC/m}^2$ . The calculated space charge is estimated as  $0.2 \text{ C/m}^3$ , which concurs with [16].

#### Modelling of the charge transport

The process of charge transport and accumulation in EHD discharge was simulated with an electrical model, containing a series-parallel combination of resistors and a capacitor. One resistor of 400 M $\Omega$  represented air conductivity as a function of space charge concentration. Another resistor represented the diffusion of ions and was controlled by the air exchange rate. The capacitor represented internal capacitance.



Fig 6. Results of model simulation

The transient process of charging and discharging modeled in the MultiSIM 14.1 software, is shown in Fig. 6. It was similar to the experimental data (Fig. 5).

To conclude, this is the first study to directly characterize charge accumulation at the gas - liquid interface in EHD drying. By combining electrostatic force measurements with current monitoring, we decoupled volumetric space charge from interfacial double-layer charge and quantified an internal capacitance introduced by the wet material. An electrical RC model reproduced the transient charging/discharging dynamics, providing new insights into interfacial charge accumulation.

#### REFERENCES

- [1] J.S. Townsend. *Electricity in Gases*. Oxford: Clarendon Press, UK, 1915.
- [2] T. Defraeye, A. Martynenko. Electrohydrodynamic drying of food: New insights from conjugate modelling. *J. Clean Product* 198: 269-284, 2018.
- [3] E. Warburg. Uber Die Spitzenentladung. Annalen 67: 69– 83, 1899 (in German).
- [4] M. Robinson. Movement of air in the electric wind of the corona discharge. *Transactions AIEE*, 80: 143-150, 1961.
- [5] K. Yamada. An empirical formula for negative corona discharge current in point-grid electrode geometry. J. Appl. Phys. 96: 2472–2475, 2004.
- [6] G. F. L. Ferreira, O. N. Oliveira, J. A. Giacometti. Pointto-plane corona: current-voltage characteristics for positive and negative polarity with evidence of an electronic component. J. Appl. Phys. 59: 3045–3049, 1986.
- [7] O. M. Stuetzer. Ion drag pressure generation. J. Appl. Phys. 30: 984–994, 1959.
- [8] B.L. Owsenek, J. Seyed-Yagoobi, R.H. Page Experimental investigation of corona wind heat transfer enhancement with a heated horizontal flat plate. *J Heat Transfer* 117: 309-315, 1997.
- [9] F.C. Lai, D.S. Wong. EHD-enhanced drying with needle Electrode. Dry Tech 21: 1291-1306, 2003.
- [10] S.E. Sadek, R.G. Fax, M. Hurwitz. The influence of electric fields on convective heat and mass transfer from a horizontal surface under forced convection. *J Heat Transfer* 5: 144-148, 1972.
- [11] T.I. Goodenough, P.W. Goodenough, S.M. Goodenough. The efficiency of corona wind drying and its application to the food industry. *J Food Eng* 80: 1233–1238, 2007.
- [12] A. Martynenko, T. Kudra. Electrohydrodynamic dryer: Effect of emitters' density and gap between discharge and collecting electrodes. *Dry Tech* 38: 158-167, 2021.
- [13] E. Moreau, N. Benard, J.D. Lan-Sun-Luk, J.P. Chabriat. Electrohydrodynamic force produced by a wire-to-cylinder dc corona discharge in air at atmospheric pressure. *J. Phys. D: Appl. Phys.* 46, 475204, 2013.
- [14] N. Monrolin, F. Plouraboue, O. Praud. Electrohydrodynamic thrust for in-atmosphere propulsion. *AIAA Journal* 55: 4296-4305, 2017.
- [15] A. Martynenko, T. Kudra, J. Yue. Multipin EHD dryer: Effect of electrode geometry on charge and mass transfer. *Dry Tech* 35: 1970-1980, 2017.
- [16] C.A. Shi, A. Martynenko, T. Kudra, P. Wells, K. Adamiak, G.S.P. Castle. Electrically induced mass transport in a multiple-pin-plate electrohydrodynamic (EHD) dryer. J Food Eng 211: 39-49, 2017.

# Effect of electric field on moisture transport in porous media during electrohydrodynamic drying

Pejman Naderi, Alex Martynenko

Department of Engineering, Faculty of Agriculture, Dalhousie University, Truro, Canada \*Corresponding author: alex.martynenko@dal.ca

*Abstract-* Drying moist porous media, such as food, remains energy-intensive, often causing thermal degradation and high operational costs. Electrohydrodynamic (EHD) drying offers an efficient alternative, leveraging electric fields to enhance moisture removal. Ionic wind generated by the electric field drives convective mass transfer. However, with the decrease in moisture content, diffusion internally restricts moisture transport. Porous structures, whether inherent or formed during drying, critically impact transport mechanisms. Electric fields interact with charged particles, dipoles, and polarizable molecules, rearranging complex structures like cell membranes and modifying diffusive resistance to moisture transport. The paper discusses possible mechanisms of electrodiffusion in porous media.

#### Keywords- Electrodiffusion, porous media, mass transfer enhancement

#### I. INTRODUCTION

Moisture transport in porous media is a two-phase transport phenomenon. Generally, it consists of two processes: (1) moisture transport inside the wet material toward its surface, and (2) vapor transport into the surrounding gas. Consequently, there are two modes of moisture transport: diffusive and convective. Details on the driving forces and mechanisms of moisture transport, the effect of internal and external conditions, and other background information can be found in the drying literature [1].

EHD-induced drying experiments demonstrated both convective and diffusive moisture transport during drying. The dominant mode of transport could be determined from drying kinetics. The exponential drying kinetics imply diffusion from the inside of the material to the surface. This behaviour has been observed in various plant-based materials, such as mushrooms, apples, bananas, carrots, garlic and berries. In diffusion-limited EHD drying, the mass flux typically does not exceed 0.1-0.2 g/(s·m<sup>2</sup>) [2].

It was experimentally found that the moisture transport occurs only if the electric field exceeds the inception point [2]. Electric field imparts surface charges on cellular components, creating unbalanced distributions and driving fluid movement through electrostatic forces. Such phenomena become pronounced as drying advances, with factors like electric permittivity and the conductivity remaining water. Moreover, dielectrophoresis of facilitates the translational motion of neutral particles in non-uniform fields, impacting both liquid and vapor transport. Electroporation of cell membranes could be another factor, accelerating internal moisture transport [3].

A review of the latest research indicates that the effect of the electric field on moisture transport in porous media is underexplored, requiring further numerical studies and experimental validation. Numerical simulation aims to explore the effect of a non-uniform electric field on moisture transport in a porous matrix, offering insights into optimizing EHD drying for industrial applications.

#### II. METHODOLOGY

#### A. Material

Fresh apples (var. MacIntosh) of visibly uniform size and ripeness were sliced to 2mm with a professional food slicer CFS–155C (Cuisinart, Canada). Then they were cut into squares  $2.54 \times 2.54$  cm using an apple cutter. Fifty-six (56) slices, arranged in  $6 \times 9$  rows, were placed on the collecting mesh electrode. Thus, the initial surface area of apple slices was  $0.0348 \text{ m}^2$  in each trial. The thickness of each slice was verified using a digital caliper (Mastercraft, Canada) with 0.1 mm tolerance.

#### B. Apparatus

The detailed description of the lab-scale experimental setup is given in [4]. It consisted of an AC power supply with a power meter, a DC transformer, discharge and collecting electrodes, a digital scale, and a computerized system for continuous weight measurements. The discharge electrode was connected to the positive pole of a high-voltage DC transformer (Model 20B, Hipotronics). The collecting electrode was connected to the ground through a precise  $1 \text{ k}\Omega$  resistor for current measurements. The primary voltage, controlled by a variac, was measured by a multimeter (Fluke 110 True RMS, Fluke Corp.), while the voltage drops on the 1 k $\Omega$  resistor was measured by another multimeter (UA9233E, Uyigao Technology Co. Ltd.). Experiments were performed in the range of applied voltages from 0 to 24 kV at a  $4.0 \pm 0.1$  cm gap between the discharge and collecting electrodes. Once the slices were placed on the mesh collecting electrode underneath the discharge electrode, the digital scale (HCB 1002, Adam Equipment) was turned on for weight measurements every 10 seconds. Airflow was measured by the hot wire anemometer (Digi-Sense, model 20250, Cole-Palmer, Canada) and maintained constant with an accuracy of 0.1 m/s. The effect of the electric field on the moisture diffusion was evaluated by comparing the EHDinduced drying rate with the control (natural drying).

#### **Theoretical model**

From the theory of drying, mass flux inside the material is driven by moisture and thermal gradients [5]:

$$j_m = -\rho D_m [\nabla m + \delta_T \nabla T] \tag{1}$$

where  $j_m$  quantifies the mass flux (kg/(m<sup>2</sup>s)), *m* is moisture content, kg/kg dry matter,  $\rho$  is material's true density, kg/m<sup>3</sup>;  $D_m$  is the water diffusivity, m<sup>2</sup>/s,  $\nabla T$  -temperature gradient, K; and  $\delta_T = D_T/D_m$  is the thermodiffusion ratio, (1/K).

It should be noted that water is an easy polarizable substance. An external electric field creates a non-uniform electric field distribution inside the material due to non-uniform electric conductivity. As a result, the electric field creates an additional driving force for moisture transport. Thermodynamic force  $F_e$ , created by the non-uniform electric field, is proportional to electric polarization p (C/m<sup>2</sup>) and the gradient of electric field strength  $\nabla E$  (V/m<sup>2</sup>):

$$F_e = p \nabla E \tag{2}$$

This force must have the dimension of the energy density gradient (J/m<sup>4</sup>). Electric polarization of a material with dielectric permittivity  $\varepsilon$  is proportional to the electric field strength *E* (V/m):

$$p = \varepsilon_o(\varepsilon - 1) \cdot E \tag{3}$$

Thus, moisture transport in the electric field is determined not only by ordinary diffusion  $\nabla m$  and thermodiffusion  $\nabla T$ , but also by electrodiffusion. Following Onsager's principle on additive action of thermodynamic forces, moisture transport in the electric field is determined by the following coupling model [6]:

$$j_m = \rho D_m [\nabla m + \delta_T \nabla T] + \delta_E D_E \varepsilon_o (\varepsilon - 1) E \nabla E$$

where  $D_E$  is the electrodiffusion coefficient, (m<sup>2</sup>/s), and  $\delta_E$  – the EHD evaporation factor (kg/J), reciprocal to the specific electric energy consumption for EHD-induced water evaporation from the material surface (J/kg). Electric field strength is determined in Volts per meter of distance between the emitter and the material surface.

The first and second terms of the equation represent mass (moisture) diffusion and thermodiffusion in the wet material. The third term is responsible for moisture transport due to a non-uniform electric field in the material and should clearly be distinguished from moisture transport due to electroosmotic force. Firstly, the non-uniform exposure of the material surface results in non-uniform mass flow. Secondly, the gradual decrease in moisture content during drying will decrease the evaporation factor  $\delta_E$  and electric permeability  $\varepsilon_o$ , but increase the gradient of electric field strength  $\nabla E$ . Therefore, the electrodiffusion coefficient  $D_E$  should be experimentally identified.

This model could serve as the first attempt to combine the effects of heat, mass and electric field transfer in EHD drying. However, quantifying moisture transport coefficients would require experimental validation.

#### Experimental validation

The moisture transport in porous media follows Fick's law of diffusion. Average moisture content is the function of time, which can be evaluated from the experiment by approximation of the exponential part of drying kinetics curves with the Lewis model:

$$m(t) = m_e + (m_o - m_e) \cdot e^{-kt}$$
 (6)

where  $m_o, m_e$  – initial and equilibrium moisture content, g/g dry matter, k – drying rate constant, s<sup>-1</sup>.

This model could be presented as a dimensionless moisture ratio MR:

$$MR(t) = \frac{m(t) - m_e}{m_0 - m_e} = e^{-kt}$$
(7)

The moisture diffusivity  $D_m$  in the infinite slab was calculated using the equation given by Crank [7]:

$$D_m = \frac{-4l^2}{\pi^2 t} \ln \left( \frac{\pi^2}{8} MR \right) \dots (8)$$

where l is the thickness of the material (m).

After simplification of (8), the effective moisture diffusivity can be evaluated from the drying rate constant and material thickness:

$$D_m = \frac{4l^2}{\pi^2}k\tag{9}$$

Moisture transport is limited either by the low inherent diffusivity in porous media or by the receding evaporation front with a liquid-gas interface. Both cases are possible in EHD drying.

In the absence of thermodiffusion, drying flux is determined by mass diffusion and electrodiffusion:

$$j_m = -\rho D_m \nabla m + \delta_E D_E \varepsilon_o (\varepsilon - 1) E \nabla E \qquad (10)$$

Considering their additive effect on the drying flux, the objective of the experimental research was to evaluate the sole effect of the electric field on the moisture transport.

#### **III. RESULTS**

To test the hypothesis of EHD-induced moisture transport, we conducted an experimental study using EHD drying of apple slices. Figure 1 shows a significant effect of EHD on the drying flux compared to the control. Calculations with equation (7) showed that effective diffusivity increased from  $0.3 \cdot 10^{-10}$  m<sup>2</sup>/s (control) to  $1.53 \cdot 10^{-10}$  m<sup>2</sup>/s at 24 kV (6.0 kV/cm electric field). Hence, it confirms the direct effect of EHD flow on the material diffusivity.

Ham et al. [8] suggested that an applied electric field could create a significant voltage drop  $V_s$  at the porous media surface, sufficient to enhance diffusive moisture transport. The voltage  $V_s$  at the material surface can be calculated as a fraction of the applied voltage V:

$$V_{\rm s} = V \frac{\varepsilon_a l}{\varepsilon_s d + \varepsilon_a l} \tag{11}$$

where l - is the sample thickness,  $\varepsilon_a$ ,  $\varepsilon_s$  – dielectric permittivity of the air and sample, respectively.



Fig. 1. Drying flux in EHD drying of apple slices, induced by electric field of different intensity

It should be considered that the dielectric permittivity changes from 80 for the very wet to almost 2 for the dry media. As a result, the voltage drop  $V_s$  is increasing toward the end of drying. For example, if 20 kV voltage is applied at a 5cm air gap, the initial voltage drop on the 3mm wet sample is around 15V, increasing to 1200 V at the end of drying. The electric field inside of the 3mm material could reach 3.6 kV/cm. Considering the material shrinkage, this value could be even larger. These simple calculations show that the voltage drop and electric field across the material can be sufficiently strong to induce electrokinetic transport phenomena.

One can be electroosmosis, where an applied electric field forces liquid flow in the material. Electroosmotic flow in EHD is generated by the accumulation of an electric charge on the surface of wet material, attracting ions in a liquid to the interface. This surface charge is compensated by counter-ions in the liquid, creating an electric double layer. Our measurements of interfacial charge showed a value of around 80-160 mC/m<sup>2</sup>, sufficient to generate electroosmotic flow. The ions in the diffusive part of the double layer then electromigrate using an internal electric field and drag the liquid molecules to move by the electric force. The mobility of water molecules is affected by the porosity and tortuosity of the material.

The external electric field can also facilitate electrocapillary flow. This phenomenon is based on the effect of surface charge on the surface tension. The change in surface tension will induce changes in the shape of the liquid interface. The pressure difference, arising from this change, will be sufficient to move water against the gradient of the electric field. It is hypothesized that this mechanism is mostly relevant to the falling drying rate period of EHD drying.

The significance of electroporation in EHD drying is still under discussion. Iranshahi et al. [3] consider membrane electroporation a major mechanism contributing to the diffusive moisture transport. Their simulation study showed a significant (up to 9%) electric field effect on the membrane permeability. On the other hand, Ham et al. [8] concluded that electroporation is not significant in the range of electric field intensities typical for EHD drying. Therefore, this phenomenon requires further research and experimental verification.

The hypothetical mechanism of moisture transport enhancement is shown in Fig. 2.



Fig. 2. Hypothetical charge distribution at the surface in wet material in EHD drying: A) Transient response after application of DC electric field; B) Formation of steady state EDL.

Positive DC corona discharge saturates the air with positive ions, which are attracted to negatively charged wet material (Fig 2A). It creates a displacement current in electroconductive material, recharging the surface layer (Fig 2B). This current exists for a short period, decaying with the charging of the surface layer. As a result, water molecules at the surface of wet material are aligned with the electric field, forming an electric double layer (EDL).

#### Numerical simulation

The simulation was performed using COMSOL Multiphysics to evaluate how electric fields influence water transport within a porous medium during EHD drying. A 2D model was developed consisting of a highvoltage pin electrode (25 kV) and a grounded counterelectrode covered by a 3-mm-thick, porous layer. Ionic wind was generated by the corona discharge, and the resulting flow field was coupled with the transport of charged water species inside the material.

Figure 3 illustrates the velocity field induced by the ionic wind and the moisture concentration within the porous medium. The arrows indicate the total flux, which includes both diffusion and electric field-driven migration. The flow accelerates toward the center axis beneath the pin, where charge accumulation distorts the electric field. This distortion results in a locally intensified flux into the material, particularly in the central region.



Fig 3. Velocity field and surface molar concentration in the porous medium under EHD flow.

Figure 4 provides a zoomed-in view of the internal concentration distribution and flux paths. The molar concentration is highest near the bottom boundary and decreases toward the top surface, consistent with the imposed boundary conditions. However, the non-uniform electric field modifies this diffusion profile, bending the flux lines upward and inward near the center. This demonstrates how charge-induced field gradients significantly affect internal mass transport, leading to enhanced moisture migration in targeted regions.



Fig 4. Molar concentration and total flux inside the porous material showing distortion of diffusion paths under a non-uniform electric field.

These results confirm that EHD effects are not limited to surface convection. Instead, electric field interactions with charged species and porous structures play a vital role in redistributing internal moisture, suggesting opportunities for more controlled and efficient drying strategies.

#### REFERENCES

- [1] Mujumdar, A.S. (2014). Handbook of Industrial Drying, 4<sup>th</sup> Ed, CRC Press, USA.
- [2] Martynenko, A. (2025). EHD-induced moisture transport from wet materials. *J Electrostatics*, 104075.
- [3] Iranshahi, K., Onwude, D. I., Martynenko, A., & Defraeye, T. (2022). Dehydration mechanisms in electrohydrodynamic drying of plant-based foods. *Food and Bioproducts Processing*, 131, 202–216. <u>https://doi.org/10.1016/j.fbp.2021.11.009</u>
- [4] Paul, A., Astatkie, E, Martynenko, A. (2022). Electrohydrodynamic drying of fruit slices: effect on drying kinetics, energy consumption and product quality. *J Food Process Preserv.* 1-11 https://doi.org/10.1111/jfpp.16812
- [5] Luikov, A.V. (1975). Systems of differential equations of heat and mass transfer in capillary-porous bodies. *Int. J. Heat Mass Transfer*, 18, 1-14.
- [6] Kudra T, Martynenko A (2020) Electrohydrodynamic drying: Theory and experimental validation. *Drying Technol* 38, 168-175.
- [7] Crank J. (1975) The Mathematics of Diffusion. Oxford University Press, London, UK.
- [8] Ham, J. C. A., Alawi, A., Rizki, Z., Boom, R. M., Garbin, V., Padding, J. T., & Schutyser, M. A. I. (2024). A multi-scale analysis on electrohydrodynamic drying technology for biobased & food products. *Trends in Food Science & Technology*, 151, 104634. https://doi.org/10.1016/j.tifs.2024.104634
- [9] Defraeye, T, Martynenko A. (2018). Electrohydrodynamic drying of food: New insights from conjugate modelling. *Journal of Cleaner Production*, 198, 269-284, 2018.

## **Evaluation of Effect of Electrode Shape on Electrohydrodynamic Heat Transfer Enhancement in Phase Change Materials**

M. Koura<sup>\*</sup>, E. Chariandy, J.S. Cotton Department of Mechanical Engineering, McMaster University 1280 Main Street Hamilton, Ontario, L8S 4L8, Canada \*Corresponding author: kouram@mcmaster.ca

*Abstract*- Latent Heat Thermal Energy Storage Systems (LHTESS) are a type of thermal storage that uses Phase Change Materials (PCMs) as a medium for thermal energy storage. An ideal system charges quickly and readily discharges when necessary. Since the PCMs used in these systems are often high Prandtl number fluids, forced convection is favorable for heat transfer enhancement. As such, the use of electrohydrodynamics (EHD) to induce forced convection in the liquid phase is a topic of interest. The complex nature of EHD requires experimentation and modelling to be fully defined. Therefore, making a practical thermal cell requires understanding the nature of the enhancement for a realistic cell design. This paper explores potential designs for a thermal cell that can be upsized for large scale use. Several electrode designs were compared to determine if an optimal design exists and what it may be. Numerical simulations were performed to compare the resultant flow and evaluate the impact of the electrode design on the induced fluid flow patterns and subsequent heat transfer enhancement.

Keywords- Electrohydrodynamics, Phase Change Materials, Electrode Geometry, Thermal Storage, Numerical Modelling.

#### I. INTRODUCTION

One of the many challenges of meeting increasing energy demand is the mismatch between when energy is available and when it is needed. This mismatch can vary in scale from seasonal to hourly and, as such, different methods are needed for different cases. One such method for short term storage is Latent Heat Thermal Energy Storage Systems (LHTESS) which utilize Phase Change Materials (PCMs). Thermal energy absorbed by a material takes one of two forms, sensible heat and latent heat. Sensible heat is thermal energy associated with a temperature change while latent heat is thermal energy associated with a phase change at a constant temperature. Since it is often logistically and practically advantageous to store energy isothermally, latent heat is the preferable means of storing thermal energy. To that end, PCMs are materials whose purpose is to store and release thermal energy via a phase change process. As such, favorable qualities in such materials include high latent heats and energy density. These properties can be found in organic paraffin waxes which makes them good candidates of LHTESS. A drawback of organic paraffin waxes, however, is that they typically have low thermal conductivity, meaning that, while they store a lot of energy, the rate at which this energy can be deposited or extracted is low. This presents another roadblock to addressing the temporal energy mismatch.

A proposed method of heat transfer enhancement in organic PCMs is the use of electrohydrodynamic (EHD) induced force convection. Since organic PCMs are also often dielectrics, introducing an electric field to the PCM in its liquid state will apply a body force on the charged species in the PCM, inducing motion with minimal energy consumption. This induced "stirring" will enhance the heat transfer into and out of the PCM. As EHD induced stirring as a method of heat transfer enhancement is still a relatively new area of research, there are still many areas of exploration with regards to achieving an optimal design of an EHD enhanced thermal cell. One such area worth exploring is the influence of electrode geometry on the induced fluid motion. More specifically, the effect of the radius of curvature of the electrode tips. A numerical study performed by Ma et al. demonstrated that a smaller radius of curvature increases electric field strength [1]. Since the electric field strength and shape dictates the applied body force magnitude and direction, varying the electrode geometry will have a significant effect on the resultant motion, both in velocity and flow regime. Both aspects play a large part in heat transfer enhancement. Therefore, by comparing geometries, an ideal design may be achieved which may result in the maximum heat transfer for a given applied voltage. Additionally, by considering the breakdown voltage of the dielectric, a limitation for the sharpest electrode edge usable can be determined.

#### II. METHODOLOGY

The radius of curvature is described by a value that will be referred to as the RB ratio. This value nondimensionalizes the radius of curvature as a ratio of the radius of curvature to half of the width of the base of the electrode. As seen in Fig. 1, an RB of 1 corresponds to a semicircle while an RB of 0 corresponds to a perfect sharp pointed triangle. Intermediate values then correspond to a triangle with a filleted tip as seen below. The numerical set up models a 2-dimensional thermal



Fig. 1. Electrode geometry at various RB values

cell that is 100 mm in height and 20 mm in depth. The left wall is the high voltage electrode consisting of nine symmetrical electrode bumps, and right wall is the ground electrode, see Fig. 2. The top and bottom walls are set as zero charge boundary conditions, and all four walls are set as no-slip boundary conditions. Since this study is mainly concerned with the effect of geometry on the steady state induced flow, charge will be induced through unipolar charge injection at the high voltage electrode, which is set to 8000 V. The high voltage electrode is a source of charged species, and the ground electrode is a sink for charged species. No other charging mechanisms are modelled. The fluid is given the properties of Octadecane, a common dielectric PCM [2], [3]. The ion mobility used for liquid Octadecane is 4.7 •  $10^{-9}$  m<sup>2</sup>/Vs as reported by Noble and Taylor [4]. The mesh parameters are set to a minimum element size of 2E-4, a maximum element size of 4E-7 and a growth rate of 1.03, and a free time step limited to a maximum of 0.05 seconds is used. A grid and time step independence test has been performed to ensure result reliability.

The simulation is performed for a simulated period of 50 seconds to allow the flow to reach steady state. The simulation is performed for RB values ranging from 0.025 to 1. The RB value of 0 will not be tested as there are numerical limitations associated with electrodes with sharp edges, as the electric field tends to infinity at the tip [1]. Since a finite element size cannot reflect that behavior irrespective of resolution, that testing condition will be omitted.



Fig. 2. Thermal cell electrode schematic for RB=0.5 test case

#### III. RESULTS AND DISCUSSION

To determine the effect of electrode curvature on the induced flow, the u-velocity profile at steady state in front of the center electrode is examined. The center electrode is examined to minimize the presence of edge effects on the resultant flow. The velocity profile provides qualitative data on the nature of the induced flow regime. Additionally, quantitative data is derived from it regarding the flow velocity directly in front the electrode, specifically the velocity magnitude, direction, and jet width. Because the absolute values of the velocity and jet width will vary based on the input conditions, the results were normalized against themselves to analyze the relative difference as a result of varying the RB value. The velocity data can be seen in Fig. 3 while the jet width data can be seen in Fig. 4. In the velocity results, a positive velocity represents fluid travelling from the high voltage electrode to the ground electrode, while a negative velocity indicates the reverse. This allows for insights regarding circulation directions induced by different geometries. The jet width was calculated by finding the distance between the two points around the center electrode protrusion where the velocity switches signs from positive to negative or vice versa.



of RB values normalized against itself.

Fig. 3. The jet velocity in front of the center electrode for a range

Fig. 4. The jet width in front of the center electrode for a range of RB values normalized against itself.

0.5

RB

0.6

0.7

0.8

0.9

0.4

0.1

0.2

0.3

This provides an indication of the total width of the region where flow is carrying fluid from or to the high voltage electrode.

The velocity and jet width results suggest the presence of two flow regime regions and a transition region between them. The first regime occurs from 0.025 < RB < 0.25, with a transition region from 0.3 < RB <0.55, and another regime from 0.6 < RB < 1. As such, analysis of each region is conducted. As seen in Fig. 5a, the first region is characterized by symmetrical circulation regions. The velocity profiles for RB=0.025 and RB=0.05 show a high positive velocity ejecting from the central jet with a wide jet with slight dip in velocity in the center. This is to be expected as the strong electrical fields induced by the sharp curvature would increase the body force on the fluid. As the RB value grows to RB=0.075, an interesting behavior is observed. The central dip in velocity drops in magnitude below zero, meaning fluid has started to recirculate back in the center. This suggests that there is a limit to how wide the jet of a single direction flow can be. Due to conservation mass, you cannot have more fluid going one way than the other, so as the jet widens, it eventually splits in two creating a new recirculation zone. As the RB values grow more towards RB=0.25, those two positive peaks around the center diverge further until meeting with other positive peaks from the surrounding jets and coalescing. At this point the flow has inverted completely with the recirculation occurring in the opposite direction. However, the magnitude of the velocity is now far greater. The reason behind this is likely that as the RB value grows, while the electric field strength at the tip does decline, the area that possesses a strong electric field grows. This suggests an optimal RB value where the maximum flow velocity can be achieved. This behavior is also reflected in the jet width, where initially it is wide and as the flow direction inverts itself, a new narrow jet forms which slowly widens with growing RB value.

Past this regime into the transition zone ranging from RB=0.3 to RB=0.6. The velocity of the jets declines in magnitude as the electric field driving the motion weakens. Past this point, for values ranging from RB=0.65 to RB=1, a new stable and symmetrical flow regime arises, see Fig. 5b. In this range values, the jet velocity and jet width mostly level out, increasing only slightly with the RB ratio. This is still likely due to the fact the arc length increases with RB value, increasing the area of fluid influenced by the stronger field, while



Fig. 6. The jet width in front of the center electrode for a range of RB values normalized against itself.

the field strength does not drop significantly. The recirculation zones do not change significantly in size or shape with RB value in this region.

Analysis of the electric field strength present at each value provides an insight into the significant change present at lower end of RB values and the lack of change present at the higher end. Fig. 6 shows the maximum field strength present at the tips of the high voltage electrode in each test. Initially, small changes in the RB value result in significant changes to the electric field strength at the high voltage electrode, with a 25% reduction in the electric field when changing from RB=0.025 to RB=0.05. The electric field then levels out as the RB ratio continues to grow with a less than 1% difference between RB=0.95 and RB=1. This behavior is expected because as the radius of curvature of the electrode grows, it more closely resembles flat surface and will asymptote towards that value.

#### IV. CONCLUSION

The results of this numerical study demonstrate that the geometry of the high voltage electrode plays a significant part in dictating the resultant flow, both with regards to structure and flow rates. An RB ratio is introduced as a dimensionless quantity that quantifies the "pointiness" of the electrodes by relating the radius of curvature of the electrode tip to half its base width. Lower RB value electrodes induce a stronger electric field at the electrode tip but do so over a smaller area and



Fig. 5. Characteristic velocity profiles in the three flow regimes.

higher RB value electrodes act on a larger area but with less force. As such there is an optimal point at which the maximum jet velocity magnitude is achieved which was around RB=0.3. Furthermore, depending on the range of RB value, different flow regimes emerge. This provides an insight into the considerations that must be taken when designing a thermal cell to achieve the optimal heat transfer, as well as presents a degree of control to achieve certain desired flows. Next steps would include running more studies while varying other parameters such as material or electrical properties to create a broader map of the fluid response to geometry based on other parameters. A broader search would allow for locating a more global optimum with regards to a design goal. Additionally, introducing heat transfer in the model would allow for quantification of the heat transfer enhancement achieved by varying the geometry. Finally, after establishing a potential optimum, experimental studies will be performed around the optimum to validate the numerical studies.

#### ACKNOWLEDGEMENTS

This research was supported by the Natural Sciences and Engineering Research Council of Canada. We would also like to acknowledge CMC Microsystems, manager of the FABrIC project funded by the Government of Canada, for the provision of products and services that facilitated this research, including COMSOL Multiphysics.

#### References

- N. Ma, V. F. Jones, E. J. Miller, and K. J. Kozaczek, "An electrostatic study of curvature effects on electric field stress in high voltage differentials," *J. Electrost.*, vol. 101, p. 103370, Sep. 2019, doi: 10.1016/j.elstat.2019.103370.
- [2] D. Nakhla, E. Thompson, B. Lacroix, and J. S. Cotton, "Measurement of heat transfer enhancement in melting of n-Octadecane under gravitational and electrohydrodynamics (EHD) forces," *J. Electrost.*, vol. 92, pp. 31–37, Apr. 2018, doi: 10.1016/j.elstat.2018.01.004.
- [3] A. Hassan and J. S. Cotton, "An investigation of the electroconvection flow and solid extraction during melting of phase-change materials," *J. Electrost.*, vol. 128, p. 103904, Mar. 2024, doi: 10.1016/j.elstat.2024.103904.
- [4] I. E. Noble and D. M. Taylor, "Electrical conduction in liquid and solid octadecane," *J. Phys. Appl. Phys.*, vol. 13, no. 11, pp. 2115–2121, Nov. 1980, doi: 10.1088/0022-3727/13/11/021.

## Adiabatic Bubble Growth and Detachment Under AC Electric Fields

Tianle Gu<sup>1</sup>, Samuel Siedel<sup>1\*</sup>

<sup>1</sup>University Grenoble Alpes, CNRS, Grenoble INP, Laboratoire SIMaP, Grenoble, 38000, France \*Corresponding author: samuel.siedel@simap.grenoble-inp.fr

*Abstract-* Bubble growth and detachment in dielectric liquids have been extensively studied under DC electric fields, where numerical models have successfully predicted steady-state bubble shapes in the absence of Coulomb effects. However, under time-dependent AC electric fields, the interplay between evolving bubble shape and dynamic electric stress introduces complex behaviors that remain poorly understood. Understanding these dynamics is essential for applications in electrohydrody-namic (EHD) control, microfluidics, and phase-change heat transfer. In this study, we experimentally investigated the growth and detachment of air bubbles injected into the leaky dielectric liquid HFE-7100 under AC electric fields with square and sine waveforms at 50 and 100 Hz. High-speed imaging and image analysis revealed that EHD forces induced significant shape oscillations and strongly influenced bubble growth rates and detachment timing. The response was highly dependent on the phase of bubble initiation, with polarity reversal often triggering detachment. Notably, under sine wave excitation, successive bubbles spontaneously organized into two alternating modes characterized by highly consistent aspect ratio evolution and volumetric growth. The bifurcation effect disappeared when a DC bias was added to the signal. These results demonstrate the critical role of waveform shape, frequency, and polarity in modulating bubble behavior in AC fields, and provide new experimental insight into transient EHD effects in leaky dielectric fluids.

Keywords- Bubble dynamics, AC electric fields, HFE-7100.

#### I. INTRODUCTION

From electrospray to submicrometer particle separation, AC electric fields have been developed as powerful tools in multiphase systems due to electrohydrodynamic (EHD) forces. The EHD forces in such systems are governed by Equation 1, which depends on multiple parameters: free charge density  $\rho_e$ , electric field intensity E, and permittivity  $\varepsilon$ . The three terms on the right-hand side correspond to electrophoresis (Coulomb force), dielectrophoresis, and electrostriction, respectively. Bubbles, on the other hand, play a critical role in many multiphase engineering applications, including but not limited to boiling heat transfer, biological sample delivery, liquid-gas management in microgravity, and bubble-assisted chemical or biological processes [1-4]. The presence of bubbles in a liquid introduces a significant discontinuity in permittivity  $\varepsilon$  at the two-phase interface, which can locally enhance dielectrophoretic and electrostrictive forces, modifying the bubble shape in an electric field.

$$\boldsymbol{f}_{e} = \rho_{e}\boldsymbol{E} - \frac{1}{2}\boldsymbol{E}^{2}\nabla\varepsilon + \frac{1}{2}\nabla\left[\rho\boldsymbol{E}^{2}\left(\frac{\partial\varepsilon}{\partial\rho}\right)_{T}\right] \quad (1)$$

Historically, cross-disciplinary studies involving bubbles and electric fields have primarily focused on bubble growth and detachment under DC electric fields, leading to significantly simplified models. However, the interaction between bubbles and AC electric fields in bulk liquids remains relatively unexplored. Equation 1 indicates that the time-dependent nature of AC electric fields can induce periodic variations in electric stress at the liquid-gas interface, which may further induce surface oscillations. In this study, the growth and detachment of air bubbles injected into bulk dielectric liquid HFE-7100 from an orifice on a flat sur-

face were investigated under AC electric fields with various frequencies and waveforms, as well as in the absence of electric fields. The surface where the bubbles emerged also served as the ground electrode, while the voltage was applied via an upper electrode. This parallel configuration generated EHD forces within the two-phase system, inducing electrical stress at the liquid-gas interface and thereby deforming the bubbles. For multiple successive bubbles in each experimental condition, volumetric growth was analyzed under the assumption of axisymmetry on each layer, and forced oscillations at different frequencies were examined based on the evolution of aspect ratios. Our preliminary study indicated that the advancing and receding contact angles played a critical role in determining whether the bubble base shrank or spread, suggesting that detachment may be triggered by the motion of the triple line rather than by a force balance [5]. Both premature and delayed detachment were observed, depending on the phase at which bubbles were initiated within the AC field cycle. Furthermore, sinusoidal waveforms of specific frequencies were found to induce an alternating pattern of bubble growth and oscillation modes between successive bubbles. This study aims to provide high-quality experimental data to enhance the fundamental understanding of bubble dynamics governed by AC electric fields.

#### II. METHODOLOGY

In this study, bubbles were generated via adiabatic air injection into the test cell half filled with hydrofluoroether (HFE) fluid HFE-7100. The experimental setup comprised 10 major components, as depicted in Fig. 1.

A typical experimental procedure involved the following steps: 1. The test cell was evacuated. 2. Dielectric liquid was injected through a valve until the upper electrode



Figure 1: 2-D Schematic diagram of the experimental equipment. 1. Highspeed camera 2. Pressure gauge 3. Valve 4. Injection sample 5. The upper electrode 6. Light 7. test cell 8. High voltage amplifier 9. Oscilloscope 10. Function generator

was fully submerged. 3. Due to the sub-atmospheric test cell pressure (the vapor pressure within the test cell equilibrated to the saturation pressure corresponding to the controlled liquid temperature), ambient air was drawn into the test cell through the capillary channel, leading to bubble growth and detachment from the immersed surface of the injection sample. 4. Bubble growth and detachment were recorded using a Phantom Miro M310 high-speed camera at 7200 or 11000 FPS.

The saturation pressure corresponding to the temperature was 0.27 bar absolute. The test cell pressure was then modulated to 0.6 bar after some gas was introduced. The bubble injection-induced pressure variation was negligible throughout the whole experiment duration due to the relatively small amount of gas compared to the space upon the liquid free surface.

#### III. RESULTS

The experiments were firstly conducted in the absence of electric fields to construct the control group data, and later under AC electric fields of 50 Hz and 100 Hz, with the bulk pressure maintained at 0.6 bar absolute. The applied voltage varies between -12 kV and +12 kV while the distance between the two electrodes remained 1 cm.

## A. Bubble growth and detachment in AC electric fields driven by square wave

The bubbles in the control group exhibited an average lifespan of around 10 ms. As the resident time is long enough for a typical bubble to experience at least one peak to peak polarity shift when 50 Hz was imposed, which is the most important event throughout its lifespan, the behavior of successive bubbles could vary significantly. Fig. 2 and Fig. 3 show the photographic sequences of 2 bubbles from the 10 successive bubbles observed, labeled as bubble no. 2 and no. 5, respectively. Compared to the control group, bubble no. 2 was subjected to a force that pushed it against the horizontal surface, resulting in a more hemispherical

shape during the early stage of its growth. Soon after, as the electric field polarity changed, the bubble appeared to be lifted from the bottom by another force, forming a shape reminiscent of an inverted hammerhead or a boxing glove, which accelerated its detachment and led to an extremely short lifespan of 4.32 ms (Fig. 2). To the authors' knowledge, bubbles of this shape have not been reported in relevant research.



Figure 2: Photographic sequence of bubble no.2, square wave 50 Hz,  $\Delta t$  =0.27 ms

In contrast, bubble no. 5 (Fig. 3) exhibited markedly different growth dynamics, as it was dragged toward the surface during the mid or early-mid stage of its growth period. This effect caused the initially spherical bubble to settle onto the injection orifice, forming a triangular shape with rounded edges. This shape is mainly due to the Coulomb effect at the change of polarity that counteracts buoyancy and prevents the bubble from detachment. After 10 ms, which is half the period of the signal, the bubble experienced a lifting force, morphed into a shape similar to bubble no. 2, rose up, and detached from the surface in less than 3 ms. Consequently, the lifespan of bubble no.5 is much longer than that of bubble no.2.



Figure 3: Photographic sequence of bubble no.5, square wave  $50\,{\rm Hz},\,\Delta t$  =0.45  ${\rm ms}$ 

The aspect ratio over time for 10 successive bubbles was investigated and is plotted in on Fig. 4. The mean aspect ratio from control group is included as a reference. These curves provide an incomplete but useful tool for monitoring bubble shapes during growth. The behavior of the bubbles varies significantly depending on the position of the signal at the time of bubble emergence. 6 out of 10 bubbles (bubbles no. 1, 3, 5, 7, 9, and 10) experienced longer growth periods compared to the control group, while the remaining 4 bubbles (bubbles no. 2, 4, 6, and 8) had significantly shorter lifespans. For all the bubbles that exhibited shorter lifespans, reflecting from their aspect ratio, they received the lifting force earlier, at 2 to 4 ms (bubbles no. 2, 4, and 8), or wasn't suppressed at all (bubble no. 6). In contrast, bubbles with delayed removal experienced a prolonged suppressing period of 8 to 10 ms before another effect elongated the bubble and facilitated its removal. All 10 bubbles in this group had a higher aspect ratio with a larger positive slope at detachment compared to the control group, indicating the significant role of EHD stress in the detachment process: the detachment is triggered by the sudden change of polarity.



Figure 4: Evolution of aspect ratios of 10 successive bubbles, square wave  $50\,\mathrm{Hz}$ 

## B. Bubble growth and detachment in AC electric fields driven by sine wave

Fig. 5 presents photographs of a typical bubble growing under an electric field controlled by a 100 Hz sine wave signal. Like bubbles formed under a square wave electric field, strong oscillations caused by the time-varying EHD stress can be observed. The bubble became elongated, with its lower part being pushed against the horizontal surface. As the EHD stress decreased or was completely removed, the bubble returned to a more spherical shape, which forced the lower surface to be lifted and ultimately led to detachment. A comparison with the square wave group reveals a notable difference in bubble shape: bubbles under the sine wave field exhibited smoother, more symmetric contours. In contrast, in the square wave group, the sudden changes in both

field intensity and polarity generated significant Coulomb stress at the interface, causing dramatic shape deformations. By contrast, the gradual evolution in the sine wave signal resulted in a more progressive redistribution of electric stress, leading to a smoother interface.



Figure 5: Photographic sequence of an example bubble, sine wave  $100\,{\rm Hz},\,\Delta t=\!0.56\,{\rm ms}$ 

In addition to photographic observations, the oscillations can be characterized by tracking the aspect ratio over time. The evolution of the aspect ratio for 10 successive bubbles growing under a 100 Hz sine wave-driven electric field is depicted in Fig. 6a. Compared to the control group, all these bubbles exhibit significant oscillations in their aspect ratios, with two distinct wave peaks during the growth cycle. The oscillation patterns of these bubbles can be categorized into two groups: one encountering the first peak earlier (marked in green) and the other later (marked in orange). The bubbles in the orange group had a larger surface area and volume when they encountered the oscillations, resulting in both wave peaks being higher than those in the green group. Despite the differences in timing, the oscillation patterns of the two groups are very similar, both oscillating at approximately 190-200 Hz, which is roughly double the frequency of the electric field change. This suggests that dielectrophoretic force, which is independent of polarity, is the primary driver of these oscillations. The distinct grouping of bubble oscillations can be attributed to the timing of bubble growth initiation, which is regulated by the electric field and falls into two categories, each corresponding to a specific phase within the sinusoidal waveform. As a result, the bubbles exhibit only two modes of behavior throughout their growth. In addition, The bubbles in these two groups always alternate, suggesting that they either influence each other or are controlled by a common factor at initiation.

In the experiments conducted under 50 Hz electric fields, two distinct patterns were again observed for 10 suc-

cessive bubbles, as shown in Fig. 6b, where the odd number bubbles are marked in green and the even number bubbles are labeled in orange. Except for bubble no. 1, the bubbles in the two groups alternated consistently, with a bubble from the orange group always following one from the green group, but all detached with an aspect ratio of 2. Each bubble in both groups exhibited a single peak in aspect ratio, and the oscillation frequency in the green group was around 100 Hz. Compared to the 100 Hz experiments, the aspect ratios of these bubbles were significantly suppressed during the first 1 ms of their lifespan. This provides compelling evidence that the electric field influences not only the oscillation during bubble growth but also the initiation of bubble growth.



(a) Evolution of aspect ratios of 10 successive bubbles, sine wave  $100\,\mathrm{Hz}$ 



(b) Evolution of a spect ratios of 10 successive bubbles, sine wave  $50\,\mathrm{Hz}$ 

Figure 6: Aspect ratio curves of 10 successive bubbles, sine wave  $100 \,\mathrm{Hz}$  50 Hz

#### IV. CONCLUSION

In this study, the impact of AC square wave and sine wave electric fields at 50 and 100 Hz on the dynamics of

injected air bubbles in HFE-7100 was investigated. EHDinduced oscillations were observed and analyzed through the evolution of aspect ratios. The growth and detachment of bubbles were found to be highly dependent on the phase at which bubble initiation occurred. While electrical stress at the liquid-gas interface reduced the growth rate for certain bubbles, the eventual polarity reversal ultimately triggered the detachment process.

One of the most unexpected findings was that the sine wave with alternating polarity modulated the initiation of bubble growth, regulating 10 successive bubbles into two distinct oscillation modes. Within each of these alternating modes, both the aspect ratio evolution and volumetric growth curves exhibited high consistency. However, this regulating effect was suppressed when a DC bias was introduced to the sine wave signal, suggesting that polarity changes and Coulomb forces play a critical role in the observed organization of bubble behavior.

#### ACKNOWLEDGMENTS

This research project was financially supported by the French national space agency CNES. The Ph.D. fellowship of Tianle Gu is supported by the French Ministry of Research and Education MESR. The laboratory SIMaP is part of the LabEx Tec 21 (Investissements d'avenir - Grant Agreement no.ANR-11-LABX-0030). We would like to express our sincere gratitude to Professor Jocelyn Bonjour from CETHIL, INSA Lyon, for kindly lending us the experimental equipment, which was instrumental in the successfully completion of this work.

#### References

- M. Cooper, "The microlayer and bubble growth in nucleate pool boiling," *International Journal of Heat and Mass Transfer*, vol. 12, pp. 915–933, Aug. 1969.
- [2] W. G. Pitt, G. A. Husseini, and B. J. Staples, "Ultrasonic drug delivery – a general review," *Expert Opinion* on Drug Delivery, vol. 1, pp. 37–56, Nov. 2004.
- [3] W. S. Bousman, *Studies of Two-Phase Gas-Liquid Flow in Microgravity*. PhD thesis, Feb. 1995.
- [4] H. Matsushima, Y. Fukunaka, and K. Kuribayashi, "Water electrolysis under microgravity: Part ii. description of gas bubble evolution phenomena," *Electrochimica Acta*, vol. 51, pp. 4190–4198, May 2006.
- [5] S. Siedel and T. Gu, "Toward a complete understanding of quasi-static bubble growth and departure," *Proceedings of the National Academy of Sciences*, vol. 121, p. e2317202121, Apr. 2024.

## Numerical Modeling of Dust Particle Motion in a Corona Discharge-Based Ionic Wind Cleaning System for Solar Panels

K. Yanallah<sup>1\*</sup>, M.R. Bouazza<sup>1,2</sup>, A. Tilmatine<sup>3</sup>, F. Pontiga<sup>4</sup>, A. Zouaghi<sup>5</sup>, N. Kadous<sup>3,6</sup>, Y. Bellebna<sup>3</sup> <sup>1</sup>LGEP Laboratory, University of Tiaret, Tiaret, Algeria

<sup>2</sup>University Blida1, Faculty of Sciences, Algeria

<sup>3</sup>APELEC Laboratory, DjillaliLiabes University of Sidi Bel-Abbes, Sidi Bel Abbes, Algeria

<sup>4</sup>Departamento de FísicaAplicada II, Universidad de Sevilla, Sevilla, Spain

<sup>5</sup>Ecole Centrale de Lyon, INSA Lyon, Université Claude Bernard Lyon 1, CNRS, Ampère, UMR5005, 69130 Ecully,

France

<sup>6</sup>Mustapha Stambouli University of Mascara, Mascara, Algeria.

\*Corresponding author:<u>k-yanallah@univ-tiaret.dz</u>

Abstract- This study explores innovative solutions to reduce efficiency losses in solar panels caused by dust accumulation, using ionic wind generated by corona discharge. Ionic wind, produced through positive or negative corona discharges, helps to mitigate dust build-up by ionizing air molecules and generating a wind that moves dust particles. The cleaning system uses a blower device that moves along the panel, carrying dust in a linear direction, providing a contactless cleaning method. The mechanisms governing dust particle motion in this ionic wind systemis investigated, emphasizing the importance of understanding how forces affect particle trajectories. A numerical model is developed, considering forces like Coulomb, gravitational, drag, and van der Waals adhesion. The model uses Poisson's equation, the continuity equation for charged particles, and the Navier-Stokes equations to calculate the Coulomb and the drag forces.

Keywords- Numerical modeling, ionic wind, corona discharge, dust cleaning, PV panel.

#### I. INTRODUCTION

Solar energy is a promising solution for sustainable green energy, but the accumulation of dust and sand on photovoltaic (PV) panels reduces their efficiency, limiting electricity generation. Developing effective cleaning techniques is crucial for maintaining panel performance. Current cleaning methods include mechanical, coating, and electrostatic techniques [1-2]. Mechanical methods, such as air-blowing, robotic cleaning, and ultrasonic vibration, are energy-intensive. Water-based cleaning is effective but requires significant water consumption, posing challenges in arid regions. Coating methods use nanotechnology to create super hydrophilic and hydrophobic films, often combined with other techniques. Electrostatic cleaning offers a contactless alternative, likeusing high-voltage induction charging or electrodynamic screens, though the effectiveness of the latteris influenced by particle properties.

The use of corona ionic wind for cleaning solar panels is a novel technique that has been studied by examining how geometric parameters influence wind speed intensity and power consumption in a laboratoryscale setup [3]. This technique can achieve over 95% cleaning efficiency at a wind velocity of 2 m/s, utilizing a cleaning actuator composed of a high-voltage electrode and a ground electrode structured as a rectangular metal frame.

Theoretical and numerical studies on cleaning PV solar panels using electric wind generated by corona discharge are crucial for understanding particle movement mechanisms and optimizing the performance

of the cleaning system. Building on previous studies that have focused on numerical modeling of dust particles under corona discharge for applications such as particle separation and filtration, this investigation aims to analyze the behavior of dust accumulated on PV panels under electric wind forces. In this context, this paper presents a numerical model of particle trajectories, taking into account key electrostatic forces that influence particle motion, including Coulomb force, gravitational force, drag force, and van der Waals adhesion force.

#### II. NUMERICAL MODELING

The electro-hydrodynamic (EHD) air blower device operates on the principle of corona discharge to generate airflow. It consists of two main components: a wire electrode connected to a high negative DC voltage and a grounded rectangular frame electrode, referred to as "plate"in Fig. 1. The airflow, often called electric wind, is induced due to the EHD force generated by the corona discharge.In this system, the corona discharge occurs at the wire electrode, ionizing the surrounding air. The resulting negative ions move toward the grounded frame, transferring momentum to neutral air molecules and producing the gas motion. The airflow exits the device through two openings located below the frame.

Dust particles deposited on the surface of the PV panel can be removed by the drag force exerted by the electric wind flow. In addition to this force, the dust particles experience other influences, including the Coulomb force, gravitational force, friction force (due to the contact with the panel surface), and the van der Waals force. The interaction and balance of these forces



Fig. 1. Schematic representation of the solar panel cleaning system based on electric wind (not to scale).

determine the motion of the dust particles, ultimately governing the cleaning process of the panel.

The simulation of the cleaning process involves three steps. First, the EHD force is calculated by solving the Poisson equation for the electric field and charge density. Second, the electric wind velocity is determined by solving the Navier-Stokes equations using the EHD force as an input. Finally, the motion of dust particles is analyzed by applying Newton's laws of dynamics, using the electric field and wind velocity to predict particle trajectories and assess the cleaning efficiency.

#### A. Electric Field and Charge Density

To numerically simulate the electric field and the charge density between the electrodes, the corona discharge is assumed to be in a stationary regime, meaning the system remains steady over time. Therefore, the equations governing the negative corona discharge are

$$-\nabla \cdot \mathbf{J}_{\mathrm{e}} = (\alpha - \eta) |\mathbf{J}_{\mathrm{e}}| \tag{1}$$

$$\nabla \cdot \mathbf{J}_{\mathrm{p}} = \alpha |\mathbf{J}_{\mathrm{e}}| \tag{2}$$

$$-\nabla \cdot \mathbf{J}_{n} = \eta |\mathbf{J}_{e}| \tag{3}$$

$$\nabla \cdot \mathbf{E} = \frac{e_0}{\varepsilon_0} \left( N_{\rm p} - N_{\rm e} - N_{\rm n} \right) \tag{4}$$

where subscripts e, p and n correspond to electrons, positive ions and negative ions;  $\mathbf{J}_i$  and  $N_i$  denotes the flux and the number density of particles of type i (i = e, p and n), respectively; **E** is the electric field,  $\alpha$  and  $\eta$  are the ionization and attachment coefficients, respectively;  $\varepsilon_0$  is the air permittivity; and  $e_0$  is the elementary charge. The flux of each particle type is given as  $\mathbf{J}_i = \mu_i N_i \mathbf{E}$ , where  $\mu_i$ is the electrical mobility of particle i.

By solving this set of coupled equations as detailed in [4], the EHD force distribution acting on air can be evaluated as [5]

$$\mathbf{F} = e_0 \left( N_{\rm p} - N_{\rm e} - N_{\rm n} \right) \mathbf{E} \tag{5}$$

#### B. Electric Wind Velocity

The EHD flow generated by the corona discharge depends on the nature of the airflow, which can be either laminar or turbulent based on the Reynolds number. At low Reynolds numbers, typically with low applied voltage, the flow remains laminar, and the laminar flow model provides a more accurate representation. However, the airflow is most often turbulent, and the gas velocity must be determined by solving the Reynolds-averaged Navier-Stokes equations [4].

#### C. Dust Particle Motion

In this model, several forces are taken into account to determine the trajectory of dust particles [6]:

#### a)Coulomb force

The Coulomb force  $\mathbf{F}_c$  acting on a particle in the region beneath the grounded electrodes is expressed as

$$\mathbf{F}_{\rm c} = q_{\rm p} \mathbf{E} \tag{6}$$

where  $q_p$  denotes the charge acquired by the particle from the corona discharge. In this work, the charge of the particle is assumed to be equal to the saturation charge value [6-7]:

$$q_{\rm p} = q_{\rm ps} = 4\pi\varepsilon_0 r_{\rm p}^2 \frac{3\varepsilon_{\rm rp}}{\varepsilon_{\rm rp}+2} E_{\rm c} \tag{7}$$

where  $\varepsilon_0$  and  $\varepsilon_{rp}$  are the dielectric permittivity of vacuum and the relative permittivity of the particle, respectively, and  $E_c$  is the dielectric strength of air ( $E_c \approx 3 \times 10^6 \text{V/m}$ ).

#### b) Drag force

The drag force  $\mathbf{F}_{d}$  on a spherical particle within the gas medium is described by the following expression:

$$\mathbf{F}_{d} = 6\pi\eta_{g}r_{p}\frac{1}{Cu}\left(\mathbf{U}_{g} - \mathbf{V}_{p}\right)$$
(8)

In this equation,  $\eta_g = 1.85 \times 10^5 \text{ kg m}^{-1} \text{ s}^{-1}$  is the dynamic viscosity of the air, Cu = 1 is the Cunninghamfactor,  $U_g$  is the velocity of the flow, and  $V_p$  is the velocity of the particle.

#### c) Gravitational force

The gravitational force  $\mathbf{F}_{g}$  is given by

$$\mathbf{F}_{\rm g} = m_{\rm p} \mathbf{g} = \frac{4}{3} \pi r_{\rm p}^3 \rho \mathbf{g} \tag{9}$$

where  $m_{\rm p}$  and  $\rho$  are, respectively, the mass and the density of the particle, and **g** is the gravitational acceleration.

#### d) Van der Waals force

The van der Waals force  $\mathbf{F}_{vdW}$  acts as an adhesive force between the particle and the surface, and it is expressed as

$$\mathbf{F}_{\rm vdW} = -\frac{A_{\rm h}r_{\rm p}}{6D^2} \left( \frac{\gamma^2}{\gamma^2 + 58.14 \, r_{\rm p} \, \rm RMS} + \frac{D^2}{(D + 1.817 \, \rm RMS)^2} \right) \mathbf{n} \quad (10)$$

with  $A_{\rm h}$  the Hamaker constant (of the order of  $10^{-19}$  J in vacuum), *D* the shortest distance between the particle and the substrate (of the order of  $10^{-10}$  m), RMS the quadratic mean value of the surface roughness ( $\approx 3$  nm),  $\gamma$  the mean distance between the peaks of the asperities ( $\approx 20$  nm) and **n** the unit normal vector to the solar panel surface.



Fig. 2. The components  $E_x$  and  $E_y$  of the electric field near the surface of the solar panel, under the blower device, at a height y = r (the radius of the dust particle), for L = 5 cm and l = 1 cm.

#### e) Static friction force

The static friction force  $F_{\text{sta},x}$ , aligned parallel to the surface of the solar panel, is considered when the particle is at rest. Its maximum value is determined as the product of the total normal force  $F_{T,y}$  to the solar panel surface acting on the dust particle (in the absence of motion) and the static friction coefficient  $\mu_e$ ,

$$F_{\text{sta},x}^{\max} = \mu_{\text{e}} F_{\text{T},y} \tag{11}$$

If the total horizontal force  $F_{T,x}$  acting on the particle does not exceed  $F_{\text{sta},x}^{\text{max}}$ , the particle remains at rest. Conversely, when  $F_{T,x} > F_{\text{sta},x}^{\text{max}}$ , the particle will move. Therefore, equation (11) serves as a significant criterion for determining the onset of particle motion.

Considering all these forces in Newton's second law allows for the determination of the equation of motion of particles.

#### III. RESULTS AND DISCUSSION

The numerical results presented in this section were obtained using a corona wire with a radius of  $r=100 \mu m$  and an inter-electrode separation of d=3 cm. A negative voltage of  $\varphi=-25$  kV was applied to the corona wire, resulting in a current intensity per unit length of 805  $\mu$ A/m. The electric field and electric wind velocity, used as input parameters in (6) and (8), were obtained by solving (1)-(4) with a novel approach detailed in [4], and solving the Navier-Stokes equations. The inclination angle of the solar panel was 10°.

The dust particle is modeled as a sphere with a diameter of  $d_p = 400 \,\mu\text{m}$  and a mass density of  $\rho_p = 2.6 \,\text{g/cm}^3$ . At time  $t = 0 \,\text{s}$ , the particle is assumed to be located on the panel surface, beneath the blower, at a distance  $x_p = 0.3L$  from its center. The blower, with a width *L*, has two electric wind outlets, and our focus is on outlet 2. Influenced by the velocity flow  $\mathbf{U}_g$  generated by the blower, the particle moves with a velocity  $\mathbf{V}_p$  along the *x*-axis.

Fig. 2 shows the components of the electric field near the surface of the solar panel just under the blower device. The strength of the component  $E_x$  of the electric field varies from 0 to nearly  $6 \times 10^5$  V/m, which is sufficient to accelerate the charged dust particles. In contrast, the component  $E_y$  of the electric field is one order of magnitude smaller than the  $E_x$ . Therefore, the



Fig. 3. 2D spatial distribution of the ionic wind velocity inside and beneath the blower device for L = 5 cm and l = 1 cm.

motion of the dust particle along the *y*direction will not be considered. The sign of  $E_y$  reverses at a distance of 1.2 cm from the center of the blower. When  $E_y$  is positive, the corresponding Coulomb force helps to lift the dust particle in the *y*-direction, opposing the Van der Waals and gravitational forces. Conversely, when  $E_y$  is negative, the Coulomb force pushes the dust particle downwards, in the same direction than van der Waals and gravitational forces, making the particle more likely to stick to the solar panel surface. Thus, the effect of the component  $E_y$  depends on the position of the dust particle.

The electric wind generated by the corona discharge transports dust particles away from the surface of the solar panel. The profile of the gas velocity distribution in the inter-electrode space, generated by the negative corona discharge for an applied voltage of -25 kV, is shown in Fig. 3. Since the corona plasma region is confined to a small layer around the wire, the flow distribution is primarily influenced by the EHD force acting in the drift zone. This EHD force serves as a propulsive mechanism, accelerating the air from the corona wire towards the two plates. As the air approaches the plates, it is deflected along the surface of each plate. Consequently, in the downstream region of the wire, the flow structure is characterized by the presence of two stable, recirculating vortices situated above each plate. The maximum air velocity, reaching approximately 2.0 m/s, is observed beneath the wire and within the deflected flow circulating parallel to the walls on both sides of the blower. Furthermore, the gas velocity remains high at the outlet boundaries due to the small outlet section, which contributes to the cleaning process of dust particles.

On the solar panel, dust particles are influenced by Coulomb force and the drag force generated by the electric wind. Due to the inclined angle of the panel, gravitational force also contributes to particle motion. Fig. 4 illustrates the component  $V_x$  of velocity for a dust



Fig. 4. The component  $V_x$  of velocity of a dust particle as a function of time.

particle, both with and without considering the Coulomb force. The component  $V_y$  is not considered, because the displacement of dust particles is mainly tangential to the solar panel surface.

The results show that the particles velocity increase from ~ 0.5 m/s to ~ 1 m/s when Coulomb force is considered, which implies a significant improvement in the cleaning efficiency. The Coulomb force primarily controls the cleaning when the initial position of the particle is beneath the blower. However, when the particle lies outside the blower, the Coulomb force has minimal impact, and its motion is mainly driven by the drag force and gravity. As shown in Fig. 5, drag and gravitational forces account for 4 to 9% of the total force beneath the blower, but nearly 100% when the particle is outside (x > 2.5 cm).

In conclusion, if a particle is initially situated next to the blower and, due to its strong adhesion to the panel, is not removed by the action of the electric wind and gravity, it will be eventually removed when the particle becomes located below the blower, which will occur as the blower device moves forward. At thatmoment, the Coulomb force supplements the drag and gravitational forces, increasing the probability of eliminating theparticle from the solar panel surface.

#### IV. CONCLUSION

This study explores the use of ionic wind generated in a corona discharge for cleaning PV panels, aiming at reducing efficiency loss due to dust accumulation. The Coulomb force predominantly influences dust particles movement when they are located beneath the blower, accelerating them away from the panel surface. On the contrary, Coulomb force has minimal effect on particleslocated outside the blower, and its movement is mainly driven by the drag force and gravity. However, if the ionic wind is unable removed these particles due its strong adhesion to the panel, they can be eliminated when they eventually end up underneath the blower, as it moves forward.At that moment, the Coulomb force and the drag force cooperate to efficiently remove the



Fig. 5. Comparison of the ratios of Coulomb force to the total force, and drag plus gravitational force to the total force, along the *x*-axis.

particles. These findings improve our understanding of the cleaning mechanism and will facilitate the design of more efficient ionic wind cleaning systems.

#### REFERENCES

- [1] S. Z. Said, S. Z. Islam, N. H. Radzi, C. W. Wekesa, M. Altimania, and J. Uddin. Dust impact on solar PV performance: A critical review of optimal cleaning techniques for yield enhancement across varied environmental conditions, *Energy Reports*, 12:1121– 1141, 2024.
- [2] J. A. P. Rodrigues, A. Sonia. A. C. Diniz, and L. L. Kazmerski.Evaluation of the impacts of various cleaning techniques on photovoltaic module glass, in 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 0958–0960, 2021. doi: 10.1109/PVSC43889.2021.9518864.
- [3] A. Tilmatine, N. Kadous, K. Yanallah, Y. Bellebna, Z. Bendaoudi, and A. Zouaghi. Experimental investigation of a new solar panels cleaning system using ionic wind produced by corona discharge, *Journal of Electrostatics*, 124:103827, 2023.
- [4] K. Yanallah, A. Chelih, M. R. Bouazza, F. Pontiga, M. Bouadi, P. A. Vázquez and Z.Bendaoudi. A new numerical approach for efficient modeling of positive corona discharge and its associated electric wind, *Journal of Physics D: Applied Physics*, 56:415201, 2023.
- [5] J. P. Boeuf and L.C. Pitchford, Electrohydrodynamic force and aerodynamic flow acceleration in surface dielectric barrier discharge, *Journalof Applied Physics*, 97:103307 (2005)
- [6] A. Zouaghiand N. Zouzou. Numerical modeling of particle motion in traveling wave solar panels cleaning device, *Journal of Electrostatics*, 110:103552, 2021.
- [7] M. Pauthenier and M. Moreau-Hanot. La charge des particules sphériques dans un champ ionisé, *Journal de Physique et le Radium*, 3:590–613, 1932.

# Magneto-electro-osmotic stirring: A pathway to enhanced molecular transport

L. Gonzalez<sup>1</sup>, C. Biscara<sup>1</sup>, J.-M. Roux<sup>1</sup> and L. Davoust<sup>2,\*</sup> <sup>1</sup>CEA/LETI, 3800 Grenoble, France

<sup>2</sup>Univ. Grenoble-Alpes/CNRS/Grenoble-INP, SIMaP Laboratory, 38402 Saint Martin d'Hères, France \*Corresponding author: <u>Laurent.Davoust@simap.grenoble-inp.fr</u>

*Abstract* - Because of a very low Reynolds number, stirring at microscale and micro-mixing are reputed challenging despite the need for enhancing molecular transfers in biological microsystems. By making use of both an electric field and a magnetic field, this paper shows how it is possible to generate an online electroosmotic flow with micro-stirring included. Due to magnetic non-uniformities, low-Rm MHD-induced vortices are made evident just above the edges of a magnet inserted at a microchannel wall. One presents numerical simulations of such an electroosmotic flow in presence of a permanent magnet. For sake of comparison, an experimental microsystem is also developed. Upstream and downstream recirculating flows can therefore be characterized. Particles Images Velocimetry (PIV) based on fluorescent seed particles is used to demonstrate experimentally the presence of vortical flows and associated stirring.

Keywords - Electroosmotic flow, Magnetohydrodynamics, Electrolyte, Micro-channel, Microstirring

#### I. INTRODUCTION

Electric fields are commonly used in microfluidic devices for biological applications (blood cells sorting for instance). Electric fields can also generate fluid pumping due to electroosmotic flows. At microscale, a high electric field is easily produced using a voltage typically produced by a function generator. When a DC voltage is applied between the two ends of a microchannel filled with an ionic liquid buffer, an electroosmotic flow is found to arise due to the presence of electric double layers (EDL) standing along the walls electrically charged by a native layer of immobilized ions. The subsequent surface charge is balanced by a diffuse layer of counter-ions (Guy-Chapman diffuse layer). Provided the ratio of the Debye thickness of the Guy-Chapman layer,  $\lambda_D$ , to the transverse size of the microchannel remains small, the external application of an axial electric field on the non-uniform distribution of the counter-ions across EDL induces a Coulomb force that makes the liquid to move[1]. A viscous plug flow is ultimately generated with a flow rate that can be monitored by the imposed electric field (Fig. 1). Numerical simulations and experiments on an electroosmotic flow are presented when a permanent magnet is also inserted at the bottom wall of the microchannel. Due to magnetic non-uniformities, low-Rm MHD-induced vortices are made evident just above the edges of the magnet. Upstream and downstream recirculating flows can therefore be made evident, that are useful to stir or to separate biological targets.



Figure 1. Schematic steps of the electro-osmotic flow establishment in a microfluidic channel.

## II. THEORETICAL DESCRIPTION AND NUMERICAL IMPLEMENTATION

#### A. ElectroMagnetoHydroDynamics

In the presence of a permanent magnet, the magnetic flux density **B** is described by the Maxwell-Thomson equation:  $\nabla \cdot \mathbf{B} = 0.$  (1)

with the magnetic vector potential A defined as:  

$$\mathbf{B} = -\nabla \mathbf{A}.$$
(1)

As the magnetic Reynolds number Rm is very low, especially in microfluidics applications, the influence of the flow on the magnetic field is negligibly small. With the ionic liquid under consideration, the magnetic field can be calculated in permanent conditions since it is decoupled from the velocity and electric fields. The electric field **E** can be written as:

$$\mathbf{E} = -\boldsymbol{\nabla}\boldsymbol{\Psi},\tag{3}$$

with  $\Psi$  the electric potential distributed all over the channel. The space charge density  $\rho_e$  is described by the Maxwell-Gauss equation:

$$\nabla \cdot \varepsilon \mathbf{E} = \rho_e, \tag{4}$$

with  $\varepsilon$  the electric permittivity. In this case, the space charge density clearly departs from zero near the walls accross the EDL. The conservation of the current density is the last ingredient to introduce here:

$$\frac{\partial \rho_e}{\partial t} + \nabla \cdot \mathbf{J} = 0, \tag{5}$$

where **J** is the current density, defined as follows for a binary monovalent electrolyte in the presence of a MHD flow:

$$\mathbf{J} = e(n^+\mu^+ + n^-\mu^-) (\mathbf{E} + (\mathbf{u} \times \mathbf{B})) + \rho_e \mathbf{u}, \quad (6)$$

with *e* the absolute value of the electron charge,  $n^+$  and  $n^-$ , the number densities of positive and negative ions,  $\mu^+$  and  $\mu^-$ , their respective mobility, and u, the velocity. By defining  $\sigma$  the electric conductivity as [2]:

$$\sigma = e(n^{+}\mu^{+} + n^{-}\mu^{-}), \qquad (7)$$

and considering a very small electric Reynolds number  $Re_{Elec}$  ( $Re_{Elec} = \frac{\varepsilon u}{\sigma\delta} \approx 10^{-9}$ ), only the electric

conduction currents need to be considered and the electric current density simplifies to:

$$\mathbf{J} = \sigma \mathbf{E} + \sigma (\mathbf{u} \times \mathbf{B}). \tag{8}$$

The velocity **u** for a Newtonian non compressible fluid moving inside a microchannel can be calculated thanks to mass conservation and the Stokes equation, the Reynolds number being very small:

$$\nabla \cdot \mathbf{u} = 0. \tag{9}$$

$$0 = -\frac{1}{\rho} \nabla P + v \nabla^2 \mathbf{u} + \mathbf{F}, \tag{10}$$

with P, the pressure,  $\rho$ , the density, v, the kinematic viscosity and F, the body force that is the sum of the Lorentz force,

$$\mathbf{F}_{\mathbf{L}} = \mathbf{J} \times \mathbf{B},$$
 (11)  
and the Coulombic force,

$$\mathbf{F}_{\mathbf{F}} = \rho_{a} \mathbf{E}.$$
 (12)

The non-uniform distribution of the Lorentz force generates pressure gradients, which are found later on to be the source of micro-stirring. Using (8), (11) and (12), the body force F can be written more explicitly as: F

$$= \rho_e \mathbf{E} + \sigma \mathbf{E} \times \mathbf{B} + \sigma (\mathbf{u} \times \mathbf{B}) \times \mathbf{B}.$$
(13)

Because the electric field is externally imposed - and not only induced by the interaction between the velocity and the magnetic field [3] -, it is worthy to assess here its real impact on the flow, justifying thus the term "EMHD flow". A fair assumption is ultimately made, considering the Joule effect to be negligibly small, thus permitting the omission of thermo-electro-hydrodynamic effects [4-5].

#### B. Numerical implementation

The three-dimensional numerical model is implemented within COMSOL Multiphysics, a commercial software platform based on the finite element method. The computational domain, depicted in Figure 2, consists of a microchannel of length L=3 cm, featuring a rectangular cross-section with a width of 1 mm and a height of 150  $\mu$ m. The working fluid is a saline solution (0.9% NaCl), widely employed as a biological buffer, whose physicochemical properties at ambient temperature (293.15 K) are summarized in Table 1. A cylindrical permanent magnet (radius d=3 mm) is positioned 1 mm beneath the lower boundary of the microchannel. This magnet, composed of Neodymium Iron Boron (BMN-42), exhibits a remanent magnetic flux density of 1.33 T at room temperature. An air box is added to enable the magnetic field to be calculated with consistent boundary conditions and with no compromise on the accuracy provided its size is chosen ten times that of the channel height.

	Symbols	Value
Relative permittivity	ε [F/m]	$78.5\varepsilon_0$
Electrical conductivity	σ [S/m]	2.5
Dynamic viscosity	$\eta$ [Pa.s]	0.001



#### C. Physical couplings and boundary conditions

Magnetic field is calculated thank to Maxwell-Thomson equation (1) and the magnetic potential (2) in all domains (air box included). Whereas, Maxwell-Gauss equation (4) with the description of the electric potential (3) and



Figure 2. Design for the numerical implementation.

conservation of the current density equation (5) are solved in the channel. The fluid velocity along the microchannel is calculated based on mass conservation (9) and the Stokes equation (10) with the body force (13).

At the initial time, the system is considered at rest: no electric potential, no flow, no magnetic potential in all domains. The Eulerian approach requires the definition of boundary conditions: a no-slip condition is imposed at the electrically-insulated side walls of the channel where the normal current density is imposed null. The inlet is grounded and maintained at a pressure P=0 while a DC potential,  $\delta V=20$  V, and an open fluid boundary condition are applied at the output. The magnetic field delivered by the magnet is calculated with a zero flux condition imposed at the air cube boundaries.

#### **III. NUMERICAL RESULTS**

The velocity map is presented in Figure 3. The axial electric field is found to generate a Poiseuille plug flow modified by the induction of a pair of two counter-rotating vortices above the edge of the magnet (vorticity aligned with the normal magnetic field produced by the magnet). Even if the velocity scale remains small, the stirring and the rotation time scale so obtained remain relevant to a significant biological stirring, considering the small size of the channel. The EMHD coupling term of the body force,  $\sigma E \times B$ , here generates a transverse force that is balanced by a transverse pressure gradient. The latter stands as a good candidate for explaining the stirring since it is only observed right above the magnet.



Figure 3. Velocity map in the normal-to-B plane, as obtained for an imposed voltage as large as 20 V and for a 3mm-sized cylindrical magnet.

#### IV. SCALING ANALYSIS

The order of magnitude for the velocity associated with micro-stirring can be found by considering the curl of the Stokes equation, more specifically the balance between the viscous torque and the EMHD torque, the latter being calculated from the EMHD coupling component in the body force (13):

$$\nabla \times (\upsilon \Delta \mathbf{u}) \sim \nabla \times (\sigma \mathbf{E} \times \mathbf{B}) \sim \sigma(\mathbf{E} \cdot \nabla) \mathbf{B}.$$
(14)

If we consider the physical scales introduced earlier, the order of magnitude predicted numerically is recovered, and also confirmed experimentally, as illustrated hereafter:

$$\mathbf{u} \sim \frac{\sigma}{v} \frac{\delta V}{L} B d^2 \sim 10^{-5} - 10^{-4} m/s.$$
(15)

#### V. EXPERIMENTAL CHARACTERIZATION

The microfluidic device presented in Fig. 4 is made respectively of: a Printed Circuit Board (PCB) for the bottom wall and the end electrodes, a microchannel (width: 2mm, height: 150  $\mu$ m) and a cover made of transparent polymer (PMMA).



Figure 4. Schematic of the microfluidic device.

The experimental setup for the observation and the characterization of the flow is presented in Fig. 5.

A green 530 nm Light-Emitting Diode (LED) is used as a lighting source. Red fluorescents seed particles (Thermo Fisher Scientific Fluoro-Max Red 36-2B) are injected at the inlet of the microchannel and transported by the electro-osmotic flow. Green light is absorbed by particles whereas emitted red light is focalized by an objective on the photosensor of a fluorescence camera. A specific 532nm filter is placed before the camera in order to remove potential light reflections. An image stacking is acquired in order to apply a Particles Images Velocimetry algorithm that allows the velocity map to be experimentally calculated. The method used for the velocity map calculation is the "sum of correlation" method. It consists of a correlation method applied upon a sequence of successive images. The result is a spaceaveraged velocity profile (Fig. 6). Experimental maps are found in good agreement with the numerical prediction. The velocity scales are of same order of magnitude, while being slightly smaller in the experimental outputs.

#### VI. CONCLUSIONS AND PERSPECTIVES

EMHD coupling between an electroosmotic flow and the magnetic field generated by a permanent wall magnet is investigated. Micro-stirring, as made evident both numerically and experimentally, is related to



Figure 5. Schematic of the experimental setup used to characterize EMHD microflow [3].

magnetic non uniformities. A stirring flow with a velocity magnitude as large as  $10-100\mu$ m/s is obtained at microscale. End-user implementation is easy at first sight since the magnetic field required to achieve micro-stirring remains relatively moderate. The integration of such an actuator in a microfluidic chip still needs to be optimized for biological separation purposes but the methodology is promising.





#### References

[1] A. Manz, C. S. Effenhauser, N. Burggraf et al., Electroosmotic pumping and electrophoretic separations for miniaturized chemical analysis systems, *J. Micromechanics Microengineering*, vol(4), 257-265, 1994.

[2] A. Castellanos, *Electrohydrodynamics*, 1998.

[3] N.T. Baker, A. Pothérat, L. Davoust, Dimensionality, secondary flows and helicity in low-Rm MHD vortices. *J. Fluid Mech.*, 779:325-350, 2015

[4] L. Gonzalez, J-M. Roux, L. Davoust, MicroPIV study of vortex produced by electrothermal flows inside a microfluidic chamber, *IEEE 22<sup>nd</sup> International Conference on Dielectric Liquids* (ICDL), Worchester, USA, 1-4, 2023.

[5] L. Davoust and P. A. Vazquez, Thermo-Electro-HydroDynamics (TEHD) Applied to Jet Micro-Pumping, *IEEE 21<sup>st</sup> International Conference on Dielectric Liquids (ICDL)*, Sevilla, Spain, 1-4, 2022.

### Heat Transfer Enhancement Driven By Thermo-Electro-Hydrodynamics (TEHD): Influence Of The Marangoni Effect

G. Braye<sup>1,2</sup>, L. Davoust<sup>2,\*</sup>, P. À. Vazquez Gonzalez<sup>3</sup>

<sup>1</sup>G2Elab, Grenoble INP, CNRS, Université Grenoble Alpes, 38000 Grenoble, France

<sup>2</sup>SIMaP Laboratory, EPM group, Grenoble INP, CNRS, Université Grenoble Alpes, 38402 Saint Martin d'Hères, France

<sup>3</sup>Departamento de Física Aplicada III, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los

Descubrimientos, s/n, 41092 Sevilla, Spain

\*Corresponding author: laurent.davoust@simap.grenoble-inp.fr

*Abstract-* A dielectric liquid subjected to a temperature gradient and a non-uniform electric field experiences two body forces, along with an additional surface stress if a liquid surface is present. A first body force is the thermal buoyancy force that is disregarded here due to microgravity conditions. A second body force, known as a thermoelectrohydrodynamic (TEHD) force, arises from the joint contribution of the non-uniform electric field and the temperature-dependent dielectric permittivity, here approximated as linear to first order. The TEHD force exists independently of thermally-induced buoyancy, making it a promising mechanism for enhancing heat transfer under microgravity conditions. This paper illustrates the competition between a Marangoni stress and a TEHD force, making use of numerical simulations. The configuration studied is a differentially-heated cavity, free of gravity, submitted to a non uniform electric field and a thermally-induced Marangoni stress along its "top and bottom" boundaries. A scaling analysis is proposed in order to identify the key parameters that contribute to heat transfer.

Keywords- Thermoelectrohydrodynamics, dielectric liquid, microgravity, flow simulations, Marangoni flow.

#### I. INTRODUCTION

The Marangoni effect is related to a stress along a fluid/fluid interface that results from a surface tension gradient. In the literature, two parameters influencing the surface tension of a fluid interface are commonly identified, the first one being the concentration of an amphiphilic chemical specie, and the second one being the temperature [5], which is the parameter we propose to retain in the present paper.

In addition to electrohydrohydrodynamics (EHD) that results from the coupling between electrostatics and fluid mechanics, thermoelectrohydrodynamics (TEHD) involves another physical mechanism, heat transfers. Among the electric forces a fluid can be subjected to, the focus here will be on the dielectrophoretic (DEP) force alone. In such conditions, Jawichian et al.[2] have shown that a temperature gradient inside a fluid can give rise to a DEP-driven flow inside a cavity provided a non uniform electric field can also be sustained, for instance between a differentially heated pair of triangular electrodes also submitted to an AC voltage. A flow is then steadily generated between the electrodes, as two counter-rotating vortices arise. Such a flow contributes to an increased heat transfer between the electrodes, as demonstrated by the evolution of the Nusselt number[2].

Here, the latter TEHD flow is revisited by considering the additional role of the Marangoni stress. To this end, the top and bottom boundaries are considered behaving like liquid surfaces subjected to a thermally-induced surface tension gradient. This configuration is relevant to the float zone method well-known in crystal growth science. Depending on the sign or the magnitude of the Marangoni stress, its interaction with the DEP body force is found either constructive or adverse, which gives rise to new regimes as shown in the following.

#### II. METHODOLOGY

A. The triangular electrode configuration



Figure 1: Configuration studied with one pair of differentiallyheated triangular electrodes.

The cavity under study is filled with a purely dielectric liquid trapped between two electrodes. The triangular shape of the electrodes creates a non-uniform electric field. The two other boundaries of the cavity are liquid surfaces that separate the inner liquid from an electrically and mechanically passive outer fluid medium. Constant temperatures are prescribed:  $T_c$  at the cold electrode and  $T_h$  at the hot electrode. A temperature gradient is therefore imposed giving rise to the DEP force in the bulk and to a Marangoni stress along the liquid surfaces. As numerically demonstrated by Jawichian et al. in case of microgravity conditions and solid boundaries, free of Marangoni effect, a jet driven from two internal counter-rotating vortices is made evident between the electrodes [2], that is found to contribute to heat transfer enhancement. Microgravity conditions are also consid-

ered in the present work while the additional role of the Marangoni stress is investigated.

#### B. Mathematical modelling

With (X,Y), the 2-D cartesian coordinates (Fig. 1), U, the velocity field, T, the temperature, V, the electrical potential, P, the pressure and  $\nabla_d$ , the nabla operator, it is possible to define respective non-dimensional counterparts such that:

$$(x,y) = \left(\frac{X}{H}, \frac{Y}{H}\right); \ u = \frac{H}{\alpha}U; \ \theta = \frac{T - T_c}{\Delta T},$$
  
 $\phi = \frac{V}{\Delta V}; \ p = \frac{H^2}{\rho \alpha^2}P; \ \nabla = H \nabla_d,$ 

where H is the length scale of the square cavity,  $\alpha$  is the thermal diffusivity of the fluid,  $T_c$  is the constant temperature of the cold electrode,  $\Delta T$  is the temperature difference between the electrodes,  $\Delta V$  is the electrical potential difference between the two electrodes and  $\rho$  is the specific mass of the fluid.

The Marangoni effect is classically[3] applied along the liquid surfaces of the fluid domain:

$$\mu \frac{\partial U}{\partial Y}\Big|_{Y=(0,H)} = \frac{d\sigma}{dT} \frac{\partial T}{\partial X}\Big|_{Y=(0,H)},\tag{1}$$

where  $\mu$  is the dynamic viscosity and  $\sigma$  the surface tension. The latter depends here on the temperature and is well approximated by a linear dependence[3]:  $\sigma = \sigma_{ref}(1 - \beta_{\sigma}(T - T_{ref}))$ . The averaged temperature,  $T_{ref} = (T_c + T_h)/2$ , is chosen as the reference temperature and  $\beta_{\sigma}$  is defined as a thermal dilatation parameter for the surface tension with  $\beta_{\sigma} = -\frac{1}{\sigma_{ref}} \frac{\partial \sigma}{\partial T}$  and  $\sigma_{ref}$ , the surface tension as defined at  $T_{ref}$ .

When an electric field is applied upon a dielectric fluid, three forces appear: the Coulomb force (CF) acting on the free charge density, q, the dielectrophoretic force (DEP) due to a permittivity gradient, and the electrostriction force (EF) [1]:  $f_{EHD} = qE + 0.5E^2\nabla\varepsilon + 0.5\nabla(\rho(\partial\varepsilon/\partial\rho)E^2)$ , where  $\varepsilon$  is the dielectric permittivity. In this work, only the DEP term is kept, as the liquid is considered as a perfect dielectric fluid free of space charges and the electrostrictive force is included in the pressure gradient term as a correction term. The DEP force remains to be considered with  $\varepsilon = \varepsilon_0 \varepsilon_r$ , where  $\varepsilon_r = \varepsilon_{ref}(1 - \lambda(T - T_{ref}))$  is supposed to linearly depend on the temperature (first order approximation). The parameter  $\lambda$  is the thermal dilatation for the permittivity, defined as  $\lambda = -\frac{1}{\varepsilon_{ref}} \frac{\partial \varepsilon_r}{\partial T}$ , where  $\varepsilon_{ref}$  is the permittivity valued at  $T = T_{ref}$ .

Thus, the non-dimensional mathematical model to be considered here writes as:

$$\begin{cases} \nabla \cdot \boldsymbol{u} = 0, \\ (\boldsymbol{u}.\boldsymbol{\nabla})\boldsymbol{u} = -\boldsymbol{\nabla}p + Pr\nabla^{2}\boldsymbol{u} + L.PrE^{2}\boldsymbol{\nabla}\theta, \\ \nabla^{2}\theta = \boldsymbol{u}.\boldsymbol{\nabla}\theta, \\ \nabla^{2}\phi = \frac{\boldsymbol{\nabla}\theta.\boldsymbol{\nabla}\phi}{a-\theta}, \\ \frac{\partial u}{\partial y}\Big|_{y=(0,1)} = Ma\frac{\partial\theta}{\partial x}\Big|_{y=(0,1)}, \end{cases}$$
[h]

where  $a = 0.5 + (\lambda \Delta T)^{-1}$  is a non dimensional parameter that results from the Gauss law, Ma, Pr and L are respectively the Marangoni number,  $Ma = \frac{\sigma \beta_{\sigma} \Delta T H}{\alpha \mu}$ , the Prantdl number,  $Pr = \nu \alpha^{-1}$ , and the Roberts number,  $L = \frac{\varepsilon_{ref} \varepsilon_0 \lambda \Delta T \Delta V^2}{\rho \nu \alpha}$  which can also be considered as a Rayleigh number of electrical origin.

#### C. Numerical approach

The finite-element method is used in the domain displayed on Figure 1 with a mesh of 91 680 triangular elements. The tips of the electrodes and their contact points with the upper and lower liquid surfaces are rounded with a radius of  $10^{-2} * H$  in order to avoid numerical artefacts. This procedure presents the advantage of matching actual manufacturing accuracy. A stationary solver is used, with a direct coupling between the Navier-Stokes, heat and electrostatic equations. The Marangoni effect described by the last equation of system **??** serves as a boundary condition for the Navier-Stokes equation.

#### III. RESULTS

Simulations are carried out for a range of the nondimensional numbers Ma, L and Pr. The interaction between DEP and Marangoni contributions are either constructive or destructive depending on the sign of the Marangoni stress, the two cases are analysed separately in the following.

#### A. Standard behavior : Ma < 0

For most fluids, the surface tension decreases for a growing temperature, and so the Marangoni number Ma takes on negative values [5]. That means that the boundary conditions imposed on the shear  $\frac{\partial u}{\partial y}$  is in a direction opposed to that of the temperature gradient. Jawichian et al. demonstrated that for a similar cavity without solid surfaces, the DEP force generates two counter-rotating convective cells responsible for an impacting jet between the two electrode tips, the latter being oriented along the temperature gradient. Hence, it can be expected that the Marangoni-induced flow adds up with the flow generated by the DEP force, provided the fluid interfaces usually behaves according to a negative Marangoni number ( $\beta_{\sigma} > 0$ ), which is the case for usual surfactants.

Simulations regarding this situation are presented in Fig. 3. Situation a) represents the case of the DEP force controlling the flow: the vorticity is generated near the electrodes walls as already reported by Jawichian et al. In situation b), the Marangoni number is increased up to  $5 \times 10^3$ . Most of the vorticity is consistently generated along the liquid surfaces with the flow dominated by Marangoni effect. The direction of the flow in the two convection cells is the same for both situations. This is confirmed by the evolution of  $V_{max}/L$  measured between the electrodes (Fig. 2). For a low Marangoni number, the ratio  $V_{max}/L$  remains constant for all values of L, which indicates that the flow results from



Figure 2: Velocity scaled by the Roberts number L, as a function of the Marangoni number Ma, for different values of L. The surface tension dilatation coefficient is usually positive:  $\beta_{\sigma} > 0$ .



Figure 3: Vorticity map and streamlines inside the cavity for Pr = 10 and L = 1000.



Figure 4: Norm of the velocity scaled by the Roberts number L, as a function of the Marangoni number Ma, for different values of L. The surface dilatation coefficient is negative:  $\beta_{\sigma} < 0$ .



Figure 5: Vorticity map and streamlines inside the cavity for Pr=10, L=1000 and three values of the Marangoni number.

a balance between the DEP and the viscous forces, with no significant influence of the Marangoni effect. When Ma increases, the Marangoni effect creates more momentum along the liquid surfaces, which adds up to the momentum generated by the DEP. This is made evident for a low value of L while for a large enough L value, that is to say a strong DEP contribution, the flow remains governed by DEP and the Marangoni effect remains secondary.

#### $B. \quad Ma > 0$

For some materials (in case of solubilised salts for instance), the surface tension coefficient is found to increase with the temperature, resulting in a positive Marangoni number [4]. The momentum created along the liquid surfaces by the Marangoni effect in such conditions is opposite to the one generated from the DEP-induced convective cells. Hence, a competition between Marangoni and DEP effects is expected, which gives rise to a variety of flow regimes.

Figure 4 shows the norm of the maximum velocity, again scaled by the Roberts number, as observed along the mid axis between the tips of the two electrodes. For a small Marangoni number, the ratio  $V_{max}/L$  is still constant since the regime is dominated by the balance between viscous and DEP forces (Fig. 3a). As Ma increases, the competitive effect of the Marangoni stress becomes non negligible compared to the DEP contribution: the flow is slowed down near the liquid surfaces, which makes the velocity fall along the mid axis. At this stage, a hybrid regime arises: a vortical flow is generated near each liquid surface, governed by the Marangoni stress while two opposite vortices are observed in the core of the cavity under the constant impact

of the DEP torque (Fig. 6b). A second asymptotic regime is made evident if the Marangoni number increases beyond a threshold, for which the flow becomes only driven by the Marangoni effect, and the core flow is no more governed by DEP effects. Only one pair of vortices remain, consistently governed by the Marangoni stress alone (Fig. 6c).

#### C. The role of the Prandtl number

Previous findings correspond to a value of the Prandtl number Pr = 10, for which the DEP and Marangoni effects can alternatively prevail. Other Pr values are tested to assess its impact.



Figure 6: Vorticity map and streamlines inside the cavity for three Prandtl values, for Ma = 700 and L = 1000

Fig. 6 shows that, for the values of the Roberts and Marangoni numbers, L = 100 and Ma = 700, the vorticity focuses on the liquid surfaces for a small value of Pr (Pr = 0.5), and its sign shows that it is caused by the Marangoni effect. Two vortices can be observed in the cavity. For Pr = 10, the system is in the state described on figure 6b : both phenomena generate their corresponding vortical flows. When Pr = 100, the vorticity is rather generated near the electrodes, and its sign shows that it is



Figure 7: Nusselt number as a function of the Marangoni number Ma for Pr = 10.

caused by the DEP effect. Jawichian et al. have previously shown that the Prandtl number illustrates the ability of the viscous stress to diffuse the DEP-induced angular momentum away from the electrodes. Considering now the vorticity induced by the Marangoni effect, the viscous friction plays a more classical role which consists in damping angular momentum as Pr increases. As a consequence, the Prandtl number can be considered as a decisive parameter that monitors the respective impacts of the Marangonidriven and dielectrophoretic-driven flows.

The curves displayed on Fig. 4 can be obtained for a range of Pr values, and display same asymptotic and hybrid behaviors than previously made evident. For a given Prandtl number, the critical Marangoni number,  $Ma_c$ , for which the norm of the velocity is minimum depends on the magnitude of the DEP force, thus on the Roberts number. When Pr decreases, the Marangoni effect is found enhanced and the role of the DEP force vanishes, so  $Ma_c$  decreases. When Pr increases, the opposite result is consistently observed.

#### D. Impact on heat transfers

In order to evaluate the impact of these regimes on heat transfers between the electrodes, a Nusselt number [2] corresponding to several relevant regimes is calculated.

Figure 7 shows the evolution of the Nusselt number, for a given Roberts number, as a function of the Marangoni number. Dotted lines exhibit the evolution of Nu in the standard case (Ma < 0). As expected, the curves follow the same evolution as the one on Fig. 3: it is constant if the flow is governed by the DEP at a low Marangoni number, then it increases with the Marangoni number, as the angular momentum generated on the liquid surfaces is of same order as the one generated by the DEP.

Solid lines show the evolution of Nu in the case where the Marangoni number is positive. Once again, the different regimes described earlier can be observed: an asymptotic regime independent of the Marangoni effect for low values of Ma is found, then a Nusselt number decreasing with the velocity as expected, the convection is slowed down, and finally, Nu number grows up again as the flow switches from a DEP-driven to a Marangoni-driven regime.

#### IV. CONCLUSION

This paper investigated the interaction between Marangoni-induced flows and dielectrophoretic flows (DEP) in a cavity filled with a purely dielectric liquid and delimited by two differentially heated triangular electrodes and two liquid surfaces. A non-dimensional analysis reveals the existence of distinct flow regimes governed either by the DEP effect or the Marangoni effect. This competition is essentially found to be monitored by the value of the Prandtl number (Pr).

For low Ma values, the flow remains DEP-dominated, and the velocity is scaled by L. As Ma increases, the angular momentum generated by the Marangoni stress prevails. For most liquids, the Marangoni stress tends to oppose the DEP-driven vortices, leading to hybrid or competing flow patterns. The Prandtl number is shown to dampen Marangoni-driven convection while it is found to enhance the DEP-induced momentum under diffusion, thereby modulating the balance between the two forces. The resulting flow patterns directly affect heat transfer efficiency, as quantified by the Nusselt number.

The scaling analysis of this paper can be extended in the near future with the aim to predict critical thresholds of the Ma, L, and Pr values that govern the changes between the different regimes, the ultimate purpose being to provide a better prediction of heat transfers inside the cavity under consideration. Extending the present analysis to a 2D axisymmetric geometry is also expected to be relevant to the floating zone process in crystal growth applications.

#### ACKNOWLEDGMENTS

Author	P.A.	Vázquez	acknowledges	the
grant	PID2022-13	38890NB-I00	funded	by
MCIN/AEI	[/10.13039/5	01100011033		

#### REFERENCES

- [1] Antonio Castellanos, editor. *Electrohydrodynamics*. CISM International Centre for Mechanical Sciences. Springer, Vienna, Austria, October 1998.
- [2] Alex Jawichian, Laurent Davoust, and Samuel Siedel. Dielectrophoresis-driven jet impingement heat transfers in microgravity conditions. *Phys. Fluids* (1994), 33(7):073609, July 2021.
- [3] Marcello Lappa. *Fluids, materials and microgravity.* Elsevier Science, London, England, November 2004.
- [4] K Nogi, K Ogino, A McLean, and W A Miller. The temperature coefficient of the surface tension of pure liquid metals. *Metall. Trans.*, 17(1):163–170, January 1986.
- [5] J R A Pearson. On convection cells induced by surface tension. J. Fluid Mech., 4(5):489–500, September 1958.

## Numerical Modelling of Electrohydrodynamic (EHD) Liquid-Vapour Flow Redistribution in Co-Axial Heat Exchangers

J. LeMoine<sup>1\*</sup>, J. S. Cotton<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering, McMaster University, Hamilton, ON, Canada \*Corresponding author: lemoinej@mcmaster.ca

Abstract- Modelling two-phase liquid-vapour flows with electric fields offers insights into how electrohydrodynamic (EHD) forces influence flow redistributions. Robust numerical models are critical for designing novel electrode designs and increasing knowledge of EHD flow structures. When modelling two-phase fluids, interface tracking methods like the Moving Mesh Model (MMM) have an infinitesimal interface which maintains surface tension and EHD forces because they are dependent on the gradient of the interface.

One common geometry used in EHD experiments is a coaxial heat exchanger. The two-phase fluid is in an annulus between a central electrode and a grounded pipe. When the fluid's void fraction is high and the fluid flow is a stratified regime, an applied electric field will pull the liquid up to the electrode. This phenomenon is called liquid extraction. Previous studies have experimentally and numerically modelled liquid extraction but were unable to equate the extraction time while implementing EHD, surface tension, and gravity forces.

In this study, liquid extraction was modelled in COMSOL using the MMM. The geometry and initial liquid level was set to model the experiment done by Sadek et al. in 2008. EHD interfacial pressures were applied with gravity and surface tension forces. The liquid extraction timing was found and was compared to experimental timing measured by Sadek et al. With the exact geometry and all physics modelled, the experimental results were reevaluated with new information gained from the numerical model and it was seen that the timing for liquid extraction was consistent with the experiment

#### Keywords- Two-Phase, Liquid-Vapour, Numerical Modelling, Flow Redistribution, Liquid Extraction

#### I. INTRODUCTION

Electrohydrodynamic (EHD) forces can be applied on two-phase heat exchangers to enhance or reduce heat transfer. It does this by causing flow redistribution that can increase the amount of wall wetting and act to stir the mixture [1].

One of the flow redistribution mechanisms is called liquid extraction. Liquid extraction is when there is an EHD force on the interface between the fluids caused by an electrical permittivity difference [2], [3]. The force pulls the phase of higher permittivity into the higher electrical field, typically the liquid [4]. This force must overcome the forces of gravity and surface tension to extract the liquid.

Liquid extraction has been studied by multiple researchers to numerically model liquid extraction timing to give insights into control systems for EHD enhanced two-phase heat exchangers [5], [6]. Sadek et al. found that full liquid extraction could be achieved at low AC frequencies but could not respond to faster frequencies [7]. Sadek et al. performed a physical and numerical study to determine the extraction timing from a stratified R134a in a 1.5mm gap under 3kV applied voltage. The time was estimated to be  $6.5 \pm 0.5$ ms using a high-speed camera analysis [5].

Several attempts have been made to make numerical models of liquid extraction. Cotton et al. calculated maximum interfacial force from the dielectrophoretic component of the EHD force [8]. Comparing with the force of gravity would predict if a liquid would extract at a given voltage. Sadek et al. performed a quasi-steady state analysis based on his liquid extraction experiment [5]. The model matched experimental testing but excluded surface tension which would slow the extraction timing.

Nangle-Smith et al. performed a fully coupled analysis using COMSOL Multiphysics with two separate geometries [6]. A square shaped tube was used due to limitations of the software. They tested different twophase modelling techniques including the Moving Mesh Model (MMM) and a Phase Field Model (PFM). The MMM was unable to converge to a solution in the actual geometry but predicted higher extraction forces. Using the square geometry, Nangle-Smith et al. found the MMM extraction time was approximately 17ms with the PFM extraction time being slower at approximately 22ms [6]. They used this ratio to then correct the circular geometry case that used the PFM and estimated an 11ms extraction time. The conclusion was that there was still physics missing from the model to increase the extraction time.

#### II. METHODOLOGY

A 2D two-phase, liquid-vapour model with fully coupled mass, momentum, and electrostatics is implemented to model liquid extraction in the commercial software, COMSOL. The mass and momentum equations, (1) & (2a), are solved in the fluid and vapour domain separately assuming the fluids are laminar, incompressible, and Newtonian. In the body force term of the momentum equation, the gravitational, surface tension, and EHD forces are modelled as shown in (2b).

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot (\boldsymbol{u}) = 0 \tag{1}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \Delta) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + F_{ext} \qquad (2a)$$



Fig. 1. Initial geometry of the numerical model. The 2D annulus geometry is consistent with previous studies.

$$F_{ext} = F_g + F_{st} + F_{ehd} \tag{2b}$$

The geometry, Fig. 1, includes a 3.18mm center electrode maintained at a voltage of 3kV with a ground condition on the 10.2mm outside tube. The initial gap between the center electrode and the liquid interface was 1.5mm which is consistent with the numerical and physical experiments done by Nangle-Smith and Sadek [5], [6]. Liquid and Vapour R134a fill the annulus between the electrode and outer tube. The surface tension of the R134a is set to 0.008N/m with a contact angle of 35 degrees [6], [9], [10].

The fluids are assumed to be linear, isotropic, homogenous, and holds no free charges. This results in an electric field in the domain that follows the Laplace equation, (3). The relative electrical permittivity of each of the phases are set to 1 and 9.5, for the vapour and liquid respectively [11].

$$\nabla \cdot \left(\varepsilon \vec{E}\right) = 0 \tag{3}$$

The force due to EHD is calculated using a stress tensor and is modelled as a surface pressure applied directly to the interface. The fluid is assumed to have no free charges and thus the Coulomb force component of the EHD is neglected which gives equation (4). The electrostriction component can be further simplified using the Clausius-Mossotti Law, (5), to make the EHD stress tensor dependent only on the electric field, E, and the relative permittivity,  $\varepsilon_r$  [12].

$$T_{ehd} = \left(\varepsilon_0 \varepsilon_r \bar{E}\right) E^T - \frac{1}{2} \varepsilon_0 E^2 \left(\varepsilon_r - \rho \left(\frac{\partial \varepsilon_r}{\partial \rho}\right)_T\right) I \quad (4)$$

$$\rho \frac{\partial \varepsilon}{\partial \rho} = \frac{\varepsilon_0(\varepsilon_r - 1)(\varepsilon_r + 2)}{3} \tag{5}$$

To model the separate phases, the MMM is employed. The MMM is an interface tracking method that models each phase domain separately with each boundary sharing an interfacial node that can move. The velocity of the interfacial nodes is given by equation (6), where it moves in the direction normal to the interface equal to the velocity of the fluid in either domain that is adjacent to the interface [13]. This equation allows for phase transfer but is set to 0 as the model is adiabatic with no phase change.

$$\boldsymbol{u}_{mesh} = \left(\boldsymbol{u}_1 \cdot \boldsymbol{n}_i - \frac{M_f}{\rho_1}\right) \boldsymbol{n}_i \tag{6}$$

After the interfacial nodes translate, the rest of the mesh deforms by stretching or compressing to the new geometry. The software tracks the updated mesh quality metrics like skewness and aspect ratio and remeshing occurs when the skewness is below a value of 0.5 which was defined by the user.

Before the simulation was run, the fluid was allowed to reach a steady state without EHD to allow for the capillary rise of the liquid on the wall of the outer tube. The models used a fully coupled approach which solved all the equation simultaneously. The models were terminated upon full liquid extraction as the MMM is incapable of topology changes arising from interfacial nodes overlapping with the nodes on the outer tube. A time step and mesh independence analysis was completed.

#### **III. RESULTS**

The electric field at the initial state of the model is shown in Fig. 2. Due to the liquid having a high relative permittivity, the liquid phase does not have high electric field strength within it and acts like a ground. The permittivity of the vapour is an order of magnitude lower, so it has a change in electric field within the domain. The discontinuity observed between the phases, shows EHD forces are present on the interface.

The polarization components of the EHD force are dependent on a gradient of permittivity in the presence of an electric field so they will only be present on the interface where the permittivity is changing. The total vertical component of the EHD pressure on the surface was plotted along the interface line and is shown in Fig. 3. The highest force is at the center of the geometry where the electrode is closest to the liquid surface.

The total EHD force is also broken down into the dielectrophoretic and electrostrictive components. Both EHD components are significant in this model where the



Fig. 2. Electric field strength in V/m for the initial geometry.



Fig. 3. The y-component of the EHD pressure on the interface. The total EHD pressure, Tsy, is made up of its individual, dielectrophoretic (DEP) and electrostriction components.

DEP component makes up 71% of the total force and the electrostrictive component makes up 29%. Importantly, both components of the EHD force are additive as they are in the same direction.

Fig. 4 shows the liquid extraction timing. The extraction ratio is the ratio of the height the center of the liquid column reached from the initial state to the height of the electrode. The liquid is said to be fully extracted when the liquid extraction ratio reaches 1. It took this model 17.5ms to reach full extraction. The extraction ratio is seen to increase in an exponential manner as the EHD force increases as the liquid rises due to a smaller distance to the electrode. The increase of the EHD force is due to a higher electric field when the liquid, which is almost grounded, gets closer to the higher voltage electrode.

The shapes of the liquid columns at different times of the model are shown in Fig. 5. As the liquid column rises, the tip of the liquid column's radius decreases. This makes a sharper "grounded side" which further increases the electric field. In the evolution of the liquid domain shape, it is also observed that the majority of the liquid extraction happens after 10ms. Before 10ms, only a change in the surface shape is observed and the highest point on the liquid interface is the edge where there is a capillary rise due to surface tension.

#### **IV. DISCUSSION**

Comparing the results from this study to previous work from Nangle-Smith et al., many similarities are found between the MMM of both studies. The initial force on the interface is seen to be larger in this work, where the maximum force located at the centerline is 12.8 Pa whereas 9.2 Pa is stated in the previous study [6]. The result is closer related to the DEP component of the EHD force which was found to be 9 Pa in this study.

The extraction timing and the surface shape was similar between the MMM in the square geometry of Nangle-Smith et al. and this study. The time for the liquid to reach the electrode was shown to be 17.5ms compared to 17.4ms [6]. This shows that the outer geometry of the tube had a 0.5% error on the extraction time. When the



Fig. 4. The extraction timing of the MMM represented as a ratio between initial liquid level and electrode height. The timing for liquid extraction is at extraction ratio of 1, occurring at 17.5ms.

PFM was used in the circular geometry and corrected, it is seen that it increases the error between these models. This is due to the VOF methods having difficulty converging in EHD cases as the force on the interface destabilizes the interface maintenance methods and make the interface a large gradient instead of the sharp interface in the MMM. The reduction of the interface gradient reduces the EHD force as well as the surface tension. Even gravity can be impacted as the control volumes have reduced density due to having a smaller volume fraction then a purely liquid domain. This compounded with the uncertainty of where the interface is precisely located, usually said to be at the line of volume fraction of 50%, means that the PFM can produce different results depending on many of the input parameters for boundary treatment.

Relating this study to the original experiment done by Sadek et al., the extraction time is seen to be much different than the experimental study. Sadek et al. found the extraction time was 6.5ms from high-speed photography [5]. The experiment used mean grey value and the derivative of mean grey value of a line located just above the initial liquid position viewed from the side of a transparent tube. When both values exceeded the standard deviation of the steady value, the experiment is said to begin. The extraction is said to be completed on the frame where the liquid is seen to touch the electrode.

From this study, it is seen that the rise of liquid on the edge of the tube would make it difficult to observe the start of the test. When the test starts the highest point on the interface is at the wall and at 11.3ms the middle column passes the original height of the fluid on the wall. This moment is when the greyness value would signal the start of the test. The fluid reaches the electrode at 17.5ms, which is 6.2ms between the two events.

With the extraction time of  $6.5 \pm 0.5$  ms, this numerical model is within the error of the experiment.

#### V. CONCLUSION

A coupled two-phase liquid extraction in a coaxial heat exchanger using a MMM in COMSOL was modelled.



Fig. 5. Liquid shape evolution over time of the liquid extraction simulation using the MMM. The red volume indicates liquid R-134a where the blue volume shows the vapour.

R134a was extracted from a 1.5mm gap using EHD force created by an electrode set to 3kV.

The initial forces were higher than previous works done by Nangle-Smith et al. It was found that liquid extraction timing was 17.5ms which is most consistent with the rectangular geometry MMM performed by Nangle-Smith et al. When comparing the results to Sadek et al., the capillary rise on the edge of the tube makes high speed photography unable to predict the beginning of the test. Considering this and using a start time when the liquid level passes the initial height, the extraction timing was within experimental error of the study.

Although there are additional complexities that can be added to this model like 3D effects, the 2D liquid extraction using MMM is the most consistent numerical model for liquid extraction experiments. It is seen to be more reliable than VOF methods as it can maintain a sharp interface and therefore maintain boundary forces including surface tension and EHD force.

#### ACKNOWLEDGMENT

This research was supported by the Natural Sciences and Engineering Research Council of Canada. We would also like to acknowledge CMC Microsystems, manager of the FABrIC project funded by the Government of Canada, for the provision of products and services that facilitated this research, including COMSOL Multiphysics.

#### References

- G. McGranaghan and A. J. Robinson, EHD Augmented Convective Boiling: Flow Regimes and Enhanced Heat Transfer, Heat Transf. Eng., vol. 35, no. 5, pp. 517–527, Mar. 2014,
- [2] Ryoichi Hanaoka, Yoji Fujita, Takuma Kajiura, and Hidenobu Anzai, Dynamic Behavior and Its Consideration of EHD Liquid Extraction Phenomenon Causing under DC or Low-Frequency AC Voltage, J. Energy Power Eng., vol. 13, no. 6, 2019,

- [3] J. Cotton, D. Brocilo, M. M. Shoukri, T. Smith-Pollard, and J. S. Chang, Mechanisms of electrohydrodynamic flow boiling heat transfer in coaxial flow channels of dielectric refrigerant R-134a, 1998 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 178–181, 1998.
- [4] A. Singh, Electrohydrodynamic (EHD) enhancement of in-tube boiling and condensation of alternate (non-CFC) refrigerants, Ph.D. Thesis, University of Maryland, 1995.
- [5] H. Sadek, J. S. Cotton, and C. Y. Ching, Numerical simulation of the liquid extraction from a stratified liquid-vapor zone using electrohydrodynamic effects, International Symposium on Advances in Computational Heat Transfer, pp. 1–15, 2008.
- [6] S. Nangle-Smith, H. Sadek, C. Y. Ching, and J. S. Cotton, Numerical Modeling of EHD-Induced Liquid Extraction in a Cylindrical Electrode Configuration, p. 7, 2016.
- [7] H. Sadek, J. S. Cotton, C. Y. Ching, and M. Shoukri, Effect of frequency on two-phase flow regimes under high-voltage AC electric fields, J. Electrost., vol. 66, no. 1–2, pp. 25–31, Jan. 2008,
- [8] J. S. Cotton, Numerical simulation of electric field distributions in electrohydrodynamic two-phase flow regimes, IEEE Trans. Dielectr. Electr. Insul., vol. 10, no. 1, pp. 37–51, 2003.
- [9] H. B. Chae, J. W. Schmidt, and M. R. Moldover, Surface tension of refrigerants R123 and R134a, J. Chem. Eng. Data, vol. 35, no. 1, pp. 6–8, Jan. 1990,
- [10] K. Stephan and M. Abdelsalam, Heat-transfer correlations for natural convection boiling, Int. J. Heat Mass Transf., vol. 23, no. 1, pp. 73–87, Jan. 1980,
- [11] S. Feja, Measurement of electrical properties of refrigerants and refrigerant-oil mixtures, Int. J. Refrig., vol. 35, no. 5, pp. 1367–1371, 2012,
- [12] A. Castellanos, Ed., Electrohydrodynamics, vol. 380. Springer, 2014.
- [13] COMSOL, Microfluidics Module User Guide. COMSOL, 2018.

## Combining Electrohydrodynamics and Biomolecular Recognition: A Study of Conductivity Effects on ACEO and Antibody–Antigen Binding

P. Zimmer<sup>1,2</sup>, E. Laurenceau<sup>1</sup>, J.-P. Cloarec<sup>1</sup>, M. Canva<sup>3,4</sup>, M. Frénéa-Robin<sup>2</sup>, J. Marchalot<sup>2</sup>

<sup>1</sup> Ecole Centrale de Lyon, INSA Lyon, CNRS, Université Claude Bernard Lyon 1, CPE Lyon, INL, UMR5270, 69130 Ecully, France

<sup>2</sup>Ecole Centrale de Lyon, Université Claude Bernard Lyon 1, INSA Lyon, CNRS, Ampère UMR5005, 69130 Ecully, France

<sup>3</sup>Laboratoire Nanotechnologies Nanosystèmes (LN2) IRL 3463, CNRS, Université de Sherbrooke - J1K 0A5 Sherbrooke, QC, Canada

<sup>4</sup>Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 3000 Boulevard de l'Université, J1K OA5 Sherbrooke, QC, Canada

*Abstract-* The detection of bacteria in health and environmental applications requires highly sensitive and specific biosensors. However, mass transfer limitations can hinder the performance of surface-based biosensors, particularly at low analyte concentrations. To address this challenge, electrohydrodynamic (EHD) phenomena such as Alternating Current Electroosmosis (ACEO) and Dielectrophoresis (DEP) are used to actively enhance mass transfer, thereby increasing target accumulation near the sensor surface. The electrical conductivity of the natural media (sprinkling or irrigation water) in which the target bacteria are to be detected can vary by several orders of magnitude. It is therefore important to assess the impact of this conductivity on the behavior of EHD phenomena, as well as on the affinity of antibody-antigen interactions that guarantee specific detection. This study introduces a novel method for real-time imaging of EHD effects, enabling direct assessment of operating parameters through vortex shape analysis and particle tracking. Experimental results are complemented by numerical simulations performed with COMSOL® to evaluate the influence of electrode geometries on particle trapping efficiency. In addition to developing this visualization tool and numerical model, ELISA assays are conducted to assess antigen-antibody affinity in low-conductivity conditions required for ACEO and positive Dielectrophoresis (pDEP). These experiments assess the feasibility of a hybrid biosensor that combines active mass transport using EHD phenomena with specific detection via efficient antigen-antibody interactions.

Keywords: Electro-osmosis, Mass Transfer, Surface-based biosensors, Conductivities, Antibodies-Antigens interaction, ELISA test.

#### I. INTRODUCTION

Biosensors play a crucial role in detecting bacterial contaminants in health and environmental applications. Among them, surface-based biosensors offer high specificity by relying on biomolecular interactions for target recognition[1]. However, their efficiency is often hindered by mass transfer limitations, particularly at low analyte concentrations, leading to extended detection times that are incompatible with real-time monitoring [2]. The combination of Alternative Current Electro-Osmosis (ACEO) and positive Dielectrophoresis (pDEP) effects has proven efficient in capturing cells and microparticles, or molecules in electrochemical [3, 4], surface plasmon resonance (SPR)[5–7] or impedance-based sensing approaches [8]. However, ACEO and pDEP effects are most effective in very low-conductivity media [9], whereas antigen-antibody interactions typically occur under physiological conditions with higher conductivity. This trade-off poses a major challenge in designing hybrid biosensors that integrate active transport and specific biomolecular recognition. To answer this question, a combined experimental and numerical approach was taken to understand the conditions under which these Electro Hydro Dynamism (EHD) phenomena dominate in order to optimize target transport while ensuring efficient antibody-antigen binding. This study introduces a realtime visualization method for EHD effects, allowing direct assessment of optimal operating parameters through vortex analysis and particle tracking. A numerical model developed in COMSOL® complements these experiments, providing insights into electrode geometry influence on particle trapping efficiency. Finally, ELISA assays are conducted to evaluate antigen-antibody interactions under different conductivity conditions, paving the way for an optimized hybrid biosensor capable of rapid and specific bacterial detection.

#### II. METHODOLOGY

1) Device fabrication for imaging vortices: The ACEO electrodes, arranged in a top-bottom configuration and separated by 160  $\mu$ m, comprise a plain gold electrode and a comb-shaped microstructured electrode (100  $\mu$ m fingers, 200  $\mu$ m gaps). They were fabricated via photolithography and wet etching on a glass slide (40 × 25 × 1.1 mm) coated with 50 nm Cr and 150 nm Au (Neyco). AZ 5214 E photoresist (Microchemicals) was patterned using spin-coating, UV exposure, and development, followed by etching and resist removal.

The microfluidic chamber was assembled using two  $80\mu$ m layers of double-sided adhesive (ISpacer®, SUNJin Lab) and sealed with a microscope glass slide at the bottom and UV glue (LOCTITE AA 3491). Fluorescent microbeads (1  $\mu$ m, Fluoresbrite®, Polysciences) were suspended in a conductivity-adjusted KCl (Sigma Aldrich) buffer and

injected using a microfluidic flow controller (OB1, ELVEFLOW). Observations were conducted with a Carl Zeiss Axiovert inverted epifluorescent microscope equipped with a Cy3 filter and a  $10 \times$  EC Plan Neofluar objective lens. High-speed imaging was captured with a Photron Fastcam series camera and analyzed using Photron Fastcam Viewer (PFV3).

An AC voltage (4–8 Vpp, 1 kHz) was applied via a signal generator (Agilent 33250A) and a low-impedance amplifier (HSA4011, NF). Conductivity (0.5–30 mS/m) were controlled by preparing KCl solutions, measured with a Mettler Toledo conductimeter. Microbeads were resuspended at  $4.55 \times 10^7$  particles/mL to ensure reliable velocity tracking.

2) *Comsol Simulations*: Numerical simulations were performed using Comsol Multiphysics® to model DEP and ACEO effects on particle behavior in a microfluidic chamber. The model assumes ideally polarizable electrodes and neglects faradaic reactions. A 2D model was used, solving Laplace's equation,  $\nabla^2 \phi = 0$  to determine the potential distribution, from which the slip electro-osmotic velocity was derived:

$$\langle \mathbf{u} \rangle = -\frac{\varepsilon_{\mathrm{m}}}{4\eta} \Lambda \frac{\partial}{\partial x} \left| \boldsymbol{\phi} - \mathbf{V}_{\mathrm{j}} \right|^{2} \tag{1}$$

where  $\varepsilon_{\rm m}$  and  $\eta$  are the medium permittivity and viscosity,  $\phi$  is the potential at any given location, V<sub>j</sub> is the potential applied to the electrode and  $\Lambda$  is the ratio between the double layer capacitance and that of the diffuse layer only, expressed as  $\Lambda = \frac{C_s}{C_d + C_s}$ . This velocity was imposed as a boundary condition in the Navier-Stokes equations to estimate fluid motion.

Particle behavior was analyzed using the "Particle Tracing for Fluid Flow" module, incorporating drag and dielectrophoretic forces. This method, which first solves the Laplace equation on the electrodes and then deduces the slip velocity [10], allows adaptability to various geometries.

#### 3) ELISA tests:

A 96-well polystyrene plate (Thermo Fisher) was coated for 1 hour at 30°C with phytopathogen bacteria *Dickeya* grown overnight at 30°C in low-salt LB broth (Duchefa Biochemie). After incubation, wells were blocked for 2 hours at room temperature with 200  $\mu$ L of blocking solution: PBS 1X (Sigma Aldrich) containing 0.05% (v/v) Tween-20 (Sigma Aldrich) and 5% BSA (w/v) (Promega France). Wells were then washed three times with 200  $\mu$ L of washing buffer: a conductivity-adjusted KCl (Sigma Aldrich) solution in DI water containing 0.05% (v/v) Tween-20.

A 50  $\mu$ L solution of rabbit anti-*Dickeya* antibody (Covalab), diluted in the selected conductivity buffer, was added and incubated for a variable duration depending on the experiment. After washing, goat anti-rabbit HRP (horseradish peroxidase)-conjugated antibody (Sigma-Aldrich) was added and incubated for 1 hour at 30°C, followed by another washing step. Detection was performed by adding 100  $\mu$ L of TMB/H<sub>2</sub>O<sub>2</sub> substrate

solution (ready-to-use, 3,3',5,5'-Tétraméthylbenzidine for ELISA) and incubating for 20 minutes. The reaction was stopped with 100 µL of stop solution: 0,16M of H<sub>2</sub>SO<sub>4</sub> (Merck). Absorbance at 450 nm was measured within 30 minutes using a Multiscan plate reader. A limit of detection (LOD) is calculated for each set of measurement as the blank signal plus three times the standard deviation.

#### III. RESULTS

#### A. Vortices' observation

Vortex formation was experimentally investigated using the setup illustrated in Fig. 1.A, enabling real-time imaging of particle motion under an applied electric field. Fluorescent microparticles served as tracers to visualize fluid flow patterns.

Fig. 1.B presents image stacks at a fixed voltage (6Vpp) and frequency (1 kHz), showing the influence of medium conductivity on vortex shape. Well-defined vortices were observed within a conductivity range of 1–5 mS/m. Outside this range, vortex formation was either suppressed or poorly defined, consistent with electrokinetic theory: at high conductivities, reduced zeta potential weakens electroosmotic velocity, while at extremely low conductivities, limited ion availability restricts fluid motion [11–13].

Additionally, this setup, presented in Fig. 2-A, allows the observation of depletion zones, where vortices transport particles away from the electrode. This tool allows for studying how different parameters—such as conductivity, voltage, frequency, electrode size, and chamber height—influence the capture volume. Within seconds, particles



*Fig. 1.* A. Zoom on the microfluidic chamber when the voltage is applied and a 3D rendering of the final device (front view). B. Vortices images at fixed voltage (6  $V_{pp}$ ) and fixed frequency (1 kHz).


*Fig.* 2. A. Experimental particle trajectories obtained with image analysis are processed with Matlab. B. Calculated particle trajectories plotted in COMSOL® corrected with a correction factor  $\Lambda_{exp} = 0,02$ . The yellow bars represent the gold electrodes. These two particle trajectories were obtained using these parameters:  $V = 6 V_{pp}$ , f = 1 kHz,  $\sigma_m = 1 \text{ mS/m}$ . Previously demonstrated in our recent study [21].

present in the solution are captured on the electrode surface, a key factor for optimizing particle capture in biosensing applications.

# B. Numerical study

Both experimental and numerical observations of vortices were conducted using the device described in the Methodology section, illustrated in Fig. 1-A, alongside the COMSOL® simulations outlined in the Methodology section. Experimental velocity data was extracted using tracking commands in ImageJ within the area of interest [14], then processed in MATLAB to generate a velocity map, as shown in Fig. 2-A. A corresponding numerical velocity map, obtained from COMSOL® simulation, is represented in Fig. 2-B. Since numerical simulation typically overestimate fluid velocities compared to experimental results, due to nonlinear dynamics under high applied voltages, a correction factor -  $\Lambda_{exp}$  - was implemented. This parameter, introduced by Green et al. [10, 15] and discussed by Bazant et al. [16, 17], was applied to the Helmholtz-Smoluchowski slip velocity, Eq. (1), in the numerical simulation as a fitting parameter. It was determined by comparing the velocity of microparticles and the formation of depletion zones between experimental and numerical results, ranged from 0.016 to 0.025. A value of 0.02 was ultimately used in COMSOL® simulation to generate the velocity map in Fig. 2-B. The relatively low value of the correction factor is attributed to the high voltages applied across the double layer in a dilute solution (several volts  $\sim 100k_BT/e$ ) which exceeds the assumptions of classical electrokinetic theory [17]. This modeling approach enables the simulation of particle behavior within the microfluidic chamber under varying conditions, including changes in chamber geometry-providing a powerful tool for design optimization and predictive analysis.

# *C. Ionic influence on Antigen/Antibody recognition according to ELISA test*

The influence of ionic strength on antigen–antibody binding efficiency was assessed using an ELISA assay, described Fig. 3-A, performed at different conductivities, adjusted by varying KCl concentrations: 1; 200; 1400 mS/m, and a PBS control (around 1400 mS/m). Incubation

times of 14, 34, and 60 minutes were tested to evaluate time-dependent binding kinetics.

In Fig. 3-B, the absorbance, obtained at 450 nm is plotted by subtracting both the blank and the non-specific adsorption of the HRP substrate. The blank corresponds to the baseline signal from wells without any antibodies, while the non-specific signal accounts for secondary antibody (Ab\_II) binding in the absence of primary antibody (Ab\_I). For each condition, three independent replicates were performed, and results are presented as mean values with standard deviation error bars. Additionally, three distinct LODs—corresponding to each incubation time—are represented as dashed horizontal lines.

The data reveal that antigen–antibody binding is stronger at an intermediate conductivity (200 mS/m), while both extremely low (1 mS/m) and high ionic strengths (PBS, 1400 mS/m) result in reduced ELISA responses. Furthermore, longer incubation times (30 and 60 minutes) consistently yield stronger signals across all conditions, emphasizing the combined influence of ionic environment and incubation duration on the assay's sensitivity and specificity.

Several studies have demonstrated that high conductivities lead to electrostatic screening, reducing the effective range of attraction and potentially destabilizing antigenantibody complexes [18–20]. In contrast, extremely low conductivity environment (1mS/m) shows a decrease in absorbance suggesting a reduced antigen-antibody recognition. This conductivity may disrupt specific interactions due to lack of stabilization of protein conformation or non-specific aggregation that could explain this observation, although this effect has not been fully characterized.

### IV. DISCUSSION

Beyond this study, the broader objective is to integrate these findings into a hybrid biosensor that combined EHD which requires low-conductivity media, to enhance convective transport and reduce incubation times with



Fig. 3. A. Schema of ELISA test steps B. Absorbance at 450nm (corrected for blank and non-specific) at varying KCl conductivities and incubation times. Error bars represent standard deviation over three replicates. LODs are shown as dashed lines.

surface-based biosensor. The later rely on specific recognition of the target with probes (antigen–antibody binding) and requires higher conductivity medium. Complementary studies using Surface Plasmon Resonance (SPR) are currently underway to further study the antigen-antibody specific recognition by following in real time the kinetics and affinities under varying ionic strengths.

#### V. CONCLUSION

This study combined experimental, numerical, and biochemical approaches to explore the conditions influencing both ACEO vortex generation and antigen– antibody interactions. While low conductivity favored fluid motion through electrohydrodynamic effects, specific molecular recognition was more effective at higher ionic strength. These findings help clarify the constraints involved in designing microfluidic biosensors where both mixing and specificity are important.

#### ACKNOWLEDGMENT

This work was supported by the OBOPHICS project (ANR-22-CE04-0015) operated by the French National Research. LN2 is a French-Canadian joint International Research Laboratory (IRL 3463) funded and co-operated by CNRS, Université de Sherbrooke, INSA Lyon, École Centrale Lyon (ECL) as well as Université Grenoble Alpes (UGA). It is also supported by the Fonds de Recherche du Québec Nature et Technologie (FRQNT). LN2 principally operated at the Institut is Interdisciplinaire d'Innovations Technologiques (3IT) at Sherbrooke. We also acknowledge support from the National Science and Engineering Research Council (NSERC) of Canada through its Discovery Grants program (MC).

#### REFERENCES

- Naresh V, Lee N. A Review on Biosensors and Recent Development of Nanostructured Materials-Enabled Biosensors. Sensors 2021; 21: 1109.
- [2] Squires TM, Messinger RJ, Manalis SR. Making it stick: convection, reaction and diffusion in surface-based biosensors. *Nat Biotechnol* 2008; 26: 417–426.
- [3] Cheng I-F, Yang H-L, Chung C-C, et al. A rapid electrochemical biosensor based on an AC electrokinetics enhanced immuno-reaction. *Analyst* 2013; 138: 4656.
- [4] Sheen H-J, Panigrahi B, Kuo T-R, et al. Electrochemical biosensor with electrokinetics-assisted molecular trapping for enhancing C-reactive protein detection. *Biosensors and Bioelectronics* 2022; 210: 114338.
- [5] Galvan DD, Parekh V, Liu E, et al. Sensitive Bacterial Detection via Dielectrophoretic-Enhanced Mass Transport Using Surface-Plasmon-Resonance Biosensors. *Anal Chem* 2018; 90: 14635–14642.
- [6] Avenas Q, Moreau J, Costella M, et al. Performance improvement of plasmonic sensors using a combination of AC electrokinetic effects for (bio)target capture. *ELECTROPHORESIS* 2019; 40: 1426–1435.
- [7] Costella M, Avenas Q, Frénéa-Robin M, et al. Dielectrophoretic cell trapping for improved surface plasmon resonance imaging sensing. *ELECTROPHORESIS* 2019; 40: 1417–1425.

- [8] Ho Y-T, Pan C-L, Sheu J-T, et al. AC electrokinetics assisted impedance biosensors for rapid bacteria detection. In: 2012 IEEE Biomedical Circuits and Systems Conference (BioCAS), pp. 49–52.
- [9] Abdelghany A, Ichikawa Y, Motosuke M. Tuning AC Electrokinetic Flow to Enhance Nanoparticle Accumulation in Low-Conductivity Solutions. *Advanced Materials Interfaces* 2023; 10: 2300478.
- [10] Green NG, Ramos A, González A, et al. Fluid flow induced by nonuniform ac electric fields in electrolytes on microelectrodes.
   III. Observation of streamlines and numerical simulation. *Phys Rev E* 2002; 66: 026305.
- [11] Pei-Yu Chiou, Ohta AT, Jamshidi A, et al. Light-Actuated AC Electroosmosis for Nanoparticle Manipulation. J Microelectromech Syst 2008; 17: 525–531.
- [12] Morgan H, Green NG. AC electrokinetics: colloids and nanoparticles. Baldock: Research Studies Press, 2003.
- [13] Ramos A, Castellanos A, Green NG, et al. AC Electric-Field-Induced Fluid Flow in Microelectrodes. *Journal of Colloid and Interface Science*, http://www.idealibrary.com.
- [14] Tinevez J-Y, Perry N, Schindelin J, et al. TrackMate: An open and extensible platform for single-particle tracking. *Methods* 2017; 115: 80–90.
- [15] Garcia-Sanchez P, Ramos A, Green NG, et al. Experiments on AC electrokinetic pumping of liquids using arrays of microelectrodes. *IEEE Trans Dielect Electr Insul* 2006; 13: 670–677.
- [16] Bazant MZ, Kilic MS, Storey BD, et al. Towards an understanding of induced-charge electrokinetics at large applied voltages in concentrated solutions. *Advances in Colloid and Interface Science* 2009; 152: 48–88.
- [17] Bazant MZ, Sabri Kilic M, Storey BD, et al. Nonlinear electrokinetics at large voltages. *New J Phys* 2009; 11: 075016.
- [18] Nguyen T-H, Greinacher A. Effect of pH and ionic strength on the binding strength of anti-PF4/polyanion antibodies. *Eur Biophys J* 2017; 46: 795–801.
- [19] Dejaegere A, Choulier L, Lafont V, et al. Variations in Antigen–Antibody Association Kinetics as a Function of pH and Salt Concentration: A QSAR and Molecular Modeling Study. *Biochemistry* 2005; 44: 14409–14418.
- [20] Engelmaier A, Arno Butterweck H, Weber A. Measurement of Low Avidity, Polyreactive Immunoglobulin G Antibodies with Increased Sensitivity by Using Low Ionic Strength Buffers. J Anal Tech Res; 04. Epub ahead of print 2022. DOI: 10.26502/jatr.24.
- [21] Zimmer P, Andreiev O, Costella M, et al. Electrohydrodynamic vortex imaging: A new tool for understanding mass transfer in surface-based biosensors. *ELECTROPHORESIS* [early view]. DOI: 10.1002/elps.8137

# Efficiency of static and alternating electric fields for EHD drying

Alex Martynenko, Tadeusz Kudra

Department of Engineering, Dalhousie University, Truro, Nova Scotia, Canada \*Corresponding author: alex.martynenko@dal.ca

*Abstract*- Electrohydrodynamic (EHD) drying is a non-thermal, scalable technology, suitable for drying heatsensitive products. The efficiency of EHD drying with an alternating electric field of 60 Hz was compared with the effect of the static electric field. The efficiency was characterized by specific energy consumption in Joules per gram of evaporated water. The experiment showed that the specific energy consumption of AC was larger because of thermal energy dissipation in the air and material under drying.

Keywords- high-voltage, discharge, energy efficiency, drying efficiency

### I. INTRODUCTION

Drying is an important unit operation, accounting for significant energy expenses in agri-food, pharmaceutical, chemical, and other allied industries. Over the last century, several types of drying technologies have been developed and commercialized, a detailed account of which is provided elsewhere [1]. With the increasing awareness about process sustainability among industries, efficient non-thermal drying technologies are attracting the attention of engineers and scientists. Electrohydrodynamic (EHD) drying is one of them, with a good potential for upscaling [2]. EHD drying involves the interaction of strong electric fields with fluid (air) flow, resulting in additional convection [3, 4]. Specifically, the ions formed in the discharge space are accelerated by the electric field and exchange momentum with neutral fluid molecules, initiating a drag force, known as "ionic wind." [5]

EHD flow is achieved via high-voltage discharge between electrodes with substantially different radii of curvature, for example, sharp pin-plate or thin wire-plate geometries [6]. Several authors have reviewed the fundamentals of EHD drying [7-9]. Coupling EHD flow with convective mass transfer is a promising approach for enhancing drying at ambient temperature [10, 11].

Among the studies reported in the literature, EHD drying has been carried out by using either direct current (DC) or alternating current (AC). A summary of the EHD drying studies alongside the use of AC or DC can be found in an earlier review [6, 9]. The majority of EHD drying research has been done using DC, likely because of the commercial availability of DC high-voltage power sources. Comparison of AC vs. DC drying was done only by a few researchers, namely Hashinaga, Kharel [12] and Zheng, Liu [13] for evaporation of free water, and Yang and Ding [14] for drying of Chinese wolfberry. All three research groups concluded that AC drying is 1.4 to 1.8 times faster than DC. However, these studies did not report energy consumption and efficiency. Yang and Ding [14] reported that AC is less energy-efficient than DC in the same drying conditions. However, significant

differences in methodology and geometry of discharge electrodes limit fair comparison of experimental results.

The reviews of the energy aspects of DC and AC for EHD drying showed their specific advantages [15, 16]. For example, AC power is the preferred option for industrial settings, where AC sinusoidal power is readily available. On the other hand, DC power is the preferred option for rural communities, assuming the availability of solar or wind energy [17]. However, DC power is not so efficient in diffusion-limited drying. To the best of our knowledge, no study has been conducted on the combination of AC and DC powers for EHD drying. The identified gap in existing knowledge is the limiting factor in scaling EHD drying technology.

The paper is organized as follows: first, the effects of DC and AC power on the total and specific energy consumption have been studied under the same conditions and electrode geometry, which allowed a fair comparison of the experimental results. The limitations of DC for a diffusion-limited period of drying have been discussed. Finally, a new concept of EHD drying, using hybrid AC/DC power, is proposed.

### II. METHODOLOGY

The experimental drying system with the multi-pin discharge electrode and plate collector is described in [16]. The set-up was open to the ambient atmospheric air at 21°C and 45% RH and included a balance ADAM HCB 1002 (Adam Equipment Co, UK) for mass measurements. The weighing balance was connected through a USB interface to data acquisition software (LabView 2018, National Instruments, USA). The distance between the electrodes was fine-tuned through a motorized rack and pinion assembly connected to a frame holding the multi-pin electrode. Control experiments were performed under the same settings and environmental conditions without an electric field.

The system was powered using either an iron-cored AC transformer (60 Hz; Scott Fetzer Company, TN, USA) or a DC (Model BAL32-10V, Voltronics, USA) power

source. For DC experiments, the applied voltage and the discharge current were measured from the indicators on the front panel. For AC experiments, the applied voltage was measured using a 1000:1 voltage divider connected to the secondary terminals of the transformer and an oscilloscope TBS 1032 (Tektronix, USA). The AC discharge power was estimated via modified Manley's method [18]. The voltage across a high-voltage capacitor (5.82 nF) was measured with a 100:1 voltage divider connected to the second channel of the Tektronix oscilloscope. This voltage, representing the total charge in the EHD system, was plotted against the applied voltage. The area of the plot, called Lissajous figure  $(A_{liss})$ , provided an estimate of the energy dissipated per cycle in Joules. The discharge power was calculated as  $P = A_{liss} f$ , where f = 60 Hz. It should be noted that the capacitor method gives the best estimate of AC discharge power. DC discharge power was calculated as the product of voltage and discharge current. Since the net discharge energy used for water evaporation is independent of the different power sources, it provided a fair comparison for the energy efficiency of AC vs DC in EHD drying [2].

The total energy consumption (TEC) was determined by the total power used by electrical equipment in EHD drying. It was quantified in J/g as the amount of total electric energy needed to evaporate the unit mass of water. This index was determined from measurable variables, namely the total primary power  $P_T$  (W), time of drying t (s), and amount of water evaporated  $\Delta m$ :

$$TEC = \frac{P_T \cdot t}{\Delta m} \tag{1}$$

The specific energy consumption (SEC) in J/g was quantified as the amount of discharge energy per unit mass of evaporated water [16]. The discharge energy  $E_d$  (J) injected into the discharge volume over the drying cycle was calculated as the product of the discharge power  $P_d$ 

(W) and time of drying t (s) or from the Lissajous plots (AC):

$$SEC = \frac{E_d}{\Delta m} = \frac{P_d t}{\Delta m}$$
 (2)

The efficiency of AC vs DC was evaluated by using two different types of discharge electrodes:  $(1 \text{ cm} \times 1 \text{ cm})$ with 146 emitters and  $(2 \text{ cm} \times 2 \text{ cm})$  with 32 emitters. Both total and specific energy consumption are key indicators of the efficiency in EHD drying.

#### **III. RESULTS**

The results of measurements of total and specific energy consumption for DC and AC electric power are presented in Figure 1. The total energy consumption (TEC) per gram of evaporated water initially increased with voltage, reflecting increased applied power (Fig. 1A). Below the inception voltage, it was almost similar for AC/DC and independent of the discharge electrode. At the inception point, TEC sharply decreased to the minimal value of 3000 J/g (AC) or even 2000 J/g (DC  $2\times 2$ ) due to increased water evaporation. Larger voltages increased TEC due to the faster increase of power, which increased proportionally to the cube of voltage, compared to the drying flux that increased linearly with voltage. It should be noted that these observations are valid for DC, directly rectified from the AC transformer, with minimum energy losses in the DC converter. The low-efficiency DC converter increases the TEC, which could lead to the conclusion about the better energy efficiency of AC [14].

The specific energy consumption (SEC) per gram of water removed with AC and DC power is shown in Figure 1B. In both AC and DC drying, the SEC increased proportionally to the squared voltage. A significant SEC in the AC below the inception could be attributed to energy dissipation due to the displacement current. This effect was not observed in the DC, with the SEC values



Fig. 1. Total (A) and specific (B) energy consumption of DC- and AC-initiated EHD drying [16]. 112

negligibly small below the inception point. The effect of the discharge electrode on the SEC was negligible in the AC mode, with a maximum of 1300 J/g at the breakdown. However, in DC mode, the SEC of the  $1\times1$  electrode was slightly smaller than  $2\times2$ . For example, at 15 kV the SEC of the  $1\times1$  electrode was around 500 J/g, while the SEC of the  $2\times2$  electrode was about 640 J/g. Maximum SEC in a DC mode did not exceed 1000 J/g. In all cases, the SEC in DC drying was significantly (2.5-3 times) lower than the SEC in AC drying. It is important to note that the advantage of AC power is the early initiation of corona discharge, which could be used to start drying at lower voltages. However, in the later stages of drying, DC power seems to be more energy efficient than AC.

The theory of drying considers two mechanisms of water removal: (1) evaporation of water from the surface (convection); 2) water transport from inside to the material surface (diffusion). The convection occurs when surface water is readily available. This drying period is characterized by a constant drying rate, which is independent of moisture content. In contrast, the diffusion mechanism dominates when surface water is exhausted [1]. In this period, the drying rate decreases proportionally to the moisture content, following Fick's law. Since the SEC depends on the drying rate, energy consumption is almost constant for the convective phase of drying and significantly increases in the diffusive phase (Fig. 2). This significant drop in energy efficiency was observed in both DC and AC drying. EHD drying was efficient only in the range of moisture contents below 6.0 g/g dm.



Fig 2. Specific energy consumption as a function of moisture content.

The limited efficiency of EHD during the diffusive phase of drying requires an additional thermal energy supply, which serves as a supplementary driving force. Thermal energy could be supplied by ohmic or dielectric heating.

Joule (ohmic) heating occurs due to the material's resistance to current flow. The average power density  $(W/m^2)$  can be calculated from the applied power and the surface area *A* exposed to the discharge current flow:

$$Q_{joule} = \frac{P}{A} \tag{3}$$

Dielectric heating occurs due to an AC electric field. Heat generation increases with the frequency of the applied electric field. This phenomenon is widely used in radio frequency (RF) drying [19]. The heat generated in the material is proportional to the loss factor  $\varepsilon$ " and squared electric field strength *E*, calculated from the RMS voltage drop across the dielectric:

$$Q = \omega \varepsilon'' \varepsilon_o E^2 \tag{4}$$

where *Q* is the heat generated per unit volume, (W·m<sup>-3</sup>);  $\omega$  is the electric field frequency, (rad·s<sup>-1</sup>);  $\varepsilon_o$  is the dielectric permittivity of vacuum, (8.85·10<sup>-12</sup> F·m<sup>-1</sup>).

#### IV. DISCUSSION

Additional thermal energy could also be delivered via conduction, convection or radiation. An example of EHDenhanced drying due to increased convection heat transfer is provided [2]. The application of low-frequency AC discharge led to material heating due to dielectric losses [20]. Although AC increases overall energy consumption compared to DC, it intensifies mass transfer.

A similar effect could be achieved by high-frequency electromagnetic fields, such as microwave (MW) or radiofrequency (RF). Microwave drving is an established technology that utilizes microwave radiation in the 915-2450 MHz range for volumetric heating of wet materials, inducing a phase change from liquid to vapor. The resulting vapor pressure enhances moisture diffusion from within the material. MW drying offers high energy efficiency and rapid drying. Its specific energy consumption is approximately 19-22 MJ/kg, about four times lower than that of hot air drying [21]. Additionally, effective moisture diffusivity can reach  $(1.12-1.25) \times 10^{-9}$ m<sup>2</sup>/s, roughly 50 times higher than in hot air drying. Although MW radiation accelerates diffusive mass transfer, it has a limited impact on convective mass transfer. Therefore, it requires external airflow to facilitate convection from the material surface. Due to its high drying intensity and non-uniform exposure, MW drying is less controllable than hot air drying, posing potential risks to product quality. Although MW radiation at 915 MHz penetrates deeper than at 2450 MHz, its penetration depth remains significantly smaller than that of radio frequency (RF) heating at 10-300 MHz [19]. The disadvantage of MW drving is the high initial cost, which presents a challenge for large-scale industrial adoption. Also, MW drying is not desirable from an environmental perspective,

since generated thermal emissions could exceed 3.2 kg CO<sub>2</sub> per kilogram of evaporated water [22]. Even though there are no reported applications of EHD-assisted microwave drying, their combination could be complementary, especially for thick materials. MWinduced heat generation, especially intensive in the watersaturated spots, could accelerate thermodiffusion as well as internal mass transfer from the material core due to a co-directed internal pressure gradient. On the other hand, EHD could mitigate deficiencies of MW drying, such as non-uniform heat distribution inside the wet material. Also, both EHD and MW technologies are based on the direct application of electricity, so this hybrid application could be easily adopted by industry. Based on this analysis, two strategies of hybrid EHD drying could be proposed. (1) Energy-saving strategy: Initiate drying with AC discharge, switch to DC to critical moisture content, then finish drying with low-intensity AC. (2) Time-saving strategy: Initiate drying with AC discharge, switch to high-power DC (6.5 kV/cm) with air flow 1.0 m/s, at critical moisture, add low-power RF or MW.

### V. CONCLUSION

From a practical standpoint, both AC and DC could initiate EHD drying. For the energy efficiency evaluation, it is important to account for specific and total energy consumption. This paper analyzes the energy efficiency in the convective and diffusive phases of EHD drying. The recommendations for the hybrid application of EHD drying together with AC, MW, and RF are given. The present work is the first step toward quantifying the efficiency of DC and AC electric fields for EHD drying.

### ACKNOWLEDGMENT

The authors appreciate the financial support of this project from the Discovery Program of the Natural Science and Engineering Research Council of Canada (grant NSERC RGPIN-2019-06081).

### REFERENCES

- [1] Mujumdar AS. Handbook of industrial drying: CRC Press, 2014.
- [2] Defraeye T, Martynenko A. Electrohydrodynamic drying of food: New insights from conjugate modelling. J. Clean. Prod. 2018;198:269-84.
- [3] Zamani E, Mehrabani-Zeinabad A, Sadeghi M. Sensitivity analysis pertaining to effective parameters on electrohydrodynamic drying of porous shrinkable materials. Dry Tech. 2019:1-12.
- [4] Dolati F, Amanifard N, Deylami M.H. Numerical investigation of mass transfer enhancement through a porous body affected by electric field. Dry Technol. 2018;36(13):1563-77.
- [5] Singh A, Vanga SKK, Raveendran Nair G, Gariepy Y, Orsat V, Raghavan V. Electrohydrodynamic drying of sand. Dry Technol. 2016;35(3):312-22.

- [6] Misra NN, Martynenko A, Chemat F, Paniwnyk L, Barba FJ, Jambrak AR. Thermodynamics, transport phenomena, and electrochemistry of external fieldassisted nonthermal food technologies. Crit Rev Food Sci Nutr. 2018;58(11):1832-63.
- [7] Martynenko A, Kudra T. Electrically-induced transport phenomena in EHD drying – A review. Trends Food Sci Technol. 2016;54:63-73.
- [8] Dalvi-Isfahan M, Hamdami N, Le-Bail A, Xanthakis E. The principles of high voltage electric field and its application in food processing: A review. Food Res Int. 2016;89(Pt 1):48-62.
- [9] Singh A, Orsat V, Raghavan V. A Comprehensive review on electrohydrodynamic drying and highvoltage electric field in the context of food and bioprocessing. Dry Technol. 2012;30(16):1812-20.
- [10] Martynenko A, Zheng W. Electrohydrodynamic drying of apple slices: Energy and quality aspects. J Food Eng. 2016;168:215-22.
- [11] Taghian Dinani S, Havet M. The influence of voltage and air flow velocity of combined convective-electrohydrodynamic drying system on the kinetics and energy consumption of mushroom slices. J Clean Prod. 2015;95:203-11.
- [12] Hashinaga F, Kharel GP, Shintani R. Effect of Ordinary Frequency High Electric Fields on Evaporation and Drying. Food Sci Technol Int. 1995;1(2):77-81.
- [13] Zheng D-J, Liu H-J, Cheng Y-Q, Li L-T. Electrode Configuration and Polarity Effects on Water Evaporation Enhancement by Electric Field. Int J Food Eng. 2011;7(2).
- [14] Yang M, Ding C. Electrohydrodynamic (EHD) drying of the Chinese wolfberry fruits. Springerplus. 2016;5(1):909.
- [15] Kudra T, Martynenko A. Energy aspects in electrohydrodynamic drying. Dry Technol. 2015;33(13):1534-40.
- [16] Martynenko, A., Kudra, T. Alternating versus direct current in electrohydrodynamic drying. Dry Technol. 2021; 40(11):2382-2395.
- [17] Dalvand MJ, Mohtasebi SS, Rafiee S. Optimization on drying conditions of a solar electrohydrodynamic drying system based on desirability concept. Food Sci Nutr. 2014;2(6):758-67.
- [18]Manley TC. The electric characteristics of the ozonator discharge. Trans. Electrochem. Soc. 1943, 84(1):83.
- [19] Zhou X, Wang S. 2019. Recent developments in radio frequency drying of food and agricultural products: A review. Dry Technol, 37:3: 271-286.
- [20] Martynenko, A., Misra, NN. Thermal phenomena in electrohydrodynamic (EHD) drying. Innov Food Sci Emerg Tech, 2021, 74:102859.
- [21] Orsat V., Changrue, V. and Raghavan GSV. 2006. Microwave drying of fruits and vegetables. Stewart Postharvest Rev 2 (6):1-7.
- [22]Martynenko, A, Vieira, GNA. Sustainability of drying technologies: system analysis. Sustainable Food Technology, 2023, 1:629-640.

# Characteristics of liquid phase continuous arc discharge plasma

Yanbin Xin<sup>1</sup>\*, Quanli Wang<sup>1</sup>, Bing Sun<sup>1</sup>, Jinglin Liu<sup>1</sup>

<sup>1</sup> College of Environmental Science and Engineering, Dalian Maritime University, Dalian 116026, China \*Corresponding author: xinyb33@dlmu.edu.cn

Abstract- Discharge plasma represents a novel approach to molecular activation, offering the potential to achieve higher energy density and active substance concentration under ambient temperature and pressure conditions. Especially in-liquid discharge significantly enhances reaction efficiency between plasma and liquid reactants, facilitating the realization of reactions that are challenging to be achieved with conventional chemistry. Gliding arc discharge plasma has garnered considerable attention due to its simple device, large processing volume, and high energy efficiency, with expectations of its scalability for industrial applications. Presently, gliding arc discharge occurs in the gaseous phase, which presents certain constraints in the treatment of liquid feedstocks. In this work, liquid phase continuous arc discharge plasma is realized, enabling the gliding arc discharge can be triggered directly in the liquid without carrier gas. The time-space, electrical, optical and active particle characteristics of the liquid phase continuous arc discharge plasma are investigated. The results demonstrate that the liquid phase continuous arc discharge plasma exhibits the property of continuous propagation, achieving a propagation distance of 1 m. The liquid phase continuous arc discharge plasma moves at speeds of up to 36.0 cm/s during propagation. The initiation of the plasma occurs in microbubbles due to Joule heating at the smallest point of the electrode gap. The generation of various activity particles (·OH, ·O, ·H, H<sub>2</sub>O<sub>2</sub>) is a continuous process during the plasma propagation. The work paves the way for potential applications of gliding arc discharge, offering new technological avenues for plasma technology in diverse fields, including water treatment, material synthesis and energy conversion.

Keywords- Liquid phase discharge, Gliding arc plasma, Discharge characteristics.

# I. INTRODUCTION

Compared with traditional chemical techniques. plasma technology enables higher energy density and concentration of active species at ambient temperature and pressure conditions, significantly enhancing reaction efficiency and making traditionally unachievable chemical reactions possible [1]. Based on the medium used to generate plasma, discharge plasma can be categorized into gas phase discharge plasma and liquid phase discharge plasma [2]. Liquid phase discharge has garnered significant attention due to its advantages of enabling direct processing of liquid substances without requiring additional vaporization equipment and enhancing gas-liquid mass transfer efficiency through direct contact; but its limitations in treatment capacity and limited working distance have hindered its largescale applications [3, 4]. Gliding arc discharge plasma, featuring two outwardly extending electrodes that generate large volume plasma in space, has been extensively applied across various fields [5, 6]. Moreover, gliding arc discharge plasma is recognized as a discharge method that combines the advantages of both thermal and non-thermal plasmas, maintaining relatively high discharge power while achieving high level selectivity [7, 8]. However, existing research on gliding arc discharge plasma has been exclusively implemented in liquids. Directly igniting gliding arc discharges within liquid media would not only overcome the limitations of small treatment capacity and restricted working distance inherent to liquid-phase discharge, but also substantially advance progress toward industrial-scale applications [9, 10].

This study demonstrates a novel method for initiating gliding arc discharge plasma in liquid media, designated as liquid phase continuous arc (LCA) discharge plasma. Comprehensive analyses were conducted on its temporalspatial characteristics, electrical properties, optical emissions, and active species generation. Furthermore, the upgrading effect on n-hexadecane, a typical heavy oil model compound, was investigated with ethanol serving as hydrogen donor under optimized conditions.





Fig. 1. Schematic diagram of the experimental setup.

Figure 1 illustrates the schematic of the LCA discharge setup employed in this work. The LCA discharge plasma was generated using two diverging 304 stainless steel electrodes. Power was supplied by a high-voltage AC source (PSPT-2000K, Nanjing Perth Point Electronic Technology Co., Ltd.) with a 1000 W rated power. Observe the spatial and temporal characteristics

of the plasma through a CCD camera (HiSpec1 2G Color, Fastec Imaging). Optical characteristics were examined multi-channel using а spectrometer (PMA-11, Hamamatsu Photonics). The voltage applied to the highvoltage electrode was measured with a high voltage probe (P6015A, Tektronix, 1000:1 division ratio). A current probe (2878, Pearson, 0.1 V/A ratio) measured the discharge current. Both voltage and current signals were recorded by an oscilloscope (TDS2024C, Tektronix) featuring 200 MHz bandwidth and 2 GS/s sampling. The liquid phase products are qualitatively and quantitatively analyzed using a gas chromatograph equipped with an FID detector and a column of DB-5.

**III. RESULTS** 



Fig. 2. The two stages of LCA discharge.

The clarity of the discharge process is the first step in the novel discharge mechanism. understanding Therefore, the spatiotemporal characteristics of the discharge process were initially investigated. A highspeed CCD camera was used to record the entire process of LCA discharge. Based on whether the liquid boils during discharge, the LCA discharge can be divided into two stages as shown in Figure 2. The discharge initiates at the point of minimal gap between the two electrodes, after which the plasma remains confined within bubbles generated by Joule heating. Driven by liquid buoyancy, the bubbles ascend upward, and the plasma propagates upward accordingly. Eventually, plasma extinguishes upon bubble rupture. Stage 1 repeats cyclically until liquid boiling occurs, at which point LCA discharge transitions to Stage 2. The LCA discharge plasma propagates upward at 16.4 cm/s while remaining unextinguished during propagation. After a brief duration in Stage I, the discharge rapidly transitions to Stage 2. In Stage 2, the plasma propagation accelerates, reaching 36.0 cm/s. Critically, plasma effectively contacts the liquid in both stages, confining the arc discharge in a "non-thermal" state that enhances reaction selectivity.



Fig. 3. The initiation and propagation process of LCA discharge plasma.

Figure 3 illustrates the initiation and propagation process of LCA discharge plasma. It can be observed that before plasma generation, a small vapor bubble gradually forms at the electrode gap due to Joule heating. When the bubble connects both divergent electrodes, plasma is generated within it. After understanding how LCA discharge initiates, the spatiotemporal characteristics during plasma propagation were investigated. In most cases, LCA discharge plasma propagates upward steadily, with the plasma separated from electrodes by a liquid film. During propagation, the discharge plasma occasionally breaks through this liquid film and contacts the electrodes. At such moments, intense white light emerges near the breakdown channel, and the discharge transitions into spark discharge mode with significantly increased peak current. However, upward propagation is not always stable. When encountering thicker liquid films, LCA discharge plasma "jump" upward across the film. This abrupt transition causes peak current to instantly surge to several amperes.



The current - voltage waveform diagram of LCA discharge can also prove that the propagation process is a continuous non - extinguishing state. As shown in Figure 4a, before the plasma starts, the peak voltage between the two electrodes can reach 4 kV. When breakdown occurs, a plasma channel is formed between the two electrodes and the voltage drops to about 1 kV. As the gap between the two electrodes slowly increases, the length of the LCA discharge plasma column continuously increases. and the peak voltage of the discharge also slowly increases. After the discharge, the plasma channel disappears and the peak voltage returns to a higher position until the next discharge channel is triggered. The voltage and current waveforms of LCA discharge basically show sinusoidal changes as shown in Figure 4b. However, different from the more stable state of the voltage waveform, the current waveform will show some differences from the propagation state of the LCA discharge plasma. When the LCA discharge plasma breaks through the liquid film during the propagation process, the current waveform will show a small strong current with the spark-like discharge. When the LCA discharge plasma stably propagates upward, the current waveform presents a standard sine wave. When the "jump" phenomenon of the LCA discharge plasma as described in Figure 3 occurs, a strong current will also appear in the current waveform.



Fig. 5. Optical characteristics of LCA discharge plasma.

Figure 5 shows the emission spectrum of LCA discharge plasma in the wavelength range from 200 to 700 nm. In the ultraviolet region, the spectral bands of  $CO(b^3\Sigma \rightarrow a^3\Pi)$ CO  $CO(A^{1}\Pi \rightarrow X^{1}\Sigma),$ and  $OH(A^2\Sigma^+ \rightarrow X^2\Pi)$  are detected. In the visible light region,  $CH(B^2\Sigma \rightarrow X^2\Pi)$ ,  $CH(A^2\Delta \rightarrow X^2\Pi)$ ,  $CO(B^1\Sigma^+ \rightarrow A^1\Pi)$  and  $C_2(A^3\Pi_g \rightarrow X^{\prime 3}\Pi_u)$  are detected. The atomic spectral line in the excited state is only found to be H $\alpha$  at 656.3 nm. Among them, the C<sub>2</sub> swan spectral line is used to fit the vibration - rotation temperature, and the vibrationrotation temperature of LCA is about 5000 K. The spectral line of  $H_{\alpha}$  is used to estimate the electron density of LCA discharge plasma, and its electron density is 7.8×10<sup>16</sup> cm<sup>-3</sup>.



Fig. 6. The effect of LCA discharge plasma treatment on nhexadecane.

As shown in Figure 6a, it can be observed that  $C_{14}$  is a typical substance in light products, accounting for 23.1% of the light products. Heavy products mainly include two substances,  $C_{17}$  and  $C_{18}$ , and the hydrocracking reaction of n - hexadecane can be divided into three parts as shown in Figure 6b. Firstly, the cracking reaction of the raw material follows the priority principle of  $\beta$ -C-C bond cleavage reaction, generating  $C_{14}$ , which has the highest content in the liquid - phase products. At the same time, the C-C bond in ethanol breaks to generate CH<sub>3</sub> and CH<sub>2</sub>OH. Then comes the polymerization reaction. The raw material n - hexadecane and CH<sub>3</sub> undergo a polymerization reaction to generate  $C_{17}$ , which has the highest content in the intermediate products. Because ethanol has the ability to inhibit the polymerization reaction, the content of heavy - quality products is not high.

#### V. CONCLUSION

This work pioneered the implementation of liquidphase continuous arc (LCA) discharge plasma and systematically characterized its spatiotemporal, electrical, optical, and reactive species properties. Key findings are summarized below:

1) LCA emission unfolds in two distinct stages demarcated by liquid boiling onset. The second-stage discharge enables sustained plasma propagation exceeding 1 m through liquid media.

2) Three plasma morphologies emerge during propagation. Plasma-liquid interaction confines arc discharge within a "non-thermal" state, enhancing reaction selectivity.

3) n-Hexadecane hydrocracking predominantly proceeds via  $\beta$ -C-C bond cleavage, yielding C<sub>14</sub> dominant liquid products.

Collectively, LCA discharge plasma exhibits significant advantages for large-volume liquid processing and long-distance transport within liquids, demonstrating substantial promise for water treatment and energy conversion applications.

#### ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China [grant numbers 12475258, 52261145695], the Natural Science Foundation of Liaoning Province, China [grant number 2023-MS-127], and the Young Elite Scientists Sponsorship Program by CIN [grant number YESSCIN2022008], and the Fundamental Research Funds for the Central Universities [grant number 3132023503].

#### References

[1] A. Fridman, Plasma Chemistry, Cambridge University Press, New York, 2008.

[2] S.-C. Kim, Y.-K. Park, S.-C. Jung, Recent applications of the liquid phase plasma process, Korean J. Chem. Eng. 38 (2021) 885-898. 10.1007/s11814-020-0739-3.

[3] H.Y. Lian, J.L. Liu, X.S. Li, A.M. Zhu, Disclosure of water roles in gliding arc plasma reforming of methanol for hydrogen production, Plasma Processes Polym. 17 (2020) 2000069. 10.1002/ppap.202000069.

[4] F. Song, Y. Wu, S. Xu, X. Yang, Y. Xuan, N-Decane Reforming by Gliding Arc Plasma in Air and Nitrogen, Plasma Chem. Plasma Process. 40 (2020) 1429-1443. 10.1007/s11090-020-10117-8.

[5] L. Guo, P. Zhao, Z. Yao, T. Li, M. Zhu, Z. Wang, L. Huang, G. Niyazi, D. Liu, M. Rong, Inactivation of Salmonella enteritidis on the surface of eggs by air activated with gliding arc discharge plasma, Food Control 148 (2023) 109662. https://doi.org/10.1016/j.foodcont.2023.109662. [6] X. Gong, L. Yanchun, L. Xiaodong, W. Angjian, Z. Hao, Y. Jianhua, C. and Du, Decomposition of volatile organic compounds using gliding arc discharge plasma, Journal of the Air & Waste Management Association 70 (2020) 138-157. 10.1080/10962247.2019.1698476.

[7] A. Rabinovich, G. Nirenberg, S. Kocagoz, M. Surace, C. Sales, A. Fridman, Scaling Up of Non-Thermal Gliding Arc Plasma Systems for Industrial Applications, Plasma Chem. Plasma Process. (2021) 10.1007/s11090-021-10203-5.

[8] S.R. Sun, S. Kolev, H.X. Wang, A. Bogaerts, Coupled gas flow-plasma model for a gliding arc: investigations of the back-breakdown phenomenon and its effect on the gliding arc characteristics, Plasma Sources Sci. Technol. 26 (2017) 015003. 10.1088/0963-0252/26/1/015003.

[9] J.-B. Tarkwa, E. Acayanka, B.T. Sop, F.B. Kenyim, S. Nzali, S. Laminsi, Effect of Gliding Arc Plasma-Induced UV Light During the Photo-Fenton Oxidation of 4-Chlorophenol in Aqueous Solution, Plasma Chem. Plasma Process. 41 (2021) 989-1007. 10.1007/s11090-021-10171-w.

[10] M. Wartel, F. Faubert, I.D. Dirlau, S. Rudz, N. Pellerin, D. Astanei, R. Burlica, B. Hnatiuc, S. Pellerin, Analysis of plasma activated water by gliding arc at atmospheric pressure: Effect of the chemical composition of water on the activation, J. Appl. Phys. 129 (2021) 233301. 10.1063/5.0040035.

# Visualization of Dust Removal Characteristics for Electrodynamic Dust Shields with Parallel Electrodes under Simulated Martian Atmosphere

FuLin Liu<sup>1,2</sup>, Zepeng Han<sup>1,2</sup>, LiangZhi Jiang<sup>1,2</sup>, and Jian Wu<sup>1,2\*</sup> <sup>1</sup>School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China <sup>2</sup>Heilongjiang Key Laboratory of Micro-and Nano-scale Fluid Flow and HeatTransfer,Harbin, China \*Corresponding author: jian.wu@hit.edu.cn

*Abstract-* The low-pressure and dust-laden environment on Mars presents critical challenges to the sustained operation of energy harvesting systems, particularly solar panels. Electrodynamic Dust Shield (EDS) technology offers a promising non-contact solution for dust removal, requiring neither mechanical components nor water. While the effectiveness of EDS has been demonstrated in various contexts, the dynamic removal behavior of parallel electrode configurations remains underexplored. This study presents a visualized experimental platform for investigating the dust removal performance of parallel-electrode EDS structures under atmospheric conditions. A two-phase high-voltage rectangular AC power supply (0–5 kV peak-to-peak, 1–10 Hz) was employed to drive the electrodes, and the dust removal process was captured using high-speed imaging. Image processing algorithms were developed to quantify the dust removal rate and analyze particle trajectories and aggregation patterns. The results reveal that electrode spacing, width, inclination angle, and driving frequency are key parameters influencing cleaning performance. This work provides dynamic insights into the dust removal characteristics of parallel-electrode EDS systems and offers a methodological foundation for optimizing electrode design in extraterrestrial dust mitigation applications.

Keywords- Martian environment; Electrodynamic Dust Shield (EDS); parallel electrodes; dust removal characteristics; visualization analysis.

# I. INTRODUCTION

Mars presents an extremely dusty and low-pressure environment, where frequent storms deposit large amounts of fine particles on exploration equipment, significantly reducing solar energy collection efficiency [1-2]. For instance, the "Opportunity" rover failed due to dust accumulation during a global storm [3]. The thin Martian atmosphere (~0.6–0.7 kPa) and low gravity promote dust suspension, while the absence of natural cleaning mechanisms further exacerbates the problem [2– 4].

Conventional cleaning methods, such as mechanical brushing, vibration, and airflow, are ineffective or impractical under Martian conditions due to wear, sealing issues, and the lack of water [5]. Therefore, a non-contact, low-power dust removal method compatible with Mars' atmosphere is urgently needed.

Electrodynamic Dust Shield (EDS) technology is a promising solution [6]. By applying multi-phase highvoltage AC signals to parallel electrodes, EDS generates dynamic electric fields that exert Coulomb and dielectrophoretic forces to remove surface dust [7–8]. EDS operates without mechanical parts or water, and has shown strong potential in lunar and Martian dust mitigation studies [1, 9].

However, challenges remain under simulated Martian conditions. Low-pressure CO<sub>2</sub> atmospheres can induce discharge near electrodes, limiting field strength [10]. Martian dust particles also exhibit strong adhesion and low charge-to-mass ratios, complicating their removal [8, 11]. Moreover, the influence of electrode geometry and signal parameters on cleaning efficiency remains unclear [12– 15]. This study develops a visualized platform to investigate the dust removal behavior of parallel-electrode EDS systems under atmospheric conditions, with a focus on the influence of two-phase standing wave signals. The roles of electrode width, spacing, inclination, and frequency are systematically examined to support future EDS optimization for Martian solar energy systems [4].

### II. METHODOLOGY

# A. EDS Electrode Structure and Materials



Fig. 1. EDS Electrode Structure

EDS electrodes were fabricated using double-sided etching on copper-clad glass substrates ( $100 \times 100$  mm, 0.33 mm thick), forming staggered parallel-line arrays (Fig. 1). A black polyimide film was applied to the surface to enhance image contrast. Two electrode series—with varied widths or spacings—were designed to evaluate structural influence, and their specific parameters are detailed in Table 1. All samples were cleaned with isopropyl alcohol and ultra-pure water before testing to ensure surface consistency. B. Dust Dispersion System



Fig. 2. Dust Dispersion Device and Relationship between Electrode Speed and Dust Mass

An automatic X-Y motorized stage with a vertical hopper was developed to ensure uniform and repeatable dust coverage (Fig. 2). The amount of deposited dust per unit area was precisely controlled by adjusting the motor speed and hopper opening. A calibration curve illustrating the relationship between motor speed and dust mass is presented in Fig. 2. Repeatability tests confirmed a mass deviation below 0.05%, offering improved consistency over manual methods.

# C. Power Supply and Signal Settings

A custom high-voltage source generated two-phase square waves ( $\pm$ 5 kV, 1–10 Hz) for electrode excitation (Fig. 3). The system allowed continuous voltage tuning (0–10 kV peak-to-peak). Symmetric square waves with 50% duty cycle were used throughout, and electrode pairs received equal-amplitude opposing voltages to create electrodynamic waves.



Fig. 3. Power Supply and Two-phase Signal Loading Method

### D. Visualization and Image Analysis

A high-speed camera recorded the dust removal process from above. The recorded videos were converted into time-sequenced frames and binarized to extract dustcovered regions. The dust removal rate (DRR) was calculated using the following expression:

$$DDR = (A_0 - A_t) / A_0$$
(1)

where  $A_0$  is the total pixel count of the dust-covered area at the initial moment, and  $A_t$  is the pixel count at time t. Higher sampling rates (0.1 s/frame) were used during the first 5 seconds to capture the rapid initial motion, followed by 1 frame per second for steady-state analysis. Particle trajectories and aggregation behavior were also qualitatively assessed.

# E. Dust Pre-treatment and Electrode Cleaning

Silica dust (125–180  $\mu$ m) were dried at 120°C prior to each test. Electrodes were cleaned with isopropyl alcohol and ultra-pure water, then dried at 200°C. Consistent cleaning ensured reliable and repeatable results across all test conditions

# III. RESULTS

# A. Effect of Electrode Width



Fig. 4. Time evolution of DRR for two electrode widths

Fig. 4 shows the dust removal rate (DRR) over time for two electrode widths. Both configurations exhibit a rapid increase in DRR during the initial 10 seconds, indicating that dust particles are quickly driven from the gaps between electrodes toward their top surfaces, followed by repetitive jumping behavior driven by alternating electric fields.

Local peaks in the DRR curve correspond to frames capturing dust adhesion events, resulting in a temporary visual reduction in surface coverage.

Narrower electrodes achieved faster dust removal, reaching 90% DRR at 120 s compared to 80% for wider ones. This enhancement is attributed to reduced dust accumulation and more efficient particle transport per cycle with narrower electrodes.

B. Effect of Electrode Spacing





Fig. 5. DRR variation with time for different electrode spacings: (a) w = 0.5 mm; (b) w = 1.0 mm

As shown in Fig. 5, increasing electrode spacing generally improves DRR. The lowest performance was observed when the electrode width-to-spacing ratio was 1:1, indicating dense configurations hinder particle transport. With increased spacing, particles traveled farther under combined electric and gravitational forces.

However, larger gaps reduce electric field strength at constant voltage, making the effect nonlinear. Optimal spacing depends on particle characteristics such as size, adhesion, and dielectric properties. For example, in the w = 1.0 mm case, 1.5 mm spacing outperformed 2.0 mm spacing.

C. Effect of Electrode Inclination Angle



Fig. 6. DRR variation with time under different electrode inclination angles: (a) w = 0.5 mm; (b) w = 1.0 mm

Fig. 6 presents DRR curves under varying tilt angles  $(0^{\circ}-20^{\circ})$ . For 0.5 mm wide electrodes, steeper angles led to better dust removal, as gravity assisted particle motion along the slope.

Interestingly, for 1.0 mm electrodes, the horizontal configuration  $(0^{\circ})$  initially outperformed the  $10^{\circ}$  case within the first 100 s. This may be due to greater lateral spreading in horizontal layouts, allowing particles to escape more easily from the electrode region.

Such behavior is relevant to small-scale setups but may differ in large-area systems (e.g.,  $1 \text{ m}^2$ ), where random spreading significantly lowers cleaning efficiency and makes inclined designs more favorable.

D. Effect of Driving Frequency



Fig. 7. DRR variation with time at different driving frequencies: (a) w = 0.5 mm; (b) w = 1.0 mm

Fig. 7 shows the influence of driving frequency (1-10 Hz) on dust removal. Higher frequencies improved the cleaning rate but had minimal effect on the final DRR value.

This suggests that frequency mainly affects the dynamic response of particles rather than the overall removal capacity. We also hypothesize that frequency interacts with particle-specific properties, such as size and charge-to-mass ratio. Further investigation is needed to explore these dependencies and identify optimal frequency ranges.

#### IV. DISCUSSION

The experimental results indicate that the structural parameters of the electrodes and the driving signal play critical roles in the dust removal performance of the EDS system. Narrow electrodes reduce dust retention and promote efficient particle hopping. Increasing the electrode spacing appropriately improves particle migration, but excessive spacing weakens the electric field strength, suggesting the existence of an optimal range.

Introducing an inclination angle enhances overall cleaning efficiency through gravitational assistance, though its effectiveness is strongly influenced by system scale. In small-scale setups, horizontal configurations may temporarily outperform inclined ones due to stronger lateral diffusion. In large-area systems, however, inclination is essential for guiding dust away effectively.

Driving frequency primarily affects the rate at which dust is removed, with higher frequencies accelerating the initial cleaning process. However, the final removal efficiency remains largely unchanged, indicating that while higher frequencies enhance the initial dust excitation, they do not significantly improve the final removal rate under the tested conditions.

# V. CONCLUSION

This study established a visualization-based experimental platform to systematically investigate the dust removal behavior of a classical parallel-electrode EDS system under atmospheric conditions. The influence of key parameters—including electrode width, spacing, inclination angle, and driving frequency—was quantitatively evaluated. The main conclusions are as follows:

(1)Narrower electrode widths and moderate spacing significantly improve dust removal efficiency;

(2)Inclination facilitates particle transport, though its effect is scale-dependent;

(3)Driving frequency strongly affects the initial removal rate, while having limited influence on final cleaning efficiency.

These findings provide practical guidance for optimizing EDS design under simulated Martian conditions and lay the groundwork for future experiments in low-pressure  $CO_2$  environments.

# ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (Grant No. 12172110), and the Fundamental Research Funds for Central Universities (Grant No. AUGA9803500921).

REFERENCES

- [1] Nima Afshar-Mohajer, Chang-Yu Wu, Jennifer Sinclair Curtis, and James R. Gaier, "Review of dust transport and mitigation technologies in lunar and Martian atmospheres," ADVANCES IN SPACE RESEARCH, vol. 56, pp. 1222–1241, 2015.
- [2] C. I. Calle, C. R. Buhler, M. R. Johansen, M. D. Hogue, and S. J. Snyder, "Active dust control and mitigation technology for lunar and Martian exploration," ACTA ASTRONAUTICA, vol. 69, pp. 1082–1088, 2011.
- [3] Rajesh Sharma, Christopher A. Wyatt, Jing Zhang, Carlos I. Calle, Nick Mardesich, and Malay K. Mazumder, "Experimental Evaluation and Analysis of Electrodynamic Screen as Dust Mitigation Technology for Future Mars Missions," IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, vol. 45, pp. 591–596, 2009.
- [4] M. Hirabayashi, C. M. Hartzell, P. M. Bellan, D. Bodewits, G. L. Delzanno, T. W. Hyde, U. Konopka, E. Thomas, H. M. Thomas, I. Hahn, and U. E. Israelsson, "Electrostatic dust remediation for future exploration of the Moon," ACTA ASTRONAUTICA, vol. 207, pp. 392–402, 2023.

- [5] S. Patel, V.S. Veerasamy, J.P. St. John, and A. Orlov, "A comprehensive review on dust removal using electrodynamic shield: Mechanism, influencing factors, performance, and progress," Renewable and Sustainable Energy Reviews, vol. 183, pp. 113471, 2023.
- [6] Hiroyuki Kawamoto, "Electrodynamic dust removal technologies for solar panels: A comprehensive review," Journal of Electrostatics, vol. 134, pp. 104045, 2025.
- [7] Malay K. Mazumder, Mark N. Horenstein, Arash Sayyah, Jeremy W. Stark, Annie Bernard, Sean Garner, Julius E. Yellowhair, David R. Crowell, Carlos Coutinho, Ryan S. Eriksen, and IEEE, Mitigation of Dust Impacts on Solar Collectors by Water-Free Cleaning with Transparent Electrodynamic Films: Progress and Challenges, pp. 2052–2057, 2016.
- [8] M. K. Mazumder, R. Sharma, A. S. Biris, J. Zhang, C. Calle, and M. Zahn, "Self-cleaning transparent dust shields for protecting solar panels and other devices," PARTICULATE SCIENCE AND TECHNOLOGY, vol. 25, pp. 5–20, 2007.
- [9] H. Kawamoto, M. Uchiyama, B. L. Cooper, and D. S. McKay, "Mitigation of lunar dust on solar panels and optical elements utilizing electrostatic travelingwave," JOURNAL OF ELECTROSTATICS, vol. 69, pp. 370–379, 2011.
- [10] Hiroyuki Kawamoto and Shusuke Hashime, "Practical performance of an electrostatic cleaning system for removal of lunar dust from optical elements utilizing electrostatic traveling wave," JOURNAL OF ELECTROSTATICS, vol. 94, pp. 38– 43, 2018.
- [11] Owen D. Myers, Junru Wu, and Jeffrey S. Marshall, "Nonlinear dynamics of particles excited by an electric curtain," JOURNAL OF APPLIED PHYSICS, vol. 114, 2013.
- [12] Yue Yu, Jan Cilliers, Kathryn Hadler, Stanley Starr, and Yanghua Wang, "A review of particle transport and separation by electrostatic traveling wave methods," JOURNAL OF ELECTROSTATICS, vol. 119, 2022.
- [13] Junping Gu, Qinggong Wang, Yuxin Wu, Lele Feng, Guang Zhang, Shuiqing Li, Lin Tian, and Wei Yao, "Numerical study of particle transport by an alternating travelling-wave electrostatic field," ACTA ASTRONAUTICA, vol. 188, pp. 505–517, 2021.
- [14] Chia-Yang Chen, Jennifer K. W. Chesnutt, Chih-Hsiang Chien, Bing Guo, and Chang-Yu Wu, "Dust removal from solar concentrators using an electrodynamic screen," SOLAR ENERGY, vol. 187, pp. 341–351, 2019.
- [15] R. A. Syrovatka, V. S. Filinov, L. M. Vasilyak, VYa Pecherkin, L. Deputatova V, V. Vladimirov I, O. S. Popel, and A. B. Tarasenko, "Cleaning dielectric surfaces by the electrical fields of the linear electrodynamic Paul trap," JOURNAL OF ELECTROSTATICS, vol. 112, 2021.

# The Mechanism of Ionic Self-Phoresis

Alvaro Domínguez<sup>1\*</sup>, Mihail N. Popescu<sup>2</sup>

<sup>1</sup>Dpto. Física Atómica, Molecular y Nuclear, Universidad de Sevilla, Spain <sup>2</sup>International Centre of Biodynamics, Bucharest, Romania \*Corresponding author: dominguez@us.es

#### Abstract-

We study critically the mechanism of ionic self-phoresis, i.e., the self-propulsion due to gradients in the ionic distribution of a chemically active particle immersed in an electrolyte. The chemical activity of the particle is not only responsible for these gradients, but also contributes to the phoretic response. As a consequence, a mechanism of phoresis is unveiled which does not rely on the existence of a double layer at the surface of the particle.

Keywords- Diffusiophoresis, active colloid, electrolytes.

### I. INTRODUCTION

Self-phoretic colloidal particles have become a common realization of microswimmers by now. A frequent scenario consists of chemically active particles that generate gradients in the chemical composition of the surrounding fluid solution, see, e.g., the insightful reviews [1, 2, 3]. This has led to the picture of *classic self-phoresis*, namely that self-diffusiophoresis is "just" diffusiophoresis in a selfgenerated chemical gradient, whereby the only relevant role of the chemical activity is the generation of the composition imbalances.

We have recently showed [4, 5] that this paradigm is incomplete: the activity also affects the particle phoretic response to the chemical gradient. This shows up in a characteristic dependence of the phoretic velocities on the system parameters, that is different from the ones predicted for "classic phoresis in an external gradient".

This new feature roots on the proper account of the correlations between the chemical species, which motivated the denomination "correlation-induced self-phoresis" introduced in [4]. The mechanism of phoresis in the classic picture [6, 7, 8] relies on the interaction between the particle and the components of the fluid solution, thus emphasising the role of, e.g., the double layer formed at the particle's surface immersed in an electrolyte; the correlations are viewed as subordinated, leading only to a quantitative correction of the picture. The correlation-induced mechanism captures the insight that the interaction between the fluid solution components - quantified by the associated correlations are also relevant on their own as driver of phoresis when the particle is chemically active. Given that the electric interactions between ions in an electrolyte can induce strong correlations, this recently identified mechanism is expected to play a significant role in modelling ionic self-phoresis.

### II. THEORETICAL MODEL

Diffusiophoresis (also called chemophoresis) is the motion of a particle immersed in a fluid solution due to gradients in the concentration of chemicals. A defining feature is

that the composed system "particle+fluid" is mechanically isolated, so that the motion of the particle necessarily induces a flow by momentum conservation. This qualifies the phoretic particle as a *swimmer*, setting the phoretic motion significantly apart from the drag of a particle by externally imposed net forces or flows.

In the theoretical modelling of ionic phoresis, one can split the problem neatly into a hydrodynamic one and an electrostatic one, coupled through the electric forces that drive the flow. In the simplest model, all the velocities are assumed so small that the particle motion is overdamped, and the velocity field  $\mathbf{u}(\mathbf{r})$  of the electrolyte solution obeys Stokes equations for incompressible flow (low Reynolds and Mach numbers):

$$\eta \nabla^2 \mathbf{u} - \nabla p = \mathbf{f}(\mathbf{r}), \qquad \nabla \cdot \mathbf{u} = 0. \tag{1}$$

Here,  $\eta$  is the dynamical viscosity, p is the hydrodynamic pressure that enforces incompressibility. The field  $f(\mathbf{r})$  is a force density that drives the flow, and it will be described in detail below. These equations are complemented with the condition that the flow vanishes at infinity (i.e., the velocities are measured in the laboratory frame),

$$\mathbf{u}(\mathbf{r}) \to 0 \text{ when } |\mathbf{r}| \to \infty,$$
 (2)

and a no-slip boundary condition on the surface  $S_p$  of the particle,

$$\mathbf{u}(\mathbf{r}) = \mathbf{V} + \mathbf{\Omega} \times \mathbf{r} \text{ when } \mathbf{r} \in \mathcal{S}_n, \tag{3}$$

where V and  $\Omega$  are the particle phoretic velocities of translation and rotation, respectively. These quantities are unknown, and must be determined by imposing the additional constraint that the composed system "particle + fluid" is mechanically isolated: consequently, the fluid cannot transmit any net force or torque through a boundary  $S_{\infty}$  located at infinity<sup>1</sup>,

$$\oint_{\mathcal{S}_{\infty}} d\mathbf{S} \cdot (\eta \nabla \mathbf{u} - \mathbf{I}p) = 0, \qquad (4)$$

$$\oint_{\mathcal{S}_{\infty}} d\boldsymbol{\mathcal{S}} \cdot (\eta \nabla \mathbf{u} - \mathbf{l}p) \times \mathbf{r} = 0.$$
(5)

<sup>1</sup>The symbol I denotes the identity tensor.

The phoretic velocities are thus determined completely by the force density  $\mathbf{f}(\mathbf{r})$ , which describes the interaction between ions and between them and the particle. The mechanism of correlation-induced self-phoresis can be illustrated already with the simplest model of a 1:1 electrolyte Assuming again a slow dynamics, one can apply local thermodynamic equilibrium and write

$$\mathbf{f} = -c_+ \nabla \mu_+ - c_- \nabla \mu_-, \tag{6}$$

where  $c_{\pm}(\mathbf{r})$  are the concentration fields of anion and cation, respectively, and  $\mu_{\pm}(\mathbf{r})$  are the corresponding chemical potentials. They are found with the Nernst–Planck–Poisson–Boltzmann theory: one writes

$$\mu_{\pm}(\mathbf{r}) = \pm e\psi(\mathbf{r}) + k_B T \ln \frac{c_{\pm}(\mathbf{r})}{c_0}, \qquad (7)$$

in terms of a reference ion concentration  $c_0$  and the electric potential  $\psi(\mathbf{r})$ . The latter depends nonlocally on the ionic distribution and can be computed at the mean-field level as solution of the Poisson–Boltzmann equation,

$$\epsilon \nabla^2 \psi(\mathbf{r}) = e \left[ c_-(\mathbf{r}) - c_+(\mathbf{r}) \right],\tag{8}$$

complemented with the boundary condition of vanishing potential at infinity and *at the particle*,

$$\psi(\mathbf{r}) = 0 \text{ when } |\mathbf{r}| \to \infty \text{ or } \mathbf{r} \in \mathcal{S}_p;$$
 (9)

that is, the particle's zeta potential is zero and, therefore, *there is no double layer*. (This value is chosen to emphasize the correlation–driven mechanism; one can solve the model with any other prescribed surface pattern of zeta potential, that would induce a double layer). Finally, one imposes a stationary current of cations and anions in bulk separately,

$$\nabla \cdot \left( D_{\pm} c_{\pm} \nabla \mu_{\pm} \right) = 0, \tag{10}$$

where  $D_{\pm}$  denote the ionic diffusivities, together with a vanishing current at infinity,

$$D_{\pm}c_{\pm}\nabla\mu_{\pm} \to 0 \text{ when } |\mathbf{r}| \to \infty,$$
 (11)

and the boundary condition of a net current at the particle's surface generated by its chemical activity,

$$D_{\pm}c_{\pm}(\mathbf{r})(\mathbf{n}\cdot\nabla)\mu_{\pm}(\mathbf{r}) = \mathbb{A}(\mathbf{r}) \text{ when } \mathbf{r} \in \mathcal{S}_p.$$
 (12)

Here, **n** is the unit normal to the surface of the particle, and  $\mathbb{A}(\mathbf{r} \in S_p)$  describes the surface pattern of activity; for simplicity, the same pattern has been taken for both cations and anions, which also preserves electro-neutrality.

The structure of the equations allows a stepwise solution. First, the set of equations (7-12) build a boundary value problem that determines the fields  $c_{\pm}(\mathbf{r})$ ,  $\mu_{\pm}(\mathbf{r})$ . In a second step, equations (1-5) provide the phoretic velocities in terms of the force field (6). Notice that, in the absence of activity ( $\mathbb{A} \equiv 0$ ), the equations give the solution  $c_{\pm}(\mathbf{r}) = c_0$ and one gets no phoretic motion ( $\mathbf{V} = \mathbf{\Omega} = 0$ ).



Figure 1: Sketch of the two different mechanisms of phoresis. The distribution of chemicals (red dots) near the particle's surface (greenish bottom wall) is affected by a gradient in chemical potential (here plotted parallel to the wall) and by the influence of the particle: either (*upper pannel*) through the electric field  $\psi_{part}$  induced by its zeta potential (double layer), or (*lower pannel*) through a distortion (pinkish half-sphere) of the "correlation cloud" for each chemical particle.

#### III. RESULTS

Regardless of the specific form of the force field  $\mathbf{f}(\mathbf{r})$ , the hydrodynamic problem (1-5) can be solved for the phoretic velocities without the need to compute the flow field  $\mathbf{u}(\mathbf{r})$  by using the Lorentz reciprocal theorem (see, e.g., [9]). The final result can be expressed as integrals over the fluid volume [10]:

$$\mathbf{V} = \int_{\text{fluid}} d\mathcal{V} \,\mathsf{M}^{(V)}(\mathbf{r}) \cdot \nabla \times \mathbf{f}(\mathbf{r}), \tag{13}$$

$$\mathbf{\Omega} = \int_{\text{fluid}} d\mathcal{V} \,\mathsf{M}^{(\Omega)}(\mathbf{r}) \cdot \nabla \times \mathbf{f}(\mathbf{r}), \tag{14}$$

where  $M^{(V)}(\mathbf{r})$  and  $M^{(\Omega)}(\mathbf{r})$  are tensors fields whose form depends only on the shape of the particle<sup>2</sup>. The most relevant features are the linear dependence of the velocities on the force field, and the fact that only its curl matters: this is a consequence of the incompressibility constraint and rules out that osmotic pressure plays any role in diffusiophoresis<sup>3</sup>; as emphasized in [10], an explicit account of this constraint, as in (13, 14), prevents one from violating it inadvertently when carrying out approximations.

Therefore, phoresis arises from the misalignment of gradients in concentration and chemical potential,

$$\nabla \times \mathbf{f} = -(\nabla c_{+}) \times (\nabla \mu_{+}) - (\nabla c_{-}) \times (\nabla \mu_{-})$$
$$= e\nabla (c_{+} - c_{-}) \times (-\nabla \psi), \qquad (15)$$

where the second line follows from using equation (7); notice that the second term in that equation, which is a local

 $^2 They are found by solving the force-free (f <math display="inline">\equiv 0)$  Stokes equations with prescribed V and  $\Omega.$ 

<sup>3</sup>Any addition of a potential to the force,  $\mathbf{f} \mapsto \mathbf{f} + \nabla \chi$ , can be adsorbed by a redefinition of the pressure field *p*.

relationship between  $\mu$  and c, drops out. In the classic scenario, the concentration gradients  $\nabla c_{\pm}$  are associated to the double layer at the surface of the particle generated by its zeta potential, whereas the gradients  $\nabla \mu_{\pm}$  are imposed externally, see Fig. 1(upper pannel). Therefore, it seems that no phoresis is possible in the absence of a double layer<sup>4</sup>. In the case of a particle with chemical activity, however, the latter creates both kinds of gradients, which are misaligned if the correlations are so relevant that a relationship between c and  $\mu$  must be modelled as nonlocal, see Fig. 1(lower pannel). More specifically, equation (15) shows that phoretic motion arises when the electric field and the charge gradient are locally misaligned.

An important feature follows straightforwardly: since the gradients in (15) are sourced by the activity, see equation (12), the phoretic velocities will be at least quadratic in the activity. This is at variance with the classic scenario, which, being an instance of linear response theory, predicts velocities linear in the activity (namely, because the nonequilibrium forces  $\nabla \mu_{\pm}$  are generated by activity, whereas  $\nabla c_{\pm}$  are determined by the equilibrium double layer).

In order to get analytical results, one can solve the equations in the limit of small activity by expanding to linear order around the equilibrium solution  $c_{\pm}(\mathbf{r}) = c_0$ . This does not differ from the analytical approach in the classic scenario, whereby the solution is found as a perturbation around the equilibrium double layer: in such case, one has to solve a substantially more involved mathematical problem, which in turn forces one to resort to the additional approximation of a thin double layer (compared to the size of the particle), so that the particle surface is approximated by an infinite plane. This is not needed in our simplified scenario (no double layer), and one can obtain explicit solutions for a spherical particle of radius R. The activity surface pattern is conveniently expanded in spherical harmonics,

$$\mathbb{A}(\mathbf{r}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\mathbf{r}), \qquad \mathbf{r} \in \mathcal{S}_p.$$
(16)

One then finds that  $\Omega = 0$  (because, having both gradients the same source — activity —, chiral symmetry is not broken [4]), whereas the translation velocity is quadratic in the activity (see details in [11]):

$$\mathbf{V} = V_0 \sum_{\ell,m} \sum_{\ell',m'} a_{\ell m} a_{\ell'm'} \, \boldsymbol{\mathcal{G}}_{\ell m;\ell'm'}(\lambda_D/R), \qquad (17)$$

in terms of the velocity scale

$$V_0 = \frac{e^2 R^5}{6\pi\eta\epsilon} \left(\frac{1}{D_+} - \frac{1}{D_-}\right)^2,$$
 (18)

the Debye length,

$$\lambda_D = \sqrt{\frac{\epsilon k_B T}{2e^2 c_0}},\tag{19}$$



Figure 2: Log-log plot of the modulus of the self-phoretic velocity (17) for a Janus particle (inset: green for active surface, black for inactive), modelled as monopole + dipole in (16). The dashed line represents the asymptotic scaling  $V \sim \lambda_D^5$ .

and a dimensionless vector  $\mathcal{G}_{\ell m;\ell'm'}$  which is a known function of the ratio  $\lambda_D/R$ . This latter function encodes "selection rules" [4, 11] that restrict the double sum in (17): the most significant one is that the only allowed couplings between multipoles  $(\ell, m)$  and  $(\ell', m')$  are those of consecutive order ( $\ell' = \ell \pm 1$ ). Another robust feature is the asymptotic behavior with  $\lambda_D$  [11]: in the small-particle limit  $(R \ll \lambda_D)$ , the phoretic velocities reach finite values independent of  $\lambda_D$  (and thus, also of  $c_0$ ); in the thin– layer limit ( $\lambda_D \ll R$ ), the phoretic velocities are predicted to vanish as  $\lambda_D^5$ . This latter result shows that spatially extended correlations, with a range quantified by the length scale  $\lambda_D$ , are a requirement for this mechanism. (A detailed and critical analysis how this approximation, which is most frequently employed, can be derived from the exact result (17) can be found in [12].)

As an illustration, Fig. 2 shows the self-phoretic velocity given by (17) with  $a_{\ell m} = 0$  except if  $\ell = m = 0$ (monopole) and  $\ell = 1, m = 0$  (dipole). This is the simplest model for a half-coated (Janus) particle, whose surface is thus chemically active only on a hemisphere. A more realistic model, e.g., including also a quadrupole, leads to a much richer behavior, with a nonmonotonous behavior, including several sign reversals [11].

#### IV. DISCUSSION

Phoresis is driven by the misalignment of the gradients in ion concentrations and chemical potentials, respectively, see (15). In the classic picture of phoresis, the mechanism relies on the existence of the equilibrium gradient in ion concentration in the double layer, in general not parallel to the nonequilibrium gradient of chemical potential imposed externally — or generated by the chemical activity of the particle in the scenario of self-phoresis.

Based on the simplest model, we have provided a proof of principle for a mechanism that does not rely on the double layer. Instead, the nonequilibrium inhomogeneities in the ionic distribution due to the chemical activity do play a role, whereby the relevant feature for the gradients mis-

<sup>&</sup>lt;sup>4</sup>Notice that, although the imposed gradient in  $\mu$  also generates gradients in *c*, these are parallel because no flow must be induced in the absence of the particle (that is, the phoretic motion cannot be considered as drag by a flow).



Figure 3: The phoretic diagram [5, 13]. The horizontal axis identifies the relative contribution to the mechanism (zeta potential vs. activity), the vertical axis captures the relative contribution to the source of nonequilibrium (external gradient vs. activity). The corners are associated to the different limiting behaviors: the "classic" picture corresponds to the leftmost part; the rightmost part encompasses "correlation-driven" phoresis.

alignment is the nonlocal nature of the ion–ion interaction, namely the electric forces over scales below the Debye length.

The fact that this same interaction is key for the formation of the double layer has undoubtedly masked the significance and conceptual difference of these two mechanisms. Diffusiophoresis in a solution of neutral chemicals provides a more appropriate model from this perspective [4], to the extent that the two kind of interactions (particlewith-chemicals and chemicals-with-chemicals) can have independent origins. However, a one-to-one mapping can be established, at the linearised approximation, between the latter model of neutral phoresis and the case of ionic phoresis [11], which illuminates the relative importance of the two mechanisms. More precisely [5, 13], one can add a nonvanishing zeta potential at the boundary condition (9) and an externally imposed chemical gradient at the boundary condition (11): the linearized theory then leads to a neat representation in the form of a "phoretic diagram", see Fig. 3, based on equation (15). The horizontal axis ("mechanism") quantifies the relative importance of two types of contribution to  $\nabla c_+$ , namely zeta potential vs. chemical activity. The vertical axis ("source") quantifies the relative magnitude of the sources of non-equilibrium ( $\nabla \mu_{\pm} \sim \nabla \psi$ ), that is, externally imposed gradient vs. chemical activity.

#### ACKNOWLEDGMENTS

The authors acknowledge financial support through ProyExcel\_00505 funded by Congrant sejería Transformación Económica, de Industria,

Conocimiento y Universidades (Junta de Andalucía), and grant PID2021-126348NB-I00 funded by MCIN/AEI/10.13039/501100011033/FEDER,UE.

#### REFERENCES

- [1] S. J. Ebbens and J. R. Howse. In pursuit of propulsion at the nanoscale, *Soft Matter*, vol. 6, pp. 726-738, 2010.
- [2] A. Aubret, S. Ramananarivo, and J. Palacci. Eppur si muove, and yet it moves: Patchy (phoretic) swimmers, *Current Opinion in Colloid & Interface Science*, vol. 30, pp. 81-89, 2017.
- [3] J. L. Moran and J. D. Posner. Phoretic self-propulsion, Annual Review of Fluid Mechanics, vol. 49, pp. 511-540, 2017.
- [4] A. Domínguez, M. N. Popescu, C. M. Rohwer, and S. Dietrich. Self-motility of an active particle induced by correlations in the surrounding solution, *Physical Review Letters*, vol. 125, p. 268002, 2020.
- [5] A. Domínguez and M. N. Popescu. A fresh view on phoresis and self-phoresis, *Current Opinion in Colloid* & *Interface Science*, vol. 61, p. 101610, 2022.
- [6] D. C. Prieve, J. L. Anderson, J. P. Ebel, and M. E. Lowell. Motion of a particle generated by chemical gradients. Part 2. Electrolytes, *Journal of Fluid Mechanics*, vol. 148, pp. 247-269, 1984.
- [7] J. L. Anderson. Colloid transport by interfacial forces, *Annual Review of Fluid Mechanics*, vol. 21, pp. 61-99, 1989.
- [8] M. De Corato, X. Arqué, T. Patiño, M. Arroyo, S. Sánchez, and I. Pagonabarraga. Self-propulsion of active colloids via ion release: Theory and experiments, *Physical Review Letters*, vol. 124, p. 108001, 2020.
- [9] J. Happel and H. Brenner. *Low Reynolds number hydrodynamics*. Noordhoff Int. Pub., 1973.
- [10] A. Domínguez and M. N. Popescu. Force-dependence of the rigid-body motion for an arbitrarily shaped particle in a forced, incompressible Stokes flow, *Physical Review Fluids*, vol. 9, p. L122101, 2024.
- [11] A. Domínguez and M. N. Popescu. Ionic self-phoresis maps onto correlation-induced self-phoresis, *arXiv:2404.16435 [cond-mat.soft]*.
- [12] A. Domínguez and M. N. Popescu. Selfchemophoresis in the thin diffuse interface approximation, *Molecular Physics*, vol. 122, p. e2396545, 2024.
- [13] A. Domínguez, M. N. Popescu, and S. Dietrich. In preparation.

# Large eddy simulation of turbulent electro-convection in dielectric liquids

Guangze Liu<sup>1</sup>, Yu Zhang<sup>1</sup>, Shuyan Liu<sup>1</sup>, Dian Li<sup>1</sup>, Jian Wu<sup>1\*</sup>

<sup>1</sup>Heilongjiang Key Laboratory of Micro- and Nano-scale Fluid Flow and Heat Transfer, School of Energy Science and Engineering,

Harbin Institute of Technology, Harbin 150001, PR China

\*Corresponding author: jian.wu@hit.edu.cn

*Abstract-* Large eddy simulation (LES) serves as a pivotal numerical approach for the investigation of turbulence, particularly in complex flow systems. Electroconvection (EC) turbulence, though crucial for advancing our understanding of electrohydrodynamics (EHD), remains insufficiently studied in this field. This study utilizes LES within the finite volume method (FVM) framework to investigate EC turbulence induced by charge injection in a cavity. The eddy-viscosity models are adopted to close the momentum equations, while the turbulent charge transport is captured using the turbulent Schmidt number. A comparison with direct numerical simulation (DNS) demonstrates that LES effectively captures the primary flow structures and dynamics of EC turbulence, showing good agreement with existing literature. The analysis reveals strong fluctuations and intermittency, with large-scale coherent structures significantly impacting charge transport and thermal plumes, ultimately influencing charge and heat transfer efficiency. This work deepens the understanding of EC turbulence and offers a foundation for exploring more complex EC turbulence mechanisms, with implications for energy and thermal management systems.

Keywords- Electrohydrodynamics, Electroconvection turbulence, Large eddy simulation, Dielectrics.

# I. INTRODUCTION

Electroconvection (EC) turbulence, a representative flow phenomenon induced by electric currents, has emerged as a key topic in the field of electrohydrodynamics (EHD)[1]. Typically observed in dielectric liquids subjected to strong electric fields, EC is characterized by complex, multi-scale flow structures and strong coupling among electric, flow, and thermal fields. Owing to its relevance in a variety of engineering applications-such as electrostatic spraying, electrothermally enhanced phase-change heat transfer, and conduction pumping[2]-the study of EC turbulence holds both fundamental and applied significance. Within confined geometries like cavities, EC turbulence exhibits pronounced nonlinear behavior and marked spatial heterogeneity, which pose significant challenges for predicting flow and heat transfer behavior[3]. Therefore, gaining a detailed understanding of EC turbulence in such configurations is essential for advancing the design and performance of electrohydrodynamic systems.

In recent years, Large Eddy Simulation (LES) has become an increasingly popular and powerful tool for turbulence modeling. Compared with the conventional Reynolds-averaged Navier-Stokes (RANS) approach, LES offers improved accuracy in resolving large-scale vortex structures while maintaining computational efficiency through subgrid-scale (SGS) modeling. These features make LES particularly suitable for simulating complex, multi-physics turbulent flows. However, the application of LES to EC turbulence remains relatively underexplored, especially in contexts involving strong electrothermal coupling[4]. Moreover, systematic assessments of LES performance, including SGS model selection and its influence on predictive accuracy in EC turbulence, are still lacking and warrant further investigation.

In this study, the finite volume method (FVM) implemented in the open-source computational platform OpenFOAM is employed to perform direct numerical simulation (DNS) and LES of EC turbulence in cavity configurations. The following two sections will respectively present the physical model, governing equations, and the significance of key driving parameters. A detailed comparison between LES and DNS is conducted, focusing on flow structures, turbulent statistics, and charge transport mechanisms under varying electric field intensities.

# II. METHODOLOGY

A two-dimensional square cavity with side length L is considered, filled with incompressible Newtonian dielectric liquid, as illustrated in Fig. 1 The bottom electrode is connected to the positive terminal ( $\varphi_1$ ) of the power supply, while the top electrode is grounded ( $\varphi_0$ ). The horizontally arranged bottom and top electrodes maintain constant but distinct temperatures ( $\theta_1 > \theta_0$ ), with the vertical side walls treated as adiabatic boundaries. The electrochemical reactions at the electrode-liquid interfaces induce charge injection from the high-voltage electrode into the bulk fluid. The model adopts homogeneous autonomous charge injection with a specified electrode charge density  $q_0$ [5].

To derive the governing equations for EC turbulence under charge injection conditions, the following assumptions are made for the system: using the Boussinesq approximation, density variations are only accounted for in the momentum equation due to temperature changes, while other material properties remain constant. The analysis neglects magnetic effects and Joule heating, as the electric current in the dielectric liquid is minimal. Additionally, the dielectric force is considered negligible compared to the dominant Coulomb force from the applied electric field. The following characteristic values are chosen for the nondimensionalization of the governing equations:



Figure 1: Schematic diagram for the problem

$$x, y \sim L; \quad t \sim \frac{L^2}{K\Delta\phi}; \quad u \sim \frac{K\Delta\phi}{L}; \quad \phi \sim \Delta\phi;$$
  
$$E \sim \frac{\Delta\phi}{L}; \quad q \sim q_0; \quad \mathbf{p} \sim \rho u_0^2; \quad \theta = \frac{\theta_1 - \theta_0}{\Delta\theta}$$
(1)

In the above equation, L represents the characteristic scale of the system, and K is the ionic mobility,  $\Delta \phi$  is the potential difference between the positive and negative plates,  $\rho_{\rm eq}$  denotes the charge density.  $\theta_0$  is the temperature of the cold source,  $\Delta \theta$  is the maximum temperature difference of the system. After nondimensionalizing the governing equations, the following dimensionless equations are obtained[1]:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{2}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \nabla^2 \boldsymbol{u} + \frac{Ra}{Pr} \theta \boldsymbol{e}_y + C \frac{T^2}{M^2} q \boldsymbol{E}$$
(3)

$$\frac{\partial \theta}{\partial t} + \boldsymbol{u} \cdot \nabla \theta = \frac{1}{Pr} \nabla^2 \theta \tag{4}$$

$$\frac{\partial q}{\partial t} + \nabla \cdot \left[ q \left( \boldsymbol{u} + \frac{T}{M^2} \boldsymbol{E} \right) \right] = \frac{1}{Sc} \nabla^2 q \qquad (5)$$

$$\nabla^2 \phi = -Cq \tag{6}$$

$$\boldsymbol{E} = -\nabla\phi \tag{7}$$

The dimensionless variables  $\mathbf{u}$ , p,  $\theta$ , q, e,  $\mathbf{E}$ , and  $\phi$ , corresponding to the velocity field, modified pressure, temperature, charge density, electric potential, electric field, and voltage, respectively. The dimensionless system is characterized by six key parameters:

$$Pr = \frac{\nu}{\kappa}, \quad Ra = \frac{g\beta L^3 \Delta \theta}{\kappa \nu}, \quad T = \frac{\epsilon \Delta \phi}{\rho_0 \nu K},$$
  
$$C = \frac{q_0 L^2}{\epsilon \Delta \phi}, \quad M = \frac{1}{K} \sqrt{\frac{\epsilon}{\rho_0}}, \quad Sc = \frac{\nu}{D}$$
(8)

# 39: Large Eddy Simulation Of Turbulent...

Pr is the Prandtl number, with  $\nu$  and  $\kappa$  denoting the kinematic viscosity and thermal diffusivity, respectively. Ra is the Rayleigh number, where g is the gravitational acceleration,  $\beta$  the thermal expansion coefficient. T is the electric Rayleigh number, with  $\epsilon$  being the fluid permittivity,  $\rho_0$  the reference density. C represents the charge injection strength. M is the mobility parameter, and Sc is the electric Schmidt number, where D denotes the charge diffusion coefficient.

In general, a condition with C > 5 is considered strong injection, corresponding to the space-charge-limited (SCL) regime. When  $C \sim \mathcal{O}(1)$ , it is referred to as moderate injection, whereas  $C \ll 1$  indicates weak injection. In many studies, representative values such as C = 10, 1, and 0.1 are commonly used to characterize strong, moderate, and weak injection scenarios, respectively[6]. In this work, we focus on the strong injection regime by setting C = 10 to investigate electro-thermo-convection within a square cavity.

The core concept of LES involves applying a spatial filter to separate any flow variable  $v(u, p, q, \phi)$  into a resolved (filtered) component  $\overline{v}$  and a subgrid (residual) component v', such that  $v = \overline{v} + v'$ . This filtering process attenuates fluctuations smaller than the filter width  $\Delta$ . Although the resulting filtered equations bear similarity to the Reynolds-averaged formulation, they retain cross terms involving filtered variables. The subgrid-scale electrohydrodynamic (EHD) equations, written in tensor notation, are provided below:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{9}$$

$$\frac{\partial \overline{u}_{i}}{\partial t} + \frac{\partial \overline{u}_{i}\overline{u}_{j}}{\partial x_{j}} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_{i}} + \frac{\partial^{2}\overline{u}_{i}}{\partial x_{j}\partial x_{j}} + \frac{Ra}{Pr}\overline{\theta}\boldsymbol{e}_{y} \\
+ C\frac{T^{2}}{M^{2}}\overline{q}\overline{E_{i}} + C\frac{T^{2}}{M^{2}}(\overline{q}\overline{E_{i}} - \overline{q}\overline{E_{i}}) - \frac{\partial(\overline{u_{i}u_{j}} - \overline{u}_{i}\overline{u}_{j})}{\partial x_{j}} \\$$
(10)

$$\frac{\partial \overline{q}}{\partial t} + \frac{\partial \overline{q} \,\overline{u}_i}{\partial x_i} + \frac{\partial \overline{q} \,\overline{E}_i}{\partial x_i} = \frac{1}{Sc} \frac{\partial^2 \overline{q}}{\partial x_j \partial x_j} - \left( \frac{\partial (\overline{qu}_i - \overline{q} \,\overline{u}_i)}{\partial x_i} + \frac{T}{M^2} \frac{\partial (\overline{qE}_i - \overline{qE}_i)}{\partial x_i} \right)$$
(11)

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial \overline{\theta} \,\overline{u}_i}{\partial x_i} = \frac{1}{Pr} \frac{\partial^2 \overline{\theta}}{\partial x_j \partial x_j} - \left( \frac{\partial (\overline{\theta u_i} - \overline{\theta} \,\overline{u}_i)}{\partial x_i} \right) \quad (12)$$

$$\frac{\partial^2 \overline{\phi}}{\partial x_i \partial x_i} = -C\overline{q},\tag{13}$$

$$\overline{E}_i = -\frac{\partial \overline{\phi}}{\partial x_i}.$$
(14)

The subgrid-scale stress term in the momentum equation is modeled using the Smagorinsky model with a fixed filter width  $\Delta$ . In the charge transport equation, the turbulent Schmidt number  $Sc_t = \nu_t/D_t$  is used to relate eddy

(



#### III. RESULTS AND DISCUSSION

Figure 2: Phase-space diagram of temperature and electric potential at a specific monitoring point in the system at T = 2000 under (a) : DNS result, (b) : LES result.

First, let us analyze the state of the system. Fig. 2 shows the phase-space diagram of temperature and electric potential at a specific monitoring point in the system at T = 2000. Both  $T-\phi$  phase-space plots exhibit elongated, ellipsoidal intertwined attractors, confirming that the system has entered a turbulent regime. However, the two simulation approaches differ markedly in attractor scale and detail: DNS resolves all small-scale eddies, producing a larger trajectory envelope with richer layering; its outer loops reach extreme fluctuations and the curves appear rougher, reflecting a wider energy channel and higher entropy production. In contrast, the LES, owing to subgridscale viscosity and filtering, compresses the attractor into a more compact and smoother core, with outer excursions strongly suppressed—implying that LES is sufficient when one is concerned only with statistical means and the dominant mode.



Figure 3: Comparison of flow structures and charge density contours between DNS and LES simulation results at T = 2000.

Fig. 3 presents a comparison of the flow structures and charge density contours obtained from DNS and LES simulations at T = 2000. DNS and LES deliver highly

consistent macroscopic pictures of EC turbulence in the square cavity. Both approaches capture a large-scale primary vortex that occupies most of the enclosure, exhibiting almost identical core position, rotation direction, and symmetry. Because DNS resolves the complete spectrum of spatial scales, it reproduces many more secondary eddies and sharper gradients at the edges of the primary vortex, in the corners, and along the walls. At the same locations the LES field appears more rounded and smooth: the intensity of secondary vortices is attenuated to varying degrees, and the extreme values of charge density are "flattened-out". This discrepancy stems from the filtering and SGS modelling inherent in LES: the filter eliminates high-wavenumber energy, while SGS dissipation (or backscatter) approximates the small-scale dynamics in a coarse manner, allowing LES to retain the main flow topology at the expense of detailed fidelity.

A comparison of the charge-density contours shows that the high-charge region is located near the same sidewall in both simulations, yet the DNS field displays steeper gradients and sharper peaks and troughs, whereas colour transitions in LES are smoother. Quantitatively, in several snapshots the LES peaks are slightly lower and the troughs slightly higher, compressing the overall range by about 5-10 %. This behaviour is consistent with the numerical diffusion of charge introduced by the LES model. Overall, LES provides an acceptable representation of the dominant flow pattern and the mean charge distribution, but DNS is preferable when the research objective emphasises small-scale vortices or spiky charge concentrations.



Figure 4: Variation of maximum velocity  $U_{\text{max}}$  with T under different simulation methods.

Fig. 4 illustrates the temporal evolution of the system's maximum velocity, revealing a pronounced intensification as the electric Rayleigh number increases from T = 1000 to T = 2000. Across all four time series, a noticeable upward shift is observed, with the mean velocity increasing by approximately 60% and the peak-to-peak amplitude nearly doubling. This amplification underscores the significant role of electro-thermal buoyancy in enhancing the strength of the convective circulation. At both parameter values, LES consistently predicts slightly higher peak values and mean velocities, this results implying a modest positive bias in large-scale kinetic energy introduced by the SGS model in LES. In contrast, DNS, by fully resolving the smaller-scale structures, captures sharper and more frequent spikes,

reflecting a more detailed representation of transient dissipative events.



Figure 5: Variation of maximum velocity  $U_{\text{max}}$  with T under different simulation methods.

As illustrated in Fig. 5, the electric Nusselt number  $Nu_e$ exhibits only a marginal increase as the electric Rayleigh number T rises from 1000 to 2000, growing from approximately 1.94 to nearly 2.00. When considered alongside the earlier analysis of the system's maximum velocity, this observation suggests that although a twofold increase in the Coulomb body force at lower T levels can substantially enhance the peak flow velocity, its effect on the net charge transport within the cavity remains limited. This implies that the intensified electro-thermal forcing predominantly strengthens convective motion rather than significantly altering the dominant conduction-controlled charge transport pathways.

Meanwhile, LES predicts mean  $Nu_e$  values that agree with DNS within 2%, yet it substantially underestimates the amplitude of fluctuations, capturing only about half the variance observed in DNS. This discrepancy likely arises from the excessive diffusive action of the classical Smagorinsky subgrid model in regions of intense shear, which acts to suppress the fine-scale structure and intermittency of charge transport phenomena.

# IV. CONCLUSION

In this study, the large eddy simulation (LES) approach combined with the finite volume method (FVM) was employed to systematically investigate electro-convective (EC) turbulence induced by strong charge injection in a dielectric liquid confined within a square cavity. A detailed comparison with direct numerical simulation (DNS) results demonstrated that LES effectively captures the primary flow structures and key features of charge transport, exhibiting good agreement with DNS in terms of macroscopic flow structures and statistical characteristics.

Specifically, both LES and DNS accurately predicted the dominant large-scale vortex structures within the cavity. However, significant differences were observed in capturing smaller-scale features. DNS provided more detailed insights into secondary vortices and high-frequency spikes in charge density. Furthermore, with an increasing electric Rayleigh number (T), the maximum velocity within

the cavity increased markedly, accompanied by enhanced turbulence intensity and intermittency. However, the efficiency of charge transport, represented by the electric Nusselt number, exhibited only modest improvements. This indicates that the enhanced Coulomb body force predominantly strengthened convective fluid motions, with limited influence on conduction-controlled charge transport pathways.

In conclusion, LES is validated as an efficient and reliable method for analyzing macroscopic EC turbulence phenomena. Nonetheless, DNS remains indispensable for detailed investigations involving small-scale structures and high-frequency intermittency phenomena.

# ACKNOWLEDGMENTS

We are very grateful for the guidance offered by Yu Zhang. This work is supported by the National Natural Science Foundation of China (Grant No. 12172110), the National Key Research and Development Program of China (No. 2020YFC2201004).

# REFERENCES

- [1] Antonio Castellanos. *Electrohydrodynamics*, volume 380. Springer, 2014.
- [2] Kamran Iranshahi, Thijs Defraeye, Rene M. Rossi, and Ulf Christian Müller. Electrohydrodynamics and its applications: Recent advances and future perspectives. *International Journal of Heat and Mass Transfer*, 232:125895, 2024.
- [3] Yu Zhang, Di-Lin Chen, Xiao-Ping Luo, Kang Luo, Jian Wu, and Hong-Liang Yi. Coulomb-driven electroconvection turbulence in two-dimensional cavity. *Journal of Fluid Mechanics*, 980:A22, 2024.
- [4] Yu Zhang, Kang Luo, Hongliang Yi, Anjun Liu, and Jian Wu. Application of large eddy simulation models to electroconvection turbulence study with lattice boltz-mann method. *Physical Review Fluids*, 9(8):083703, 2024.
- [5] Mengqi Zhang. Weakly nonlinear stability analysis of subcritical electrohydrodynamic flow subject to strong unipolar injection. *Journal of Fluid Mechanics*, 792:328–363, 2016.
- [6] Kang Luo, Yu Zhang, Jian Wu, Hong-Liang Yi, and He-Ping Tan. Lattice boltzmann modeling of two-phase electrohydrodynamic flows under unipolar charge injection. *Physical Review E*, 105(6), 2022.
- [7] F Ducros, F Nicoud, and Thierry Poinsot. Walladapting local eddy-viscosity models for simulations in complex geometries. *Numerical Methods for Fluid Dynamics VI*, 6:293–299, 1998.

# Numerical Simulation Of AC Electrified Jets In A Flow-Focusing Device

Q. Wang<sup>1,2</sup>, A. Ramos<sup>3</sup>, P. García Sánchez<sup>3</sup>, P. A. Vázquez<sup>4</sup>

<sup>1</sup>School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

<sup>2</sup> Suzhou Research Institute of HIT, Suzhou 215104, China

<sup>3</sup>Dept. of Electronics and Electromagnetism, Faculty of Physics, Universidad de Sevilla, Sevilla, Spain

<sup>4</sup>Dept. of Applied Physics III, ETSI, Universidad de Sevilla, Sevilla, Spain

\*Corresponding author: pvazquez@us.es

*Abstract-* In this work, we present results of a numerical simulation reproducing previous experiments with AC electrified micro-jets. Numerical studies allow us to access physical magnitudes that are difficult or impossible to measure in experiments. In particular, we are interested in the structure of the electric potential and field. We compare the results with experimental data, checking the dependence of the breakup length with the applied electric field via the electric Bond number BoE, and the frequency of the applied AC voltage.

Keywords- Multiphase flows, Electrokinetics, Droplet microfluidics.

### I. INTRODUCTION

Electric forces applied in liquids are especially relevant in small length scales, making electrokinetics a very active research field for the control of fluid flows and the manipulation of particles in microfluidic devices [5]. In a previous paper [1], some of the authors described experiments performed in a microfluidic flow focusing device to produce water-in-oil droplets. Fig. 1 shows the effect of applying an AC voltage to a coflow microdluidic system. The continuous phase is mineral oil containing 5 wt% of the nonionic surfactant Span 80 (Sigma-Aldrich), while the dispersed phase is an aqueous KCl solution. The viscosity of the outer liquid (liquid 2) is one hundred times greater than the viscosity of the inner liquid (liquid 1). Metallic electrodes are placed parallel to the channel walls, while the conductive phase is grounded. In the absence of an electric field, the flow rates of each liquid are adjusted in such a way that liquid 1 breaks down into small droplets near the junction. The electric conductivity of liquid 2 is much lower than the electric conductivity of liquid 1. Therefore, when an AC electric field is applied, a net electric charge appears at the interface of the liquids. The AC electric field acting on this surface charge stretches the jet. The length of the jet increases with increasing applied AC voltage and with decreasing frequency.

This paper builds on previous work presented in ISEHD20219 [6]. Our aim is to numerically reproduce this experiment. Linear stability analysis shows that a purely normal field acting on the trunk of the jet should have a destabilizing effect [2]. The presence of a tangential electric field could explain the stability observed in the experiments. In order to better understand the physics of this system, we try to reproduce numerically these experimental results. In this work, we discuss the relevant physical equations describing the problem, both in dimensional and non-dimensional form. The non-dimensional parameters are identified. We also present some preliminary results of our simulations, showing that we can qualitatively repro-



Figure 1: This series of images from [1] shows the effect of increasing applied voltage on the jet length. The width of the channel is  $100 \,\mu\text{m}$ .

duce the observed stretching of the jet when an AC electric field is applied.

#### II. PHYSICAL MODEL

#### A. Dimensional model

Fig. 2 shows the computational domain of the problem, along with the boundary conditions. The geometry is axisymmetric. The inner (outer) liquid has mass density  $\rho_1$  ( $\rho_2$ ), dynamic viscosity  $\mu_1$  ( $\mu_2$ ), dielectric constant  $\varepsilon_1$  ( $\varepsilon_2$ ) and electric conductivity  $\sigma_1$  ( $\sigma_2$ ). The inner liquid enters the domain through the left boundary, whereas the outer liquid enters the domain radially through the cylindrical boundary, next to the left boundary. The inner liquid, much more conductive than the outer one, is grounded. An AC electric voltage with frequency f is applied to the outer cylindrical boundary.

The ohmic relaxation frequency in the experiment is  $\omega_{\Omega} \approx \sigma_1/\varepsilon_1$ , which is of the order of MHz. As the fre-



Figure 2: Computational domain for the numerical simulation of the jet subjected to an AC field. The geometry is axisymmetric around the z axis.

quency of the applied AC is of the order of tens of kHz, the electric problem is described by the complex charge conservation equation for the complex electric potential and the complex electric field

$$\nabla \cdot (\tilde{\sigma} \nabla \tilde{V}) = 0, \qquad \tilde{\mathbf{E}} = -\nabla \tilde{V}. \tag{1}$$

Here,  $\tilde{V} = V^R + iV^I$  is the complex electric voltage,  $V^R$ and  $V^I$  are the real and imaginary parts, respectively, and  $\tilde{\sigma} = \sigma + i\omega\varepsilon$  is the complex conductivity, *i* being the imaginary unit, and  $\omega = 2\pi f$ .

The boundary conditions for the complex voltage V are shown in Fig. 1. The upper boundary requires special care. In the experiment depicted in Fig. 1, there is a non-conducting PDMS layer between the metallic electrode where the voltage is applied and the fluid. To take into account the voltage drop induced by the presence of the PDMS, we apply a distributed capacitance boundary condition (see Fig. 3). The AC charge conservation equation at the boundary between the outer liquid and the PDMS is

$$\tilde{\sigma}_2 \nabla \tilde{V}_2 \cdot \mathbf{n}_2 = \tilde{\sigma}_3 \nabla \tilde{V}_3 \cdot \mathbf{n}_2. \tag{2}$$

The voltage gradient in the PDMS is

$$\nabla \tilde{V}_3 \cdot \mathbf{n}_2 = \frac{V_0 - \tilde{V}_b}{h},\tag{3}$$

where  $V_0$  is the electric voltage applied on the electrode. As both the oil and the PDMS are very good insulators, it is  $\sigma_{2,3} \ll \omega \varepsilon_{2,3}$ . Therefore, the final expression of the boundary condition at the top boundary is

$$\frac{\varepsilon_3}{h} V^R \big|_b + \varepsilon_2 \mathbf{n}_2 \nabla V^R \big|_b = \frac{\varepsilon_3}{h} V_0, \tag{4}$$

$$\frac{\varepsilon_3}{h} V^I \Big|_b + \varepsilon_2 \mathbf{n}_2 \nabla V^I \Big|_b = 0, \tag{5}$$

with  $\tilde{V}_b = V^R |_b + i V^I |_b$ . These are mixed boundary conditions for the real and imaginary parts of the complex electric potential.

The Navier-Stokes equations for velocity  ${\bf u}$  and pressure p are

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \, \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left(\mu \left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right)\right) \quad (6)$$
$$+ \gamma \, \kappa \, \delta_I \mathbf{n} + \mathbf{f}_E,$$
$$\nabla \cdot \mathbf{u} = 0. \tag{7}$$



Figure 3: Boundary between the outer liquid (oil) and the PDMS dielectric.

The second to last term on the right side in (6) describes the effect of the capillary force. Here,  $\gamma$  is the surface tension coefficient,  $\kappa$  is the curvature of the interface, **n** is the unit vector perpendicular to the surface and  $\delta_I$  is a Dirac delta centered on the interface. The capillary force is treated as a volume force, with a scalar function, the tracer *f* that takes the value 0 inside liquid 1 and 1 inside liquid 2. This tracer obeys the advective equation

$$\frac{\partial \zeta}{\partial t} + \mathbf{u} \cdot \nabla \zeta = 0. \tag{8}$$

The physical properties of the viscosity,  $\mu$ , electric conductivity,  $\sigma$ , and dielectric permittivity  $\varepsilon$ , of the liquids are expressed as a continuous function of the tracer  $\zeta$ . The boundary conditions for velocity, pressure, and the tracer function are shown in Fig. 2.

The last term is the AC electric body force, which can be computed from the complex Maxwell tensor [3] as

$$\mathbf{f}_E = \frac{1}{2} \operatorname{Real}(\nabla \cdot \underline{M}). \tag{9}$$

The complex Maxwell tensor is

$$\underline{M} = \varepsilon \mathbf{E} \otimes \mathbf{E}^* - \frac{1}{2} \varepsilon (\mathbf{E} \cdot \mathbf{E}^*) \underline{U}, \qquad (10)$$

where  $\otimes$  represents the tensor product,  $\mathbf{E}^*$  is the complex conjugate of the complex electric field and  $\underline{U}$  is the unit tensor. There are two sources for the electric force, namely, the surface free charge and the surface polarization charge appearing at the interface of the liquids.

#### B. Non-dimensional equations

We use the following scales

$$r, z \sim R, \quad t \sim \rho_2 R^2 / \mu_2, \quad |\mathbf{u}| \sim U_2,$$
 (11)

$$p \sim \mu_2 U_2/R, \quad V \sim V_{rms}, \quad |\mathbf{E}| \sim V_{rms}/R.$$
 (12)

Here, R is the width of the channel,  $U_2$  is the average velocity of the outer fluid, and  $V_{rms}$  is the applied RMS voltage. The non-dimensional equations are (all magnitudes are non-dimensional from now on)

$$\overline{\rho} \, \frac{\partial \mathbf{u}}{\partial t} + \operatorname{Re} \overline{\rho} \, \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left(\overline{\mu} \left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right)\right) \\ + \frac{1}{\operatorname{Ca}_2} \kappa \delta_L \mathbf{n} + \frac{2\operatorname{Bo}_E}{\operatorname{Ca}_2} \, \mathbf{f}_E, \quad (13)$$

$$\nabla \mathbf{u} = 0, \tag{14}$$

$$\nabla \cdot \left( \tilde{\sigma} \, \nabla V \right) = 0. \tag{15}$$

We assume both liquids to have the same mass density value. Therefore,  $\bar{\rho} = 1$ . For the non-dimensional dynamic viscosity it is

$$\bar{\mu} = \begin{cases} \mu_1/\mu_2 & \text{liquid 1} \\ 1 & \text{liquid 2} \end{cases}$$
(16)

The non-dimensional boundary conditions are

$$z = 0: \quad \mathbf{u} = \frac{\operatorname{Ca}_{1}}{\operatorname{Ca}_{2}} \frac{\mu_{2}}{\mu_{1}} \mathbf{u}_{z}, \qquad (17)$$
$$\mathbf{n} \cdot \nabla V^{R} = \mathbf{n} \cdot \nabla V^{I} = 0,$$
$$\zeta = 1.$$
$$z = L/R: \quad \mathbf{n} \cdot u_{z} = u_{r} = 0,$$
$$\mathbf{n} \cdot \nabla V^{R} = \mathbf{n} \cdot \nabla V^{I} = 0,$$
$$\mathbf{n} \cdot \nabla \zeta = 0.$$
$$r = 1: \quad \mathbf{u} = -\frac{\operatorname{Ca}_{1}}{\operatorname{Ca}_{2}} \frac{\mu_{2}}{\mu_{1}} \mathbf{u}_{r},$$
$$z \le L_{2}/R \quad \mathbf{n} \cdot \nabla V^{R} = \mathbf{n} \cdot \nabla V^{I} = 0,$$
$$\mathbf{n} \cdot \nabla \zeta = 0.$$
$$r = 1: \quad \mathbf{u} = \mathbf{0},$$
$$z > L_{2}/R \quad \mathbf{n} \cdot \nabla V^{R,I} + \Lambda \, \mathbf{n} \cdot \nabla V^{R,I} = (1,0),$$
$$\mathbf{n} \cdot \nabla \zeta = 0.$$

We are imposing plug inlet velocity profiles for both liquids for simplicity.

The relevant non-dimensional parameters are

$$Re = \frac{\rho_2 U_2 R}{\mu_2}, \qquad Ca_{1,2} = \frac{\mu_{1,2} U_{1,2}}{\gamma}, Bo_E = \frac{\varepsilon_1 V_{rms}^2}{2\gamma R}, \qquad \Lambda = \frac{\varepsilon_2 h}{\varepsilon_3 R}.$$
(18)

The typical value of the Reynolds number in the experiments in [1] is  $\mathrm{Re}\approx 10^{-3}$ . Therefore, we can neglect the convective term in the momentum equation in (13). The numbers  $\mathrm{Ca}_1$  and  $\mathrm{Ca}_2$  are the capillary numbers of the inner and outer liquids, respectively. They express the ratio of viscous and capillary effects. The typical values in [1] are  $\mathrm{Ca}_1\approx 10^{-4}-10^{-3}$  and  $\mathrm{Ca}_2\approx 10^{-2}-10^{-1}$ . The number  $\Lambda$  describes the influence of the external PDMS dielectric on the potential drop. Finally, the electric Bond number,  $\mathrm{Bo}_E$ , gives the relative importance of the electric and capillary forces.

#### III. RESULTS

The numerical calculations were performed with Basilisk [4]. This is an extension of the C language that allows for the implementation of numerical schemes in an easy way. The interface was treated with the VOF technique, while the hydrodynamic and electric equations were computed with the finite-volume technique.

Fig. 4 shows the results of the simulations for different values of the  $Bo_E$  number, that is, of the applied potential. The values of the physical properties of the liquid



Figure 4: Results of the numerical simulation of the jet length for  $f = 100 \,\mathrm{kHz}$ ,  $\Lambda = 10$  and (from top to bottom)  $\mathrm{Bo_E} = 0$ , 5, 10 and 20. The color represents the magnitude of the axial velocity of the fluid. The outer fluid enters through the portion of the border in magenta color at the top left corner. The plots are stretched a factor two in the vertical direction for better visualization.

were  $\mu_1 = 1 \text{ cP}$ ,  $\mu_2 = 100 \text{ cP}$ ,  $\sigma_1 = 3 \times 10^{-3} \text{ S/m}$ ,  $\sigma_2 = 10^{-10} \text{ S/m}$ ,  $\varepsilon_1 = 80$ ,  $\varepsilon_2 = 2.1$ ,  $\varepsilon_3 = 2.5$ . The input velocities and the value of the surface tension coefficient were chosen so that the capillary numbers were  $\text{Ca}_1 = 1.25 \times 10^{-3}$  and  $\text{Ca}_2 = 5 \times 10^{-2}$ .

Fig. 4 shows snapshots of the jet when the periodic breaking regime has been established. The color map corresponds to the axial component of the velocity. With no applied electric field, the system is in the dripping regime, and the droplets are created next to the inlet boundary of the outer fluid (in magenta color in the top left corner of each plot). When the AC voltage is applied, the jet becomes longer. The other three plots show the jet for  $Bo_E = 5$ , 10 and 20, respectively. The calculations were performed with f = 100 kHz and  $\Lambda = 10$ . The length of the jet increases with increasing AC applied voltage, as observed in the experiments.

Fig. 5 shows the magnitude of the logarithm of the absolute value of the axial and transverse electric force acting on the jet. The force is concentrated at the interface between the two liquids, where the surface density of the free electric charge and the gradient of permittivity become relevant. The axial electric force stretches the jet, while the transverse electric force pushes outward, opposing the capillary force.

Fig. 6 shows the time evolution of the jet length in a simulation with a varying value of the frequency of the AC voltage. The simulation was performed with  $Bo_E = 20$  and the same values for  $Ca_1$  and  $Ca_2$  as in the previous figure. The value of the frequency of the AC voltage was increased after enough time to obtain periodic breaking. The insert shows the details of the time evolution of the breaking once the periodic state is established. The repeated maxima cor-



Figure 5: Logarithmic plot of the magnitude of the axial  $(FE_z)$  and transversal  $(FE_r)$  electric force acting on the jet. The plots are stretched a factor 4 in the vertical direction for better visualization.

respond to the maximum length of the jet. The results are shown for computations with three decreasing elements in element size  $\Delta$ . The length of the jet increases with decreasing frequency value, down to f = 20 kHz. Below this value, the breaking becomes more erratic. This behavior is similar to what is observed in the experiments.

### IV. CONCLUSION

This paper presents a numerical simulation of AC electrified micro-jets in a flow-focusing device, building upon previous experimental and numerical work. The purpose of the study was to compute the values of physical magnitudes, particularly the structure of the electric potential and field, which are challenging to measure experimentally. The physical model and special treatment of the electric boundary conditions have been described. The numerical results successfully reproduce the observed stretching of the jet with increasing magnitude of the applied AC voltage and decreasing frequency, down to a critical frequency at which this behavior changes. The simulations also show that the electric force is concentrated at the liquid interface, with the axial component stretching the jet and the transverse component opposing the capillary force.

In future work, we will study in detail the correlation between the electric force and the jet behavior. In particular, we will compare the results of these numerical computations with the transmission line model of the jet described in [1].

### ACKNOWLEDGMENTS

Author Q. Wang supported by the Heilongjiang Province Postdoctoral General Funding (Grant No. AUGA4110006724) and Postdoctoral research start-up funds, HIT (Grant No. AUGA5710027524). Authors



Figure 6: Dependence of the length of the jet on the applied frequency for three different sizes,  $\Delta$ , of the mesh elements.

P.A. Vázquez, A. Ramos and P. García Sánchez acknowledge the grant PID2022-138890NB-I00 funded by MCIN/AEI/10.13039/501100011033.

# REFERENCES

- Elena Castro-Hernández, Pablo García-Sánchez, Javier Alzaga-Gimeno, Say Hwa Tan, Jean Christophe Baret, and Antonio Ramos. Ac electrified jets in a flowfocusing device: Jet length scaling. *Biomicrofluidics*, 10, 2016.
- [2] Heliodoro González, F. Javier García, and Antonio Castellanos. Stability analysis of conducting jets under ac radial electric fields for arbitrary viscosity. *Physics* of Fluids, 15:395–407, 2 2003.
- [3] Manuel Nieto-Vesperinas and Xiaohao Xu. The complex maxwell stress tensor theorem: The imaginary stress tensor and the reactive strength of orbital momentum. a novel scenery underlying electromagnetic optical forces. *Light: Science & Applications*, 11:297, 10 2022.
- [4] Stéphane Popinet. An accurate adaptive solver for surface-tension-driven interfacial flows. *Journal of Computational Physics*, 228:5838–5866, 2009.
- [5] Antonio Ramos, editor. *Electrokinetics and Electrohydrodynamics in Microsystems*. Springer, 2011.
- [6] P A Vázquez, P García-Sanchez, E Castro-Hernández, and A Ramos. Numerical simulation of flow-focused ac electrified jets. In *Proceedings of the ISEHD2019*, 2019.

# Problem Of Recombination Coefficient Specified By The Langevin Formula When Describing EHD Flows

Karina Poluektova\*, Albert Gazaryan, Vladimir Chirkov, Sergei Vasilkov

St. Petersburg State University, St. Petersburg, Russia \*k.poluektova@spbu.ru

Abstract- Electrohydrodynamic (EHD) flows are often modeled using the Langevin recombination coefficient, expressed as  $\alpha = e(b_+ + b_-)/\epsilon\epsilon_0$ , where  $b_+$  and  $b_-$  are the mobilities of positive and negative ions, respectively. This study examines the limitations of the Langevin formula and the need for its modification. We analyze discrepancies between experimental and numerical results by comparing current–voltage (I–U) and flow rate–pressure (Q–P) characteristics for three distinct EHD configurations: (1) a "plane–six wire–plane" setup, (2) an EHD pump with a perforated metallized insulating barrier, and (3) an EHD pump with a conical hole in a dielectric barrier. Two dielectric liquids are used: transformer oil GK-1700 mixed with 23% cyclohexanol, and dodecane containing 10% Span 85. In all configurations, numerical simulations based on the unmodified Langevin coefficient significantly overestimate both current and flow compared to experimental data. A 14-fold reduction in the Langevin coefficient yields good agreement between simulation and experiment for the I–U characteristic of the "plane–six wire–plane" setup, and for I–U and Q–P characteristics of the EHD pump with a hole in the metallic barrier. This correction also improves the I–U agreement for the system with a hole in the dielectric barrier, though it does not fully resolve discrepancies in the corresponding Q–P characteristics, despite significantly affecting them.

# Keywords- Electrohydrodynamics, Dissociation-Recombination Processes, EHD Pump, Recombination I. INTRODUCTION

Electrohydrodynamics (EHD) is a field of science that studies the flow of liquids under the influence of an electric field. EHD flow can occur only if an electric force acts on the liquid dielectric. In particular, this can happen if there is an uncompensated charge within the liquid volume. Two main mechanisms of charge generation in liquid dielectrics are considered to be ion injection from electrode surfaces and dissociation of ion pairs within the liquid.

Mathematical modeling in this area is based on solving a system of differential equations that describe the distribution of the electric field, charge transport, and fluid motion. The main equations include the Navier–Stokes equation coupled with the continuity equation, the differential form of Gauss's law, and the Nernst–Planck equations for the concentrations of ionic species:

$$\gamma\left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}, \boldsymbol{\nabla})\boldsymbol{v}\right) = -\boldsymbol{\nabla}p + \eta \Delta \boldsymbol{v} + \rho \boldsymbol{E}$$
(1)

$$(\nabla, v) = 0 \tag{2}$$

$$(\nabla, \varepsilon \varepsilon_0 E) = \rho, \qquad E = -\nabla \varphi \tag{3}$$

$$\frac{\partial n_{\pm}}{\partial t} + (\nabla, \boldsymbol{j}_{\pm}) = W_0 F(E) - \alpha_{\rm r} n_{\pm} n_{-} \tag{4}$$

where  $\nu$ —velocity, E—electric field strength, p pressure,  $\rho$ —volumetric charge density,  $\gamma$ —density,  $\eta$  dynamic viscosity,  $\varphi$ —electric potential,  $\varepsilon$ —relative permittivity,  $\varepsilon_0$ —electric constant,  $n_{\pm}$ —concentration of positive and negative polarity ions,  $j_{\pm}$ —ion flux density,  $W_0$ —dissociation intensity in the absence of the electric field, F(E)—dissociation intensity enhancement function due to electric field (Onsager function),  $\alpha_r$  recombination coefficient. Expression for ion flux density:  $\boldsymbol{j}_{\pm} = \pm n_{\pm} b_{\pm} \boldsymbol{E} - D_{\pm} \nabla n_{\pm} + n_{\pm} \boldsymbol{\nu}$ (5)

where  $b_{\pm}$ —mobility of ions, note that here and further the charge of ions is considered to be equal to  $\pm e$ , where e—elementary charge.  $D_{\pm}$ —the diffusion coefficient. Ion injection is a surface charge generation

Ion injection is a surface charge generation mechanism and, therefore, is incorporated into computational models as a boundary condition on the ion concentration or ion current density in the Nernst–Planck equation.

The generation of ions due to dissociation in the volume is described by the Onsager function. The Onsager function is described as follows:

$$F(E) = \frac{I_1(4\vartheta)}{2\vartheta}, \qquad \vartheta = \sqrt{\frac{r_b}{l_E}}, \qquad l_E = \frac{2k_BT}{eE}$$
(6)

where  $I_1$ —modified Bessel function of the first order first kind,  $l_E$ —ratio of thermal energy and Coulomb force,  $r_b$ —Bjerrum radius [1]:

$$r_b = \frac{e}{8\pi \,\varepsilon\varepsilon_0 k_B T} \tag{7}$$

The Bjerrum radius is an important characteristic length scale in the processes of dissociation and recombination. It corresponds to the distance between an ion pair at which the energy of their electrostatic interaction equals the thermal energy. This is the distance at which two oppositely charged ions can recombine into an ion pair under the influence of electrostatic attraction.

Debye derived the value of the recombination coefficient by estimating the collision frequency of an ion undergoing both Brownian motion and electrostatic interaction with surrounding ions:

$$\alpha_r = \frac{e(b_+ + b_-)}{\varepsilon \varepsilon_0} \left( 1 - e^{-\frac{r_B}{a}} \right) \tag{8}$$

where *a*—ion radius. Since many nonpolar liquids have a dielectric permittivity close to 2, the characteristic value of the Bjerrum radius at a temperature of 20 °C is  $r_b = 28$  nm. In turn, the characteristic size of ions is on the order of 1 nm. Thus, in the case where  $r_b \gg a$ , we arrive at the Langevin relation for the recombination coefficient in gases:

$$\alpha_r = \frac{e(b_+ + b_-)}{\varepsilon\varepsilon_0} \tag{9}$$

In [2], it was observed that the addition of surfactant molecules (such as Span 85) leads to the surrounding of ions by surfactant molecules and the formation of reverse micelles (Fig. 1). Thus, in solutions of nonpolar liquids with surfactants, reverse micelles, whose size can be an order of magnitude larger than that of bare ions (~10 nm), act as the charge carriers. This significantly hinders recombination processes and makes the use of the Langevin relation inappropriate.



Fig. 1. Illustration of dissociation and recombination processes: (a) without the addition of surfactant molecules and (b) with the addition of surfactant molecules. Taken from Sukh, 2012 [2].

In the present work, we investigate whether the Langevin expression (9) overestimates the ion recombination coefficient. To this end, we rely on data from Refs. [3]–[5], which report both experimental measurements and numerical simulations based on the classical Langevin formulation. Our goal is to determine the effective value of the recombination coefficient that ensures agreement between experimental and numerical results. Specifically, we introduce a correction factor  $k_L \in [0,1]$ , applied to the original Langevin coefficient during numerical calculations, and examine its influence on the accuracy of the modeled results:

$$\alpha_{\rm r} = k_L \frac{e(b_+ + b_-)}{\varepsilon \varepsilon_0} \tag{10}$$

#### **II. INSTALLATIONS AND MODELS**

Three experimental setups were analyzed:

- 1. "plane-six wires-plane" cell,
- 2. EHD pump with a conical hole in the dielectric,
- 3. EHD pump with a cylindrical hole in the dielectric barrier.

Numerical modeling was performed for each system.

The "plane–six wires–plane" configuration was studied in [3]. The working liquids were: 1) transformer oil GK-1700 with the addition of 23% cyclohexanol, with a low-voltage conductivity  $\sigma_0 = 1.1 \cdot 10^{-8}$  S/m; 2) dodecane with 10% Span 85, with a low-voltage conductivity  $\sigma_0 = 8 \cdot 10^{-9}$  S/m. At these conductivity values, the primary contribution to the current characteristics is made by the Onsager effect.

The EHD pump system based on a holed metal-clad insulation barrier pair was described in [4]. A feature of the system is the focusing of electric field lines inside the holes, which increases the electric field strength and activates charge formation processes. Dodecane with 10% Span 85 was used as the working dielectric liquid with a conductivity of  $8 \cdot 10^{-9}$  S/m. The Onsager effect is believed to be the dominant charge formation mechanism in the pump with some injection contribution.

The system with an EHD pump with a conical hole in the dielectric barrier was considered in [5]. The basic idea of the installation is EHD pump operating due to the Wien effect in a conical hole located in the solid insulation barrier. GK-1700 transformer oil with the addition of 23% cyclohexanol ( $C_6H_{11}OH$ ) is used as the working liquid.

For the pump configurations, both current–voltage (I– U) and flow rate–pressure (P–Q) characteristics were obtained. In both instances, the numerical simulations overestimated the values compared to the experimental data. In the case of the wire system, the current predicted by the numerical simulation was also higher than the experimentally measured current.

#### II. RESULTS

Fig. 2 presents the current–voltage characteristics of the "plane–six wires–plane" system, obtained from both experimental measurements and numerical simulations. Applying a correction to the Langevin coefficient with  $k_L$ =0.07 yields a significantly improved agreement between the two sets of data, consistently across both dielectric liquids. Notably, the measured currents for opposite polarities were identical in both dodecane and transformer oil, suggesting that the observed high-voltage conductivity is primarily driven by enhanced dissociation (the Wien effect).

For dodecane, the difference between the experiment and the corrected simulation agrees slightly worse than for the case of GK-1700. This difference can be explained, possibly, by the higher concentration of reverse micelles when adding the surfactant Span 85 to dodecane than is present in transformer oil with the addition of cyclohexanol.

Figs. 3 and 4 show the current–voltage and flow rate– pressure characteristics for the EHD pump with a holed metal-clad insulation barrier. As in the "plane–six wires– plane" system, when the recombination coefficient is lowered, the total current in the system decreases (Fig. 3). At the maximum voltage, the differences decreased from 127% to 30%, which significantly improved the agreement between the characteristics in the experiment and the computer model. In the voltage range up to 12 kV, the computer model yields values slightly lower than those in the experiment.



Fig. 2. (a) experimental current–voltage characteristics in the "plane–six wires–plane" system for dodecane with 10% Span 85 and (b) transformer oil GK-1700 with 23% cyclohexanol for two polarities and with extrapolated linear sections.

Let us consider the comparison of the Q–P characteristic, but supplemented with a calculation in the computer model for the lowered recombination. The correspondence of the mechanical characteristics has significantly improved. At the pressure maximum for both 16.6 and 21 kV, the head in the model and in the experiment fully coincided. At the maximum flow rate, there remains a slight difference of about 20%. The fact that the difference is manifested only for the flow rate suggests that it is associated with the difference in hydraulic resistances in the experiment and modeling. Possibly, there is an influence of the non-alignment of holes relative to each other.

Figs. 5 and 6 show the current–voltage and flow rate– pressure characteristics for an EHD pump with a conical dielectric barrier. The correction to the recombination coefficient was used in the same way as for the previously described systems. It is evident that the current obtained using the numerical study became closer to the experimental values (Fig. 5). At the same time, the Q–P characteristic became significantly lower than the experimental one, despite the fact that the slope angle began to match. It is worth noting that the recombination underestimation coefficient of different liquids and impurities does not have to match. It is possible to select such a coefficient  $k_L$  so that the match is better.



Fig. 3. Experimental and numerical current–voltage characteristics for  $k_L = 1 \text{ if } k_L = 0.07$ . EHD pump system with metal barriers.



Fig. 4. Numerical and experimental Q–P characteristics for 16.6 and 21.4 kV. EHD pump system with metal barriers.



Fig. 5. Experimental and numerical current–voltage characteristics for  $k_L = 1$  and  $k_L = 0.07$ . EHD pump system with dielectric barrier.



Fig. 6. Numerical and experimental Q–P characteristics. EHD pump system with dielectric barrier.

### V. CONCLUSION

This study provides independent confirmation of hypothesis that the recombination coefficient is lower than the value predicted by the Langevin relation.

For all systems considered — the "plane–six wires– plane" configuration, the EHD pump with a metallic barrier, and the EHD pump with a dielectric barrier reducing the Langevin coefficient by approximately a factor of 14 resulted in significantly better agreement between the numerically simulated and experimental current–voltage characteristics. At the same time, for this value of the Langevin coefficient, the Q–P characteristic showed good agreement in the case of the EHD pump with metallic barrier, but not for the EHD pump with the dielectric barrier. This discrepancy requires further investigation.

### REFERENCES

- Castellanos, A. Electrohydrodynamics / A. Castellanos, A. I. Zhakin, P. K. Watson, P. Atten, J. S. Chang. — Wien : Springer-Verlag, 1998. — 363 p
- Y. K. Suh, "Modeling and simulation of ion transport in dielectric liquids - Fundamentals and review," *Dielectr. Electr. Insul.* IEEE Trans., vol. 19, no. 3, pp. 831–848, 2012, doi: 10.1109/TDEI.2012.6215086.
- [3] A. Gazarian, "Numerical and physics-related problems in the development of single-phase electrohydrodynamic heat removal systems.", PhD thesis, St. Petersburg State University, St. Petersburg, 2023.
- [4] A. V. Gazaryan, S. A. Vasilkov, and V. A. Chirkov, "Simple in fabrication and highperformance electrohydrodynamic pump," *Phys. Fluids*, vol. 34, no. 12, 2022, doi: 10.1063/5.0124657.

[5] S. A. Vasilkov, K. D. Poluektova, and Y. K. Stishkov, "Experimental and numerical study of an electrohydrodynamic pump operating due to the field-enhanced dissociation near a dielectric barrier," *Phys. Fluids*, vol. 32, no. 10, 2020, doi: 10.1063/5.0022353.

# NUMERICAL ANALYSIS OF THREE-DIMENSIONAL ELECTRO-CONVECTION OF DIELECTRIC LIQUIDS IN A CUBICAL CAVITY

Jian Wu<sup>1\*</sup>, Yuxing Peng<sup>1</sup>, Junxiu Wang<sup>1</sup>

<sup>1</sup>School of Energy Science and Engineering, Harbin Institute of Technology, Harbin.

\*Corresponding author: jian.wu@hit.edu.cn

*Abstract-* Buoyancy-driven natural convection is a fundamental research topic with both scientific significance and industrial applications. Among various characteristics of natural convection, heat transfer efficiency remains one of the most critical properties of concern. The application of an external electric field to natural convection systems introduces an additional volumetric force, the Coulomb force, which significantly influences both the flow characteristics and heat transfer efficiency of the system. Through numerical investigation of electrothermal convection in a three-dimensional sidewall-heated cubic cavity, we find that the imposed electric field consistently reduces flow velocity in the considered configuration. Furthermore, the applied electric field suppresses the heat transfer efficiency of natural convection, and the suppression effect intensifies with increasing the conduction number.

# Keywords- natural convection, electrohydrodynamic conduction, electric-thermal-convection.

# I. INTRODUCTION

Electrohydrodynamics (EHD) is an interdisciplinary field that studies the interaction between electric fields and fluids. The complex coupling of governing equations, diverse bifurcation phenomena, and broad application prospects in heat transfer enhancement have attracted significant research interest. When thermal effects are considered in EHD, the problem becomes electro-thermalconvection (ETC). The interaction between electric and flow fields occurs through multiple pathways, the most significant of which involves free charges in the fluid medium and the resulting Coulomb force. In liquid media, free charges can be generated either from charge injection (due to electrochemical reactions at the electrode-fluid interface under high voltage) or from charge dissociation (due to the presence of electrolytes).

Buoyancy-driven natural convection is a fundamental problem with both scientific significance and industrial applications. Among the various characteristics of natural convection, heat transfer efficiency is one of the most crucial properties. In some cases, enhancing heat transfer is necessary to reduce internal system temperatures, while in others, suppressing heat transfer is required to minimize thermal losses. When an electric field is applied to a natural convection system, it introduces an additional volumetric force, the Coulomb force, which significantly alters the flow structure and heat transfer efficiency of the natural convection.

In recent decades, many numerical and experimental investigations of electro-thermal-convection have been reported. Experimental studies by Atten et al. [1] on electrothermal convection demonstrated that the Nusselt number (Nu), a key indicator of heat transfer efficiency, can increase by an order of magnitude under an applied electric field compared to pure natural convection. Yan et al. [2] numerically investigated electro-thermal-convection in a sidewall-heated cavity and found that non-uniform electric fields further enhance heat transfer efficiency. Peng et al. [3] studied bifurcation phenomena

in 3D cubic electrothermal convection, obtaining both linear and nonlinear critical thresholds of the system.

Although numerous studies on electro-thermalconvection have been conducted, most existing works focus on the charge injection mechanism. In addition, previous studies considering the conduction mechanism have predominantly employed two-dimensional models, which exhibit significant deviations from realistic threedimensional systems. Therefore, this study extends previous work to investigate the effects of electric fields on natural convection in a three-dimensional cubic cavity. The remainder of this paper is organized as follows: Section II describes the physical problem and presents the governing equations with corresponding boundary conditions. Section III presents and discusses the results. Finally, Section IV provides the concluding remarks.

### II. MATHEMATICAL MODEL

# A. Problem description

As illustrated in Figure 1, a three-dimensional cubic cavity with length, width, and height of *L* is filled with a dielectric liquid. The right electrode plate is grounded at a potential  $V_0$  and maintained at ambient temperature  $\theta_0$ , while the left electrode plate is kept at a high voltage  $V_1$  and a constant high temperature  $\theta_1$ . The dielectric liquid is assumed to be a Newtonian, incompressible fluid whose properties (except density) remains invariant with respect to both temperature and electric field intensity. Furthermore, the electric current in the dielectric liquid is sufficiently weak to render both magnetic effects and Joule heating negligible.



Fig. 1. Sketch of ETC problem in a cubic box.

#### B. Governing equations

The conduction model adopted here refers to the work of Atten et al. [4]. The dissociation recombination of weak electrolyte in liquids is the only way to generate charges, which is a reversible process expressed as:

$$k_{D}c = k_{R}N_{p}^{eq}N_{n}^{eq} = k_{R}(N_{eq})^{2}$$
(1)

where *c* denotes the concentration of neutral molecules,  $N_p^{eq}$  and  $N_n^{eq}$  represent the equilibrium concentrations of positive and negative ions, respectively.  $k_D$  and  $k_R$  are the dissociation and recombination rate, respectively. Notably, the electroneutrality condition of the solution is  $N_p^{eq} = N_{nq}^{eq} = N_{eq}$ . Under the influence of an external electric field, the charge transport equation can be expressed as:

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \overrightarrow{J_+} = k_D N_p N_n - k_R N_p N_n \tag{2}$$

$$\frac{\partial N_n}{\partial t} + \nabla \cdot \vec{J_-} = k_D N_p N_n - k_R N_p N_n \tag{3}$$

where the positive and negative electric current densities can be expressed as:

$$\vec{J_+} = \vec{u}N_p + K_+N_pE - D_+\nabla N_p \tag{4}$$

$$\vec{J}_{-} = \vec{u}N_n - K_- N_n \vec{E} - D_- \nabla N_n \tag{5}$$

Here,  $K_+$  and  $K_-$  represent the mobility of positive and negative ions, respectively, while  $D_+$  and  $D_-$  denote their corresponding diffusion coefficients. The vector  $\vec{u}$ indicates the fluid velocity. In this study, we consider the case where the mobilities and diffusion coefficients of positive and negative ions are equal, i.e.,  $K_+ = K_- = K$  and  $D_+ = D_- = D$ . We can derive the electric field expression from Maxwell's equations as:

$$\nabla \cdot (\varepsilon \vec{E}) = N_p - N_n \tag{6}$$

$$\vec{E} = -\nabla V \tag{7}$$

where  $V, \vec{E}$ , and  $\varepsilon$  represent the voltage, electric field intensity, and dielectric permittivity, respectively. Furthermore, this study accounts for the Onsager-Wien effect, where the  $k_R$  remains constant and the  $k_D$  exhibits significant enhancement with increasing electric field strength. The relationship between the  $k_D$  and electric field intensity is given by:

$$k_D(\vec{E}) = k_{D_0} (1 + 2\gamma |\vec{E}|)$$
(8)

$$\gamma = e^3 / (16\pi \varepsilon k_B^2 \theta^2) \tag{9}$$

Here,  $k_B$  is the Boltzmann constant, *e* denotes the elementary charge, and  $\theta$  is the absolute temperature. In

addition, the governing equations include the continuity equation, momentum equation, and energy equation:

$$7 \cdot \vec{u} = 0 \tag{10}$$

$$\rho(\frac{\partial u}{\partial t} + \nabla \cdot (\vec{u}\vec{u})) = -\nabla p + \rho \vec{g} + \mu \nabla^2 \vec{u} + F_e \quad (11)$$

$$F_e = (N_p - N_n)\vec{E} \tag{12}$$

$$\frac{\partial \theta}{\partial t} + u \cdot \nabla \theta = \nabla \cdot (D_T \nabla \theta)$$
(13)

where  $\rho$ , p,  $\vec{g}$ ,  $\mu$ ,  $D_T$ ,  $\beta$  denote the density, pressure, gravitational acceleration vector, dynamic viscosity, thermal diffusivity, and thermal expansion coefficient, respectively. To derive the dimensionless governing equations, the following characteristic scales are employed:

$$\begin{split} x_i^* &= \frac{x_i}{L}; t^* = \frac{tK_0(V_1 - V_0)}{L^2}; u_i^* = \frac{u_iL}{K_0(V_1 - V_0)}; \\ p^* &= \frac{pL^2}{\rho K_0^2(V_1 - V_0)^2}; N_p^* = \frac{N_p}{N_{eq}}; \theta^* = \frac{\theta - \theta_0}{\theta_1 - \theta_0}; \\ V^* &= \frac{V - V_0}{V_1 - V_0}; E^* = \frac{EL}{V_1 - V_0}; N_n^* = \frac{N_n}{N_{eq}}. \end{split}$$

The dimensionless governing equations are:

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \left( \left( \vec{u} + K\vec{E} \right) N_p \right) = \alpha \nabla \cdot \left( \nabla N_p \right) + 2C_0(F(b) - N_p N_n)$$
(14)  
$$\frac{\partial N_n}{\partial N_n} + \nabla \cdot \left( \left( \vec{u} + K\vec{E} \right) N_n \right) = \alpha \nabla \cdot \left( \nabla N_n \right) +$$

$$\frac{\partial t}{\partial C_0} (F(b) - N_p N_n) \tag{15}$$

$$\nabla(\nabla V) = -C_0(N_p - N_n) \tag{16}$$

$$\vec{E} = -\nabla V \tag{17}$$
$$\nabla \cdot \vec{v} = 0 \tag{18}$$

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u}\vec{u}) = -\nabla p + \nabla^2 \nabla \vec{u} + \frac{Ra}{PrRe^2} \vec{e_y}\theta +$$
(18)

$$M^2(N_p - N_n)C_0\vec{E}$$
<sup>(19)</sup>

$$\frac{\partial\theta}{\partial t} + \vec{u} \cdot \nabla\theta = \frac{1}{PrRe} \nabla^2 \theta \tag{20}$$

### C. Boundary conditions

$$\begin{aligned} &(x=0):\\ &u=v=w=0; \ V_1=1; \ \theta_1=1; \ \frac{\partial N_n}{\partial x}=0; N_p=0;\\ &(x=1):\\ &u=v=w=0; \ V_0=1; \ \theta_0=1; \ \frac{\partial N_p}{\partial x}=0; \ N_n=0;\\ &(y=0,1) \ \text{and} \ (z=0,1):\\ &u=v=w=0; \ \frac{\partial V}{\partial y}=\frac{\partial \theta}{\partial y}=\frac{\partial N_p}{\partial y}=\frac{\partial N_n}{\partial y}=0. \end{aligned}$$

### III. RESULTS

This work mainly focuses on the saturation regime with  $C_0$  varying from 0.05~0.2 and the driving parameter Ra varies from  $10^3 \sim 10^5$ . In this study, the non-dimension numbers Pr and M are set as 157.1 and 54.1 according to the physical properties of transform oil.

### A. The flow characteristics of ETC

Figure 2 presents the variation of the maximum velocity magnitude  $U_{max} = |\vec{u}|_{max}$  within the computational domain as a function of the Rayleigh number Ra for different conduction numbers  $C_0$ . Within the parameter range considered in this study, the applied electric field consistently leads to suppression of flow intensity, with the suppression effect becoming more significant at higher  $C_0$ . The  $U_{max}$  exhibits distinct scaling behavior with Ra. At low Ra values,  $U_{max}$  demonstrates a weak dependence on Ra (shallow slope). As Ra increases, the slope initially grows, reaching a maximum before gradually decreasing.



Fig. 2. The relationship between  $U_{max}$  and Ra.

The flow field structures under different control parameters are presented in Figure 3. The domain is divided by the line x = y = 0.5, with the vertical velocity component w > 0 (upward flow) in the region z < 0.5 and w < 0 (downward flow) in z > 0.5. For a given conduction number  $C_0$ , the flow intensity significantly increases with increasing *Ra*. Specifically, as *Ra* increases, the vertical velocity v profile at the y = 0.5 plane becomes narrower. Therefore, the effective cross-sectional area for fluid transport across the y = 0.5 plane gradually decreases. Furthermore, at fixed *Ra* values, the flow intensity exhibits attenuation with higher  $C_0$ . Notably, for Ra =  $10 \times 10^3$  and  $50 \times 10^3$  cases, increasing  $C_0$  leads to expansion of the effective flow area penetrating the y = 0.5 plane.

Figure 4 presents the distribution of dimensionless physical quantities on the cross-section z = 0.5 at steady state for  $Ra = 10 \times 10^3$  and  $C_0 = 0.1$ . The negative charges accumulate near the high-voltage electrode, while the positive charges concentrate around the grounded electrode. The ETC causes the fluid to transport both positive and negative charges, resulting in asymmetric charge distributions. In addition, the Coulomb force generates a torque opposing the fluid rotation, therefore suppressing the fluid motion. To characterize the torque magnitudes generated by electric field forces and buoyancy forces, dimensionless electric torque  $T_e$  and buoyancy torque  $T_b$  relative to the cubic cavity center are defined as:

$$T_e = \int \vec{r} \times (\rho_e \vec{E}) \, dx \, dy \, dz / (\rho_e \vec{E} L^4) \tag{21}$$

$$T_b = \int \vec{r} \times (-\rho \vec{g} \beta \theta) \, dx dy dz / (\rho_e \vec{E} L^4) \tag{22}$$

The values of  $T_e$  and  $T_b$  under different parameters are provided in Table 1. Here, we define that a positive torque drives the fluid in a clockwise rotation, whereas a negative torque induces a counter-clockwise rotation. As showed in Table 1, with increasing  $C_0$ , the  $T_e$  gradually increases while the  $T_b$  decreases, leading to a reduction in the ratio of  $T_b/|T_e|$ .



Fig. 3. Velocity and streamline contours for different parameters.



Fig. 4. The contour chart of each dimensionless physical quantity 141 for  $Ra = 10^4$  and  $C_0 = 0.1$ : (a) Net charge density; (b) Horizontal electric field; (c) Horizontal Coulomb force; (d) The direction of velocity and horizontal Coulomb force in different regions.

$C_0$	0.05	0.1	0.2
$T_b$	$6.55 \times 10^{-3}$	$3.69 \times 10^{-3}$	$2.26 \times 10^{-3}$
-Te	$9.19 \times 10^{-4}$	$1.28 \times 10^{-3}$	$1.61 \times 10^{-3}$
$T_b/ T_e $	713	2.88	140

Table 1 Electric torque and buoyancy torque for  $Ra = 2 \times 10^4$ .

# B. The heat transfer characteristics of ETC

Figure 5 presents the average Nusselt number Nu on the high-voltage electrode under different control parameters. Generally, as the Ra increases, the temperature difference between the two electrodes enlarges, the flow intensity strengthens, and the convective heat transfer becomes more effective, leading to a higher value of Nu. For the electrode configuration considered in this study, the applied electric field reduces the average Nu, indicating that the electric field suppresses the heat transfer process, which is consistent with experimental observations [5]. Figure 6 shows the temperature distribution under typical parameters. At Ra =  $1 \times 10^3$ , the lower temperature difference between electrodes and weak flow intensity result in a thick thermal boundary layer. As  $C_0$  increases, the boundary layer further thickens, thereby causing Nu to decrease. In cases with  $Ra = 10 \times 10^3$  and  $50 \times 10^3$ , the stronger flow intensity leads to more pronounced temperature gradients and thinner thermal boundary layers, enhancing convective heat transfer.



Fig. 5. The variation of *Nu* with *Ra*.

### IV. CONCLUSION

This study numerically investigates the ETC characteristics in a three-dimensional cubic cavity. The applied electric field was found to suppress flow intensity, with this effect strengthening as the  $C_0$  increases. Results demonstrated that increasing  $C_0$  will enhance electric torque while weaken buoyancy torque. Furthermore, the electric torque acts in opposition to the buoyancy torque, thereby generating a counteracting effect that suppresses fluid motion and consequently reduces the overall flow intensity. Finally, a quantitative analysis of the heat transfer characteristics is provided. Within the parameter

range of the study, the external electric field will decrease the Nu compared with the case of natural convection.



Fig. 6. Isothermal surface for different governing parameters.

#### ACKNOWLEDGMENT

The authors thank the support from the National Natural Science Foundation of China (Grant No. 12172110).

#### REFERENCES

- Atten P., McCluskey F. M. and Perez A. T. Electroconvection and its effect on heat transfer. IEEE Transactions on Electrical Insulation, 1988, 23(4):659-67.
- [2] Yan Y. Y., Zhang H. B. and Hull J. B. Numerical modeling of electrohydrodynamic (EHD) effect on natural convection in an enclosure. Numerical Heat Transfer, Part A: Applications, 2004, 46(5):453-71.
- [3] Peng, Y., Liu, Q., Li, Z. and Wu, J. Finite amplitude electro-thermo convection in a cubic box. Fluid Dynamics Research, 2022, 54(6): 065501.
- [4] Atten P. Electrohydrodynamic instability and motion induced by injected space charge in insulating liquids. IEEE Transactions on Dielectrics and Electrical Insulation, 1996, 3(1):1-7.
- [5] Sun, Z., Yang, P., Luo, K. and Wu, J. Experimental investigation on the melting characteristics of noctadecane with electric field inside macrocapsule. International Journal of Heat and Mass Transfer, 2021, 173, 121238.

# Experimental Investigation of Relation between Surface Charging and Ionic Wind in Facing Plasma Actuator

Y. Ishii<sup>1\*</sup>, A. Komuro<sup>2</sup>, Y. Kaneko<sup>3</sup>, S. Ōtomo<sup>4</sup>, H. Nishida<sup>4</sup>

<sup>1</sup>Department of Industrial Technology and Innovation, Tokyo University of Agriculture and Technology 2-24-16,

Nakacho, Koganei City 184-8588, Tokyo, Japan

<sup>2</sup>Environmental Management Research Institute, National Institute of Advanced Industrial Science and Technology, 16-1, Onogawa, Tsukuba City, 305-8569, Ibaraki, Japan

<sup>3</sup>Institute of Fluid Science, Tohoku University 2-1-1, Katahira, Aoba-ku, Sendai City 980-8577, Miyagi, Japan

<sup>4</sup>Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology 2-24-16,

Nakacho, Koganei City 184-8588, Tokyo, Japan

\*Corresponding author: yuki@st.go.tuat.ac.jp

*Abstract*- Dielectric Barrier Discharge Plasma Actuator (DBD-PA) is a fluid control device consisting of only two electrodes separated by a dielectric. Facing-PA, which has an additional AC electrode, is known to enhance discharges compared to general DBD-PA when the distance between AC electrodes is appropriate. This enhancing mechanism is due to an increased electric charge on the dielectric surface compared to that of the conventional DBD-PA. This study aims to understand how electric charges affect Facing-PA discharge. To achieve this aim, we investigated the length of visible-light of discharge, flow field, and surface charging of Facing-PA via direct camera imaging, the Particle Image Velocimetry (PIV), and the Pockels measurement. From the length of visible-light of discharge and velocity field measurements, it was found that the discharge strength and momentum flow rate varied and peaked when the distance between the AC electrodes was varied. The results of the potential distribution measurements confirmed a further charge accumulation and electric field enhancement effects in the Facing-PA. This result suggests that, the strengthening of the electric field due to the accumulation of charge contributed to the enhanced discharge.

Keywords- Plasma actuator, Dielectric Barrier Discharge, Pockels effect.

### I. INTRODUCTION

Dielectric Barrier Discharge Plasma Actuator (DBD-PA) is one of fluid control devices consisting of a dielectric sandwiched between AC high voltage electrode and a ground electrode (Fig. 1a). When high AC voltage (several kV, several kHz) is applied between the electrodes, Dielectric Barrier Discharge occurs, and jets are produced due to the electrohydrodynamic (EHD) force. From the perspectives of expanding the control range and increasing control capability, configurations that integrate multiple DBD-PA called Array-type PA are proposed. Due to their high control performance, they have attracted significant attention. It was reported that one of the parameters affecting the performance of Array-type PA is the distance between AC electrodes  $\lambda$ . Previous studies have investigated Facing-PA (Fig. 1b), which focuses on a pair of Array-type PA, and have reported that varying  $\lambda$ leads to changes in jet vorticity as well as discharge intensity-under certain conditions, the discharge intensity is enhanced compared to that of Single-electrode PA [1-2]. Especially, the significant enhancement of the negative-polarity discharge, which plays a major role in increasing jet strength, was observed. This suggests that it may have a considerable impact on the jet performance. However, no studies have yet investigated the mechanism in detail, and the mechanism has not been clarified.

This study aims to clarify the discharge enhancement mechanism of Facing-PA. It is hypothesized that the

enhancement is caused by the strengthening of the electric field due to surface charging on the Facing-PA, and the influence of the electric field during Facing-PA operation is investigated. To investigate this hypothesis, Pockels measurement—an optical technique for visualizing electric potential distributions—are conducted for various  $\lambda$ . To perform these measurements, a Pockels crystal, which exhibits anisotropy in its constant response to an external electric field, must be used as the dielectric of the Facing-PA. In this study, the electric potential distribution obtained from the Pockels measurements is discussed in comparison with flow velocity fields and visible-light measurements of discharge emission, with the aim of clarifying the mechanism of discharge enhancement.



Fig. 1 Schematic of DBD-PA.



#### II. METHODOLOGY

### A. Facing-PA

The configuration of Facing-PA is shown in Fig. 3. We used a 1 mm-thick Pockels crystal, Bi<sub>4</sub>Ge<sub>3</sub>O<sub>12</sub> (BGO), as the dielectric material. For the AC electrodes, we used 0.04 mm-thick copper tape with a serrated edge to promote uniform discharge, and for the ground electrode, we used indium tin oxide (ITO), a transparent electrode. The AC electrode length in the spanwise direction is 30 mm. The surface on the AC electrode side of the dielectric is mirror polished. The applied voltage waveform was a 5 kHz, 10  $kV_{pp}$  sinusoidal waveform, and the distance of AC electrodes  $\lambda$  varied from 4 to 20 mm.

#### B. Visible-light Measurement of Discharge Emission

We conducted visible-light imaging of the discharge emission using a digital single-lens reflex camera. The exposure time was 3 second and the f value was set to f/4. The captured images (Fig. 4) were converted to grayscale, and the luminance values were averaged over 26 mm span in the electrode-span direction to obtain luminance profiles (Fig. 5). We defined the discharge extension length as the distance along the profile where the luminance value remained above 5.0 and used this metric for comparison.



Fig. 4 Discharge photographs of Facing-PA.



Fig. 5 Definition of discharge extension length.



Fig. 3 Geometrical configuration of Facing-PA.

#### C. Measurement of Flow Velocity Fields

We measured the flow velocity field using Particle Image Velocimetry (PIV). An Nd-YAG laser was used as the light source, and an sCMOS camera was used for imaging. Incense smoke was employed as the tracer particles. The measurements were conducted for timeaveraged flow fields, and data were acquired three times for each of several cross-sectional positions. From the time-averaged velocity fields obtained by PIV (Fig. 6), we calculated the y-direction momentum flux at a height of 5 mm and compared the results.

#### D. Measurement of Electric Potential Distribution

We measured the Electric Potential Distribution using Pockels measurement [3]. The measurement system consisted of an LED, a polarizing beam splitter (PBS), a 1/8 wave plate, and a high-speed camera (Fig. 7a). Measurements were taken at six specific phases of the applied voltage waveform: during the rising and falling slopes, specifically at the start of the discharge, during the discharge, and at the end of the discharge  $(-0.05\pi, 0.2\pi,$  $0.45\pi$ ,  $0.95\pi$ ,  $1.2\pi$ , and  $1.45\pi$ , Fig. 7b). Two phases were measured simultaneously at a frame rate of 10,000 fps. The measurements were conducted over 99 discharge cycles, and the results from cycles 66 to 99 were phaseaveraged and compared.



Fig. 6 Time-averaged velocity field of Facing-PA.



Fig. 7 Pockels measurement (a) Systems, (b) Phases.


Fig. 8 Normalized extension length of Facing-PA.

#### **III. RESULTS**

The results for the discharge extension length obtained from the visible-light measurement are shown in Fig. 8, and the results for the *y*-direction momentum flux obtained from the flow velocity field measurements are shown in Fig. 9. The discharge extension lengths are normalized by the results of the Single-electrode PA. From these results, both the discharge extension length and the *y*-direction momentum flux increase as  $\lambda$  becomes larger when  $\lambda$  is small, reach their maximum values at  $\lambda =$  14-16 mm, and then begin to decrease. At this point, the discharge extension length of the Single-electrode PA, suggesting an enhancement of the discharge.

The electric potential distributions obtained from the Pockels measurements are shown in Fig. 10. Fig. 10a and Fig.10b present the results during the rising slope of the applied voltage, while Fig. 10c and Fig.10d show the results during the falling slope. For each slope condition, the results for  $\lambda = 8$  mm are shown on the left (Fig. 10a and Fig. 10c), and those for  $\lambda = 16$  mm are shown on the right (Fig. 10b and Fig.10d). Solid lines represent the results from the Facing-PA, and dashed lines represent



Fig. 9 Momentum flow of Facing-PA.

those from the Single-electrode PA. First, comparing the results during the rising slope of the applied voltage shown in Fig. 10a and Fig. 10b, no significant difference is observed between the Facing-PA and the Single-electrode PA at  $\lambda = 16$  mm (Fig. 10b). In contrast, at  $\lambda = 8$  mm (Fig. 10a), a noticeable upward shift in the potential profile is observed near the center region, around  $\lambda = 3-5$  mm. This indicates that a greater amount of charge has accumulated in a localized region due to the presence of the opposing AC electrode. Next, comparing the results during the falling slope (Fig. 10c and Fig. 10d), a similar upward shift in the potential profile is observed for  $\lambda = 8 \text{ mm}$  (Fig. 10c), consistent with the trend seen during the rising slope. This suggests that the charges accumulated during the rising slope remain present into the falling slope period, indicating a potential enhancement of the electric field in falling slope period due to residual surface charges.

Next, the electric field profiles, obtained by calculating the gradients of the potential distributions, are presented in Fig. 11. In a typical PA operation process, the electric field in the positive direction during the rising slope and the negative direction during the falling slope accelerates charged particles, contributing to discharge generation and electrohydrodynamic effects. Therefore, regions where







Fig. 11 Electric field profiles of Facing-PA. (a), (b) Rising slope, (c), (d) Falling slope, (a), (c)  $\lambda = 8$  mm, (b), (d)  $\lambda = 16$  mm.

the electric field is positive during the rising slope and negative during the falling slope are of particular interest.

Focusing first on the rising slope results in Fig. 11a and Fig. 11b, no significant difference is observed for  $\lambda = 16$  mm (Fig. 11b) compared to the Single-electrode PA. However, at  $\lambda = 8$  mm (Fig. 11a), a notable reduction in the region with strong positive electric field is observed at the phase of  $0.45\pi$ . This can be attributed to charge accumulation, which raises the average potential near the center region, thereby reducing the local field gradient.

Turning to the falling slope results in Fig. 11c and Fig. 11d, for  $\lambda = 8$  mm, the electric field at phases  $0.95\pi$  and  $1.2\pi$  appears shifted toward the lower right compared to both the Single-electrode PA and the  $\lambda = 16$  mm condition. This indicates an enhanced electric field effect under the  $\lambda = 8$  mm condition.

### IV. DISCUSSION

The observed weakening of the electric field during the rising slope and the strengthening during the falling slope at  $\lambda = 8$  mm, as well as the absence of field enhancement during the falling slope at  $\lambda = 16$  mm, do not align with the discharge enhancement and performance improvement trends obtained from visible-light measurement and flow field measurement. One possible reason for this discrepancy is that the PA operation may not have reached a quasi-steady state during the potential distribution measurements. Since the potential distribution was measured as an instantaneous field, any deviation from a quasi-steady state by the 99th cycle could lead to inconsistencies in the results. Future work should involve potential distribution measurements over longer time scales, as well as detailed analyses such as simultaneous imaging of the potential distribution and UV/visible-light emissions from the discharge.

#### V. CONCLUSION

To investigate the discharge enhancement mechanism of the Facing-PA, visible-light imaging of the discharge, flow velocity field measurement, and potential distribution measurement were conducted while varying the distance between AC electrodes  $\lambda$ . As a result, enhanced discharge and improved performance of the Facing-PA were observed in the range of  $\lambda = 14-16$  mm. However, enhancement of the electric field was not observed at  $\lambda = 16$  mm, but rather at a smaller distance of  $\lambda = 8$  mm. This discrepancy in  $\lambda$  may be attributed to the duration of the potential distribution measurements.

#### ACKNOWLEDGMENT

The authors are grateful to Takuma Uemura for supporting the measurements in this research. This works was partially supported by JSPS KAKENHI Grant Number 25K01419.

- M. Wicks, F. O. Thomas, and T. C. Corke, "Mechanism of Vorticity Generation in Plasma Streamwise Vortex Generators", *AIAA Journal*, Vol. 53, 3404-3413, 2015
- [2] T. Saito, H. Nishida, Y. Kaneko and Y. KakuyaS, "Effect of Interference Between Two Facing Plasma Actuators on Discharge and Flow Field". AIAA SCITECH 2023 Forum, 0863. 2023
- [3] T. Uemura, H. Nishida, R. Ono and A. Komuro, "Effect of nitrogen/oxygen ratios on surface charge distributions generated by repetitive surface dielectric barrier discharges", *Plasma Sources Sci. Technol.*, 33,065011, 2024

# **Design And Performance of Swirling Flow-Based Electrostatic Precipitator**

K. Takamure<sup>1,2\*</sup>, T. Haruki<sup>3</sup>, H. Amano<sup>2</sup>, T. Yagi<sup>4</sup>, T. Degawa<sup>2</sup>, T. Uchiyama<sup>2</sup>

<sup>1</sup> Cooperative Major in Sustainable Engineering, Akita University, Akita 010-8502, Japan

<sup>2</sup> Department of Infectious Diseases, Nagoya University Hospital, Nagoya, Aichi 466-0065, Japan

<sup>3</sup> Graduate School of Informatics, Nagoya University, Nagoya, Aichi 464-8601, Japan

<sup>4</sup> Cooperative Major in Sustainable Engineering, Akita University, Akita 010-8502, Japan

\*Corresponding author: takamure@gipc.akita-u.ac.jp

*Abstract-* An electrostatic precipitator is a technology that uses electrical mechanisms to collect dust and particles. In this study, a device was developed that generates a swirling flow inside a double cylindrical tube. Particles are charged through corona discharge from a disk installed inside the cylinder and are collected on the dust-collecting electrode part of the inner wall. Numerical simulations and experiments are used to visualize the flow, investigate particle behavior, and measure collection efficiency.

Keywords- Numerical simulation, Electrostatic Precipitator, Swirling flow

# I. INTRODUCTION

Electrostatic precipitators (ESPs) are widely used for removing fine particles from gas streams by applying an electric charge to the particles and collecting them on electrodes under the influence of an electric field [1]. This technology has become essential in various fields, including air purification, industrial exhaust treatment, and aerosol sampling in medical environments. However, conventional ESPs often face challenges in effectively collecting particles with large inertia or in maintaining high efficiency under high-flow-rate conditions. These limitations arise because particle motion is predominantly governed by electrical forces, which may be insufficient for particles with greater momentum.

To overcome these issues, researchers have explored various hybrid mechanisms that enhance particle transport toward collecting electrodes. Among these, introducing a swirling flow into the main channel has attracted attention as a means to generate centrifugal forces acting on particles. This approach allows particles with relatively high inertia to be directed toward the walls of the device, increasing the likelihood of capture.

In this study, we propose a novel cylindrical electrostatic precipitator that combines the Coulomb force induced by corona discharge with centrifugal force generated by a swirling airflow. The device consists of a coaxial double-cylinder structure, where a tangential slit nozzle introduces a swirling flow into the annular region. A sharp-edged disk electrode located along the axis generates a corona discharge, imparting electrical charge to airborne particles as they pass through the central region. The synergistic effect of centrifugal and electric forces promotes efficient particle deposition onto the collecting electrodes on the inner wall of the outer cylinder.

To evaluate the performance of the proposed system, numerical simulations were conducted to analyze the flow characteristics and particle behavior within the device. In addition, experiments were performed to assess the collection efficiency under typical operating conditions. The results reveal that this hybrid approach provides a high collection efficiency even for submicron particles, and offers a promising solution for compact and energy-efficient particle collection systems.

# II. METHODOLOGY

Figs. 1(a) and 1(b) show a schematic and dimensional overview of the cylindrical electrostatic precipitator developed in this study. The device consists of a coaxial double-cylinder structure, in which a swirling flow is introduced through a slit nozzle at the inlet. Charged particles are guided along the outer wall by the combined effect of centrifugal and electrostatic forces and are collected on the collecting electrodes mounted on the inner surface of the outer cylinder.

The main flow channel is composed of an inner pipe and an outer pipe. The outer pipe has an inner diameter of 50 mm, while the inner pipe has an outer diameter of 10 mm, resulting in an annular flow region with a radial gap of 20 mm. The total length of the cylindrical part is 500 mm. The collecting electrodes are installed along the inner surface of the outer cylinder in the region  $75 \le z' \le 475$  m, where a uniform electric field is formed for particle collection.

Air is introduced tangentially into the annular region through a slit nozzle at the inlet, generating a swirling flow with a strong tangential velocity component. This swirling motion promotes centrifugal force that pushes particles toward the outer wall.

Two sharp-edged disk electrodes are mounted coaxially in the annular channel at positions z' = 125 mm and 275mm, respectively. Each disk electrode has a diameter of 23 mm and a thickness of 0.3 mm. When a high-voltage DC power supply is applied, a corona discharge occurs at the sharp edge of each disk, imparting electrical charge to particles passing through the central region of the channel.

A voltage of 16 kV is applied between the disk electrodes and the collecting electrodes on the outer wall. The discharge current is limited to a maximum of 1 mA to ensure stable corona discharge operation. The airflow rate through the device is maintained at 0.75 m<sup>3</sup>/min using a blower located downstream of the device. Particles entrained in the incoming air are charged as they pass the disk electrodes and are subsequently driven toward the collecting electrodes by the combined action of swirling-induced centrifugal force and electrostatic attraction.

Numerical simulations were conducted to analyze the flow field and particle trajectories inside the device. The airflow was modeled under steady-state, incompressible conditions using a finite-volume-based computational fluid dynamics (CFD) solver. Particle motion was calculated using a Lagrangian particle tracking approach. The particles were assumed to be spherical water droplets with a diameter of 1  $\mu$ m. The particles are given a charge of  $2.7 \times 10^{-16}$  C as they pass through the disk electrode.



Fig. 1. Schematic diagram of an electrostatic precipitator. (a) Description of each part and (b) dimensions.

#### **III. RESULTS**

Fig. 2(a) shows the particle collection distribution inside the device obtained from numerical simulations, while Fig. 2(b) presents the velocity vector field in the x-z plane. The slit nozzle introduces a swirling component into the flow, which induces centrifugal force acting on the particles. As the particles pass through the disk electrode inside the cylindrical channel, they are immediately charged by corona discharge. Subsequently, the charged particles are transported toward the wall and collected by the collecting electrodes.

The particle collection efficiency was found to be 99.6%. These results confirm that the combined effect of swirling flow and electrostatic charging enables efficient particle removal. In this study, we developed a novel electrostatic precipitator that generates a swirling flow inside a double cylindrical tube, charges particles via corona discharge from a central disk electrode, and collects them at the electrodes on the inner wall of the outer cylinder. Numerical simulations demonstrated that particles adhered to the collecting electrodes, validating the proposed mechanism.



Fig. 2. Inside the electrostatic precipitator. (a) Distribution of collected particles, (b) average velocity distribution

#### V. CONCLUSION

This study developed a novel cylindrical electrostatic precipitator (ESP) that combines swirling flow and corona discharge for efficient particle collection. The device features a coaxial double-cylinder structure and sharp-edged disk electrodes that charge airborne particles. Numerical simulations showed that the swirling-induced centrifugal force and Coulomb force work synergistically to transport charged particles toward the collecting electrodes. The collection efficiency was found to be 99.6% for 1  $\mu$ m particles, confirming the effectiveness of this hybrid approach. This compact system shows strong potential for applications in air purification and aerosol control where high efficiency and miniaturization are required.

#### ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number JP25K17538. Part of this research was supported in part by the Japan Science and Technology Agency, Japan Science and Technology Agency, Research Results Deployment Support Program, A-STEP development type JPMJTR22R6, and by the Inverse Innovation Materials Creation Project for International and Academia-Industry Collaboration.

#### REFERENCES

 L. Bakke. Wet Electrostatic Precipitators for Control of Submicron Particles, *Journal of the Air Pollution Control Association*, 25:163–167, 1975.

# Molecular dynamics simulation on the collision of ionic liquid nanodroplets with surfaces in an electrospray environment

Yuxiang Chen<sup>1</sup>, Weizong Wang<sup>2\*</sup>, Yufeng Cheng<sup>1</sup>, Guangchuan Zhang<sup>1</sup> <sup>1</sup>Advanced Space Propulsion and Energy Laboratory (ASPEL), School of Astronautics, Beihang University, Beijing 100191, China <sup>2</sup>Key Laboratory of Spacecraft Design Optimization and Dynamic Simulation Technologies, Ministry of Education, Beijing, 100091, China \*Corresponding author: wangweizong@buaa.edu.cn

*Abstract-* Collisions between nanodroplets and solid surfaces can occur across various fields of electrospray applications. To explore this phenomenon, this study employs molecular dynamics simulations to investigate the collision behavior of ionic liquid nanodroplets under different electric field strengths and charge conditions. The results indicate that under high-speed impact, the droplet completely fragments into cations and anions, accompanied by significant splashing. In this process, the deposition characteristics are primarily governed by the oscillation between cations and anions and the applied electric field. When the electric field strength is low, the ion oscillation facilitates preferential deposition of cations, causing neutral droplets to deposit a small amount of positive charge after the collision. At higher electric field strengths, the field separates cations and anions, leading to substantial charge deposition on the surface due to the imbalance in ion numbers. The amount of deposited charge is positively correlated with the electric field strength.

Keywords- Droplet collision, electrospray, ionic liquid, molecular dynamics

### I. INTRODUCTION

Ionic liquid electrospray thrusters (ILETs) are a type of space electric propulsion offering high specific impulse and precise thrust control. In these thrusters, conductive liquids like ionic liquids form Taylor cones under strong electric fields, emitting charged droplets or ions from the cone tips[1]. After emission, particles spread due to electrostatic repulsion, forming a beam. Particles with large off-axis angles may collide with the extractor grids, leading to the accumulation of ionic liquid (Fig. 1). This droplet deposition can degrade grid performance and is considered a key factor limiting thruster lifetime[2]. Research on the specific collision processes between particles and the grid forms the basis of electrospray lifetime models.

Due to the small scale of collision particles in electrospray processes, most related studies employ molecular dynamics (MD) simulation methods. Saiz et al. conducted MD simulations on the impacts of an electrospray ionic liquid nanodroplet with ceramic surface at high velocities (~ km/s), primarily focusing on sputtering, surface amorphization, and crater formation, with simulation results aligning well with experimental data[3]. However, the simulation did not consider the effects of an external electric field, droplet charge, and atomic-level molecular detail. These conditions make the study more applicable to fields such as electrospray coating rather than electrospray propulsion.

Beyond electrospray-specific studies, research on high-speed droplet-surface impacts (mainly water) under electric fields also offers insights. Li et al. studied the spreading and breakup of a nanodroplet impinging on a surface using MD simulations, analyzing different breakup modes of the droplet and providing theoretical criterion for predicting droplet collision-induced breakup[4],[5].

In summary, there are currently few simulation studies on the collision of ionic liquid nanodroplets emitted by electrospray with surfaces. The existing studies tend to focus on a limited set of factors and do not consider conditions such as droplet charging and electric field effects, which are precisely the conditions present in electrospray grid impingement. While some studies on water droplet collisions have considered the role of electric fields, the collision velocities studied are much lower than those encountered in electrospray beams, and the properties of water molecules differ significantly from those of ionic liquid molecules. In short, the characteristics and mechanisms of ionic liquid droplet collisions with surfaces in the context of droplet charging, electric field effects, and high-velocity impacts remain unclear in the electrospray process.

To address these issues, this work presents a simulation study on the collision of an ionic liquid nanodroplet with grids during the electrospray process, using molecular dynamics simulation. The study employs a full-atom model of the ionic liquid EMIM-Im and considers the effects of an external electric field and droplet charge.



Fig. 1. Electrospray beam particle collision with extractor

#### II. METHODOLOGY

In this study, molecular dynamics simulations were performed using the LAMMPS[6] (large-scale atomic and molecular massively parallel simulation) package. The simulation configuration is shown in Fig. 2. The bottom region of the simulation domain represents an iron atomic surface to be impacted by the droplet. The top region of the domain is an evaporation region where any ions reaching this area are removed from the simulation. At the center of the simulation domain is an ionic liquid droplet of EMIM-Im, consisting of 200 cations and 200 anions, with a droplet diameter of 6 nm. In the initial state, the center of the droplet is 6 nm above the surface, and a uniform electric field is applied along the Z-axis.

The potential used for the ionic liquid EMIM-Im is the optimized potential for liquid simulations all-atom (OPLS-AA) model developed by Sambasivarao et al[7], and improved by Doherty et al[8]. The intermolecular potential between all atoms is calculated using the Lennard-Jones (L-J) 12-6 potential function. The L-J potential parameters between different atoms are computed using the Lorentz-Berthelot mixing rules.

In the simulation process, the system is first equilibrated under the canonical (NVT) ensemble at 298 K to ensure that the droplet and wall reach equilibrium. Subsequently, the ensemble is switched to microcanonical (NVE) ensemble, and an initial velocity is imparted to the droplet. Simultaneously, an electric field is applied in the Z direction, initiating the droplet impinging simulation.

The simulated droplet in this study has a radius of 3 nm. Assuming an acceleration voltage of 1000 V, the maximum droplet charge is estimated to be approximately 15 e and the collision velocity about 5000 m/s, based on energy conservation and the Rayleigh limit.



Fig. 2. Configuration of simulation system. (a) Global view of the simulation domain; (b) Dimensions of the simulation domain.

#### III. RESULTS AND DISCUSSION

Droplet collisions in the ionic liquid electrospray process are complex, involving variations in velocity, charge, and surface electric field strength. Directly simulating charged droplet collisions under an electric field makes it difficult to isolate the influence of individual factors. To address this, separate simulations were conducted for neutral droplets at different velocities, neutral droplets under electric fields, and charged droplets under electric fields. This allows for a clearer assessment of how velocity, electric field strength and polarity, and droplet charge affect collision and deposition behavior.

### A. Collision of neutral droplets without an electric field

In the absence of an electric field, simulations were conducted for neutral droplet collisions at different velocities. The number of ions deposited on the wall surface was recorded. The variation in the ratio of the deposited mass of anions or cations to the total mass of anions or cations ( $m_d/m_0$ ) and charge deposition during collisions are shown in Fig. 3.

Collision simulations at different velocities indicate that the droplet splashing threshold velocity is approximately 2700 m/s, defined as the point where the deposition rate md/m0 reaches 0.1. Below this threshold, the droplet fully deposits on the surface, resulting in zero charge deposition on the wall. Once the velocity exceeds the threshold, splashing occurs and increases with impact velocity, as shown in Fig. 3(a). In the absence of an electric field, the deposited amounts of cations and anions are almost equal. However, when the droplet breaks up and splashes, their deposition characteristics show slight differences. As seen in Fig. 3(b), once the system stabilizes, slightly more cations than anions remain on the wall, leading to a small net positive charge deposition, even though the droplet was neutral.

Taking the 5000 m/s case as an example, the differences in cation and anion deposition during high-speed collisions are analyzed. As shown in Fig. 4, after impacting the wall, the droplet first spreads along the XY plane and then diffuses in the Z direction. Due to the high collision velocity, the droplet completely breaks into cation and anion monomers, with only a few intact EMIM-Im molecules remaining. Since deposition primarily depends on motion along the Z direction, the observed charge imbalance suggests different behaviors between cations and anions in this direction.



Fig. 3. Ion and charge deposition behavior during neutral droplet collisions. (a) Ion deposition; (b) Charge deposition.



Fig. 4. Snapshots of droplet collisions at 5000 m/s.

To verify this hypothesis, the relative changes of the centroids of the cation group ( $z_c$ ) and the anion group ( $z_a$ ) compared to the overall droplet centroid ( $z_d$ ) were plotted, as shown in Fig. 5. The two curves in the figure represent  $z_c$ - $z_d$  and  $z_a$ - $z_d$  respectively. The results indicate non-monotonic oscillations of ion group centroids due to the combined effects of Coulomb forces and inertia. After the first crossover, the centroids no longer intersect, as more cations deposit on the wall, lowering the overall centroid of the cation group. This oscillatory motion resembles plasma oscillations, the oscillation frequency ( $\omega_{pi}$ ) is given by the following formula:

$$\omega_{\rm pi} = \sqrt{\left(e^2 n_0\right) / \left(\varepsilon_0 m_{\rm i}\right)} \tag{1}$$

Where  $n_0$  and  $m_i$  represent the ion number density and mass. The oscillation frequency is positively correlated with the ion number density. As ions deposit or leave the simulation domain, the oscillation frequency decreases, reflected in the lengthening oscillation period. Due to the mass difference (cation: 111, anion: 280), the cation group exhibits a larger oscillation amplitude.

As shown in Fig. 3 (a), the deposition rate initially stabilizes at around 20 ns, indicating that the behavior within the first 20 ns mainly influences the deposition. Therefore, the focus below will be on analyzing the movement of cations and anions in the early stage of the collision. Although cations exhibit lower centroid positions overall, they initially splash more rapidly. Faster cation splashing raises the cation centroid, generating downward attraction from anions, which in turn gain momentum. This results in momentum transfer from cations to anions, increasing anion splashing and cation deposition. Although subsequent oscillations may reverse centroid positions, most ions have already deposited by that time, and further momentum exchange is limited.



Fig. 5. Changes in the positions of the centroids of the ion groups relative to the overall centroid of the droplet in the Z-direction.

In summary, at low collision velocities, nanodroplets fully deposit on the wall. At higher velocities, the droplets

break apart and splash, with deposition decreasing as velocity increases. The dissociated cations and anions undergo oscillations and momentum exchange, with the first oscillation playing a key role due to minimal early deposition. Cations splash earlier and transfer momentum to anions, leading to slightly more cation deposition and a net positive charge on the wall.

# B. Collision of neutral droplets under an electric field

The results of ion deposition from droplet collisions (5000 m/s) under different electric field strengths and polarities are shown in Fig. 6, and the results of charge deposition are shown in Fig. 7, with the upward direction of the electric field considered positive.

As shown in Fig. 6, high-speed collisions cause the droplet to dissociate into cations and anions, which are separated by the external electric field. A positive field promotes cation splashing and anion deposition, while a negative field promotes anion splashing and cation deposition. Ion deposition reaches equilibrium when the surface charge builds up a reverse electric field that offsets the applied field. A stronger applied field requires more deposited charge to reach this balance.



Fig. 6. Ion deposition behavior of droplet collisions under different electric field strengths and polarities. (a) Positive electric field; (b) Negative electric field.

Fig. 7 shows that when the field is weak ( $\leq 0.02 \text{ V/nm}$ ), its influence on droplet behavior is negligible, and ion oscillation dominates, resulting in net positive charge deposition regardless of field polarity. When the field exceeds 0.02 V/nm, its effect becomes significant. For example, at 0.1 V/nm, a positive field causes -31 e of deposition, while a negative field causes +51 e, indicating a transitional regime where both electric field and oscillation influence deposition. At higher field strengths (0.5 and 1 V/nm), deposition becomes nearly symmetric under opposite polarities (e.g.,  $\pm 155$  e at 1 V/nm), and the electric field becomes the dominant factor in determining charge deposition.



Fig. 7. Charge deposition behavior of droplet collisions under different electric field strengths and polarities.

In summary, as the electric field increases from 0 to 1 V/nm, droplet collisions transition through three regimes: ion oscillation-dominated, combined influence, and electric field-dominated. In the oscillation-dominated regime, positive charge tends to deposit. At low field strengths, negative charge deposition under a positive field is less than positive charge deposition under a negative field. As the field strengthens, this difference narrows and eventually equalizes.

### C. Collision of charged droplets under an electric field

Based on high-speed collision simulations under an external electric field, neutral droplets are replaced with charged ones. Simulations were performed for droplets with charges ranging from -16 e to +16 e, at a collision velocity of 5000 m/s. The polarity of droplet charge corresponds to the direction of the external electric field: a positive field leads to negatively charged droplets impacting the grid, while a negative field corresponds to positively charged droplets. Fig. 8 shows the surface charge deposition results under a weak electric field (0.01 V/nm). Even with charged droplets, cations still deposit more readily. At this low field strength, the electric field has little influence on the collision process, and the net deposited charge remains positive unless the droplet charge reaches -16 e. As the droplet becomes more negatively charged, the deposited positive charge decreases.

Overall, the deposited charge equals the initial droplet charge plus a certain amount of additional positive charge. For negatively charged droplets, this increase averages about +12 e; for positively charged droplets, the increase is only about +4 e. As explained in Sec. III B, once a certain amount of charge accumulates on the surface, the resulting electric field suppresses further deposition of the same charge type. Therefore, excessive positive surface charge in the case of positively charged droplets limits additional cation deposition, leading to a smaller net increase.

In summary, like neutral droplets, charged droplet collisions are affected by both ion oscillations and the applied electric field. At low field strength (0.01 V/nm), cations tend to deposit more, so even negatively charged droplets can result in net positive surface charge. Only when the droplet charge approaches the Rayleigh limit (-16 e) does the deposited charge become negative. At higher field strength (0.5 V/nm), deposition and splashing are mainly governed by the electric field.



Fig. 8. Charge deposition under different droplet charges. (a) Negatively charged droplets; (b) Positively charged droplets.

#### IV. CONCLUSION

In this study, MD simulations were used to investigate the collision of ionic liquid nanodroplets with a wall in electrospray conditions. The main conclusions are: (1) When the collision velocity is below the splashing threshold (2700 m/s for 6 nm droplets), droplets deposit almost entirely on the wall. As velocity increases, deposition decreases, the splashed fragments are mainly cation and anion monomers. (2) At low electric field strength (< 0.02 V/nm), deposition is mainly influenced by ion oscillation, resulting in more cation deposition. At higher fields (> 0.02 V/nm), the electric field separates ions, leading to surface charge accumulation. (3) Charged droplet collisions resemble those of neutral droplets, affected by both ion oscillation and the electric field.

#### ACKNOWLEDGMENT

This research is supported by National Natural Science Foundation of China (Grant No. 52277133).

- [1] I. Romero-Sanz, R. Bocanegra, J. Fernandez De La Mora, M. Gamero-Castaño. Source of heavy molecular ions based on Taylor cones of ionic liquids operating in the pure ion evaporation regime, *J. Appl. Phys.*, 94: 3599-3605, 2003.
- [2] A. Thuppul, P. L. Wright, A. L. Collins, J. K. Ziemer, R. E. Wirz. Lifetime considerations for electrospray thrusters, *Aerospace*, 7: 108, 2020.
- [3] F. Saiz, M. Gamero-Castaño. Molecular dynamics of nanodroplet impact: The effect of the projectile's molecular mass on sputtering, *AIP Adv.*, 6: 065319, 2016.
- [4] B. Li, X. Li, M. Chen. Spreading and breakup of nanodroplet impinging on surface, *Phys. Fluids*, 29: 012003, 2017.
- [5] X. Li, X. Zhang, M. Chen. Estimation of viscous dissipation in nanodroplet impact and spreading, *Phys. Fluids*, 27: 052007, 2015.
- [6] S. Plimpton. Fast parallel algorithms for short-range molecular dynamics, J. Comput. Phys., 117: 1-19, 1995.
- [7] S. V. Sambasivarao, O. Acevedo. Development of OPLS-AA force field parameters for 68 unique ionic liquids, J. Chem. Theory Comput., 5: 1038-1050, 2009.
- [8] B. Doherty, X. Zhong, S. Gathiaka, B. Li, O. Acevedo. Revisiting OPLS force field parameters for ionic liquid simulations, *J. Chem. Theory Comput.*, 13: 6131-6145, 2017.

# **Oscillatory Behavior of Electrospray under Periodic Electric Fields**

Qiyou Liu<sup>1</sup>, Bingqiang Ji<sup>1,2</sup>, Qingfei Fu<sup>1,2\*</sup>, Lijun Yang<sup>1,2</sup>

<sup>1</sup>School of Astronautics, Beihang University, China

<sup>2</sup>Aircraft and Propulsion Laboratory, Ningbo Institute of Technology, Beihang University, China

\*Corresponding author: fuqingfei@buaa.edu.cn

Abstract- Electrospray has been widely used in various areas, especially in drop-on-demand techniques including electrohydrodynamic printing, nanomaterial production, and drug delivery, due to its ability to produce fine uniform droplets. The oscillating electric fields are adopted for additional control over EHD jetting behavior. This study focuses on an experimental investigation, systematically examining the oscillatory behavior of electrospray under alternating voltage electric field excitation. Using a high-speed camera, the pulsating modes of the electrospray were recorded under the influence of a continuous sinusoidal voltage waveform. The responses of different oscillation modes and their geometric characteristics to various disturbance parameters were analyzed and comprehensively discussed. The research identified five distinct oscillation modes of the electrospray under sinusoidal voltage excitation. The dynamic characteristics of each mode were explored, and phase diagrams of all five modes were constructed by dimensionless parameterization of the relevant variables.

Keywords- Electrospray, oscillatory behavior, instability.

### I. INTRODUCTION

As a classic EHD phenomenon, electrospray can produce fine liquid ejections from a capillary by applying a high voltage, resulted from the local interfacial instability at the conical tip of liquid meniscus when the electric stress overcomes the surface tension [1,2]. Though extensive efforts have been made over the past century, the precise control of the EHD ejection has long been a challenge, due to the complex electrohydrodynamics and the strong multiscale nature of electrospray. Even in simple situations with a steady electric field, electrospray is modulated by plenty of parameters such as liquid properties and flow rate and the system geometry, yielding various ejection modes [3]. Thus, understanding and controlling the ejection in electrospray is of both fundamental and technical significance.

Following the rise of drop-on-demand techniques in pharmaceutical industries, manufactural and the oscillating electric fields are adopted for additional control over EHD jetting behavior [4,5]. Using voltage waveforms such as pulses or sine waves, the ejection frequency and droplet size can be individually controlled by adjusting the applied voltage amplitude and frequency [6-8]. However, the physical nature underlying the complex electrospray phenomena in oscillating electric fields remains elusive, severely limiting its application in drop-on-demand techniques. In this work, we report a series of subharmonic electrosprav modes under periodic electric fields. The dynamic characteristics of each mode were explored, and phase diagrams of all five modes were constructed by dimensionless parameterization of the relevant variables.

### II. METHODOLOGY

A. Experimental setup

We conduct the electrospray experiments under an oscillating electric field, which is provided by a horizontal grounded electrode plate and a vertical metal nozzle connecting to a signal generator [Fig. 1(a)], with a voltage signal of  $V = V_{DC} + V_{AC} \cos(2\pi f t)$  [Fig. 1(b)]. Here,  $V_{DC}$ represents the DC offset voltage, while  $V_{AC}$  and f denote the amplitude and frequency of the AC voltage, respectively. The nozzle has an outer radius of R = 0.9 mm which sets the perimeter of the liquid meniscus, and the distance between the nozzle and the electrode plate is H =2.0 mm. We adopted 1-octanol, a widely employed leaky dielectric liquid, as the working fluid, supplied by a syringe pump with a stable flow rate Q. Motion of the meniscus and EHD jets are recorded using a high-speed camera (Photron, Fastcam Nova S16). VDC is set high enough to stretch the meniscus but remains below the threshold required to trigger EHD tip streaming [4,9].

# *B.* Proper orthogonal decomposition (POD) of experimental images

POD is used to process the grayscale time series of experimental images [10,11]. The collected twodimensional grayscale images of meniscus fluctuations and ejection phenomena at time t have grayscale data  $G(\mathbf{x},t)$ , and G' is G minus its temporal mean. G' is decomposed into a set of spatially orthogonal modes modulated by time coefficients  $a_k(t)$ 

$$\mathcal{G}'(\boldsymbol{x},t) = \sum_{k=1}^{\infty} a_k(t) \boldsymbol{\Psi}_k(\boldsymbol{x}), \qquad (1)$$

where  $\Psi_k(\mathbf{x})$  is the *k*-th POD mode and  $a_k(t)$  is the corresponding time coefficient. By applying a fast Fourier transform (FFT) to the temporal coefficients of the dominant (first) POD mode, we obtain the power spectral density (PSD), which reveals the presence of harmonics or

subharmonics.

#### III. RESULTS

#### A. Oscillatory electrospray experiments

By superimposing a sufficiently large  $V_{AC}$ , pulsed EHD jetting is triggered. At a relative low frequency, the liquid meniscus oscillates axisymmetrically, producing periodic jetting at the tip of the curved meniscus (Fig. 1b). This jetting occurs at the voltage peak in each period (T = 1/f), which is known as the classic pulsating Taylor-cone jet [6,12].

In stark contrast, with increasing AC frequency, we observed a diverse range of dancing electrospray phenomena as shown in Fig. 1 (c-f). Different from the classic pulsating cone jet with a single crest at the axis, the dancing electrospray exhibits distinct spatial characteristics along the radial and azimuthal directions at the meniscus. Through proper orthogonal decomposition (POD) analysis of the high-speed camera images, we categorize the modes of the dancing electrospray using pairs of numbers (n, m), where n denotes the number of radial nodes and m denotes the azimuthal wavenumber. Four dancing modes, (1, 1), (1, 0), (1, 2), and (2, 1), are identified. Specifically, the (1, 1) mode is characterized by alternating jets on opposite sides [Fig. 1(c)], the (1, 0)mode is axisymmetric [Fig. 1(d)], and the (1, 2) mode exhibits jets simultaneously emitted in two opposing directions [Fig. 1(e)]. The (2, 1) mode features alternating jets on two sides, with an additional smaller crest on the meniscus opposite the larger one. This smaller crest does not produce EHD jets, as EHD tip streaming tends to occur



Fig. 1. Dancing EHD tip streaming experiments. (a) Sketch of the experimental setup. (b) The voltage V with a period T applied to the nozzle and the corresponding harmonic pulsating Taylor-cone jets at a low frequency (f = 1/T) of 90 Hz. (c-f) Experimental snapshots and POD analyses of different dancing electrospray modes with  $V_{DC} = 1.9$  kV,  $V_{AC} = 1.8$  kV, and Q = 20 µL/min at (c) f = 160 Hz, (d) 230 Hz, (e) 335 Hz, and (f) 450 Hz. Scale bars represent 0.5 mm.



Fig. 2. Mechanism and regulation of dancing electrospray. (a) Frequency response of the dancing electrospray to the applied voltage. Insets are the corresponding Faraday wave patterns obtained numerically. (b) Mechanism of the dancing electrospray.

at peaks with the highest curvature [Fig. 1(f)]. All these dancing electrospray modes are found to be periodic and sustainable at a constant flow rate.

#### B. Mechanisms underlying different ejection modes

The frequency response of the electrospray to the applied voltage across various modes are illustrated in Fig. 2(a). At a low applied voltage frequency, the ejection frequencies of the conventional pulsating electrospray,  $f_D$ , well matches f, indicating a harmonic ejection (HE) mode. However, at an elevated f, the dancing electrospray repeats at a frequency  $f_D = f/2$ , exhibiting subharmonic ejection (SE) modes. The subharmonic nature and spatially regular patterns of the dancing electrospray are reminiscent of the surface Faraday waves [13,14]. The oscillating electric field can excite Faraday waves on the liquid meniscus, where the curvature outstands at the wave crests, forming tips with high charge density [15], as shown in Fig. 2(b). The resulted localized electric shear stress overcomes surface tension, destabilizing the stagnation point and driving the tip streaming [2,16]. In fact, the tip streaming is an intrinsically transient flow that can be sustained by an appropriate flow rate Q, as it leads to the loss of mass and charge from the precursor fluid shape [17]. When we shut off the liquid supply (Q = 0), Faraday waves with exact same patterns remain on the meniscus while tip streaming is killed, evidencing that the origin of the dancing electrospray is Faraday instability.

To pin down the parameter space for different modes of the dancing electrospray, we conducted systematic experiments with different oscillating electric fields. The regime map of the ejection modes with respect to f and  $V_{AC}$ is depicted in Fig. 3. The harmonic ejection occurs at a low f. As f increases, four subharmonic ejection modes, SE (1, 1), SE (1, 0), SE (1, 2) and SE (2, 1) are progressively excited. Higher order modes were not observed in our experiments, which may be due to the fact that the



Fig. 3. Regime map of the dancing EHD tip streaming with respect to the frequency and the amplitude of the AC electric field. Vertical dashed lines are twice the natural frequencies of the meniscus obtained numerically.

frequencies of the Faraday wave driven by the electric field are limited by the charge relaxation time  $t_e = \varepsilon/\sigma$  ( $\approx 1$  ms), where  $\varepsilon$  and  $\sigma$  are respectively the dielectric coefficient and conductivity of the liquid. The boundaries of these regions show completely different features compared to that of the classic harmonic ejection mode. First, the subharmonic ejections require a much higher  $V_{AC}$  in comparison. Second, the lower boundaries of the SE mode exhibit a V-shape, known as the Faraday tongue [13,14], indicating there exists an optimal frequency ( $f_m$ ) with a critical AC voltage amplitude ( $V_{AC,c}$ ). The critical voltage amplitude increases as f deviates from  $f_m$  for each mode.

It is well-known that the optimal frequency  $f_m$  of the Faraday tongue is set by the natural frequency of the corresponding Faraday wave patterns [16,20]. We then calculate the natural frequencies of the Faraday waves on the meniscus via numerical simulation. We consider a meniscus anchored at the nozzle exit of the same geometry parameters in an electric field, and adopt the leaky dielectric model to formulate the electrohydrodynamic governing equations at a cylindrical coordinate  $(r, \theta, z)$  [19,20]. For any variable  $\boldsymbol{\Phi}$  representing the surface location, velocity, pressure and electric potential, its temporal and azimuthal dependence is expressed based on the small perturbation assumption

$$\boldsymbol{\Phi}(r,\theta,z;t) = \boldsymbol{\Phi}_0(r,z) + \epsilon \hat{\boldsymbol{\Phi}}(r,z) e^{i\omega t + im\theta}, \qquad (2)$$

where  $\boldsymbol{\Phi}_0$  is the axisymmetric base flow,  $\boldsymbol{\hat{\Phi}}$  is the spatial dependence of the perturbation,  $\epsilon$  is a small perturbation parameter, and  $\omega$  is the eigenfrequency of meniscus oscillation. The numerical method proposed by Herrada and Montanero [21] is used to solve the base flow  $\boldsymbol{\Phi}_0$  and the generalized eigenvalue problem

$$\mathbf{J}_{0}\hat{\boldsymbol{\Phi}} = \mathrm{i}\omega\mathbf{Q}_{0}\hat{\boldsymbol{\Phi}},\tag{3}$$

where  $\mathbf{J}_0$  and  $\mathbf{Q}_0$  are Jacobians. The solution of Eq. (3) gives the natural frequencies

$$f_n = \omega_r / (2\pi t_c), \tag{4}$$

and the corresponding eigenmodes (n, m) of the meniscus in an electric field, where  $\omega_r$  (the real part of  $\omega$ ) is the dimensionless angular frequency, and  $t_c = (\rho R^3/\gamma)^{1/2}$  with  $\rho$  and  $\gamma$  respectively denoting the density and surface tension of the liquid. The eigenmodes associated with the first four natural frequencies are consistent with the experimentally observed Faraday wave patterns [see insets in Fig. 2(a)]. We plot  $f = 2f_n$  as vertical lines in Fig. 3, and found that they agree well with the optimal frequencies of the subharmonic ejection modes, with relative deviations < 10%. This demonstrates that the mode of the dancing electrospray is set by the natural frequency of the Faraday instability.

### IV. CONCLUSION

We report а distinct dancing electrospray phenomenon, characterized by a set of subharmonic ejection modes under high-frequency electric fields. We unveil the mechanism behind this intriguing phenomenon as the local interfacial instability at the surface wave crests modulated by the Faraday instability. By theoretically elucidating the parameter limits of different ejection modes in terms of frequency and amplitude of the applied voltage, we establish a control strategy for the precise modulation of ejection behavior. Furthermore, our findings inspire us that broader approaches beyond Faraday waves could be considered to alter or create surface stagnation points to achieve more complex dancing electrospray behaviors. This work not only advances the fundamental understanding of electrospray, but also provides a framework for manipulating local instability through controlled global flow, opening new opportunities for electrospray applications in biological, pharmaceutical, and manufacturing industries.

#### ACKNOWLEDGMENT

We acknowledge support from the National Natural Science Foundation of China (grant no. U2341281 and no. 12272026).

- I. Hayati, A. I. Bailey, and T. F. Tadros. Mechanism of stable jet formation in electrohydrodynamic atomization. *Nature*, 319: 41–43, 1986.
- [2] R. T. Collins, J. J. Jones, M. T. Harris, and O. A. Basaran. Electrohydrodynamic tip streaming and emission of charged drops from liquid cones. Nature Physics, 4: 149–154, 2008.
- [3] M. Cloupeau and B. Prunet-Foch. Electrohydrodynamic spraying functioning modes: a critical review. *Journal of Aerosol Science*, 25: 1021–1036, 1994.
- [4] M. S. Onses, E. Sutanto, P. M. Ferreira, A. G. Alleyne, and J. A. Rogers. Mechanisms, capabilities, and applications of high-resolution electrohydrodynamic jet printing. *Small*, 11: 4237–4266, 2015.
- [5] W. Yang, H. Li, Y. Duan, and Z. Yin. Electrohydrodynamic eigenfrequency and jetting frequency analysis via Lagrangian dynamical model. *Physics of Fluids*, 36: 062006, 2024.

- [6] S. Mishra, K. L. Barton, A. G. Alleyne, P. M. Ferreira, and J. A. Rogers. High-speed and drop-on-demand printing with a pulsed electrohydrodynamic jet. *Journal of Micromechanics and Microengineering*, 20: 095026, 2010.
- [7] J. Cheng, et al. Pulsating modes of a Taylor cone under an unsteady electric field. *Physics of Fluids*, 34: 012007, 2022.
- [8] T. A. Cohen, et al. Direct patterning of perovskite nanocrystals on nanophotonic cavities with electrohydrodynamic inkjet printing. *Nano Letters*, 22: 5681–5688, 2022.
- [9] Y. Guan, et al. Numerical investigation of highfrequency pulsating electrohydrodynamic jet at low electric Bond numbers. *Physics of Fluids*, 34: 012001, 2022.
- [10]L. Sirovich. Turbulence and the dynamics of coherent structures. I. Coherent structures. *Quarterly of Applied Mathematics*, 45: 561–571, 1987.
- [11]K. E. Meyer, J. M. Pedersen, and O. A. Özcan. A turbulent jet in crossflow analysed with proper orthogonal decomposition. *Journal of Fluid Mechanics*, 583: 199–227, 2007.
- [12]K. Kim, B. U. Lee, G. B. Hwang, J. H. Lee, and S. Kim. Drop-on-demand patterning of bacterial cells using pulsed jet electrospraying. *Analytical Chemistry*, 82: 2109–2112, 2010.
- [13]J. Miles, and D. Henderson. Parametrically forced surface waves. *Annual Review of Fluid Mechanics*, 22: 143–165, 1990.
- [14]X. Shao, P. Wilson, J. R. Saylor, and J. B. Bostwick. Surface wave pattern formation in a cylindrical container. *Journal of Fluid Mechanics*, 915: (2021).
- [15]K. Ward, S. Matsumoto, and R. Narayanan. The electrostatically forced Faraday instability: theory and experiments. *Journal of Fluid Mechanics*, 862: 696–731, 2019.
- [16]Y.-H. Tseng, and A. Prosperetti. Local interfacial stability near a zero vorticity point. Journal of Fluid Mechanics, 776: 5–36, 2015.
- [17]J. M. Montanero. Tip streaming of simple and complex fluids. Springer-Cham, 2024.
- [18]S. Douady. Experimental study of the Faraday instability. *Journal of Fluid Mechanics*, 221: 383–409, 1990.
- [19]A. Ponce-Torres, N. Rebollo-Muñoz, M. A. Herrada, A. M. Gañán-Calvo, and J. M. Montanero. The steady cone-jet mode of electrospraying close to the minimum volume stability limit. *Journal of Fluid Mechanics*, 857: 142–172, 2018.
- [20]M. A. Herrada, et al. Numerical simulation of electrospray in the cone-jet mode. *Physical Review E*, 86: 026305, 2012.
- [21]M. A. Herrada and J. M. Montanero. A numerical method to study the dynamics of capillary fluid systems. *Journal of Computational Physics*, 306: 137–147, 2016.

# Experimental investigation of the influence of electrode spacing on the intensity of electric wind

Francisco Pontiga<sup>1\*</sup>, Khelifa Yanallah<sup>2</sup>, and M'hamed Guemou<sup>3</sup> <sup>1</sup>Dpt. Física Aplicada II, Universidad de Sevilla, Spain <sup>2</sup>LGEP Laboratory, University of Tiaret, Tiaret, Algeria <sup>2</sup>Dpt. des Sciences et de la Technologie, Faculté des Sciences Appliquées, University of Tiaret, Tiaret, Algeria \*Corresponding author: pontiga@us.es

Abstract- The generation of electric wind in a rectangular duct using corona discharge was investigated to evaluate the effect of electrode separation on the gas flow velocity. The corona discharge was produced by a tungsten wire subjected to high positive voltage, positioned transversely at the center of the duct. To minimize airflow obstruction, two rods in contact with the duct walls, arranged parallel to the wire, were used as ion collectors. The velocity of the ionic wind was measured at the duct outlet using a hot-ball probe. Experimental results revealed that the spatial distribution of the velocity exhibited characteristics consistent with turbulent flow. The highest ionic wind velocities were recorded when the electrode separation was at its minimum. However, for a constant discharge current, the ionic wind velocity increased with greater electrode spacing. Regarding the electrical power required for the electric wind generation, no significant differences were observed across the various electrode separation configurations.

Keywords- Ionic wind, electric wind, corona discharge.

# I. INTRODUCTION

Electrical discharges in gases are often accompanied by the generation of fluid motion, which is called electric wind or ionic wind [1]. The physical origin of the ionic wind lies in the momentum transfer through collisions between the ions produced in the electrical discharge and the neutral molecules of the gas. Therefore, there is a conversion of electrical energy into mechanical energy that results in a macroscopic gas flow.

Among other discharges, corona discharge has long been known to be an important source of electric wind, and there is currently growing interest in its possible applications in a wide range of technologies, such as in heat exchangers [2], EHD drying [3], fluid pumping [4], ion thrusters [5], etc. The intensity of electric wind generated by corona discharge is influenced by several interrelated factors, particularly the voltage polarity and corona discharge regime [6].

A fundamental question for the development of applications that make use of electric wind is to determine which electrode configuration provides the highest velocity for the same electrical power. For that reason, many different electrode configurations have been considered depending on the intended application, such as needle to mesh, needle to ring, needle cylinder, wire to net, wire to cylinder, etc. [2]. Additionally, to achieve greater velocities, multiple corona needles or wires are often used, whether in single-stage or multi-stage corona wind reactors [7].

In this paper, we present a preliminary study on the generation of ionic wind in a rectangular duct using a wire to two-cylinders electrode configuration. The corona wire is arranged transversally in the center of the duct, while the cylinders, parallel to the wire, are attached to the duct walls. It is of particular interest to determine how the separation between the wire and the cylinders affects the electric wind caused by the corona discharge. Small distances between the wire and the cylinder favor the generation of strong fields but, presumably, the direction of the field will be better aligned with the direction of the flow when the wire-cylinder separation is larger. Therefore, the ionic wind intensity and the power required for its generation will be measured for three different separations between the corona wire and the charge collecting cylinders to elucidate this question.

# II. MATERIALS AND METHODS

Fig. 1 shows the schematic representation of the corona wind reactor used in the experiments. It consisted of a prismatic duct, 10 cm wide, 1 cm high, and 24 cm long, open at both ends. The lower and upper plates of the duct were made of PTFE, while the lateral walls were made of PMMA. The corona electrode was a tungsten wire with length L = 10 cm and diameter 0.1 mm, equidistant between the two PTFE plates. The distance between the duct entrance and the corona wire was 6.3 cm. Two stainless steel rods, 1.45 mm in diameter, acted as ion collectors. These rods were arranged parallel to the wire and in contact with the PTFE plates. Three different separations between the wire and the rods were considered in the experiments: d = 1 cm, 1.5 cm, and 2 cm.

The corona wire was energized with positive DC voltage using a high voltage power supply (Spellman RHR Series), and the corona current was measured using a digital multimeter (Keithley 196). Regarding the intensity of the electric wind, it was measured at the exit of the channel using a thermal anemometer with a hot ball probe  $(\emptyset \ 3 \ mm)$ , which provides a non-directional flow



Fig. 1. Schematic representation of the experimental setup (not to scale).

measurement. The gas velocity was sampled at 11 consecutive points located along the centerline of the outlet section. These points were equidistant 1 cm from each other, except the first and last points, which are located 0.15 cm from each PMMA sidewall.

#### **III. RESULTS**

#### A. Current-voltage characteristic.

The current intensity I measured during the experiments follows the usual dependence with the applied voltage V, given by

$$I = kV(V - V_0), \tag{1}$$

where k is a constant that depends on the geometrical configuration, and  $V_0$  is the onset voltage of corona discharge. This dependence can be clearly seen in Fig. 2, where the ratio I/V is plotted as a function of the applied voltage for the three different interelectrode separations considered in the present work. The dashed lines in this figure correspond to the linear fit of the experimental data using the least squares method. The onset voltage of corona discharge can be determined from the intersection of the linear fitting with the abscissa axis. The values so obtained are  $V_0 = 9.1$  kV for d = 1 cm,  $V_0 = 12.4$  kV for d = 1.5 cm, and  $V_0 = 15.7$  kV for d = 2 cm. Therefore, the threshold voltage increases linearly with the interelectrode separation at a rate of 6.6 kV/cm.

On the other hand, as the separation between the corona wire and the collector electrodes increases, the growth rate of the current intensity with the applied voltage is strongly reduced. Thus, for example, for a separation of 1 cm, the current intensity increases at a rate of about  $\sim 22 \,\mu A/kV$ , reaching more than 100  $\mu A$  at 14 kV. In contrast, for a 2 cm gap, the growth of current is much slower,  $\sim 4.7 \,\mu A/kV$ , reaching only 20  $\mu A$  at 20 kV.

The last point on each current-voltage characteristic curve corresponds to the maximum value of the applied voltage before sparks begin to develop between the wire and the cylinders.



Fig. 2. Current-voltage characteristic curves of corona discharge for three different separations between the corona wire and the ground rods. The linear interpolation of each set of measurement data is shown as a dashed line.

#### B. Electric wind velocity

Fig. 3 presents the spatial distribution of the electric wind generated by the corona discharge for the three electrode separations considered in this study: d = 1 cm (Fig. 3a), 1.5 cm (Fig. 3b), and 2 cm (Fig. 3c). As previously noted, the velocity measurements were conducted at the outlet of the reactor, along a line equidistant from the upper and lower PTFE plates that form the horizontal boundaries of the duct. The lateral walls, made of PMMA, correspond to the coordinates x = 0 cm and x = 10 cm.

In all cases, the velocity profile at the reactor outlet increases progressively with rising voltage and current intensity. For applied voltages close to the corona onset threshold, the electric wind intensity is weak, the velocity profile is irregular, and the outlet air velocity is comparatively higher on one side of the duct outlet. This asymmetry may arise from various causes, in particular, because of the inhomogeneities of the corona discharge along the wire. However, it could also be a purely hydrodynamic effect, originating from the air entering the duct, which influences the downstream flow distribution.

As the applied voltage and discharge current increase, the intensity of the ionic wind grows and the velocity profile becomes more uniform. For sufficiently high values of the applied voltage, the shape of the velocity profile corresponds to that expected for a turbulent flow, that is, the profile is approximately flat in the central region (indicating an almost uniform velocity), with sharp velocity gradients near the lateral walls, where the boundary layer develops. However, when the electrode separation is 2 cm, the velocity profile obtained is less uniform than that observed for smaller separations, 1 cm or 1.5 cm. This is most likely due to the fact that, in that case, the intensity of the ionic wind is too weak, even at the highest applied voltages.



Fig. 3. Air velocity at different points along the centerline of the corona reactor outlet section, for different values of the applied voltage. The lateral walls are located at x = 0 cm and x = 10 cm. Interelectrode separation: (a) d = 1 cm, (b) d = 1.5 cm, (c) d = 2 cm.

The highest recorded velocity, exceeding 1.5 m/s, was observed when the separation between the discharge wire and the collector electrodes was the smallest (d = 1 cm) and the applied voltage was at its maximum (V = 14 kV).

Based on the velocity distribution at the outlet section, the total gas flow rate and the average air velocity across the duct section were evaluated. In that evaluation, the



Fig. 4. Average velocity evaluated at exit of the corona reactor as a function of the square root of the electric current intensity, for different separations between the corona wire and the ground rods.

possible variations of the gas velocity in the direction perpendicular to the centerline along which measurements were performed were neglected. Therefore, the computed average velocity can be somewhat overestimated. Several authors have developed approximate theoretical models aiming to relate the relevant electrical and aerodynamic parameters of the ionic wind [5,8]. The findings of these studies suggest that the velocity of the ionic wind is proportional to the square root of the corona discharge current. For this reason, Fig. 4 presents the average velocity of the ionic wind,  $\bar{\nu}$ , as a function of that quantity.

The results presented in Fig. 4 indicate that the expected linear behavior is only observed for low to moderate values of the discharge current. In contrast, as the current increases, the data as a whole deviate from the linear dependence on  $\sqrt{I}$ . This deviation from the linear behavior has also been reported by other researchers [9]. It is interesting to note that, for a constant current intensity, the highest average velocity was found when the separation between the wire and the rod was greater. This observation is consistent with the fact that, under such conditions, the electric field lines (and the current density) are better aligned with the longitudinal direction of the duct, along which the gas flows.

As noted earlier, an important question for the development of applications that make use of electric wind is to determine which electrode configuration provides the highest gas velocity for the same electrical power input. This information is provided in Fig. 5, in which the average gas velocity at the outlet of the corona reactor is plotted as a function of the electrical power consumed by the electrical discharge. As evidenced by the overlap of the measurements corresponding to different distances, there are no substantial differences between the experiments conducted with varying separations between the corona wire and the ground rods. Therefore, for the set of experiments performed in this investigation, the ionic



Fig. 5. Average velocity evaluated at exit of the corona reactor as a function of the electric power, for different separations between the corona wire and the ground rods.

wind velocity is mainly determined by the electric power of the corona discharge.

#### V. CONCLUSION

The purpose of this study was to investigate how the separation distance between a corona discharge wire and two parallel collector electrodes (rods) influences the airflow velocity and the electrical power required to produce the gas flow. The onset voltage for corona discharge was found to increase linearly with the separation between the corona wire and the rods, at an approximate rate of 6.6 kV/cm. At voltages close to the corona threshold, the velocity profiles were asymmetric, likely due to corona inhomogeneity or inlet flow effects. However, for sufficiently high voltages, they became more uniform and exhibited features characteristic of turbulent flow.

For the same discharge current, higher gas velocities were obtained using larger electrode spacing. However, since sparking limits the applicable voltage range in each case, the highest ionic wind velocity (>1.5 m/s) was achieved with the smallest electrode spacing (1 cm), for an applied voltage of 14 kV. For the same electric power, the electric wind velocity was very similar for different electrode spacing. This suggests that, within the experimental conditions tested, the gas velocity is primarily governed by the electric power input.

#### ACKNOWLEDGMENT

This work was partially supported by the Spanish State Research Agency (contract PID2022-138943OB-I00, funded by MICIU/AEI/10.13039/501100011033 and by FEDER, EU).

- [1] E. D. Fylladitakis, M. P. Theodoridis, and A. X. Moronis. Review on the History, Research, and Applications of Electrohydrodynamics, *IEEE Transactions on Plasma Science*, **42**:358–374, 2014.
- [2] J. Wang, T. Zhu, Y. Cai, J. Zhang, and J. Wang. Review on the recent development of corona wind and its application in heat transfer enhancement, *International Journal of Heat and Mass Transfer*, 152:119545, 2020.
- [3] T. Anukiruthika, J. A. Moses, and C. Anandharamakrishnan, Electrohydrodynamic drying of foods: Principle, applications, and prospects, *Journal of Food Engineering*, **295**:110449, 2021.
- [4] B. Komeili, J. S. Chang, G. D. Harvel, C. Y. Ching, and D. Brocilo. Flow characteristics of wire-rod type electrohydrodynamic gas pump under negative corona operations, *Journal of Electrostatics*, 66:342– 353 (2008).
- [5] E. Moreau, N. Benard, J.-D. Lan-Sun-Luk, and J.-P. Chabriat. Electrohydrodynamic force produced by a wire-to-cylinder dc corona discharge in air at atmospheric pressure, *Journal of Physics D: Applied Physics*, **46**:475204, 2013.
- [6] E. Moreau, P. Audier, and N. Benard. Ionic wind produced by positive and negative corona discharges in air. *Journal of Electrostatics*, **93**:85–96, 2018.
- [7] C. Kim, D. Park, K. C. Noh, and J. Hwang. Velocity and energy conversion efficiency characteristics of ionic wind generator in a multistage configuration, *Journal of Electrostatics*, 68:36–41, 2010.
- [8] M. Robinson. Movement of air in the electric wind of the corona discharge, *Transactions of the American Institute of Electrical Engineers, Part I: Communication and Electronics*, **80**: 143–150, 1961.
- [9] B. A. Kozlov, and V. I. Solovyov, Electric wind in electrode systems with corona points. *Technical Physics*, 52: 892–897, 2007.

# Investigation of Underwater Discharge Phenomena and Shock Wave Regulation

Siwei Liu\*, Tomoki Nakajima, Takehiko Sato

Institute of Fluid Science, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577, Japan \*Corresponding author: s.liu@tohoku.ac.jp

Abstract- Underwater discharge phenomena exhibit significant variability depending on experimental conditions such as voltage amplitude, polarity, liquid properties, current density, and pulse duration. Compared to microsecond pulsed discharges with low current density, high current density discharges (as studied in this work) display discharge characteristics that vary strongly with the electric circuit. These variations are manifested in mode changes in the discharge morphologies and propagation velocities. Understanding the factors influencing discharge characteristics, particularly the mode transitions, offers opportunities to modify energy conversion in the discharges. This study explores methods to regulate the profiles of shock waves, aiming to enhance energy efficiency. To achieve this, discharge current interception experiments were designed and executed using a novel experimental setup. This setup delivers a microsecond pulsed discharge current with a relatively slow rise time, enabling precise control for the current through the water gap. By extinguishing the current at specific times, the shock wave generation processes were systematically studied both experimentally and numerically. The results reveal that only the initial stage of the discharge (approximately 5  $\mu$ s in the studied cases) significantly contributes to shock wave intensity. These findings suggest potential methods for optimizing energy efficiency, which could be developed based on the insights gained from this study.

Keywords- Plasma, current regulation, energy efficiency.

### I. INTRODUCTION

Electrohydraulic shock waves (EHSWs) have a wide range of environmental and biomedical applications, including electrohydraulic forming [1], extracorporeal shock wave lithotripsy [2], and drug delivery [3]. In addition, EHSWs are used to enhance the local permeability of oil reservoirs by generating micro-cracks in rock formations through strong, repetitive mechanical impacts. This makes them a valuable adjunct to secondary oil recovery techniques such as hydraulic fracturing [4]. The effectiveness of EHSW-based treatments is closely linked to key characteristics such as rise time, peak pressure, and pulse duration. Among these, the shock wave intensity, typically defined by its peak pressure, is a crucial parameter for assessing mechanical effects.

Shock waves in liquids are primarily generated through the implosion of vapor cavities or bubbles, which play a crucial role in converting electrical energy into mechanical energy. When a high-voltage pulse is applied across submerged electrodes, it induces rapid plasma expansion, which in turn initiates a shock wave in the surrounding fluid. However, achieving efficient energy conversion and maximizing shock wave intensity remain challenging due to the saturation effect observed at higher levels of electrical input. To fully harness the energy stored in capacitors for generating high-intensity shock waves, a deeper understanding of the underlying shock wave generation mechanisms is essential.

This study focuses on the generation and regulation of shock waves induced by underwater plasma discharges. The relationship between shock wave intensity and the deposited energy is investigated through both simulations and experimental measurements.

# II. METHODOLOGY

A microsecond pulsed discharge platform was developed and has been comprehensively described in previous studies [5-6]. A key feature in the setup involves the introduction of a bypass branch arranged in parallel with the main water gap. This configuration enables precise control of the discharge process by allowing for the interception and termination of the discharge current at designated time intervals, thereby facilitating targeted investigations into transient plasma dynamics and energy transfer mechanisms.Optical imaging of the plasma channel was conducted using a high-speed camera (Phantom V1612) equipped with a Nikon AF 24-85 mm f/2.8–4D lens. To manage the intense light emissions from the plasma and avoid sensor saturation, neutral density filters (NiSi ND 1000 and ND 400) were applied in tandem. This optical setup enabled the capture of highfidelity temporal and spatial evolution of the discharge channel. The shock wave profile was measured using a piezoelectric pressure transducer (PCB 482C05).



Fig. 1. Captions are centered in the column if they are shorter than the column width. Otherwise, they must be justified in the column. Use 9-point Times New Roman for the captions.

#### III. RESULTS

Figure 2 presents the optical visualization results of the underwater discharge channel, which exhibits intense luminescence. This strong emission indicates a high degree of plasma ionization and a rapid expansion of the discharge channel following the application of the highvoltage pulse. The bright region captured in the image corresponds to the active plasma zone, where energy is concentrated and rapidly dissipated into the surrounding medium. The outer boundary of the luminous region serves as an effective indicator for identifying the spatial extent and position of the plasma channel [5, 7]. By analyzing this boundary over time, valuable insights can be obtained into the dynamic evolution of the discharge process, including the rate of plasma expansion and the influence of surrounding fluid properties.



Fig. 2. Optical visualization results of the underwater discharge channel.

#### **IV. DISCUSSION**

To further investigate the effect of circuit parameters on the peak pressure of the shock wave, this section will perform a parametric analysis based on the Response Surface Methodology (RSM), which uses statistics and mathematics to model the behavior of the response



Fig. 3. Comparison of the shock wave peak pressures under different circuit parameters. This figure shows the surface plot and contour plot of  $P_m$  versus  $L_0$  and  $C_0$ , while  $R_0 = 0.15 \Omega$ .

variable [8]. Figure 4 shows the RSM analysis results, and it suggests a six-order relation between  $P_{\rm m}$  and  $C_0$ ,  $L_0$ , and  $R_0$  with a fitting  $R^2$ =0.9993.

#### V. CONCLUSION

This work presents an experimental and analytical investigation into the shock wave regulation in underwater plasma discharges. The experimental results suggest that only the initial stage of the discharge (approximately 5  $\mu$ s in the studied cases) significantly contributes to shock wave intensity. Through RSM-based analysis, the study establishes a robust predictive framework for optimizing discharge parameters to achieve maximum shock wave intensity.

#### ACKNOWLEDGMENT

This study was supported by JSPS KAKENHI (Grant No. 22K14174, 23KK0265, 25K17536). The authors would also like to gratefully appreciate the academic support from Prof. Y. Liu (Huazhong University of Science and Technology, China), Mr. Y. Tang (Huazhong University of Science and Technology, China), and Mr. Y. Ren (Huazhong University of Science and Technology, China).

- V. Psyk, D. Risch, B. Kinsey, A. Tekkaya, M. Kleiner. Electromagnetic forming—a review. *Journal of Materials Processing Technology*. 2011 May 1;211(5):787-829.
- [2] C. Chaussy. Extracorporeal shock wave lithotripsy: past, present, and future. InShock wave lithotripsy: state of the art 1988 (pp. 1-9). Boston, MA: Springer US.
- [3] V. Menezes, S. Kumar, K. Takayama. Shock wave driven liquid microjets for drug delivery. *Journal of Applied Physics*. 2009,106(8), 086102.
- [4] S. Liu, Y. Liu, H. Li, Q. Zhang, F. Lin. Influence of Electrohydraulic Discharge on Its Application in Oil Well Stimulation. In2018 IEEE International Power Modulator and High Voltage Conference (IPMHVC) 2018 Jun 3 (pp. 54-57). IEEE.
- [5] S. Liu, Y. Liu, Y. Ren, F. Lin, H. Li, Y. Zhao. Analysis of shock wave induced by underwater pulsed discharge using discharge current interception. *Journal of Applied Physics*, 2020, 127(14): 143301.
- [6] S. Liu, Y. Liu, Y. Ren, F. Lin, Y. Liu, Y. Shen. Influence of plasma channel impedance model on electrohydraulic shockwave simulation. *Physics of Plasmas*, 2019, 26(2): 023522.
- [7] S. Liu, Y. Liu, Y. Ren, F. Lin, H. Li, Y. Zhao. Influence of conductivities on electrical breakdown of water under microsecond pulsed voltage. *Physics* of *Plasmas*, 2020, 27, (6), 063512.
- [8] A. Khuri, S. Mukhopadhyay. Response Surface Methodology. *Wiley Interdisciplinary Reviews: Computational Statistics*, 2010, 2, 128–149

# Influence on Ionic Liquid Electrospray Emission Processes in Hybrid Emitters under Rapid Electric Field Variation

Yihua Zhang<sup>1</sup>, Weizong Wang<sup>1,2\*</sup>, Yufeng Cheng<sup>1,3,4</sup>, Yuxiang Chen<sup>1</sup>

<sup>1</sup>Advanced Space Propulsion and Energy Laboratory (ASPEL), School of Astronautics, Beihang University, Beijing

100191, China

<sup>2</sup>Aircraft and Propulsion Laboratory, Ningbo Institute of Technology, Beihang University, Ningbo, 315100, China.

<sup>3</sup>Departamento de Electrónica y Electromagnetismo, Facultad de Física, Universidad de Sevilla, Sevilla 41012, Spain

<sup>4</sup>Shen Yuan Honors College, Beihang University, Beijing, 100191, China.

\*Corresponding author: wangweizong@buaa.edu.cn

Abstract- Ionic liquid electrospray thrusters (ILETs) are promising candidates for attitude and orbit control of microsatellites, owing to their structural simplicity, miniaturization potential, high specific impulse, and low energy consumption. Compared to conventional electrospray thrusters, hybrid-emitter ILETs offer a wider thrustto-specific impulse tuning range by supporting dual emission modes—capillary emission and externally wetted emission—allowing them to adapt to a broader range of mission scenarios. In this study, a periodic alternating positive-negative polarity voltage was applied as the extraction voltage to a hybrid-emitter ILET prototype. Under rapidly varying electric fields, redistribution of internal charges within the ionic liquid led to surface deformation and mode transitions between emission states. These transitions resulted in a transient increase in emission flow rate and beam current. By analyzing the transition dynamics from non-steady to steady states under various operating modes and charge polarities, it was found that, when using EMIM-Im as the propellant, the externalwetting emission mode achieved a smoother transition than the capillary emission mode. Moreover, negatively charged beams demonstrated faster recovery to stable emission states compared to positively charged beams. These results provide valuable insights for enhancing the dynamic response and operational stability of hybridemitter ILET systems.

Keywords- Electrospray Thrusters, Hybrid emitter, Ionic Liquid, Electric field variation.

### I. INTRODUCTION

Electrospray is a technique that utilizes electrostatic forces to charge and atomize liquids into micro- or nanoscale droplets. It has been widely employed in applications such as mass spectrometry, material synthesis, electrostatic coating, and space electric propulsion<sup>[1]-[4]</sup>. As early as the 1960s, researchers identified the potential of electrospray for space propulsion and initiated related investigations<sup>[5]-[7]</sup>. However, the use of conventional working fluids posed significant challenges in terms of performance and reliability, limiting the practical deployment of electrospray-based propulsion systems.

Ionic liquid electrospray, which uses molten salts composed entirely of charged ions as propellants<sup>[8]</sup>, significantly lowers the onset voltage for electrospray emission, thereby enhancing the feasibility of space propulsion applications<sup>[5]</sup>. With the rapid proliferation of micro- and nanosatellite missions, ionic liquid electrospray technology has shown great potential for tasks such as orbit maintenance and attitude control, due to its low power consumption, compact and scalable architecture, and high specific impulse. Traditional ionic liquid electrospray thrusters typically employ one of three emitter configurations: capillary, externally wetted, or porous media types<sup>[9]</sup>, as illustrated in Figure 1. Capillary emitters generally provide higher flow rates but lower specific impulse, whereas externally wetted and porous media emitters yield higher specific impulse at reduced flow rates. These conventional configurations, however, restrict the achievable range of performance modulation in electrospray thrusters.



Fig. 1. Conventional emitter configuration: (a) Capillary (b) Externally wetted (c) Porous media

To improve performance adaptability for diverse mission requirements, UCLA proposed a novel hybrid emitter architecture in 2019<sup>[10]</sup>, as illustrated in Figure 2. This design integrates structural features of two conventional emitter types, enabling transitions between capillary emission and externally wetted emission modes within a relatively narrow voltage range. Subsequent development of molecular dynamics simulation models for this composite structure has further facilitated the mechanistic analysis of the emission mode transition process<sup>[11]</sup>.



Fig. 2. Hybrid emitter ion liquid electrospray thruster As an electric propulsion technology, ionic liquid electrospray thrusters require precise control of beam charge neutrality to maintain overall charge balance[12].

Current implementations often utilize alternating-polarity extraction voltages to periodically emit positively and negatively charged beams. Compared to conventional steady-state electrospray operation under direct current (DC) voltages, alternating-polarity operation introduces additional complexity into hybrid emitter systems. This complexity is characterized by rapid meniscus dynamics and frequent emission mode transitions, leading to increased performance variability and operational uncertainty. Therefore, a comprehensive understanding of the dynamic behavior of hybrid-emitter ionic liquid electrospray systems under alternating-polarity conditions is essential. In particular, elucidating the effects of transient electric field variations during polarity switching on the ionic liquid interface, as well as the mechanisms governing the transition from unstable to stable emission states, is critical for optimizing control strategies and ensuring long-term operational stability.

In this study, a self-developed hybrid-emitter ionic liquid electrospray thruster was employed. First, DC voltage was applied to validate the system's multimode emission capability. Then, a periodic high-voltage waveform with alternating polarity was introduced to investigate the influence of rapidly changing electric fields during polarity reversal on the morphology of the liquid interface. Finally, by analyzing electrospray current waveforms within each voltage cycle, the transition process from unstable to stable emission was characterized. Comparative analyses were conducted across different emission modes and beam polarities to assess their effects on transient behavior and recovery dynamics.

# II. EXPERIMENT METHOD

# A. Hybrid emitter electrospray thruster

The schematic of the hybrid-emitter ionic liquid electrospray thruster prototype is shown in Fig. 3. The thruster has overall dimensions of  $40 \times 40 \times 20$  mm<sup>3</sup>. Its hybrid emitter architecture determines both the capability for emission mode switching and the range of performance modulation.



Fig. 3. Hybrid emitter ion liquid electrospray thruster: (a) Exploded assembly view (b) Actual component photo (c) Emitter cutaway illustration

Design parameters were selected based on empirical optimization through prior experiments. The capillary structure has an outer diameter of 0.8 mm, an inner diameter of 0.6 mm, and houses an internal needle emitter with a diameter of 0.4 mm. The needle tip is positioned 0.5 mm from the capillary outlet, as illustrated in the cross-sectional view in Fig. 3(c). To achieve precise flow

regulation, a microchannel with a cross-sectional area of  $0.2 \times 0.2$  mm<sup>2</sup> was machined into the emitter mounting plate.

# B. Vacuum experience system

Ionic liquid electrospray experiments were conducted under vacuum conditions, with the ambient pressure maintained below $1 \times 10^{-4}$  Pa using a vacuum chamber, as illustrated in Fig. 4. A three-way valve was employed to control ionic liquid handling and delivery, allowing the reservoir to be alternately connected to either the vacuum environment or a nitrogen gas source. Prior to testing, the ionic liquid container was evacuated for a minimum of 3 hours to remove dissolved gases. After degassing, the valve configuration was adjusted to pressurize the reservoir with nitrogen, enabling pressure-driven delivery of the ionic liquid. A micro-flow meter was installed between the reservoir and the thruster to provide real-time flow rate monitoring.





The hybrid-emitter ionic liquid electrospray thruster was installed inside a vacuum chamber, with the highvoltage power supply located externally. Electrical connection to the thruster's remote electrode was achieved via a vacuum feedthrough flange. A PVX-4110 pulse generator was used to enable rapid high-voltage switching, with alternating polarity voltage amplitudes set between 2.5 and 4.0 kV, and a switching rise time of approximately 20 ns. To observe the surface morphology of the ionic liquid at the emitter tip, a long-working-distance microscopic lens coupled with a high-speed camera was utilized for diameter measurements, aided by backlighting for enhanced contrast. A metallic target was positioned to collect electrospray emission currents, while an oscilloscope simultaneously monitored the output voltage and recorded the corresponding current waveforms, enabling time-domain analysis of both signals.

# III. RESULTS

# A. Operational Stability Characteristics

A systematic investigation was conducted on the steady-state operational characteristics of a hybrid-emitter ionic liquid electrospray thruster using 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMIM-Im) as the propellant. Electrospray emission

currents were analyzed under controlled ionic liquid flow rates and extraction voltages.

At low flow rates (0.5 nL/s, 1 nL/s, and 1.5 nL/s), the onset voltage for electrospray emission was approximately  $\pm 2.8$  kV, with the 0.5 nL/s case requiring a slightly higher onset voltage of  $\pm 3.1$  kV, indicating operation in the capillary emission mode. When the extraction voltage is below the onset operating voltage, the electric field is insufficient to support the formation of a Taylor cone. As a result, the liquid, under the influence of surface tension, moves along the outer edge of the emitter and accumulates at the base of the emitter. As the applied extraction voltage amplitude gradually increases, the emission current shows a slight increasing trend. When the extraction voltage reaches  $\pm 3.5$  kV, the electrospray operation mode transitions from the capillary emission mode to the externally wetted emission mode, and the rate of increase in the beam emission current also rises accordingly.



Fig. 5. Electrospray emission current Variation: (a) High flow rate (b) Low flow rate

At higher flow rates (3 nL/s, 4 nL/s, and 5 nL/s), the onset voltage for stable electrospray operation was slightly lower, approximately  $\pm 2.7$  kV ( $\pm 2.8$  kV for the 5 nL/s case), while the electrospray remained in the capillary emission mode. Unlike low-flow conditions, sub-threshold extraction voltages at higher flow rates triggered unstable droplet emission. Gradual increases in extraction voltage led to a slow rise in emission current. Transitioning to the externally wetted mode at high flow rates would require excessively high extraction voltages, which could risk electrochemical reactions under DC operation. Therefore, current variations were analyzed within the same voltage range( $\pm 2.8$ kV~ $\pm 3.5$ kV) as capillary emission mode operations under low-flow conditions.

# B. Transient Characteristics of Electrospray

After validating the multimode operational capability of the ionic liquid electrospray thruster, the stable externally wetted mode and capillary mode were selected for further investigation. A periodic voltage with alternating polarity (<20 ns polarity reversal duration) was generated using a PVX-4110 pulse generator to create rapidly varying electric fields. This setup enabled a systematic investigation of the dynamic behavior of the ionic liquid at the composite emitter tip under transient electric field conditions.

Under rapidly alternating electric fields, the original charge distribution within the ionic liquid is disrupted: outer-layer charged particles are repelled by the polarityswitched fields, while inner counter-ions are attracted. This destabilizes the Taylor cone morphology and induces flow-rate-dependent behavioral variations.

Figure 6 shows the hybrid emitter operating in the stable externally wetted mode. The evolution of the meniscus consists of three phases:

(1) Stationary Phase: The ionic liquid meniscus remains below the internal emitter structure, with electrohydrodynamic transport sustaining tip-directed emission.

(2) Elongation Phase: The liquid column extends toward the extractor under transient fields, submerging the emitter apex and forming a transient Taylor cone.

(3) Retraction Phase: After polarity reversal, the meniscus recedes, exposing the internal emitter structure under restored DC-like fields.



Fig. 6. Dynamic variations under externally wetted mode: (a) Stationary Phase (b) Elongation Phase (c) Retraction Phase

When the composite emitter operates stably in the capillary emission mode, the evolution of the ionic liquid meniscus exhibits similar behavior to that of conventional capillary emitters and can be divided into several stages: stable, elongation, and concave meniscus phases.

(1) stable phase: The ionic liquid meniscus forms a distinct Taylor cone shape, sustaining stable emission.

(2) elongation phase: The ionic liquid is stretched toward the extractor, forming a larger Taylor cone structure, with the instantaneous emission flow rate exceeding the supply flow rate.

(3) meniscus phase: The ionic liquid surface exhibits significant curvature but does not form a Taylor cone, and no electrospray emission occurs.



Fig. 7. Dynamic variations under capillary regime: (a) Stationary Phase (b) Elongation Phase (c) Meniscus Phase

### C. steady-state recovery process of electrospray

Under rapidly varying electric fields, the ionic liquid electrospray thruster transitions through an unstable operational phase before gradually stabilizing, with distinct transitional behaviors observed across different operational modes and emission polarities. As shown in Figure 8, in the externally wetted mode, under a polarity-switching period of 1 s, no emission interruption occurs, and both positive and negative polarities exhibit similar stabilization dynamics. For negative polarity operation, the emission current rapidly increases to a peak value of  $-1.8 \mu$ A, then stabilizes at -0.5  $\mu$ A within 200 ms. During positive polarity operation, the emission current initially surges to  $1.1 \mu$ A, then decays to 0.4  $\mu$ A within 150 ms before stabilizing.

In contrast, in the capillary mode, significant emission interruptions and asymmetric stabilization are observed during polarity transitions, as shown in Figure 8. To achieve prolonged stable operation in this mode, the polarity-switching period was extended to 60 s. Under negative polarity, a transient current spike occurs immediately after polarity reversal, followed by a brief non-emission period and gradual stabilization. For positive polarity operation, an initial current spike is followed by a prolonged non-emission phase, with stable emission resuming abruptly only after sufficient liquid accumulates at the emitter tip.



Fig. 7. Emission current and extraction voltage variations: (a) Positive Charge emission under externally wetted mode (b) Negative Charge emission under externally wetted mode c) Positive Charge emission under capillary mode (d) Negative Charge emission under capillary mode

The primary reason for this difference is the distinct emission characteristics of positive and negative ions in the ionic liquid. Negative charge particles in the EMIM-Im liquid are more easily emitted, allowing the liquid to form a Taylor cone structure more quickly after polarity reversal, thus initiating emission faster. However, due to the limited amount of liquid at the emitter tip, the emission current gradually increases until it stabilizes. In contrast, positive charge particles are more difficult to emit. After polarity reversal, the liquid initially accumulates at the emitter tip, forming droplet clusters. When the droplet size becomes large enough, it is stretched by the electric field to form a Taylor cone and rapidly stabilizes the emission.

### V. CONCLUSION

This study examines the dynamic operational characteristics of a hybrid emitter ionic liquid electrospray thruster under alternating-polarity voltage conditions. Experiments confirmed the thruster's multimode operational capability and analyzed beam emission currents across various voltage and flow rate settings. An alternating-polarity voltage was applied to control thruster operation, with optical imaging capturing meniscus changes at the emitter tip, and a metal target collecting spray current to investigate transient behaviors and transition processes under rapidly varying electric fields.

The results indicate that rapidly changing electric fields disrupt the charge distribution within the ionic liquid,

leading to abrupt meniscus deformation and unstable emission. In the externally wetted mode, meniscus stretching induces short-term emission variations but allows rapid stabilization with minimal differences between polarities. Conversely, in the capillary mode, meniscus stretching does not trigger emission mode transitions but temporarily exceeds the liquid supply capacity, resulting in emission interruptions. Significant polarity asymmetry is observed in the transition processes during capillary mode operation.

#### ACKNOWLEDGMENTS

This research is supported by, the National Natural Science Foundation of China (Grant No. 52277133), and the Outstanding Research Project of Shen Yuan Honors College, BUAA (230123101).

- [1] A. Tycova, J. Prikryl, A. Kotzianova, et al. Electrospray: More than just an ionization source, *Electrophoresis*, 42:103-121, 2021.
- [2] J. Xue, T. Wu, Y. Dai, et al. Electrospinning and electrospun nanofibers: Methods, materials, and applications, *Chemical reviews*, 119:5298-5415, 2019.
- [3] A. Bailey. Electrostatic spraying of liquids, *Physics Bulletin*, 35:146, 1984.
- [4] J. Cheng, L. Yang, Q. Fu, et al. Pulsating Modes of a Taylor Cone under an Unsteady Electric Field, *Physics of Fluids*, 34:012007, 2022.
- [5] M. Gamero-Castano, V. Hruby. Electrospray as a source of nanoparticles for efficient colloid thrusters, *Journal of Propulsion and Power*, 17:977-987, 2001.
- [6] M. Huberman, J. Beynon, E. Cohen, et al. Present Status of Colloid Microthruster Technology, *Journal* of Spacecraft and Rockets, 5:1319-1324, 1968.
- [7] A. Bailey. Investigation of a Single Spraying Site of a Colloid Thruster, *Journal of Physics D: Applied Physics*, 6:276-288, 1973.
- [8] J. Wilkes, M. Zaworotko. Air and Water Stable 1ethyl-3-methylimidazolium Based Ionic Liquids, *Journal of the Chemical Society, Chemical Communications*, 13:965-967, 1992.
- [9] J. Howell, B. Canfield, L. Costa, et al. Analysis of the Effects of Ionic Liquid Properties on Electrospray Thruster Performance, *The Journal of Physical Chemistry B*, 128:10661-10674, 2024.
- [10]P. Wright, H. Huh, N. Uchizono, et al. A novel variable mode emitter for electrospray thrusters, in *36th International Electric Propulsion Conference*, 650, 2019.
- [11]J. Zhang, G. Cai, A. Shahzad, et al. Ionic liquid electrospray behavior in a hybrid emitter electrospray thruster, *International Journal of Heat and Mass Transfer*, 175:121369, 2021.
- [12]F. Blázquez-Plaza, A. Barrado, M. Wijnen. Emitted current self-balancing for spacecraft charging mitigation in a high-voltage power converter for electrospray thrusters, *Journal of Electric Propulsion*, 3: 26, 2024.

# Hydrophilic treatment of graphite by using controlled plasma-induced liquid flow

Kecheng Shen<sup>1\*</sup>, Toshiyuki Kawasaki<sup>2</sup>, Nozomi Takeuchi<sup>1</sup> <sup>1</sup>Department of Electrical and Electronic Engineering, Institute of Science Tokyo, Japan <sup>2</sup>Department of Electrical Engineering, Nishinippon Institute of Technology, Japan \*Corresponding author: shen.k.aa37@m.isct.ac.jp

Abstract- Plasma-induced liquid flows play an indispensable role in recent plasma science and technology. Clarifying the mechanisms of plasma-induced liquid flows is necessary to understand the plasma-liquid interaction. In the present work, we investigated the effects of supply gas (helium and argon gases) on plasma-induced liquid flows using particle image velocimetry. The results indicated that only the downward flow that extended to the liquid depth direction was generated when helium gas was supplied. However, the liquid flows switched with the increase in voltage when argon gas was supplied. We also discovered current waveforms and the optical emission spectroscopy results were greatly changed with the types of plasma-induced liquid flows. According to the experimental results for the argon gas, we also successfully switched and controlled the plasma-induced liquid flow by changing the voltage only. While trying to elucidate the mechanism of plasma-induced liquid flows, we have come up with new ideas for its application.

Keywords- Atmospheric pressure plasma, plasma-induced liquid flow, hydrophilic treatment of graphite.

# I. INTRODUCTION

Graphite, with its excellent electrical conductivity, thermal conductivity, and high mechanical strength, is expected to be applied in areas such as reaction sites for fuel cell catalyst supports and conductive inks. However, graphite is hydrophobic, making it difficult to use in water organic solvents; therefore, it requires or а hydrophilization treatment. Currently, the most used method is chemical oxidation. This method, however, involves the use of strong oxidizing agents such as sulfuric acid and potassium permanganate, which leads to issues such as degradation in quality and a significant environmental impact. To solve these problems, a modification method using plasma has gained attention [1-6]. This approach is expected to enable high-quality hydrophilization with low environmental impact. In this study, we proposed a method to hydrophilize graphite using controlled plasma-induced liquid flow. In the hydrophilization treatment of graphite using plasmainduced liquid flow, we considered that efficient hydrophilization of graphite could be achieved by utilizing the property of hydrophobic graphite to gather on the water surface and by controlled plasma-induced liquid flow [7-8].

# II. EXPERIMENTAL SETUP

# A. Plasma-jet generator

A schematic representation of the experimental equipment is shown in Fig. 1. A needle electrode (high-voltage electrode made of tungsten) was placed at the center of a glass tube with outer and inner diameters of 6 and 4 mm, respectively. The ground electrode was installed outside of the glass tube 10 mm away from the tip of the high-voltage electrode. We supplied 3 L/min of Ar gas into the glass tube using a mass-flow controller. A

sinusoidal frequency of 1 ~ 12 kHz at 12 kV<sub>p-p</sub> was used to generate plasma. We used a digital oscilloscope (Iwatsu, DS-8104) to record the voltage and current waveforms. The discharge power was calculated using the power calculation function that comes with the digital oscilloscope (average power consumption for 1000 times).

# B. PIV measurement

Fig. 1 shows that a green laser sheet was directly irradiated under the plasma jet irradiation area, and the flow in a 2-D cross-section  $(25 \times 30 \text{ mm}^2)$  that was cut out of the sheet was analyzed using the PIV method to determine the direction and velocity of the particle flow in the liquid. Surfactant solution (lauryl betaine, 50, 100, 200 and 500 mg/L) was used to uniformly distribute tracer particles (Nylon, 50-µm diameter, 1.03 g/cm<sup>3</sup>) in distilled water in a glass cup (I.D.: 30 mm, L: 50 mm). The total volume of the liquid target was 20 mL. The PIV analysis was completed using processing software (Ditect Flownizer2D) for the area below the plasma jet and liquid target contact point. To complete the PIV measurement, we utilized a digital camera (1920  $\times$  1080 pixels, 30 frames per second) to record a video of the liquid flows. The PIV measurement was performed more than three times under all experimental conditions.

# C. Measurement of the hydrophilic effect of graphite

For the experimental procedure, a dispersion was prepared by mixing 20 mg of graphite with 20 mL of ultrapure water, followed by ultrasonic treatment for 10 minutes. After plasma irradiation, the graphite was collected by filtration, rinsed thoroughly with ultrapure water, and subsequently dried in an oven at 100 °C for 24 hours. To evaluate the hydrophilic effect induced on the graphite surface, we employed two main characterization techniques: absorbance measurement and Fourier transform infrared spectroscopy (FT-IR). The absorbance



Fig. 1. Schematic diagram of the experimental setup and PIV measurement conditions.

measurement was performed to assess the dispersibility of the plasma-treated graphite in water. Improved dispersibility indicates an increase in hydrophilicity, as hydrophilic surfaces tend to interact more favourably with water molecules, leading to more uniform suspension and reduced sedimentation. FT-IR was conducted to analyse surface chemical changes of the graphite, with a particular focus on the presence of hydroxyl (·OH) functional groups. The emergence or increase in the intensity of absorption peaks corresponding to ·OH vibrations would suggest successful surface functionalization, further supporting the enhancement of hydrophilicity through plasma treatment.

# III. RESULTS AND DISCUSSION

# A. PIV measurement results

Fig. 2 illustrates the relationship between surfactant concentration and particle flow speed in the v direction under Ar plasma irradiation, with an applied voltage of 12 kV and a frequency of 5 kHz. These data were obtained from PIV measurements to illustrate the stable plasmainduced liquid flow characteristics at a depth of 5 mm below the plasma-liquid interface, under surfactant concentrations of 50, 100, 200, and 500 mg/L. These results indicate that at a surfactant concentration of 50 mg/L, the plasma-induced liquid flow at a depth of 5 mm below the plasma-liquid interface is directed upward. This upward motion is referred to as vortex flow, with a flow speed of approximately 11 mm/s. At a concentration of 100 mg/L, the flow direction reverses, becoming downward, with a speed of approximately 11.5 mm/s. However, as the surfactant concentration increases further, the downward flow speed gradually decreases measuring 10 mm/s at 200 mg/L and 9 mm/s at 500 mg/L.



Fig. 2. Results of PIV measurements at different surfactant concentrations.

# B. Absorbance results

The absorbance measurement was conducted by dispersing dried graphite in 20 mL of ultrapure water, followed by 10 minutes of sonication. The absorbance was measured after allowing the suspension to stand for 90 minutes. Fig. 3 shows the dispersibility of graphite in ultrapure water at various surfactant concentrations. Based on the results, the dispersibility of graphite in ultrapure water varies significantly with surfactant concentration. Specifically, the order of dispersibility from highest to lowest is observed at 100, 500, 200, and 50 mg/L.

# C. FT-IR results

It is well known that absorbance in the range of  $3000-3700 \text{ cm}^{-1}$  is attributed to the stretching vibrations of hydroxyl (·OH) groups. Fig. 4 shows the peak intensity



Fig. 3. Results of absorbance at different surfactant concentrations.

corresponding to hydroxyl ( $\cdot$ OH) groups in the range of 3000–3700 cm<sup>-1</sup> at various surfactant concentrations. The results indicate that at a surfactant concentration of 50 mg/L, the peak intensity of the  $\cdot$ OH groups were slightly higher than that of the untreated sample. The peak intensity of the  $\cdot$ OH groups reached a maximum at a surfactant concentration of 100 mg/L, after which it gradually decreased with further increases in surfactant concentration.

### IV. CONCLUSION

The hydrophilic treatment of graphite using controlled plasma-induced liquid flow was systematically investigated. PIV measurements revealed that the flow direction and velocity at a depth of 5 mm below the plasma-liquid interface were strongly influenced by surfactant concentration. Upward vortex flow was observed at 50 mg/L, whereas a transition to downward flow occurred at 100 mg/L, with the flow velocity decreasing progressively at higher concentrations. Absorbance measurements demonstrated that graphite dispersibility in ultrapure water was highest at 100 mg/L, indicating enhanced surface modification at this concentration. These results were further supported by FT-IR analysis, which showed a peak in OH group intensity at 100 mg/L, followed by a gradual decline with increasing surfactant concentration. Overall, the findings suggest that plasma-induced liquid flow velocity plays a critical role in determining the hydrophilic treatment of graphite. Moreover, there appears to be an optimal surfactant concentration that maximises both the dispersibility and hydrophilic surface functionalisation of graphite under plasma treatment.

#### ACKNOWLEDGMENT

This work was supported by JST SPRING, Japan Grant Number JPMJSP2180.



Fig. 4. Results of FT-IR at different surfactant concentrations.

- B. C. Brodie, On the properties of graphite, in Proceedings of the Royal Society, vol. 149, pp. 249– 287, 1859.
- [2] L. Staudenmaier, Verfahren zur Darstellung der Graphitsäure, in Berichte der Deutschen Chemischen Gesellschaft, vol. 31, pp. 1481–1499, 1898 [in German].
- [3] W. S. Hummers, *Preparation of graphitic oxide*, in *Journal of the American Chemical Society*, vol. 80, pp. 1339–1343, 1958.
- [4] H. L. Poh, F. Sanel, A. Ambrosi, G. Zhao, Z. Sofer, and M. Pumera, *Graphenes prepared by Staudenmaier, Hofmann, and Hummers methods with consequent thermal exfoliation exhibit very different electrochemical properties*, in *Nanoscale*, vol. 4, pp. 3515–3522, 2012.
- [5] M. Hirata, T. Gotou, S. Horiuchi, M. Fujiwara, and M. Ohba, *Thin-film particles of graphite oxide 1: Highyield synthesis and flexibility of the particles*, in *Carbon*, vol. 42, no. 14, pp. 2929–2937, 2004.
- [6] K. Sakaguchi, A. Fujito, S. Uchino, A. Ohtake, N. Takisawa, K. Akedo, and M. Era, *Oxidation time dependence of graphene oxide*, in *IEICE Transactions on Electronics*, vol. E96-C, no. 3, pp. 369–371, 2013.
- [7] T. Kawasaki, K. Shen, H. Shi, K. Koga, and M. Shiratani, *Instant switching control between two types* of plasma-driven liquid flows, in Japanese Journal of Applied Physics, vol. 62, no. 6, Article number 060904, 2023.
- [8] K. Shen, H. Shi, K. Koga, M. Shiratani, and T. Kawasaki, *Effects of Supplied Gas on Plasma-Induced Liquid Flows*, in *IEEE Transactions on Plasma Science*, vol. 52, no. 6, pp. 2130–2136, 2024.

# Numerical Simulation of Electrodeformation of a Droplet Immersed in Oil under the Influence of an Alternating High-Frequency Electric Field

Dmitrii Kudinov<sup>\*</sup>, Vladimir Chirkov, Sergey Vasilkov, Ilia Elagin, Petr Kostin St. Petersburg State University, Saint Petersburg, Russia \*Corresponding author: d.kudinov@spbu.ru

*Abstract-* A droplet placed in an immiscible liquid under the influence of an electric field is deformed by surface tension and Coulomb forces. However, the usual outcomes of deformation can become different at high-frequency approach. In such a case, the electric charge will not have time to accumulate at the boundary of the fluids due to which the magnitude of the Coulomb force will be determined by the ratio of dielectric permittivities of the fluids. The results show a decrease in the deformation of the droplet at the high frequency field. It is also observed that the type of deformation changes from compression to stretching of the droplet when the high-frequency field is switched on in certain cases.

Keywords- two-face liquid, unsteady-state, charge accumulation, water in oil.

# I. INTRODUCTION

In this paper, we consider the problem of numerical modeling of the electrodeformation of a droplet immersed in oil under the action of a high-frequency alternating electric field. The case of a constant electric field has been repeatedly considered in other works [1, 2]. The cases of alternating field with small deformations were considered in [3] and with the phase field method in [4]. The world scientific community has collected numerous experimental data on these problems, including the case of high-frequency alternating field. The influence of frequency and magnitude of the electric field affects the outcome in the process of electrocoalescence decoalescence [5], the shape and width of droplet spraying from the meniscus [6], and the quality of liquid mixing.

Particularly important is the case of a high frequency alternating field, where the electric charge does not have time to form at the boundary between two phases of different liquids or media. In this formulation, the previously tensile force of electric attraction will cease to have a significant effect on the hydromechanical process, resulting in a decrease in the amplitude of deformation down to zero at certain configurations of the system. The constraints (26) in [7] begin to affect, since it is possible to select the parameters so that in the stationary case the drop will be compressed under the action of the electric field, and on the contrary, it will be stretched in the highfrequency regime.

The lack of verified numerical models for calculating such high-frequency problems limits the predictive capabilities of researchers. The creation of such a numerical model describing relaxation processes at the interfacial boundary is the main task of this work.

# II. MATHEMATICAL AND NUMERICAL MODEL

Numerical modeling of electrode deformation of a droplet uses the software package COMSOL Multyphysics based on the finite element method. We consider arbitrary Lagrangian-Eulerian method with the electric current model described in [8]. The model considers only the geometric boundary between phases with surface charge. In our case, the charge accumulation at the interface between the drop and oil is taken into account. The electric field distribution is derived as represented by the following expression:

$$\vec{E} = -\nabla \varphi. \tag{1}$$

Here  $\vec{E}$  is the electric field strength,  $\varphi$  is the electric field potential.

The expression for the electric field is the differential form of Gauss's law:

$$\operatorname{div}(\varepsilon\varepsilon_0\vec{E}) = \operatorname{div}(\vec{D}) = 0.$$
(2)

Here  $\varepsilon$  and  $\varepsilon_0$  are the relative permittivities of the fluid and vacuum, respectively, *D* is the electric induction.

To calculate the flow of electric charges, it is necessary to add mathematical module of differential equations BODE for the accumulation of surface charge.

$$\frac{d\lambda}{dt} = j_{diff} + j_{geom}.$$
(3)

$$i_{accur} = -\frac{\lambda \, d\xi}{4} \tag{4}$$

$$j_{diff} = up(\sigma E_n) - down(\sigma E_n)$$
(5)

Here  $\lambda$  is the surface charge density, up and down represent the values of the function "above" and "below" the boundary,  $j_{diff}$  is the density of the electric current due to the charge conservation,  $j_{geom}$  is the change in the surface charge due to the movement of the surface.

The Navier-Stokes equation is used to describe the hydromechanical motion of a droplet:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u}, \nabla) \vec{u} = -\nabla p + \eta \Delta \vec{u}.$$
(6)

Here  $\vec{u}$  is the fluid velocity, *p* is the pressure,  $\rho$  is the mass density,  $\eta$  is the dynamic viscosity.

The boundary conditions are defined by the electric potential. The connection between the hydrodynamics and electrostatics modules is provided by the terms at the boundary of the two phases, corresponding to the surface tension force and the Coulomb force acting on a unit surface.

$$F_{st} = -2\gamma H \tag{7}$$

$$F_{c} = F_{n} + F_{\tau}$$

$$F_{c} = \frac{1}{2} \epsilon_{c} F_{c}^{2} - \frac{1}{2} \epsilon_{c} F_{c}^{2} - \frac{1}{2} (\epsilon_{c} - \epsilon_{c}) F^{2}$$
(8)

$$F_{\tau} = (\varepsilon_2 E_{n2} - \varepsilon_1 E_{n1}) E_{\tau}$$
(10)

Here  $\overrightarrow{F_{st}}$  is the surface tension force,  $\gamma$  is the interfacial tension, *H* is the mean curvature of the surface,  $\overrightarrow{F_c}$  is the Coulomb force,  $\varepsilon_2$  and  $\varepsilon_1$  is the outer and inner dielectric permittivities respectively,  $\overrightarrow{n}$  is the normal vector,  $\overrightarrow{\tau}$  is the tangent vector.

The boundary conditions are presented in Fig. 1.



Fig. 1. Boundary conditions.

Parameters of liquids are presented in the table 1. The changing surface area of the droplet should influence the surface charge density. Equation 3 came from the law of conservation of charge divided by area *S*:

$$\frac{d\lambda S}{dt} = I_{diff} \tag{11}$$

$$S\frac{d\lambda}{dt} + \lambda \frac{dS}{dt} = I_{diff}$$
(12)

Here  $I_{diff} = Sj_{diff}$ .

Now, if we use the expansion coefficient  $\xi = \frac{s}{s_0}$  of the surface element, we get the following:

$$\frac{d\lambda}{dt} + \frac{\lambda}{\xi S_0} \frac{d\xi S_0}{dt} = \frac{I_{diff}}{S}$$
(13)

$$\frac{d\lambda}{dt} = j_{diff} - \frac{\lambda}{\xi} \frac{d\xi}{dt}$$
(14)

Here  $\xi$  is the expansion coefficient of the surface element,  $S_0$  is the undeformed surface area.

Table 1: Properties of liquids

	Droplet	Oil
γ	16 m	N/m
ρ	1000 kg/m <sup>3</sup>	910 kg/m <sup>3</sup>
η	0.91 mPa×s	65 mPa×s
ε	80	2.85
σ	10 <sup>-7</sup> S/m	10 <sup>-11</sup> S/m

#### III. RESULTS AND DISCUSSION

A. Comparison of simulation results with DC and highfrequency AC fields

Firstly, consider the model in the case with a constant electric field at standard system parameters. The deformation is described by the expression:

$$D = \frac{a-b}{a+b}.$$
 (15)

Here D is the degree of the deformation, a is the major semi-axis, b is the minor semi-axis of an ellipse.



Fig.2. Time dependence of deformation.

It is also important to distinguish the accumulated charge at the droplet-oil boundary, and the forces acting on the droplet boundary (Fig.3 - 4). In this example, the charge has accumulated to a stationary value and it is important to compare its maximum value with the values of surface charge density amplitudes in cases with an alternating field, where the charging process will be visible.



Fig.3. Time dependence of the maximum of the surface charge density.



Fig.4. Normal component of the electric force distribution on the droplet surface.

Now let us consider a problem with an alternating electric field that varies in sine with a frequency of 500 Hz, i.e. with a period of 2 ms. Let us choose different cases:

case 1 - the period of oscillation of the alternating electric field is much longer than the Maxwell relaxation time  $(T >> \tau_m)$ ;

case 2 - the period of oscillation of the alternating electric field is approximately equal to the Maxwell relaxation time  $(T \approx \tau_m)$ ;

case 3 - the period of oscillation of the alternating electric field is much shorter than the Maxwell relaxation time ( $T \ll \tau_m$ ).

Considering these cases, we will see how the accumulated charge affects the resulting force acting on the surface of the droplet. This subsequently influences the type and magnitude of the deformation, which can be fundamental in some problems, such as the problems of electrocoalescence and spraying of droplets from the meniscus [6].

The same effective voltage value was used for DC and AC fields that equals to the 9 kV. We multiply the amplitude value of the voltage at the model boundaries by the square root of 2, since we want the effective value to correspond to the stationary case.



Fig.5. Time dependence of deformation for different cases.



Fig.6. Time dependence of deformation for different cases, zoom in.

The magnitude of the surface charge density on the droplet surface at different conductivities is shown here (Fig.7). As we can see, the accumulated charge becomes much lower at high field frequency. Table 2 lists the cases considered in the simulation.



Fig.7. Time dependence of the surface charge density for different cases.

In this paper, the presented liquid parameters are chosen for ease of modeling and to demonstrate possible cases. The illustrated effect will be seen also for a water droplet, but at higher frequencies.

Table 2: Cases of alternating electric field

Conductivity	Amplitude	Maximu	Relaxation
of the	surface charge	m	time, ms
droplet, S/m	density, C/m <sup>2</sup>	deformat	
		ion	

3x10 <sup>-7</sup> ,	3x10 <sup>-5</sup>	0.118	2.3
Stationary			$(T \approx \tau_m)$
$3x10^{-5}$	$4 \times 10^{-5}$	0.118	0.023
5/10	4710	01110	$(T >> \tau)$
1 2.10-6	$1 \leq 10^{-5}$	0.002	$(1 >> i_m)$
1.2X10 °	1.0X10*	0.092	$(\mathbf{T}_{2}) = \mathbf{i}$
0	0		$(1 \approx \tau_m)$
3x10 <sup>-9</sup>	3x10-8	0.085	230
			$(T \ll \tau_m)$

# IV. CONCLUSION

The frequency of the alternating electric field affects the magnitude of the accumulated surface charge on the surface of the droplet, which has a very strong influence on the type and magnitude of the deformation. Using the characteristic Maxwell relaxation time, three cases can be distinguished:

Case 1: The degree of deformation is practically unchanged,  $T \ll \tau_m$ ;

Case 2 – The degree of deformation changes significantly,  $T \approx \tau_m$ ;

Case 3 – The degree of deformation changes significantly,  $T \gg \tau_m$ .

In addition, the consistency of the type of the deformation with expression 10 in the case of a constant electric field was demonstrated, and a completely different outcome was obtained for an alternating electric field.

Further work on the model shall include the consideration of the charge convection along the droplet surface during rotational motion.

# REFERENCES

- G. O. Utiugov, V. A. Chirkov and I. A. Dobrovolskii. The experimental verification of electrodeformation and electrocoalecence numerical simulation based on the arbitrary Lagrangian-Eulerian method, *Proceedings of the 2020 IEEE 3<sup>rd</sup> International Conference on Dielectrics, ICD 2020*, 529-532, 2020.
- [2] R. Pillai, J.D. Berry, D. J. E. Harvie and M. R. Davidson. Electrolytic drops in an electric field: A numerical study of drop deformation and breakup, *Physics review*, 2015.
- [3] O. Vizika and D. A. Saville. The electrohydrodynamic deformation of drops suspended in liquids in steady and oscillatort electric fields, *Journal of Fluid Mechancs*, 1-21, 1992.
- [4] Xi Yang, Zhong Zeng, Jiayu Lu and Liangqi Zhang. Effect of alternating electric field frequency on deformation and coalescence of weakly conducting droplets, *Journal of Chongqing University*, 58-70, 2022.
- [5] Tao Liu, Bauyrzhan Sarsenbekuly and Wanli Kang. Breakdown mechanism and application of high frequency pilsed electric field-demulsifier combination on water-in-oil emulsion, *Colloid and Surfaces A: Physicochemical and Engineering Aspects*, 2025.
- [6] M. Rubio, P. Rodriguez-Diaz, J. M. Lopez-Herrera, M. A. Herrada, A. M. Ganan-Calvo and J. M.

Montanero. The role of charge relaxation in electrifed tip streaming, *Physics of Fluids*, 2023.

- [7] D. A. Saville. ELECTROHYDRODYNAMICS: The Taylor-Melcher Leaky Dielectric Model, *Annual Review of Fluid Mechanics*, 1997.
- [8] D. A. Kudinov, V. A. Chirkov, S. A. Vasilkov, I. A. Elagin. Features of numerical simulation of unsteady-state electric current passage processes in COMSOL Multiphysics in relation to the capacitive energy storage simulation, *Journal of Physics: Conference Series*. In Press.

# Energy analysis of 2D electro-thermo-hydrodynamic turbulent convection

Yifei Guan<sup>1\*</sup> and Jian Wu<sup>2</sup>

<sup>1</sup>Department of Mechanical Engineering, Union College, NY 12308, USA <sup>2</sup>School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

\*Corresponding author: guany@union.edu

*Abstract-* Turbulent convection is ubiquitous in fluid systems. In particular, multi-physical convection problems involve mass, heat, and particle transfer. When the particles are charged and driven by a high-voltage electric field, both buoyancy and electric forces contribute to driving and maintaining the convection. In this work, we perform numerical analysis using a high-fidelity Fourier-Chebyshev spectral solver. We further derive the dynamical systems governing the kinetic energy, the enstrophy, the potential energy, and the electric energy analytically. Finally, we perform a data-driven modal decomposition to show the coherent structures that contain energy in turbulent convection.

Keywords- Electro-thermo-hydrodynamic, energy analysis, coherent structures, model decomposition.

#### I. INTRODUCTION

Electro-thermo-hydrodynamic (ETHD) convection has been a research focus since its first introduction to model the geo-convection of the mantle [1, 2]. In recent years, many studies have focused on the linear stability analysis of the ETHD systems [3, 4] and transition routes to chaos [5, 6]. Despite the broad interests in the stability analysis of laminar or mildly chaotic ETHD convection, only a few studies have attempted to analyze the turbulent regime [7, 8]. In particular, the recent paper of our group presents the relationship between the potential energy and electric energy budgets and the kinetic energy dissipation [8].

In the current study, we follow up upon our recent work [8] to (1) derive the governing equations for kinetic energy, enstrophy, potential energy, and electric energy; (2) perform data-driven modal decomposition using the proper orthogonal decomposition (POD); and (3) compare the modal analysis and identify the coherent structures related to energy concentration.

The remainder of the paper is as follows. Section II discusses the dimensionless governing equations of the original 2D ETHD system and the dynamical systems of the energy terms. Section III and IV presents the numerical results and discussion. Conclusion and future work discussion is presented in Section V.

#### II. METHODOLOGY

#### A. Governing equations of the ETHD system

The dimensionless equations governing the ETHD system can be written as:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P + \nu \nabla^2 \mathbf{u} + F_E q \mathbf{E} + F_\theta \theta \mathbf{e}_y, \quad (2)$$

$$\frac{\partial q}{\partial t} + \nabla \cdot [q(\mathbf{u} + \mathbf{E})] = \nu_E \nabla^2 q, \qquad (3)$$

$$\nabla^2 \phi = -Cq/4,\tag{4}$$

$$\mathbf{E} = -\nabla\phi,\tag{5}$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta - u_y = \nu_{\theta} \nabla^2 \theta.$$
 (6)

Here,  $\mathbf{e}_y = (0, 1)$  is the unit vector pointing towards the y direction (opposite of gravity);  $\mathbf{u} = (u_x, u_y)$  is the 2D velocity vector; p is the pressure scalar;  $\mathbf{E} = (E_x, E_y)$  is the 2D electric field vector;  $\theta$  is the temperature anomaly defined as the difference between the temperature and conductive temperature profile ( $T_{\text{conduction}} = -y$ ); q is the net charge density; and  $\phi$  is the electric potential. Note that all parameters are dimensionless [8].

The system is controlled by the initial and boundary conditions, together with the six dimensionless parameters:  $\nu$  is the molecular viscosity;  $F_E$  is the electric forcing magnitude;  $F_{\theta}$  is the buoyancy forcing magnitude;  $\nu_E$ is the charged particle viscosity; C is the charge injection strength; and  $\nu_{\theta}$  is the thermal diffusivity.

#### B. Boundary conditions

The non-slip boundary condition  $(\mathbf{u}_{y=\pm h} = 0)$  are applied to the fluid flow at the upper (y = h) and lower (y = -h) planes. The boundary conditions of the other variables are listed as follows.

$$\phi_{y=-h} = 1, \ \phi_{y=h} = 0, \tag{7}$$

$$q_{y=-h} = 1, \ (\partial q/\partial y)_{y=h} = 0, \tag{8}$$

$$\theta_{y=\pm h} = 0. \tag{9}$$

In this work, we investigate 8 cases with the dimensionless parameters shown in Table.1. In addition to these four parameters, the other two dimensionless governing parameters remain constants:  $F_E = 250$  and  $\nu_E = 2.00 \times 10^{-4}$ . For Cases 1 and 5 where C = 0, the ETHD system reduces to the classical Rayleigh-Bénard Convection. The dimensionless parameters chosen here cover a broad range:  $Pr \in [7, 100], Ra \in [5 \times 10^7, 10^9]$ , and  $T \in [10^3, 4 \times 10^3]$ , where Pr is the Prandtl number, Ra is the Rayleigh number, and T is the Taylor number or electric Rayleigh number [8].

Case	ν	$F_{\theta}$	$ u_{ heta}$	C
1	0.050	$1.12 \times 10^{3}$	$7.14 \times 10^{-3}$	0
2	0.050	$1.12 \times 10^{3}$	$7.14 \times 10^{-3}$	10
3	0.033	$4.96 \times 10^{2}$	$4.76 \times 10^{-3}$	10
4	0.025	$2.79 \times 10^{2}$	$3.57 \times 10^{-3}$	10
5	0.10	$6.25 \times 10^{3}$	$1.00 \times 10^{-3}$	0
6	0.10	$6.25 \times 10^{3}$	$1.00 \times 10^{-3}$	10
7	0.050	$1.56 \times 10^{3}$	$5.00 \times 10^{-4}$	10
8	0.033	$6.94 \times 10^{2}$	$3.33 \times 10^{-4}$	10

 
 Table 1: Dimensionless parameters governing the dynamics of the turbulent ETHD convection

# *C. Kinetic, potential, and electric energy and enstrophy equations*

The kinetic energy,  $E_u = \frac{1}{2}\mathbf{u}^2 = \frac{1}{2}(u_x^2 + u_y^2)$ , can be obtained by multiplying the momentum equation by the velocity vector  $\mathbf{u}$  and domain averaging  $\langle \cdot \rangle_V$ :

$$\frac{\partial \langle E_u \rangle_V}{\partial t} = -\langle \epsilon_K \rangle_V + F_E \langle q \mathbf{u} \cdot \mathbf{E} \rangle_V + F_\theta \langle \theta u_y \rangle_V.$$
(10)

The enstrophy,  $\Omega = \frac{1}{2}\omega^2$ , where  $\omega = \nabla \times \mathbf{u}$ , can be obtained in a similar way:

$$\frac{\partial \langle \Omega \rangle_V}{\partial t} = -\langle \epsilon_\omega \rangle_V + F_E \langle \omega \nabla \times (q\mathbf{E}) \rangle_V + F_\theta \langle \omega \frac{\partial \theta}{\partial x} \rangle_V.$$
(11)

Here,  $\langle \epsilon_K \rangle_V = \nu \langle \omega^2 \rangle_V$ , and  $\langle \epsilon_\omega \rangle_V = \nu \langle |\nabla \omega|^2 \rangle_V$  are energy and enstrophy dissipation terms.

The potential energy,  $E_p = -F_{\theta}y(\theta - y)$ , can be obtained by multiplying the equation for  $\theta$  by y, followed by a domain averaging:

$$\frac{\partial \langle E_p \rangle_V}{\partial t} = F_\theta \nu_\theta (N_u - 1) - F_\theta \langle \theta u_y \rangle_V \qquad (12)$$

Here,  $N_u$  is the Nusselt number that varies in time. The potential energy equation is consistent with the previous studies on Rayleigh-Bénard Convection [9, 10].

Similarly, the electric energy,  $E_e = F_E q \phi$ , can be obtained by multiplying the equation for q by  $\phi$ , followed by a domain averaging:

$$\frac{\partial \langle E_e \rangle_V}{\partial t} = F_E \langle p_E \rangle_V - F_E \langle q \mathbf{u} \cdot \mathbf{E} \rangle_V \quad (13)$$

$$- F_E q \langle \nabla \phi \cdot \nabla \phi - \frac{\partial \phi}{\partial t} \rangle_V \tag{14}$$

$$- F_E \nu_E \langle \nabla \phi \cdot \nabla q \rangle_V. \tag{15}$$

Here,  $\langle p_e \rangle_V = \Delta \phi I_0 N_e / H$  is the total electric energy injection into the ETHD system across the boundary, where  $\Delta \phi$  is the electric potential difference between the lower and upper planes, and H is the height.  $I_e = \langle \mathbf{i} \rangle_{A, y=-1}$  and

Table 2: Domain and time averaged kinetic energy and enstrophy for 8 cases

Case	$\langle E_u \rangle_{V,t}$	$\langle \Omega \rangle_{V,t}$
1	50.68	1792.90
2	52.78	1891.20
3	27.88	978.97
4	21.85	722.85
5	49.98	1558.30
6	51.74	1598.10
7	16.90	489.90
8	12.34	340.15

 $N_e = I_e/I_0$  is the electric Nusselt number.  $I_0$  equals  $I_e$  at the hydrostatic state [11, 8].

The relation among the kinetic, potential, and electric energy can be summarized as follows.

$$\frac{\partial \langle E_u \rangle_V}{\partial t} = -D_u + \Phi_E + \Phi_\theta \tag{16}$$

$$\frac{\partial \langle E_p \rangle_V}{\partial t} = N_\theta - \Phi_\theta \tag{17}$$

$$\frac{\partial \langle E_e \rangle_V}{\partial t} = N_E - \Phi_E - D_{elec}$$
(18)

Here,  $D_u = \langle \epsilon_K \rangle_V$  is the viscous dissipation;  $\Phi_E = F_E \langle q \mathbf{u} \cdot \mathbf{E} \rangle_V$  is the electric energy transferred into kinetic energy;  $\Phi_{\theta} = F_{\theta} \langle \theta u_y \rangle_V$  is the potential energy transferred into kinetic energy;  $N_{\theta} = F_{\theta} \nu_{\theta} (N_u - 1)$  is the net potential energy injection by heat flux across the boundary;  $N_E = F_E \Delta \phi I_0 N_e / H$  is the net electric energy injection by current flux across the boundary; and  $D_{elec} = F_E q \langle \nabla \phi \cdot \nabla \phi - \frac{\partial \phi}{\partial t} \rangle_V + F_E \nu_E \langle \nabla \phi \cdot \nabla q \rangle_V$  is the electric dissipation [12, 8].

#### III. RESULTS

Table 2 shows the domain and time averaged kinetic energy and enstrophy for the 8 cases. It can be observed that for constant parameters, the electric field has a positive impact on both kinetic energy and enstrophy, by comparing Cases 1 and 2 or Cases 5 and 6. However, when  $F_{\theta}$  decreases, both the kinetic energy and the enstrophy decrease.

Next, we show the results of POD modal analysis of  $E_u$ ,  $\Omega$ ,  $E_p$ , and  $E_E$  of Case 8, as shown in Fig. 1. It can be observed that for all the energy-related properties, the first mode weights significantly over the others as its singular value is much larger than the second one. Furthermore, the first POD mode captures the large-scale dynamics (coherent structures) of the corresponding energy, as shown in the comparison between a snapshot and the first mode in Fig. 1. Also, the potential energy is more evenly distributed within



Figure 1: The POD analysis of  $E_u$ ,  $\Omega$ ,  $E_p$ , and  $E_e$  for Case 8.

the whole domain while the electric energy is more concentrated in the plume. The findings here are consistent with our previous results on  $\Phi_{\theta}$  and  $\Phi_{E}$  [8].

# IV. CONCLUSION

In this work, we analyze the energy terms in 2D ETHD turbulent convection systems. We first derive the governing equations (as in a dynamical system) of the kinetic energy, potential energy, and electric energy. We then remark the transitional terms ( $\Phi_{\theta}$  and  $\Phi_{E}$ ) which are the different contribution to kinetic energy due to potential energy and electric energy. This analysis completes the energy transfer picture described earlier in our previous work [8], and it is firstly reported in this work. Furthermore, we perform POD analysis on the energy terms and show that the coherent structure that contains the energy can be well described by the first POD mode. However, due to the same feature, POD analysis cannot reveal the information contained in small structures which may be important for turbulent modeling using e.g., large eddy simulations.

In our future work, we aim to extend our modal analysis by using different data-driven modal analysis such as dynamic mode decomposition (DMD), empirical mode decomposition (EMD), and variational mode decomposition (VMD) and compare their performance on analyzing the energy in a 2D ETHD turbulence system.

# REFERENCES

- M.J. Gross and J.E. Porter. Electrically induced convection in dielectric liquids, *Nature*, vol. 212, pp. 1343-1345, 1966.
- [2] F. Pontiga, A. Castellanos, and AT Richardson. The onset of overstable motions in a layer of dielectric liquid

subjected to the simultaneous action of a weak unipolar injection of charge and a thermal gradient, *The Quarterly Journal of Mechanics and Applied Mathematics*, vol. 45, pp 25-46, 1992

- [3] Y. Guan, X. He, Q. Wang, Z. Song, M. Zhang, and J. Wu. Monotonic instability and overstability in twodimensional electrothermohydrodynamic flow, *Physical Review Fluids*, vol. 6, pp. 013702, 2021
- [4] X. He and M. Zhang. On the flow instability under thermal and electric fields: A linear analysis, *European Journal of Mechanics-B/Fluids*, vol. 88, pp. 34-46, 2021
- [5] T.F. Li, Z.G. Su, K. Luo, and H.L, Yi. Transition to chaos in electro-thermo-convection of a dielectric liquid in a square cavity, *Physics of Fluids*, vol. 32, 2020
- [6] Q. Wang, Y. Guan, T. Wei, and J. Wu. Transition sequences and heat transfer enhancement in electrothermo-convection of a dielectric liquid between two parallel electrodes, *International Journal of Thermal Sciences*, vol. 179, pp.107705, 2022
- [7] A. Kourmatzis and J.S. Shrimpton. Turbulent threedimensional dielectric electrohydrodynamic convection between two plates, *Journal of Fluid Mechanics*, vol. 696, pp. 228-262, 2012
- [8] Y. Guan, Q. Wang, M. Zhang, Y. Zhang, and J. Wu. Numerical investigation of two-dimensional electrothermo-hydrodynamic turbulence: Energy budget and scaling law analysis, *International Journal of Heat and Mass Transfer*, vol. 247, pp. 127094, 2025
- [9] K.B. Winters, P.N. Lombard, J.J. Riley and E.A. D'Asaro. Available potential energy and mixing in density-stratified fluids, *Journal of Fluid Mechanics*, vol. 289, pp. 115-128, 1995.
- [10] G.O. Hughes, B. Gayen, and R.W. Griffiths. Available potential energy in Rayleigh–Bénard convection, *Journal of Fluid Mechanics*, vol. 729, pp. R3, 2013.
- [11] Y. Zhang, D.L. Chen, X.P. Luo, K. Luo, J. Wu, and H.L. Yi. Coulomb-driven electroconvection turbulence in two-dimensional cavity, *Journal of Fluid Mechanics*, vol. 980, pp. A22, 2024.
- [12] C.L. Druzgalski, M.B., Andersen, and A. Mani. Direct numerical simulation of electroconvective instability and hydrodynamic chaos near an ion-selective surface, *Physics of Fluids*, vol. 25, 2013.
- [13] L. Onsager. Deviations from Ohm's law in weak electrolytes, *Journal of Chemical Physics*, vol. 2, pp. 599–615, 1934.
- [14] A. Castellanos (ed). *Electrohydrodynamics*. Springer-Verlag, 1998.

- [15] J. E. Monzon. EHD of multi-phase flows, in *Proceedings of the 3rd Conference on Complex Fluids*, T. Taylor and G. Bachmann (ed.), pp. 50–53, 2021.
- [16] V. Medina, R. Valdes, J. Azpiroz, and E. Sacristan. Title of paper if known, unpublished.
- [17] E. H. Smith. A note on particles and cells manipulation, *Microfluidics and Nanofluidics*, in press.

# Visualization Of Electrohydrodynamic Convection Cells in a Phase Change Material Using Schlieren Imagery

E. Chariandy<sup>\*</sup>, J.S. Cotton <sup>1</sup>Department of Mechanical Engineering, McMaster University, \*Corresponding author: chariane@mcmaster.ca

*Abstract-* An experiment was designed to assess the potential of schlieren imagery for visualizing EHD induced convection cells in the liquid phase of a PCM (Phase Change Material). The motivation behind using this new methodology has been to avoid the potential error from seeding particle charging when using PIV (Particle Image Velocimetry). In PIV if the employed seeding particles have a different electrical permittivity to the working fluid, they can accumulate charge on their surface. This will lead to an additional coulomb force on the seeding particles which could be a significant source of error in the velocity measurement of the fluid. In this work, we use schlieren imagery to visualize EHD induced convection cells in the liquid phase of a PCM in a differentially heated macrocapsule. The methodology is totally non- intrusive and does not require joule heating to create the density gradients necessary for visualization. Instead, density gradients are created by differentially heating the macrocapsule. The advection of temperature gradients (density gradients) in the working fluid are recorded through a Z type schlieren system with a DSLR. Using a customized optical flow measurement code, the videos are converted into velocity field measurements. EHD induced jet velocities of 18mm/s are recorded with a 99.7% confidence interval of +/- 1.6mm/s

Keywords- Schlieren, Phase Change Material, Visualization, Heat Transfer

# I. INTRODUCTION

For several years, Latent Heat Thermal Energy Storage Systems (LHTESS) have been studied as a technique due to bridge the mismatch between energy supply and demand. Most LHTESS use organic PCMs (Phase Change Materials) as a working fluid. This is due to their chemical stability, relatively high latent heat of fusion, and low melting point [1]. However, a drawback of organic PCMs is that they have a very low thermal conductivity (~0.3 W/mK) [2, 3]. This restricts heat transfer to the PCM and results in either a slow rate of "charging" (time for the PCM to melt) or requirement for a higher temperature heat source for the desired rate of heat transfer.

Several methods have been implemented to improve the rate of heat transfer within PCMs. These methods can be divided into passive and active techniques. The main advantage of passive techniques is that they do not require an external power source. However, passive techniques are unable to control heat transfer with respect to the system demands [4], and as a result tend to have a comparatively lower limit in heat transfer enhancement. Some of the most studied passive techniques are the usage of extended surfaces, thermal conductivity enhancement, as well as microencapsulation of the PCM [5, 6]. Lacroix et. al [7] investigated the efficacy of extended surfaces for heat transfer enhancement for PCMs numerically and found that melting time could be reduced by 70%, but with a 7% reduction in the capacity of the PCM cavity due to the space taken by the fins. Veraj et. al [8] reported a similar issue when attempting to enhance the thermal conductivity by adding thermal conductive rings in the cavity. They were able to reduce melt time by 88%, but the rings occupied 20% of the cavity.

A promising new method of active heat transfer enhancement is electrohydrodynamics (EHD). EHD involves the application of an electric field to the liquid phase of the PCM. This applies a body force on the liquid PCM that will drive motion, resulting in a highly efficient [10] type of forced convection. This mechanism of heat transfer enhancement is analogous to mechanical stirring, however with the advantage of no moving parts to take up space within the cavity like some passive methods [10-12].

In recent years there has been much interest in studying the mechanism of heat transfer enhancement from EHD induced convection in LHTESS. The motivation is that with an improved understanding of the mechanism, more efficient EHD LHTESS can be optimally designed. These systems would feature an optimized configuration of electrodes to maximize convection heat transfer induced by EHD. Alternatively, a more efficient electrode configuration would also allow for the desired heat transfer enhancement at lower voltages/electric fields. This reduces the risk of dielectric breakdown, degradation in material properties, and cost to implement the EHD solution.

Various studies have attempted to study EHD convection cells [13-17] using PIV. However, these studies used a time averaged velocity field. To gain further insight into the transient behaviour of EHD induced convection, we have designed an experiment that uses Schlieren imagery to visualize EHD induced jets in live time. This allows the study of transient behaviour of the jets during the melting process.

# II. METHODOLOGY

# A. Test Cell



Fig. 1 Test cell schematic. "Bumped" electrode on left side, and "Flat" electrode on right.

The test cell is an acrylic cavity designed to melt a PCM in a vertically oriented configuration and visualize the EHD driven convection cells in the liquid phase. The PCM used for the present experiment was octadecane, as its melting temperature is slightly above room temperature (28°C) which reduces heat loss through the sides of the test-cell. The thermophysical and electrical properties of octadecane from literature [2, 18] are summarized in table 1.

	Table 1	
Property	Value	
$T_m$	28.0	°C
$c_{p,l}$	2.24	kJ/(kg K)
$C_{p,s}$	1.90	kJ/(kg K)
$k_l$	0.16	W/(m K)
k <sub>s</sub>	0.32	W/(m K)
$\rho_l$	775.6	$kg/m^3$
$ ho_s$	867.0	$kg/m^3$
H <sub>fusion</sub>	243.7	kJ/kg K

On opposing ends of the cavity are copper electrodes. The "bumped" electrode on the left in figure 1 is heated at a constant temperature, while the "flat" electrode is insulated. The test cell inner cavity measures 118 mm x 20 mm x 32 mm in dimensions with the electrodes in place, where 118 mm is the vertical height of the cavity and 20 mm is the spacing between electrodes. The solid PCM occupies the space between the electrodes and then expands into a 20 mm air gap above the electrodes as it melts. The "bumped" electrode features 10 semi-circular profiles, with a radius of 3mm. This choice in configuration was motivated from observations from Nakhla et. al [19], where they found that the heat transfer coefficient within the liquid PCM was greatest between rows of cylindrical electrodes. The goal of this configuration was to create an electric field of a similar profile to Nakhla et. al's [19] cylindrical rows, with less complexity.

The bumped electrode is heated by a Kapton polyimide heater located outside the inner cavity. The heater is electrically insulated from the electrode by a 1mm thick layer of acrylic. This configuration was chosen as opposed to the previously employed thermal baths [10,19-20] to reduce complexity in electrically insulating the heater.

# B. Schlieren System

The test cell was placed in the interrogation area of a Z type schlieren system, and the flow was visualized using a Canon DSLR. The benefit of using a DSLR is that the flow could be viewed in live time. This was convenient for studying the long-term evolution of the flow (> 1 min) without the need for excessive storage.



Fig. 2 Schlieren system schematic. Test section is placed such that the top of the cell is out of the page. Schlieren system is z type.

The viewing area of the schlieren system is a 20 mm x 30 mm rectangle as shown in figure 3.



Fig. 3 Camera viewing area schematic. Viewing area for visualization is highlighted by black outline. The melt fraction depicted here is a rough depiction of  $\sim$ 60% melt fraction, showing the effect of natural convection on the melt front.

# C. Optical Flow Measurement

The fluid velocity was measured using a customized optical flow measurement code implemented in MATLAB. The code interprets each image from the video of the flow (as seen through Schlieren) as a 1080 x 1920 matrix of light intensities. It assumes that between each set of frames the overall light intensity is conserved, or in partial terms:

$$\Delta I \cdot \vec{U} = -\frac{\partial I}{\partial t} \tag{1}$$

Equation 1 is the optical flow equation, which relates spatial and temporal light intensity (I) distributions to the velocity field  $(\vec{U})$ . For a 2D problem, there are two unknowns  $(\partial x/\partial t, \partial y/\partial t)$  and one equation, so an additional equation is required for closure. This is known as the "aperture" problem. There are several closure
solutions to this problem; in this case we used the Farneback method [21].

The optical flow measurement code then divides the video into groups of two adjacent frames (i.e. frame 1 and 2, frame 2 and 3...) and calculates a velocity field between each set of frames. The output velocity measurement for the video is the average of all the velocities fields measured from each frame set, so for a video of 100 frames there will be 99 unique frame sets and corresponding velocity field measurements that are averaged.

#### **III. RESULTS**



Fig. 4 Velocity field magnitude 8kV. 50% melt fraction, in 10 second intervals: a) 0s, b) 10s, c) 20s, d) 30s, e) 40s, f) 50s, g) 60s

Initially the heater was turned on and left to melt the PCM in the absence of electro-convection. Once the test cell had reached approximately 50% melt fraction the high voltage power supply was turned on and 8kV was applied across the electrodes, and the DSLR started recording the flow.

When the applied voltage was increased to 8 kV, jets of a maximum velocity of ~18 mm/s formed around the apex of each "bump" on the electrode. In figure 4 we can see the temporal evolution of the velocity field for 8 kV applied voltage in 10 second intervals, where time 0 s, is 1 second after the voltage was applied. For discussion we will refer to the jets originating from each bump as "top", "middle" and "bottom" jets, where the top jet is centered at +10 mm in the y axis, the middle is 0 mm and bottom is -10 mm.

Immediately after 8 kV was applied (fig 4 a), the jets were roughly horizontal in orientation, this suggests that the electric forces are dominant over natural convection.

At 20 seconds after 8 kV was applied the top two jets started to interact with each other and appeared to be drawn together (fig 4 c). After 40s the top jet splits into two separate streams and becomes weaker (maximum velocity reduced from 18 mm/s to 14 mm/s) (fig 6 d). Although it was not visible on the camera, it appears that

this is due to the top jet interacting with the jet from the bump above the camera viewing area.

#### IV. DISCUSSION

The mechanism of jet transience is of interest to us, as previous experiments have only studied the steady flow induced from charge injection. The transience in the jets can originate from several sources. For example, we can expect flow instabilities in the shear layer between the jet and the recirculation zone, like those found in turbulent jets. An instability in the flow structure will lead to a change in the space charge distribution, which will change the magnitude and direction of the applied electrical force to the fluid. This could either suppress or exacerbate the instability.

It is also hypothesized that the changing melt front shape may interact with the flow structure. Besides functioning as a wall for the jet, the solid PCM also represents a change in the charge transport mechanism, as there is no advection, and the ionic mobility is greater (roughly by one order)  $1E - 7 m^2 V^{-1} s^{-1}$  [22].

With this in mind, we propose two potential mechanisms for the jet splitting seen in figures 4 d): Initially the jet forms in the direction of shortest distance (the horizontal direction) with the maximum electric field strength toward the opposite PCM. However, as the jet impact point melts faster, the distance increases, and the electric field strength decreases. This causes the jet to shift toward the periphery of the original impact area where the electric field strength is higher. This process creates a periodic formation that alternates between horizontal and oblique directions. The low velocity may be a result of the flow forming as a ring-like jet. In addition, the jets advects charge the same polarity of the electrode on to the nearby PCM, which accumulates. This accumulation of charge reduces the electric field strength between the bumped electrode and the PCM, thus preventing the EHD jet from propagating toward the horizontal direction. Consequently, the flow is directed toward the periphery of the charged area, which is an uncharged region where the electric field strength is stronger. As the charge accumulates in this area, the flow shifts back as the charge in the initially charged area is transported away and reduced. This fluctuation repeats, causing the position of the flow to oscillate.

## V. CONCLUSION

In this work, we have developed a new methodology to study the transient behaviour of EHD induced convection in PCMs. Using Schlieren imagery, we have seen that in the time scaler of ~10s, EHD jets can interact with each other, and change in direction and strength significantly.

## REFERENCES

 B. Zalba, J.M. Marın, L.F. Cabeza, H. Mehling Review on thermal energy storage with phase change: materials, heat transfer analysis and applications Appl. Therm. Eng., 23 (3) (2003), pp. 251-283
 G.J. McGranaghan, A.J. Robinson, The mechanisms

of heat transfer during convective boiling under the influence of AC electric fields, Int. J. Heat Mass Tran., 73 (2014), pp. 376-388

[3] M Faden, S Hhlein, J Wanner, et al., Review of Thermophysical Property Data of Octadecane for Phase-Change Studies, Materials 12 (18) (2019) 2974.
[4] Alam, Tabish, and Man-Hoe Kim. "A comprehensive

review on single phase heat transfer enhancement techniques in heat exchanger applications." Renewable and Sustainable Energy Reviews 81 (2018): 813-839 [5] S. Jegadheeswaran, S.D. Pohekar Performance enhancement in latent heat thermal storage system: a review Renew. Sustainable Energy Rev., 13 (9) (2009), pp. 2225-2244

[6]1F. Agyenim, N. Hewitt, P. Eames, M. Smyth A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS) Renew. Sustainable Energy Rev., 14 (2) (2010), pp. 615-628

[7] M. Lacroix, M. Benmadda Numerical simulation of natural convection-dominated melting and solidification from a finned vertical wall Numer. Heat Transfer A Appl., 31 (1) (1997), pp. 71-86

[8] R. Velraj, R.V. Seeniraj, B. Hafner, C. Faber, K. Schwarzer Heat transfer enhancement in a latent heat storage system Sol. Energy, 65 (3) (1999), pp. 171-180 [9] D. Nakhla, J.S. Cotton, Effect of

electrohydrodynamic (EHD) forces on charging of a vertical latent heat thermal storage module filled with octadecane, Int. J. Heat Mass Transf. 167 (2021) 120828, https://doi.org/10.1016/j.

## ijheatmasstransfer.2020.120828.

[10] J.E. Bryan, J. Seyed-Yagoobi Influence of flow regime, heat flux, and mass flux on electrohydrodynamically enhanced convective boiling J. Heat Transfer, 123 (2) (2001), p. 355 [11] H. Sadek, A.J. Robinson, J.S. Cotton, C.Y. Ching, M. Shoukri Electrohydrodynamic enhancement of intube convective condensation heat transfer Int. J. Heat Mass Transfer, 49 (9-10) (2006), pp. 1647-1657 [12] G. McGranaghan, A.J. Robinson EHD augmented convective boiling: flow regimes and enhanced heat transfer Heat Transfer Eng., 35 (5) (2014), pp. 517-527 [13] Z. Sun, P. Yang, K. Luo, J. Wu, Experimental investigation on the melting characteristics of noctadecane with electric field inside macrocapsule, Int. J. Heat Mass Transf. 173 (2021) 121238, https://doi.org/10.1016/j. ijheatmasstransfer.2021.121238.

[14] Z. Sun, Y. Zhang, K, Luo, A. Perez, H. Yi, J. Wu, Experimental investigation on melting heat transfer of an organic material under electric field, Experimental Thermal and Fluid Science 131 (2022) 110530 [15] Z. Sun, D. Sun, J. Hu, P. Traoré, H.-L. Yi, J.
WuExperimental study on electrohydrodynamic flows of a dielectric liquid in a needle-plate configuration under direct/alternating current electric fieldJ. Electrostat., 106 (2020), p. 103454, 10.1016/j.elstat.2020.103454
[16] V.A. Chirkov, S.A. Vasilkov, Y.K. Stishkov, The role of field-enhanced dissociation in electrohydrodynamic flow formation in a highly non-uniform electric field, J. Electrostat. 93 (2018) 104–109.
[17] Louste, C., Romat, H., Traore, P., Daaboul, M., Vazquez, P., & Sosa, R. (2018). Electroconvective Cavity Flow Patterns Created by Asymmetric Electrode

Configuration. IEEE Transactions on Industry Applications, 54(5), 4851–4856.

## https://doi.org/10.1109/TIA.2018.2843797

[18] P. Zhang, Z.W. Ma, R.Z. Wang, An overview of phase change material slurries: MPCS and CHS, Renew. Sustain. Energy Rev. 14 (2010) 598–614, https://doi. org/10.1016/j.rser.2009.08.015.

[19] D. Nakhla, H. Sadek, J.S. Cotton, Melting performance enhancement in latent heat storage module using solid extraction electrohydrodynamics (EHD), Int.J. Heat Mass Transf. 81 (2015) 695–704.

[20] D. Nakhla, E. Thompson, B. Lacroix, J.S. Cotton, Measurement of heat transfer enhancement in melting of n-Octadecane under gravitational and

electrohydrodynamics (EHD) forces, J. Electrostat. 92 (2018) 31–37.

[21] Farneback, G. "Two-Frame Motion Estimation Based on Polynomial Expansion." In Proceedings of the 13th Scandinavian Conference on Image Analysis, 363 -370. Halmstad, Sweden: SCIA, 2003.

[22] Deepak Selvakumar, R., Wu, J., Ding, Y., & Alkaabi, A. K. (2023). Melting behavior of an organic phase change material in a square thermal energy storage capsule with an array of wire electrodes. *Applied Thermal Engineering*, 228.

https://doi.org/10.1016/j.applthermaleng.2023.120492

## Coupling Characteristics of Shock Waves Induced by Nanosecond Pulse Three-Electrode Dual-Spark SDBD and Plasma Diagnostics

Fangyuan Wang<sup>1</sup>, Nan Jiang<sup>1</sup>, Jie Li<sup>1\*</sup> <sup>1</sup>Department of Electrical Engineering, Dalian University of Technology, Dalian, \*Corresponding author: lijie@dlut.edu.cn

Abstract- Ice accumulation on windward components of the wind turbine can lead to a significant reduction in efficiency and even trigger security incidents. This work introduces a novel three-electrode dual-spark discharge structure, that combines both common streamer discharge mode for deicing and spark discharge mode for ice removal via shockwaves. Pre-position two symmetrical tips in this reactor could induce a large accumulation of charge. This will strengthen the localized electric field under the same power supply excitation, thereby facilitating the simultaneous discharge of two sparks. The characteristics in different discharge stages and the discharge mode transition are investigated using both electrical and optical diagnostics. Additionally, the spatiotemporal evolution of aerodynamic performance induced by pulse spark discharge is examined through schlieren imaging system. It was observed that simultaneous dual-spark discharge leads to the formation of two shock waves simultaneously. And a pronounced enhancement of pressure wave intensity is observed at the interaction region of the two shockwaves. Simultaneous dual-spark discharges exhibit potential to enable multi-point ice breakdown and reduce discharge intensity required for effective deicing. What's more, these intersections do not affect the propagation behavior, thus preserving the waves' independent propagation properties.

## Keywords- Spark discharge, shock wave, pulsed discharge, plasma deicing.

## I. INTRODUCTION

With the rapid development of the world economy, lots of countries are increasingly demanding energy resources. Wind power generation, recognized for its costeffectiveness and eco-friendly characteristics, now ranks as the third most significant energy source globally. Furthermore, wind turbines are extensively installed in cold regions due to their abundant wind resources[1]. In these environments, turbine blades are prone to ice accumulation, which can significantly reduce energy conversion efficiency[2], shorten blade service life, and potentially cause safety incidents. Although a range of methods have been proposed and applied for de-icing, there is a series of issues still far from being completely addressed, including environmental impact and highenergy consumption.

To overcome these obstacles, a plasma-based technique using the traditional two-electrode surface dielectric barrier discharge (SDBD) for deicing has received growing attention in recent years because of fast reaction time[3], low power consumption, and pollutionfree[4]. Based on the gas heating mechanism, the traditional pulsed SDBD can not only generate thermal effects for de-icing[5] but also induce weak shock waves[6]. However, the intensity of these shock waves is too weak to achieve direct ice removal. Subsequently, a three-electrode configuration is developed to enhance the intensity of the discharge and the shock wave. A second grounded electrode (GE) is arranged on the same side of high voltage (HV) electrode, which can generate pulsed unilateral spark discharge between the HV electrode and the grounded electrode. A single pulsed discharge can generate only one shockwave, and a distinct ice - breaking effect can be achieved after several consecutive pulsed discharges. [7].

To further enhance the shock wave intensity, a threeelectrode dual-spark SDBD actuator was proposed, which enables simultaneous dual-spark discharge. Electrical and optical diagnostics were employed to investigate the two operational modes of the reactor: streamer discharge and spark discharge. Considering the randomness of spark discharge, statistical studies on the spark mode transition were emphasized to guide subsequent applications. The generation and coupling characteristics of single-pulse shock waves were examined using a Schlieren system, along with an assessment of the aerodynamic performance in continuous discharge operation.

## II. EXPERIMENTAL SETUP

A schematic diagram of electrical and optical diagnostics for three-electrode dual-spark pulsed SDBD is presented in figure 1. HV pulse (HVP-20P, Xi'an Smart Maple Electronic Technology Co. Ltd., China) is applied on the HV electrode to produce the plasma. The applied pulse on HV electrode and current crossed the gap are measured through voltage probe (Tektronix P6015A) and current probe (Tektronix P6021A), respectively. Both of them are linked with the digital phosphor oscilloscope (Tektronix DPO 3012) to obtain the wave-forms. In order to investigate the discharge modes, images are taken through Intensified Charge-Coupled Device (ICCD)camera (Andor DH334T-18U-03 equipped with Canon 50mm f/1.8 UV lens). And the ICCD is synchronized with the HV pulse via a signal exported from pulse power.

To make an effective observation of pulsed surfacespark discharge, the tip with an angle of 90° for HV electrode and the second grounded electrode are arranged on the same surface of barrier dielectric. Both of them are made of copper foil with thickness of 0.1 mm. Two highvoltage (HV) electrodes are symmetrically arranged, measuring 5 mm in length and 6 mm in width. And the second grounded electrode features a rectangular configuration with 20 mm length and 2 mm width. The discharge gap between HV electrode and second grounded electrode is set at 5 mm. The barrier dielectric is epoxy resin with the 0.8 mm thickness. On the other surface of barrier dielectric, the first grounded electrode constructed from 0.1-mm-thick copper foil with dimensions of 32 mm  $\times$  20 mm, is placed under the HV electrode and second grounded electrode can enhance the electric field strength around the HV electrode region, which is beneficial for the initial discharge.





To systematically observe shock waves generation and propagation, a Schlieren system is configured as schematically shown in Figure 2. The optical assembly comprised a tungsten halogen lamp (24 V, 300 W) as the light source. The emitted beam passed through a pinhole spatial filter, reflected off a flat mirror onto a concave mirror. Two parabolic mirrors ( $\Phi$ =30 cm, f/10) subsequently collimated the beam to establish a parallel light field. The modulated light was then redirected via another flat mirror through a knife-edge aperture before being captured by a high-speed camera (Phantom VEO1010L-36G), enabling time-resolved visualization of compressible flow density gradients.



Fig. 2. Schlieren system

## III. RESULTS

## A. Electrical and optical characteristics of streamer-tospark transition

The plasma discharge topography and electrical characteristics of the streamer discharge under a pulse peak voltage, pulse repetition rate, and pulse width of 14 kV, 1 kHz, and 50 ns, respectively, are shown in figure 3(a) (b). It can be observed from the current waveform that there are three discharge phases that exist during the overall discharge. They are primary streamer, transitional streamer and secondary reverse streamer, which are reported in [8]. The plasma topography demonstrates that more intense discharge occurs at the high-voltage electrode tip, resulting from its reduced curvature radius that concentrates charges and intensifies the local electric field. The streamer discharge will induce heat generation for deicing through the mechanism of fast heating of gas. This is the most widely used approach for SDBD-based deicing currently.

As the applied voltage increases, the HV electrode tip will induce spark discharge. Figures 3(c) and 3(d) are obtained under a pulse peak voltage, rising time and pulse width of 20 kV, 50 ns and 50 ns, respectively. And figure 3(c) was taken by an ICCD camera with the gate width of 5 ns at 220 ns after voltage application. This nanosecondscale observation confirms the simultaneous occurrence of bilateral spark discharge, a phenomenon previously unreported in SDBD research. This is because pre-position two symmetrical tips in this reactor could induce a large accumulation of charge. This will strengthen the localized electric field under the same power supply excitation, thereby facilitating the simultaneous discharge of two sparks.

After the spark voltage of 20 kV was applied, the first discharge current corresponding to the streamer phase

sustains at 72 ns, as shown in Fig.3(d). Then, the current rises sharply while the voltage collapses rapidly, indicating the onset of spark breakdown. And the current reaches a maximum of 138 A at 94 ns. The voltage collapse cannot sustain the high current, leading to gradual current decrease. During 408-2360 ns, an underdamped oscillatory current tail appears, which is because the single-pulse spark discharge system can be modeled as an energy-storing RLC circuit. During discharge, the capacitive energy releases through the nonlinear plasma channel, where dynamic circuit impedance variations and capacitor-inductor energy exchange generate the underdamped oscillatory waveform[9,10].



Fig. 3. (a) Plasma photograph and (b) voltage-current (U-I) waveform during the streamer phase; (c) ICCD image and (d) U-I waveform during the spark phase.

Subsequent studies revealed that the reactor exhibits two additional discharge modes under varying voltages: left unilateral spark and right unilateral spark. Since the breakdown voltage changes from shot to shot, a statistical experiment of 420 breakdowns was performed. The time interval between each measurement is 30s. While the lowest breakdown voltage is only 11.5 kV, the highest one reaches 18.5 kV. Therefore, there are 60 discharges in each voltage range in figure 4. The 11-12 kV range represents the critical breakdown voltage where both streamer and spark discharges coexist. As the voltage increases, the streamer discharge mode gradually disappears, accompanied by a declining probability of unilateral spark formation and an increasing probability of bilateral spark occurrence. This phenomenon occurs because the increased voltage enhances energy injection from the power source, thereby facilitating the ignition of bilateral spark discharge. Furthermore, the probability of dual-spark discharge can reach over 88% under singlepulse excitation when the voltage is above 16 kV. This establishes the fundamental basis for potential application of bilateral spark discharge in de-icing technologies.



Fig. 4. Probability density distribution of breakdown voltage.

## B. Aerodynamic performance diagnosis in spark stage

Captured by the Schlieren system, figure 5 shows the shock waves generated by surface spark discharges induced by the first pulse and subsequent pulses, respectively. During experiments, the high-speed camera was set with a sampling rate of 51,000 fps and an exposure time of 5.0 µs. The results demonstrate that simultaneous discharges from two spark channels induce two shock waves concurrently. This phenomenon occurs because spark discharge significantly enhances fast gas heating, causing thermal expansion that generates pressure waves. The two shock waves then propagate outward over time. Furthermore, the light - dark gradient in the schlieren image is positively correlated with the intensity of the shock wave. At 22 µs, a pronounced enhancement of pressure wave intensity is observed at the interaction region of the two shockwaves. This enhancement results from vector superposition of pressure waves at the intersection. In practical applications, this effect reduces the required surface discharge intensity for equivalent ice removal, thereby mitigating dielectric aging. Furthermore, the simultaneous generation of dual spark discharges enables multi-point breakdown in de-icing applications, improving operational efficiency. What's more, these intersections do not affect the propagation behavior, thus preserving the waves' independent propagation properties.

In the process of impact propagation generated by subsequent pulses, there is airflow disturbance in the discharge area, forming a gas disturbance similar to the formation of a synthetic jet from the discharge area to the upper space. The height of the airflow disturbance continues to grow with the increase of the number of pulses. The height of the airflow disturbance increases from 11 mm when the number of pulses is 2 to 33.2 mm when the number of pulses is 10. The reason for the airflow disturbance is that on the one hand, the heat continues to accumulate to achieve the effect of temperature rise, thus forming an upward airflow disturbance. On the other hand, after the shock wave is formed and propagated, a negative pressure zone is formed in the discharge zone. The air on both sides of the high-voltage electrode and the second grounding electrode flows into the negative pressure zone, which makes the

bottom size of the air disturbance smaller. After the air enters the negative pressure zone, it will collide with the surface of the medium, which further leads to the upward growth of the air disturbance. In the actual deicing application, these airflow disturbances are conducive to promoting heat conduction and heat convection to the surrounding air, and promoting the formation of a large area of temperature rise.



Fig. 5. Schlieren images under the pulse voltage of 20 kV and pulse frequency of 1 kHz (a) shock wave in first pulse and (b) shock wave in subsequent pulses

## V. CONCLUSION

In summary, a novel three-electrode dual-spark SDBD actuator capable of simultaneously generating two spark discharges has been developed and investigated experimentally. Different electrical characteristics and discharge morphologies indicate that streamer discharge and surface-spark discharge appear in the sequential pulse. The probability of dual-spark discharge exceeds 90% under single-pulse excitation when the voltage is above 16 kV. And a pronounced enhancement of pressure wave intensity is observed at the interaction region of the two shockwaves. What's more, these intersections do not affect the propagation behavior, thus preserving the waves' independent propagation properties. During continuous pulsed discharges, gas jet phenomena emerge due to thermal energy accumulation.

## ACKNOWLEDGMENT

This work has been supported by National Natural Science Foundation of China (Grant No. 52177130 and No. 52377137).

- Tautz-Weinert J, Yürüşen N Y, Melero J J and Watson S J 2019 Sensitivity study of a wind farm maintenance decision - A performance and revenue analysis *Renewable Energy* 132 93–105
- [2] Pinar Pérez J M, García Márquez F P and Ruiz Hernández D 2016 Economic viability analysis for icing blades detection in wind turbines *Journal of Cleaner Production* **135** 1150–60
- [3] Zhu Y, Wu Y, Wei B, Xu H, Liang H, Jia M, Song H and Li Y 2020 Nanosecond-pulsed dielectric barrier discharge-based plasma-assisted anti-icing: modeling and mechanism analysis *J. Phys. D: Appl. Phys.* 53 145205

- [4] Liu Y, Kolbakir C, Hu H and Hu H 2018 A comparison study on the thermal effects in DBD plasma actuation and electrical heating for aircraft icing mitigation *International Journal of Heat and Mass Transfer* **124** 319–30
- [5] Tian Y, Zhang Z, Cai J, Yang L and Kang L 2018 Experimental study of an anti-icing method over an airfoil based on pulsed dielectric barrier discharge plasma *Chinese Journal of Aeronautics* **31** 1449–60
- [6] Takashima (Udagawa) K, Zuzeek Y, Lempert W R and Adamovich I V 2011 Characterization of a surface dielectric barrier discharge plasma sustained by repetitive nanosecond pulses *Plasma Sources Sci. Technol.* **20** 055009
- [7] Peng B, He J, Liu Z, Yao X, Jiang N, Shang K, Lu N, Li J and Wu Y 2019 Ice-breaking by three-electrode pulsed surface dielectric barrier discharge: breakdown mode transition *J. Phys. D: Appl. Phys.* 52 50LT01
- [8] Peng B, Shang K, Liu Z, Yao X, Liu S, Jiang N, Lu N, Li J and Wu Y 2020 Evolution of three-electrode pulsed surface dielectric barrier discharge: primary streamer, transitional streamer and secondary reverse streamer *Plasma Sources Sci. Technol.* 29 035018
- [9] Oshita D, Hosseini S H R, Miyamoto Y, Mawatari K and Akiyama H 2013 Study of underwater shock waves and cavitation bubbles generated by pulsed electric discharges *IEEE Transactions on Dielectrics and Electrical Insulation* **20** 1273–8
- [10] Oshita D, Hosseini S H R, Mawatari K, Nejad S M and Akiyama H 2014 Two successive shock waves generated by underwater pulse electric discharge for medical applications *IEEE Transactions on Plasma Science* 42 3209–14

## Enhanced Hydrogen Production Through Plasma Methane Decomposition With Soot

K. Kurokawa<sup>1\*</sup>, E. Takahashi<sup>2</sup>

<sup>1</sup> Graduate School of Industrial Technology, Nihon University, Japan <sup>2</sup>College of IndustiralTechnology, Nihon University, Japan \*Corresponding author: takahashi.eiichi@nihon-u.ac.jp

Abstract- Hydrogen production via methane decomposition was investigated utilizing plasma generated by an ignition coil, which is an inductive high-voltage power source. The ignition coil generates warm plasma with a submillisecond pulse width and adjustable energy, controlled by varying its charging duration, referred to as dwell time (DT). The dependency of hydrogen production on DT indicated that the long-pulse inductive component enhances hydrogen generation. Furthermore, frequency-dependent analysis revealed that the formation of discharges interacting with product gases produced by pre-discharges improves efficiency. The phenomenon might be attributed to interactions with soot and/or polycyclic aromatic hydrocarbons (PAHs) potentially formed during previous discharges. A comparison of the specific energy required for hydrogen production demonstrated that the values obtained in this study were nearly comparable to the previously reported best values.

Keywords- hydrogen, methane decomposition, warm plasmas, ignition coil.

## I. INTRODUCTION

Hydrogen (H<sub>2</sub>) is expected to play an important role for realizing decarbonized society. Currently, research and development on electrolysis as a method for H<sub>2</sub> production utilizing renewable energy are being actively pursued. Meanwhile, methane (CH<sub>4</sub>) decomposition has been gained attention in recent years due to its lower enthalpy requirement compared to water electrolysis and the potential for utilizing the carbon byproduct as a feedstock, thereby facilitating overall cost benefits [1-3]. In particular, CH<sub>4</sub> decomposition using non-thermal plasma has excellent switch on/off characteristics, making it suitable for the use of electricity derived from renewable energy sources.

H<sub>2</sub> production via CH<sub>4</sub> decomposition using plasmas has been extensively studied [3]. Warm to hightemperature plasmas have demonstrated relatively high efficiency for H<sub>2</sub> production. Zhang et al. utilized a rotating gliding arc discharge to decompose CH<sub>4</sub> diluted with N<sub>2</sub>, achieving a specific energy consumption (SEC) for H<sub>2</sub> of 14.3 kJ/NL [4]. Spectral analysis of the C<sub>2</sub> molecule highlighted its warm plasma characteristics, revealing vibrational temperatures in the range of 0.56-0.86 eV and rotational temperatures between 1325-1986 K. Moreover, reduced N2 dilution improved both SEC and H<sub>2</sub> selectivity. Morgan et al. employed a pulsed DC discharge with pipe electrodes in pure CH4 gas and reported an SEC of 23.5 kJ/NL [5]. The estimated vibrational and rotational temperatures in their study were 12130 K and 2873 K, respectively. Kheirollahivash et al. achieved an energy yield of 8.73 kJ/NL by creating an arc discharge between a rotating electrode and a helicalshaped electrode, effectively preventing short circuits caused by carbon filaments [6].

These discharges, characterized by relatively high  $H_2$  production efficiency, are initiated when the gap voltage reaches the discharge threshold. However, the initiation

timing is spontaneous, and the power input is influenced not only by voltage but also by several parameters such as gap distance and gas flow rate, which complicates precise control. In contrast, the use of inductive power supplies, such as ignition coils, enables the formation of longduration pulsed discharges with greater control. Ignition coils allow for easy manipulation of inductive energy accumulation time and discharge frequency through the input of external pulses. To the best of the authors' knowledge,  $CH_4$  decomposition and  $H_2$  generation using ignition coil-powered discharges have not been previously reported.

In this study,  $CH_4$  decomposition experiments were conducted using an ignition coil to investigate the dependence of  $H_2$  production on discharge frequency and coil energy storage through optical emission spectroscopic analysis (OES) to examine temperature effects. Additionally, the interaction between products (e.g., soot and/or PAH) generated during the previous discharge and the subsequent discharge was analyzed under conditions of constant flow rate with varying discharge frequency. Through the optimization of discharge conditions, the ignition coil enabled a reduction in SEC, achieving improved energy efficiency of  $H_2$ .

## II. METHODOLOGY

Fig. 1(a) illustrates the experimental setup used for  $H_2$  generation. Electrodes were positioned inside a quartz tube of the reactor. The gap distance of electrodes was set to 8 mm. CH<sub>4</sub> and N<sub>2</sub> gases were introduced into the quartz tube with flow rates controlled by mass flow controllers. The flow rate of methane was set at 23 mL/min. A high voltage was applied to the electrodes using an ignition coil (TOYOTA90919-02218). The discharge current and voltage were measured using a high-voltage probe (TESTEC TT-HVP2379) and a current transformer (Magnelab CT-B0.5), respectively, and the waveforms were recorded with an oscilloscope (Tektronix MDO3054



Fig. 1. Experimental setup.

500MHz). The product gases were analyzed by gas chromatography (GC: GL Sciences GC3210) with TCD.

The OES of the discharge was conducted using a spectrometer (Andor SR-303i) via quartz optical fibers with collecting optics, as detailed in Fig. 1(b). In this study,  $C_2$  Swan  $(d^3\Pi_g - a^3\Pi_u)$  and  $N_2$  second positive  $(C^3\Pi_u - B^3\Pi_g)$  bands were observed, and the vibrational and rotational temperatures were evaluated using the software, Specair [7]. Unless otherwise noted, a gas mixture of pure CH<sub>4</sub> with 3% N<sub>2</sub> was used in this study. Since soot adheres to the walls of the quartz tube, the optical emission analysis was performed 1 and 3 minutes after the initiation of discharge, before significant soot deposition on the tube walls occurred.

An ignition coil was employed as the inductive highvoltage power supply in this study. The ignition coil, a type of flyback transformer, generates high voltage on the secondary side by stopping the current on the primary side. The time duration of the current supplied to the primary side, referred to as the dwell time (DT), was adjusted to vary the inductive energy stored in the coil. Typical current and voltage waveforms of the discharge are shown in Fig. 2. The waveforms initially feature a short-pulse, high-voltage, high-current component known as the capacitive component (C-comp.), followed by a lowvoltage, long-pulse discharge known as the inductive component (L-comp.). Most of the energy stored in the ignition coil is released as the L-comp as shown. However, the high voltage of the initial C-comp. enables dielectric breakdown of the gas even with a wide electrode gap.



Fig. 2 Typical discharge voltage and current waveforms of ignition coil.

In this research,  $CH_4$  conversion ratio and SEC for  $H_2$  production are defined as following equations:

$$CH_{4,conv}[\%] = \frac{n_{CH4in} - n_{CH4out}}{n_{CH4in}} \times 100$$
(1)

$$SEC[kJ/NL] = \frac{E_{eng}}{V_{H2}} \quad . \tag{2}$$

where  $E_{eng}$  and  $V_{H2}$  are discharge energy estimated by the product of discharge voltage and current and H<sub>2</sub> volume in normal condition, respectively.

The main gas species observed in the product gas were CH<sub>4</sub>, H<sub>2</sub>, and C<sub>2</sub>H<sub>2</sub>, with very low amounts of C2 and C3 chemical species such as C<sub>2</sub>H<sub>6</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>3</sub>H<sub>8</sub>. Therefore, the main CH<sub>4</sub> decomposition reactions can be approximated by the following two equations, where the fractions of the reactions leading to the formation of C and C<sub>2</sub>H<sub>2</sub> are denoted as  $a_C$  and  $a_{C2H2}$ , respectively,

$$CH_4 \xrightarrow{a_C} C + 2H_2 \tag{3}$$

$$CH_4 \xrightarrow{a_{C2H_2}} \frac{1}{2}C_2H_2 + \frac{3}{2}H_2.$$
(4)

#### III. RESULTS AND DISCUSSION

#### A. Dwell time dependences

Fig. 3 presents the discharge energy—comprising Cand L-comp., as well as their sum—in relation to the DT. As mentioned previously, these discharge energies were obtained by temporally integrating the product of the discharge voltage and current. Since the capacitive and inductive components of the discharge have different characteristic time scales, the waveforms were separately obtained from distinct discharges, and their respective integrations were summed to evaluate the overall discharge energy.

Furthermore, the  $H_2$  and  $C_2H_2$  concentrations in the product gas were measured using GC, as shown in Fig. 4. As observed in Fig. 3, the discharge energy generally exhibits a linear relationship with DT.  $H_2$  production also shows a linear relationship with DT, although there is an



Fig. 3 The dependence of discharge energies on DT.



Fig. 4 The dependence of  $H_2$  and  $C_2H_2$  concentration in the product gas on DT.

offset in relation to the discharge energy threshold, indicating less contribution of C-comp.

Fig. 5 illustrates the CH<sub>4</sub> conversion rate,  $a_C$ ,  $a_{C2H2}$ , as well as the DT dependency of SEC, derived from the obtained results. The curve was drawn based on the B-spline method. The CH<sub>4</sub> conversion begins to increase when DT exceeds approximately 1 ms. In fraction of reactions with a DT of up to 2 ms,  $a_C$  is greater than  $a_{C2H2}$ . However, at a DT of 3 ms, this relationship is reversed. The SEC value is large at DT = 1.5 ms but asymptotically approaches a constant value as DT increases.

To evaluate the plasma temperature under corresponding experimental conditions, spectroscopic measurements were conducted. The typical observed spectrum is shown in Fig. 6. In low-energy discharges, the emission of  $C_2$  becomes remarkably weak. A 3% concentration of  $N_2$  was mixed to evaluate the temperatures using the 2nd Positive band, even under lowenergy discharges with low DT.

Fig. 7 illustrates the DT dependency of temperatures. As DT increases, the vibrational temperature rises, while the rotational temperature remains almost constant or slightly increased. Some temperatures evaluated from the Swan band are plotted, showing good agreement in both vibrational and rotational temperatures with the values derived from the 2nd Positive band. During the C-comp. discharge period, only the rotational temperature could be evaluated, revealing similar temperatures to those observed during the induction component discharge period. Considering this temperature along with SEC, it is



Fig. 5 The dependence of CH<sub>4</sub> conversion,  $a_C$ ,  $a_{C2H2}$  and SEC on DT. Discharge frequency was 10 Hz.



Fig. 6 Typical spectra of N<sub>2</sub> second positive  $(C^3\Pi_u - B^3\Pi_a)$ .

suggested that vibrational temperatures above 4000 K are preferable for hydrogen production, while exceeding 6000 K leads to an increased reaction ratio toward  $C_2H_2$  rather than C.

#### B. Frequency dependences

Fig. 8 shows the frequency dependency of H<sub>2</sub> and C<sub>2</sub>H<sub>2</sub> concentrations in the product gas. The DT was set to 3 ms and pure CH<sub>4</sub> gas was used as reactant gas. It was observed that both H<sub>2</sub> and C<sub>2</sub>H<sub>2</sub> concentrations increase with frequency and exhibit saturation characteristics relative to frequency. Fig. 9 presents the dependency of CH<sub>4</sub> conversion rate,  $a_c$ ,  $a_{C2H2}$  and SEC under the same conditions. In this experiment, the maximum CH<sub>4</sub> conversion rate was 44 % at 100 Hz discharge, while the minimum SEC was 8.8 kJ/NL at 10 Hz. The fractions of the reactions leading to the formation of C,  $a_c$ , was larger in the low-frequency region; however, as the frequency increases, the fractions of the reactions leading to the formation of C<sub>2</sub>H<sub>2</sub>,  $a_{C2H2}$ , became larger.

The conversion rate remaining at 44 % is attributed to  $CH_4$  decomposition caused by discharge between electrodes positioned in the central part of the quartz reactor. This suggests that a certain amount of  $CH_4$  flowed out without interacting with the plasma.

The following reasons are considered to explain why the SEC reached its minimum value at 10 Hz. CH<sub>4</sub> gas was



Fig. 7 The dependence of various temperatures on DT.



Fig. 8 The concentration of  $H_2$  and  $C_2H_2$  in the product gas dependent on discharge frequency.

passed through a quartz tube with an inner diameter of 8 mm at a flow rate of 23 mL/min. At a discharge frequency of approximately 1 Hz, it was assessed whether the discharge occurred in gas influenced by the preceding discharge. The results suggest that successive discharges in gas affected by the previous discharge are more favorable for H<sub>2</sub> production than a single discharge in CH<sub>4</sub> gas. At high frequencies, the proportion of product gas in the discharge region increases, leading to the deterioration of SEC and a increase in  $a_{C2H2}$ . To investigate the detailed mechanisms, it is necessary to conduct reactive fluid simulations.

Table 1 compares the SEC obtained in this study with reported values from previous papers. As shown in the table, the optimal value obtained in this experiment is found to be nearly comparable to those reported values.

The practicality of the ignition coil is limited due to the presence of iron losses, which are expected to reduce the wall plug efficiency even further, making its practical implementation difficult. However, the experiment has yielded valuable insights into the optimization of temperature and frequency. Furthermore, the practicality of this type of power source could be enhanced by employing magnetic materials with superior performance, such as nano-crystalline magnetic materials.

#### V. CONCLUSION

An CH<sub>4</sub> decomposition and  $H_2$  production experiment was conducted with controlling the frequency and energy of warm plasma discharge using an ignition coil. As a result, it was observed that the vibrational temperature of the plasma increases with increasing DT and SEC remained constant. Moreover, optimal value was found on

Table 1: Comparison of specific energy consumption of H<sub>2</sub>

Process	feed	SEC	ref.
		(kJ/NL)	
rotating gliding arc	$CH_4$	14.3-45	[4]
	$+N_2$		
DC spark	$CH_4$	23.5-47	[5]
rotating electrode	$\mathrm{CH}_4$	8.73	[6]
inductive discharge	CH <sub>4</sub>	8.8	present
			work



Fig. 9 The dependence of CH<sub>4</sub> conversion,  $a_C$ ,  $a_{C2H2}$ , and SEC on discharge frequency.

the SEC in frequency dependency. The efficiency improved when the gas between the electrodes was not fully replaced during the discharge cycle, meaning that the discharge occurred in the presence of the gas products from the previous discharge. This could be attributed to the decomposition-promoting effect of the soot and/or PAH formed during the previous discharge.

#### ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number JP23K03370.

- [1] G. Chen, X. Yu, K. Ostrikov, B. Liu, J. Harding, G. Homm, H. Guo, S. Andreas Schunk, Y. Zhou, X. Tu, A. Weidenkaff, Methane up-carbonizing: A way towards clean hydrogen energy?, *Chemical Engineering Journal*, 476, 2023.
- [2] N. Sánchez-Bastardo, R. Schlögl, H. Ruland, Methane Pyrolysis for Zero-Emission Hydrogen Production: A Potential Bridge Technology from Fossil Fuels to a Renewable and Sustainable Hydrogen Economy, *Industrial & Engineering Chemistry Research*, 60: 11855-11881, 2021.
- [3] M. Wnukowski, Methane Pyrolysis with the Use of Plasma: Review of Plasma Reactors and Process Products, *Energies*, 16, 2023.
- [4] H. Zhang, C. Du, A. Wu, Z. Bo, J. Yan, X. Li, Rotating gliding arc assisted methane decomposition in nitrogen for hydrogen production, *International Journal of Hydrogen Energy*, 39:12620-12635, 2014.
- [5] N. N. Morgan, M. ElSabbagh, Hydrogen Production from Methane Through Pulsed DC Plasma, *Plasma Chemistry and Plasma Processing*, 37:1375-1392 2017.
- [6] M. Kheirollahivash, F. Rashidi, M.M. Moshrefi, Hydrogen Production from Methane Decomposition Using a Mobile and Elongating Arc Plasma Reactor, *Plasma Chemistry and Plasma Processing*, 39:445-459, 2019.
- [7] Specair, http://www.specair-radiation.net/index.php, SpecralFit S.A.S.

## **Charged Phenomenon of High-speed Nanodroplet Impact on the Copper Plate**

J.-S. Lee<sup>1,2\*</sup>, Y.-C. Cheng<sup>3</sup>, S. Liu<sup>2</sup>, T. Nakajima<sup>2</sup>, T. Sato<sup>2</sup>

<sup>1</sup>Department of Mechanical System Engineering, Tohoku University, Japan

<sup>2</sup>Institute of Fluid Science, Tohoku University, Japan

<sup>3</sup>Department of Mechanical Engineering, National Yang Ming Chiao Tung University, Taiwan

\*Corresponding author: lee.jiun.shian.t4@dc.tohoku.ac.jp

*Abstract-* This study presented the electrical behavior of high-speed nanodroplets impinging on the copper plate. Within the 100 mm distance between the copper plate and the nozzle, the electric potential was -2250 V at 1 mm, peaked at -3250 V at 5 mm, and decreased to 500 V at 20 mm. Beyond 20 mm, the electric polarity gradually reduced to zero and remained in the 30 to 100 mm range. The electric current emphasized the negative charge on the copper plate and had similar trends to the potential result. It was -32 nA at 1 mm and decreased to zero in the 20 mm range. The peak in the potential result was related to the high-speed flow blowing away the accumulated water and charged particles at a closer distance. This result highlights the tremendous change in electric potential and current over distance, which is strongly related to the rapid decline in flow speed, and this is evidence of impingement-induced charge effect.

## High-speed nanodroplets, Charging phenomena, Impingement, Copper plate

## I. INTRODUCTION

Microdroplets have attracted wide attention. They have the potential for cleaning, sterilization, cooling, power generation, and energy harvesting. One of the interesting features of microdroplets is their charging phenomenon, which has been observed and reported for many years.

In nature, ball lightning is reported due to the contact of condensed water and evaporated vapor. The significant thermal status transfer causes unstable energy to generate charges.[1] Lenard observed that the separation of the drops falling will charge the water drop positively and the ambient air negatively from the waterfall.[2] Nolan reported that electrification happens on the water splashing and spraying.[3] Recently, the electric polarity in the bulk microdroplet flow was found to be not unipolar but bipolar. The net charge can be changed due to the water source.[4] Triboelectric nanogenerator technology is well-known and developed; some researchers have tried to harvest the energy from droplet collision, transforming the mechanical energy into electrical energy.[5]

Our laboratory developed a nanodroplet generator, which reduces water use, unwet after treatment, and enhances functions. The charging phenomenon can even be found after spraying nanodroplets on the aluminum plate.[6] This study aims to observe the charging effect of nanodroplet spraying on the copper plate.

## II. METHODOLOGY

1) *High-speed nanodroplet generation*: Fig. 1 shows the high-speed nanodroplet generator and nanodroplet generation. The device consists of a stainless-steel vessel with an inside water heater (SAKAGUCHI ELECTRIC HEATERS CO., 21B058), a pressurized gas inlet, and a nozzle (Spraying Systems Co., HB-1/8-VV-SS-15-01) as

a flow outlet. The distilled water used in each operation is 300 mL for water evaporation to form nanodroplets. A pressure gauge is set upstream at the inlet to control the air pressure from the gas cylinder. The water is evaporated while the air-vapor mixture is compressed. Two thermal meters (AS ONE Corporation, KTO-16150C) are in the system; one monitors the water temperature, and the other monitors the nozzle temperature. Another wire heater covers the pipe to the nozzle, preventing the vapor from condensing prematurely at the nozzle upstream. Water vapor inside the mixture flow condenses into nanodroplets when the mixture flows out of the nozzle. The nanodroplet generation condition is under 280 W of the water heater power ( $W_H$ ), 170°C of the nozzle temperature ( $T_N$ ), and 5 atm of the absolute pressure (P) from the gas cylinder.

2) *Electric potential measurement*: One vibrationtype surface potential probe (KASUGA DENKI, INC., KSD-3000) measured the surface potential of the copper



Fig. 1 Schematic of the nanodroplet generator

plate's backside. The copper plate is  $50 \text{ mm} \times 45 \text{ mm} \times 3$  mm. The probe-to-plate distance is fixed at 10 mm below the copper plate. By changing the distance, *D*, between the copper plate and the nozzle, the electric potential of nanodroplet flow impinging on the copper plate at each position within the distance can be measured.

3) *Electric current measurement*: A cable connects the same copper plate used for the electric potential measurement to one electrometer (ADC CORPORATION, 5350). One hundred data points are directly recorded in a computer with a sampling rate of 33 Hz. By varying the plate-to-nozzle distance, *D*, the electric current behavior of the entire flow can be investigated.

#### III. RESULTS

In Fig. 2, the electric potential was extraordinarily high and negative while the copper plate was close to the nozzle. It was -2250 V at 1 mm and maintained around - 3250 V at around 5 mm. The magnitude sharply decreased to 500 V at 20 mm and gradually decayed to 0 V at 100 mm. There was one peak that happened at a distance of around 5 mm.

Fig. 3 shows the electric current. The current, as was the electric potential result, was negative when the plate was close to the nozzle. It was -32 nA, rapidly decreasing to zero at 20 mm, and remaining until 100 mm.

#### **IV. DISCUSSION**

Figs. 2 and 3 show similar trends beyond 10 mm. They both demonstrate that the negative charge induced on the copper plate is significant when positioned close to the nozzle. The magnitude of potential and current sharply declined is related to the velocity gradient. The exit shows a supersonic flow, but the velocity of the flow downstream decays to  $50 \sim 60$  m/s.[6] Since the distance between the copper plate and the nozzle was short, the collision of nanodroplets was significant, resulting in high electric potential and current values.



Fig. 2 The electric potential of spraying nanodroplets on a copper plate at different plate-to-nozzle distances under  $W_H = 280$  W,  $T_N = 170^{\circ}$ C, and P = 5 atm.



Fig. 3 The electric current of spraying nanodroplets on a copper plate at different plate-to-nozzle distances under  $W_H = 280$  W,  $T_N = 170^{\circ}$ C, and P = 5 atm.

Nanodroplets condensed immediately when the mixture flow was emitted and impinged on the copper plate. At a closer distance of 10 mm, nanodroplets could not remain on the copper plate due to the high-speed flow. With increased distance, the droplets enlarged through aggregation and condensation, accumulating on the copper plate as the flow no longer displaced them.

Besides, the potential measurement was applied using a non-contact probe; the accumulated water could contain the charges and affect the potential on the copper plate. On the contrary, the current measurement directly collected the charge through a cable and sent it to an electrometer. The charge went to the electrometer instead of being accumulated on the copper plate and displaced by the high-speed flow. These indicate that the potential has a slight drop near the nozzle.

As the distance increases beyond 20 mm, both potential and current decay to zero and remain. The flow speed is slow for exceeding 20 mm distance, and the impact is no longer strong enough to induce potential and current. These results explain that the charged phenomenon is related to the high-speed flow.

#### V. CONCLUSION

The results of the electric potential and current present similar trends and the same electric polarity. At 1 mm, both electric potential and current are negative, -2250 V and -32 nA. Then, the trend indicates a drastic change in potential and current to zero in the 20 mm range distances near the nozzle, the section with the highest velocity gradient. The results illustrate that high speed and impingement are related to charge generation.

#### ACKNOWLEDGMENT

This study was supported by the Collaboration Research Project of the Institute of Fluid Science, Tohoku University, and JST SPRING, Grant Number JPMJSP2114. This study was also supported by JSPS KAKENHI, Grant Numbers 25H00405 and 25K17536.

- [1] A.S. Tarnovskii, Water vapor condensation and the collapse of superheated water drops as possible causes of ball lightning, Tech. Phys. 48 (2003) 1211–1215. https://doi.org/10.1134/1.1611911.
- P. Lenard, Ueber die Electricität der Wasserfälle, Annalen der Physik 282 (1892) 584–636. https://doi.org/10.1002/andp.18922820805.
- [3] J.J. Nolan, J.A. McClelland, Electrification of water by splashing and spraying, in: Proceedings of the Royal Society of London., The Royal Society, 1914: pp. 531–543. https://doi.org/10.1098/rspa.1914.0081.
- [4] T.A.L. Burgo, F. Galembeck, On the spontaneous electric-bipolar nature of aerosols formed by mechanical disruption of liquids, Colloids and Interface Science Communications 7 (2015) 7–11. https://doi.org/10.1016/j.colcom.2015.11.002.
- [5] Q.-T. Nguyen, K.-K.K. Ahn, Fluid-Based Triboelectric Nanogenerators: A Review of Current Status and Applications, Int. J. of Precis. Eng. and Manuf.-Green Tech. 8 (2021) 1043–1060. https://doi.org/10.1007/s40684-020-00255-x.
- [6] Y. Xiao, S. Liu, T. Nakajima, T. Sato, Characteristics of high-speed mist generated by condensation of water vapor in pressurized air, Int. J. Plasma Environ. Sci. Technol. 16, e03003, 2022.

## Hydrodynamic and electrostatic contributions to tracer-particle dynamics near a patch, which actively releases ion-pairs, located on a planar wall

Mihail N. Popescu<sup>1\*</sup>, Alvaro Domínguez<sup>2</sup>

<sup>1</sup>International Centre of Biodynamics, 1B Intrarea Portocalelor, 060101 Bucharest, Romania <sup>2</sup>Física Teórica, Universidad de Sevilla, Apdo. 1065, 41080 Sevilla, Spain \*Corresponding author: mpopescu@biodyn.ro

*Abstract-* Patches of catalyst imprinted on supporting walls induce motion of the fluid around them once they are supplied with the chemical species ("fuel") that are converted by the catalytic chemical reaction. In many cases (e.g., enzymes catalyzing the breakup of molecular substrates), pairs of (oppositely charged) ionic species are released in the surrounding solution as a result of the reaction at the patch. By using a simple model for an ion-pairs releasing activity of a patch imprinted on a planar wall, we determine analytically the auto-induced chemical composition inhomogeneities and electric field in the solution, as well as the resulting Stokes flow of the Newtonian solution that occupies the half space above the wall. Their dependencies on the patterns of activity and electric charge distributions at the patch and wall permit interpretation of the motion of point-like tracers particles – typically studied in experimental investigations — which are drifted by the ambient flow and electric field.

Keywords- chemical activity, diffusiophoresis, Stokes flow.

## I. INTRODUCTION

The first realizations of chemically active patches made of catalysts imprinted on planar walls, which induce motion of the fluid solution around them by developing inhomogeneities in its chemical composition, have been published two decades ago [1]. A variety of such systems (Pt patches on Au walls, Ag on glass, or various types of enzymes on glass [2, 3]) have been reported since then. Their functioning, in particular the auto-induced hydrodynamic flow, has been studied for simple models of activity: numerically in closed-cell geometries [4] and, recently, analytically for half-space geometry [5]. In many experimental realizations, the catalytic reaction involves the break-up of a molecular "fuel" into pairs of oppositely-charged ionic species. Here, we employ the methods in Ref. [6] to extend the analysis by Ref. [5] to the case of a model chemically active patch releasing pairs of oppositely charged ions in the ambient electrolyte solution above the wall with the patch.

#### II. MODEL SYSTEM

The model system we consider is shown schematically in Fig. 1. A dilute liquid electrolyte solution occupies the half space z > 0 above a planar wall located at z = 0. The whole system is kept at a constant temperature T and is in contact with distant reservoirs of solvent and ionic species (thus their bulk chemical potentials are fixed). The electrolyte contains two (point-like) ionic species of charges  $q_{\pm} = \pm q$ , with q > 0, and bulk (far from the wall) average densities  $c_{\pm}^{(\infty)} > 0$  (fixed by the reservoirs). The diffusion constants of the  $\pm$  ions are denoted by  $D_{\pm}$ ; the associated mobilities are given by the Stokes-Einstein relation as  $\Gamma_{\pm} = \beta D_{\pm}$ , where  $\beta = 1/(k_B T)$  and  $k_B$  denotes the Boltzmann constant. Electrical neutrality of the bulk electrolyte is assumed, thus  $c_{+}^{(\infty)} = c_{-}^{(\infty)} =: c_{\infty}$ . On the wall there is a region which is chemically active (the "patch"):



Figure 1: Schematic depiction of the model system. A planar wall (at z = 0;  $\mathbf{n} \equiv \mathbf{e}_z$  is the inner, into the fluid, normal unit vector) contains a chemically active patch region (the orange disk) of characteristic size R; the wall also carries a (fixed) surface charge distribution. An electrolyte solution (solvent, reactants, and ionic product species) occupies the half-space z > 0. The chemical activity of the patch-region consists of releasing pairs of ions (a positive and a negative one) into the electrolyte solution (the red and green arrows), which drives the system out of thermodynamic equilibrium. The color gradient indicates that both the chemical activity  $\mathbb{A}(\mathbf{r})$  and the surface charge density  $\sigma(\mathbf{r})$  can vary over the patch. The non-equilibrium inhomogeneities within the solution induce the body-force density field  $\mathbf{f}(\mathbf{s})$  (blue arrow).

pairs (negative and positive) of ions are released there into the surrounding electrolyte (see Fig. 1), with a certain timeindependent rate  $\mathcal{A}\mathbb{A}(\mathbf{r})$  per unit area<sup>1</sup>. The dimensional  $\mathcal{A} > 0$  denotes a characteristic value, while the "activity pattern distribution"  $\mathbb{A}(\mathbf{r}) \ge 0$  is dimensionless. For simplicity, here we consider the case that the ionic species released are the same as those in the bulk electrolyte. The wall carries a (fixed) surface-charge, which can vary along the wall (e.g., due to the presence of the patch):  $\sigma(\mathbf{r}) = \varsigma \mathbb{S}(\mathbf{r})$ , with  $\varsigma > 0$  (dimensional) denoting a characteristic value of the surface-charge and  $\mathbb{S}(\mathbf{r})$  (dimensionless) describing the

<sup>&</sup>lt;sup>1</sup>The case in which pairs of ions are removed from the solution can be straightforwardly accommodated by taking  $\mathbb{A}(\mathbf{r}) < 0$  at such points.

spatial pattern of the surface-charge distribution. Finally, we assume the wall dielectric constant to be much smaller than the one,  $\epsilon$ , of the electrolyte, such that electric fields are confined to the electrolyte domain.

When the patch is inactive, the system is in an equilibrium state (fixed by the distant heat bath and reservoirs of ions and solvent), in which the classic equilibrium electrostatic double layer forms at the wall, the corresponding electrostatic potential is established within the electrolyte, and the fluid is motionless. Upon turning on the activity, a non-equilibrium steady state emerges, in which the distributions of the densities of ions and the electrostatic field differ from the equilibrium ones and a hydrodynamic flow is induced in the electrolyte. Motivated by the typical observations in experimental realizations, one can safely assume that the fluid flow occurs at small Reynolds number ("creeping flow") and that the diffusion of the ionic species dominates their transport. Accordingly, the state of the solution is characterized by the instantaneous incompressible flow  $\mathbf{u}(\mathbf{s})$  of the solution and the stationary concentrations  $c_{\pm}(s)$  of each ionic species at small Péclet number (i.e., convection is neglected); an electric field, characterized by the electric potential  $\psi(\mathbf{s})$ , is also induced.

#### III. MATHEMATICAL FORMULATION

The chemical potentials  $\mu_{\pm}(s)$  of the ionic species are

$$\mu_{\pm}(\mathbf{s}) = \mu_{id}(c_{\pm}(\mathbf{s})) \pm q\psi(\mathbf{s}), \qquad (1)$$

where  $\mu_{id}$  denotes the ideal gas chemical potential. At steady state, the ionic currents (in the classic Nernst-Planck form) obey the conservation of mass

$$\nabla \cdot \mathbf{j}_{\pm}(\mathbf{s}) = 0, \quad \mathbf{j}_{\pm}(\mathbf{s}) = \beta D_{\pm} c_{\pm}(\mathbf{s}) \nabla \mu_{\pm}(\mathbf{s}), \quad (2)$$

(Owing to the condition of small Péclet number, the "chemical composition" problem above decouples from the hydrodynamic one.) The current is subject to boundary conditions (BC) at the wall and at infinity

$$(\mathbf{n} \cdot \mathbf{j}_{\pm})(\mathbf{r}) = \mathcal{A}\mathbb{A}(\mathbf{r}), \quad \mathbf{j}_{\pm}(|\mathbf{s}| \to \infty) \to 0, \quad (3)$$

the former modeling the source of ions at the wall (i.e., the activity at the patch) as a current into the solution.

The electric potential is obtained, at the mean field level, as the solution of the Poisson-Boltzmann equation

$$\nabla^2 \psi(\mathbf{s}) = -(q/\epsilon) \left[ c_+(\mathbf{s}) - c_-(\mathbf{s}) \right] \tag{4}$$

that obeys the BCs at the wall and at infinity<sup>2</sup>

$$(\mathbf{n} \cdot \nabla \psi)(\mathbf{r}) = -(\varsigma/\epsilon) \,\mathbb{S}(\mathbf{r}) \,, \quad \psi(z \to \infty) \to 0 \,.$$
 (5)

Under the assumption of local equilibrium, the thermodynamic forces (gradients in chemical potential) translate into a body-force density, acting on the solution,

$$\mathbf{f}(\mathbf{s}) = -[c_+(\mathbf{s})\nabla\mu_+(\mathbf{s}) + c_-(\mathbf{s})\nabla\mu_-(\mathbf{s})]. \quad (6)$$

Assuming a Newtonian-fluid behavior for the electrolyte, the flow obeys the incompressible Stokes equation

$$\eta \nabla^2 \mathbf{u}(\mathbf{s}) - \nabla p(\mathbf{s}) = \mathbf{f}(\mathbf{s}), \quad \nabla \cdot \mathbf{u} = 0,$$
 (7)

where p(s) denotes the hydrodynamic pressure (which enforces incompressibility) and  $\eta$  the dynamic viscosity, respectively. This is subject to BCs at infinity (quiescent fluid) and at the wall (no slip)

$$\mathbf{u}(|\mathbf{s}| \to \infty) \to 0, \quad \mathbf{u}(\mathbf{r}) = 0.$$
 (8)

The solution is straightforwardly written in terms of the Green function (actually a tensor) of the system as

$$\mathbf{u}(\mathbf{s}) = \int_{\text{fluid}} d^3 \mathbf{s}_0 \mathsf{G}(\mathbf{s} - \mathbf{s}_0) \cdot \mathbf{f}(\mathbf{s}_0) \,. \tag{9}$$

For our system, the Green function, which is that for a Stokeslet in a fluid bounded by a no-slip planar wall, is known analytically [7-9];<sup>3</sup> therefore, the flow is known once the body force distribution **f** is provided.

These boundary value problems (bvps) provide the complete description of the problem: the bvps (2) - (5) are solved first, after which the body force density f, (6), can be computed, and (9) provides u. But, typically, the nonlinear coupling in (2) prevents analytical tractability and only numerical solutions are feasible, unless additional approximations are possible. One such case is when the departures from equilibrium are small, case that we discuss below.

#### IV. THE QUASI-HOMOGENEOUS APPROXIMATION

Following the approach in Ref. [6], we note that when the system is inactive and the wall uncharged (i.e.,  $\mathcal{A} = 0$ and  $\varsigma = 0$ ), the spatially homogeneous state  $c_+(\mathbf{s}) \equiv c_{\infty}$ ,  $c_-(\mathbf{s}) \equiv c_{\infty}$  (which ensures electric neutrality of the electrolyte and no flow) is the equilibrium state. We consider and analyze the case in which the activity at the patch and the surface charge are both sufficiently small so that the system is only weakly out of this homogeneous equilibrium state. Thus, the equations governing the ionic distribution and the electric potential are solved perturbatively to leading order in the deviations  $\delta c_{\pm}(\mathbf{s}) := c_{\pm}(\mathbf{s}) - c_{\infty}$  and  $\psi$  (the equilibrium state being one of zero potential). From (1), it follows that  $\delta \mu_{\pm} = \delta \mu_{id}(c_{\pm}) \pm q \psi$ ; thus, the expansions of the Nernst-Planck equation and of the conservation laws to first order in deviations render

$$\delta\mu_{\pm}(\mathbf{s}) = \frac{\mathcal{A}R}{\beta c_{\infty} D_{\pm}} \delta\mu(\mathbf{s}), \qquad (10)$$

where the dimensionless  $\delta \mu(\mathbf{s})$  is the solution of the Laplace byp

$$\nabla^2 \delta \mu(\mathbf{s}) = 0, \qquad (11)$$
$$\mathbf{n} \cdot \nabla \delta \mu(\mathbf{r}) = -\mathbb{A}(\mathbf{r}), \ \delta \mu(|\mathbf{s}| \to \infty) \to 0.$$

<sup>3</sup>Being a somewhat cumbersome expression, we do not list it here.

R(

<sup>&</sup>lt;sup>2</sup>Note that here we allow for a charged wall, thus there could be sources of field also at  $|\mathbf{r}| \rightarrow \infty$ ; accordingly, the vanishing of the potential is required only far from the wall.

By using the linear relation between  $\delta \mu_{\pm}$  and  $\delta c_{\pm}$  (see the lines above (10)), and recalling that  $\delta \mu_+$  are harmonic func- mediately obtains the integral representations of  $\delta \mu$  and  $\Psi$ tions, the electric potential  $\psi$  is obtained as

$$\psi(\mathbf{s}) = \frac{1}{2q} (\delta \mu_+ - \delta \mu_-) + \Psi(\mathbf{s}), \qquad (12)$$

where the auxiliary electric potential  $\Psi(\mathbf{s})$  is the solution of the byp (see also the byps obeyed by  $\psi$  and  $\delta \mu_+$ )

$$\nabla^{2} \Psi(\mathbf{s}) - \lambda_{D}^{-2} \Psi(\mathbf{s}) = 0, \qquad (13)$$
$$(\mathbf{n} \cdot \nabla \Psi)(\mathbf{r}) = -\frac{\varsigma}{\epsilon} \mathbb{S}(\mathbf{r}) + \frac{\mathcal{A}}{2\beta c_{\infty} q \,\Delta} \mathbb{A}(\mathbf{r}), \qquad \Psi(z \to \infty) \to 0,$$

with the Debye length and the inverse diffusivity contrast

$$\lambda_D := \sqrt{\frac{\epsilon}{2\beta c_{\infty} q^2}}, \quad \frac{1}{\Delta} := \left(\frac{1}{D_+} - \frac{1}{D_-}\right). \quad (14)$$

Finally, after performing some simple algebraic manipulations and dropping from the definition of the body force density  $\mathbf{f}$  any term that is an exact gradient (such terms are absorbed in the definition of the dynamic pressure p(s), (6) renders in the quasi-homogeneous approximation

$$\begin{aligned} \mathbf{f}(\mathbf{s}) &\mapsto \mathbf{f}(\mathbf{s}) = -q \left( \delta c_{+}(\mathbf{s}) - \delta c_{-}(\mathbf{s}) \right) \nabla \psi(\mathbf{s}) \\ &\mapsto \mathbf{f}(\mathbf{s}) = + \left( \mathcal{A} R q / \Delta \right) \Psi(\mathbf{s}) \nabla \delta \mu(\mathbf{s}) \,, \end{aligned} \tag{15}$$

This concludes the explicit calculation of the activity induced distribution of ions, electric field, body force density and, by (9), hydrodynamic flow.

Before proceeding with a particular configuration as an example calculation, we emphasize a few insightful features of the result (15), in that (similarly to the case of self-(ionic)diffusiophoretic particles, see Ref. [6]) an induced hydrodynamic flow is possible:

i) only because of non-local effects, as encoded by the electric potential  $\psi(\mathbf{s})$ , see the first line in (13);

ii) only if an out of equilibrium state exists ( $A \neq 0$ ) and the two ions have different diffusion constants ( $\Delta^{-1} \neq 0$ ), see the second relation in (13);

iii) even if the wall is uncharged ( $\varsigma = 0$ ), because  $\Psi$  is independently sourced by the surface charge at the wall and by the chemical activity, see the second relation in (13).

#### V. ILLUSTRATIVE EXAMPLE: AXI-SYMMETRIC PATCH

For the half-space geometry discussed here, the bvps (11) and (13) are most conveniently solved in cylindrical coordinates. Furthermore, we will focus on the case (typical for experiments) of a radially-symmetric shape of the patch (e.g., as shown in Fig. 1), case in which the system possesses axial-symmetry (via a suitable choice of the origin of the system of coordinates). Finally, for technical simplicity (and due to space constraints) we consider here only the case in which far from the patch the wall is uncharged:  $\mathbb{S}(|\mathbf{r}| \to \infty) \to 0$  sufficiently fast.

By using the standard separation of variables, one im-

$$\delta\mu(r',z') = \int_{0}^{\infty} d\xi \, a(\xi) \, \mathcal{J}_{0}(\xi r') \, \mathrm{e}^{-\xi z'} \,, \qquad (16)$$

$$\Psi(r',z') = \int_{0}^{\infty} d\xi \, b(\xi) \, \mathcal{J}_{0}(\xi r') \, \mathrm{e}^{-\sqrt{\xi^{2} + \xi_{0}^{2}} z'} \,, \qquad (17)$$

with  $J_0$  the Bessel function of first kind of order 0 [10], dimensionless coordinates r' = r/R, z' = z/R, and parameter  $\xi_0 := R/\lambda_D$ . The functional coefficients  $a(\xi)$  and  $b(\xi)$  are determined from (11) and (13) by the patterns of activity  $\mathbb{A}(\mathbf{r})$  and "effective surface charge"

$$\mathbb{Q}(\mathbf{r}) = \varsigma \mathbb{S}(\mathbf{r}) - \frac{\mathcal{A}\epsilon}{2\beta c_{\infty} q \Delta} \mathbb{A}(\mathbf{r})$$
(18)

$$a(\xi) = \int_{0}^{\infty} dr' r' \mathbb{A}(r') \operatorname{J}_{0}(\xi r'), \qquad (19)$$

and

as

$$b(\xi) = \frac{R}{\epsilon\sqrt{\xi^2 + \xi_0^2}} \int_0^\infty dr' r' \mathbb{Q}(r') \,\mathcal{J}_0(\xi r') \,.$$
(20)

In typical experiments, the active patches have radii in the order of tens of micrometers while for the aqueous electrolytes solutions the Debye length  $\lambda_D \lesssim 100$  nm; thus, the parameter  $\xi_0 \gtrsim 10^3$ . By (17) one infers that the auxiliary electric potential  $\Psi$  vanishes exponentially with the distance from the wall; therefore,  $\Psi$ , as well as — by (15) — the force density  $\mathbf{f}$ , is effectively confined within a layer of thickness  $z' \sim \xi_0^{-1} \simeq 10^{-3}$  above the wall. On the other hand, by (11)  $\delta\mu$  varies solely over length scales of order R(as reflected also in the integral representation (16)). This means that, for the purpose of calculating the body force  $\mathbf{f}$ , (15) for the integrand in (9), the gradient of the chemical potential can be approximated as

$$\nabla \delta \mu(\mathbf{s}) \approx \mathbf{e}_r \left(\frac{\partial \delta \mu}{\partial r}\right)_{z=0} =: \nabla_{\parallel} \delta \mu(\mathbf{r});$$
 (21)

Therefore, the hydrodynamic flow given by (9) (which, by continuity, extends over length-scales of the order R) is the result of a "surface actuation" (the body-force distribution is confined within a layer seen as of microscopic thickness  $\lambda_D \ll R$  and the force-field is parallel to the wall), which is proportional to the relevant thermodynamic force  $\nabla \delta \mu$ .

Finally, one notes that while  $\Psi$  is confined within the thin layer near the wall, the electric potential  $\psi$ , which is what would be felt by a tracer particle, extends into the solution over length-scales  $\sim R \gg \lambda_D$  owing to the activityinduced term  $\sim \delta \mu$  (see (12)).

These results are illustrated in Fig. 2 for the simple choice of the patch activity and surface charge patterns

$$\mathbb{A}(\mathbf{r}) = e^{-(r/R)^2}, \ \mathbb{S}(\mathbf{r}) = \mathbb{A}(\mathbf{r}), \tag{22}$$

which allows closed-form expressions for the coefficients  $a(\xi)$  and  $b(\xi)$  and a smaller number of system parameters. (The case  $S(\mathbf{r}) \neq A(\mathbf{r})$  will be discussed elsewhere.)

### VI. CONCLUSIONS

In the limit of small deviations from the homogeneous equilibrium state, we have derived analytically the steadystate (distribution of ionic species, electric field, and hydrodynamic flow) for a weak electrolyte in contact with a wall possessing a chemically-active, ion-pairs releasing region (patch). This allows interpretation of experimental observations of the motion of charged tracer particles within such solution, which are drifted by the electric field  $-\nabla\psi$ and the ambient flow. Our results spell out that the first component is basically the phoretic response to the thermodynamic force  $\nabla \delta \mu$ , while the flow is sourced by a "surface actuation" field  $\propto \nabla_{\parallel} \delta \mu$ . In this sense, these drifts are agnostic to what the source of the thermodynamic force is, all the specific details being hidden in the "response-like" prefactors; all that matters is the chemical activity. This may be the reason why heuristic application of models that account for activity, but with uncharged species, could so far be used with reasonable success for interpreting the tracer motion as a "simpler" chemo-phoretic response plus a drift by a



Figure 2: (Top) The force field  $\mathbf{f}/F_0$  (arrows) and its magnitude (color coded); and (Bottom) the electric potential  $\psi/\psi_0$  (color coded) and the flow field  $\mathbf{u}$  (streamlines) for the patch pattern in (22), for which the dimensional factors are:  $F_0 := \frac{qA}{\Delta} \left(\frac{R_{\varsigma}}{\epsilon} - \frac{AR}{2\beta c_{\infty} q \Delta}\right)$  and  $\Psi_0 := \frac{AR}{2\beta c_{\infty} q \Delta}$ . Note the different scales of the *z* (vertical) axes.

chemo-osmotic induced ambient flow, see, e.g., Ref. [11].

## ACKNOWLEDGMENTS

Financial support through grant ProyExcel\_00505 funded by Junta de Andalucía and grant PID2021-126348NB-I00/AEI/10.13039/501100011033/FEDER,UE is gratefully acknowledged.

- [1] T.R. Kline, W.F. Paxton, Y. Wang, D. Velegol, T.E. Mallouk, and A. Sen. Catalytic micropumps: Microscopic convective fluid flow and pattern formation. *J. Am. Chem. Soc.*, 127:17150–17151, 2005.
- [2] C. Zhou, H. Zhang, Z. Li, and W. Wang. Chemistry pumps: a review of chemically powered micropumps. *Lab Chip*, 16:1797–1811, 2016.
- [3] B.A. Nicola, M.N. Popescu, and S. Gáspár. Substratecontrolled bidirectional pumping by a bienzymatic micropump. ACS Appl. Mater. Interf., 16:59556–59566, 2024.
- [4] L. Valdez, H. Shum, I. Ortiz-Rivera, A.C. Balazs, and A. Sen. Solutal and thermal buoyancy effects in self-powered phosphatase micropumps. *Soft Matter*, 13:2800–2807, 2017.
- [5] M.N. Popescu, B.A. Nicola, W.E. Uspal, A. Domínguez, and S. Gáspár. Hydrodynamic Stokes flow induced by a chemically active patch imprinted on a planar wall. *Journal of Colloid and Interface Science*, 690:137296, 2025.
- [6] A. Domínguez and M.N. Popescu. Ionic self-phoresis maps onto correlation-induced self-phoresis. *arXiv*:2404.16435, 2024.
- [7] J.R. Blake. A note on the image system for a Stokeslet in a no-slip boundary. *Math. Proc. Cambridge Phil. Soc.*, 70:303–310, 1971.
- [8] J.R. Blake and A.T. Chwang. Fundamental singularities of viscous flow. Part I: The image systems in the vicinity of a stationary no-slip boundary. *J. Eng. Math.*, 8:23–29, 1974.
- [9] S. Spagnolie and E. Lauga. Hydrodynamics of selfpropulsion near a boundary: predictions and accuracy of far-field approximations. J. Fluid Mech., 700:105– 147, 2012.
- [10] M. Abramowitz and I.R. Stegun. Eds. *Handbook of mathematical functions*. Dover, New York, 1972.
- [11] M. Bekir, M. Sperling, D. Vasquez Muñoz, C. Braksch, A. Böker, N. Lomadze, M.N. Popescu, S. Santer. Versatile microfluidics separation of colloids by combining external flow with light-induced chemical activity. *Adv. Mater.*, 35: 2300358, 2023.

## **Concentration Polarization Electroosmosis: Theory And Microfluidic Applications**

R. Fernández-Mateo<sup>1\*</sup>, V. Calero<sup>2</sup>, H. Morgan<sup>3</sup>, A. Ramos<sup>1</sup>, P. García-Sánchez<sup>1</sup> <sup>1</sup>Departamento de Electrónica y Elecctromagnetismo, Universidad de Sevilla, Sevilla, Spain

<sup>2</sup>Departamento de Física Aplicada, Universidad de Oviedo, Oviedo, Spain

<sup>3</sup>School of Electronics and Computer Science, University of Southampton, Southampton, United Kingdom

\*Corresponding author: rfernandez12@us.es

*Abstract-* We describe experimental characterization and theoretical modeling of a new AC electrokinetic effect termed Concentration-Polarization Electroosmosis, or CPEO. The phenomenon refers to steady-state electroosmotic flows around charged insulating micro-structures subjected to low-frequency AC electric fields. CPEO arises from concentration polarization (CP) due to surface conductance. The phenomenon is studied around (i) features fabricated within microfluidic channels, such as pillars and constrictions and (ii) charged microparticles. A theoretical framework is presented based on recent analytical approaches in the limits of weak electric fields or small surface conductance. The new description gives explanation to different phenomena observed in electrokinetics, such as wall-particle repulsion of particles undergoing electrophoresis in microfluidic channels or trapping in microfluidic constrictions. Applications of CPEO have been proposed for particle fractionation based on size or surface charge.

Keywords- Electrokinetics, Microfluidics, Concentration Polarization.

## I. INTRODUCTION

In the context of microfluidics for continuous flow particle isolation and characterisation, fluid flow control at micrometric scales is key for an efficient manipulation. Electric fields are successfully used to this end by exploiting the net surface charge that builds on solid surfaces in contact with aqueous electrolytes. The surface charge is screened by an ionic layer which is known as Electric Double layer or EDL [1]. Fluid motion is achieved when an external field acts on the charges of the interface causing, for example, Electroosmosis (EO), AC electroosmosis (ACEO) [2] or induced-charge electroosmosis (ICEO) [3].

Concentration-Polarization Electroosmosis (CPEO) was first observed around charged dielectric pillars made of polydimethyl siloxane (PDMS), a common material used in the fabrication of microfluidic devices. CPEO consisted in quadrupolar fluid flow patterns around the posts arising when applying a low-frequency AC electric field. An example of CPEO flows is shown in Figure 1 through fluorescent tracers which reveal the patterns when several video frames are stacked. These flows resembled ICEO ones, and observations of similar flows around dielectrics were previously reported and attributed to ICEO. However, as detailed in next section, CPEO and ICEO have a distinct origin.

In our work, we describe the key theoretical aspects of CPEO and show experimental verification of flows around different dielectric objects in microfluidics such as pillars, constrictions and micro-spheres. We also exploit the latter to show applications of the hydrodynamic flows to particle manipulation leading to fractionation of populations based on their size and/or surface charge. This is of particular interest for future biomedical applications.



Figure 1: Image stack showing fluid tracers describing CPEO flows around a PDMS pillar. Tracers are 500 nm fluorescent beads, and pillar has a diameter of 20  $\mu$ m. Fluid is an aqueous solution of KCl of 1.5 mS/m conductivity. Applied electric field has an amplitude of 80 kV/m and an AC frequency of 100 Hz.

## II. THEORY

The thickness of the EDL is given by the Debye length and is typically around tens of nanometers or smaller [1]. This allows modeling the physics as two separate regions the fluid bulk domain and the EDL. In this picture, when an electric field is applied causes a fluid motion within the EDL by acting on its charge imbalance. This is modeled via an effective slip velocity tangential to the solid wall,  $\mathbf{u}_{slip}$ . The Helmholtz-Smoluchowski formula relates the slip velocity with the applied electric field  $\mathbf{E}$  and the zeta potential  $\zeta$  (typically defined as the electric potential at the slip plane with the bulk solution [4]) of the interface [1]:

$$\mathbf{u}_{\rm slip} = -\frac{\varepsilon \zeta}{\eta} \mathbf{E},\tag{1}$$

where  $\varepsilon$  and  $\eta$  are, respectively, the electrolyte permittivity and its viscosity.

CPEO theory builds on the concept of surface conductance [4]. Moderately charged surfaces induce an excess ionic concentration within the EDL which gives rise to an excess surface current with respect to the fluid bulk. The non-dimensional number that characterizes the ratio of surface to bulk conductance is the Dukhin number Du  $= K_s/\sigma a$ , where  $K_s$  is the surface conductance (typically of the order of 1 nS),  $\sigma$  the bulk conductivity and a typical length scale. Within the thin EDL, conservation of current is expressed as the balance between surface currents and a normal flux of ions, which alters the electrolyte concentration c beyond the double layer. This induces a perturbation on the concentration  $\delta c$ , leading to concentration polarization (CP). Mathematically, in the limit of weak surface conductance this is expressed as a boundary condition to the concentration of the electrolyte c in the fluid bulk which can be written as:

$$\frac{\partial \delta c}{\partial n} = -\mathrm{Du} \nabla_s^2 \phi \tag{2}$$

In this equation, **n** is the unit vector normal to the surface,  $\phi$  is the electric field potential and  $\nabla_s^2$  stands for the surface Laplacian. Figure 2 gives a physical interpretation of the equation and the resulting CP that arises around a charged sphere.

CP drives two different phenomena which give rise to the observed time averaged (stationary) fluid flows in an AC electric field. First, Gouy-Chapmann equation [1] implies a change in the zeta potential  $\delta \zeta$  because of the fixed charge of the dielectric surface,

$$\delta\zeta = -\phi_{\text{ther}} \frac{\delta c}{c} \tanh \frac{\zeta}{2\phi_{\text{ther}}},\tag{3}$$

where  $\phi_{\text{ther}}$  is the scale for the electric potential, known as the thermal voltage. The action of the electric field on the perturbed zeta potential produces an electroosmotic contribution as in eq. (1). Following the CP pictured in Fig. 2(b), we will then have a positive  $\delta\zeta$  under the dielectric and a positive perturbation above the dielectric, with contributions to the slip fluid velocity as marked by the black arrows in Fig. 3(a).



Figure 2: Figures illustrating the concept of concentration polarization (CP). (a) The surface current within the EDL is balanced by an ion concentration exchange between the EDL and the bulk [see eq. (2)]. (b) Blue colour map showing the ion concentration polarization around a charge dielectric sphere.



Figure 3: Arrows showing direction of time-averaged electroosmotic slip driven by concentration polarization (CP) around a sphere. (a) Perturbation of Debye length modifying zeta potential [see eq. (3)]. (b) Induced charge in the fluid bulk [see eq. (4)].

Secondly, CP creates a bulk concentration gradient around the dielectric which induce a bulk charge. This induces a perturbed electric potential  $\delta\phi$  which is described as:

$$\nabla^2 \delta \phi = -\frac{1}{c} \nabla \delta c \cdot \nabla \phi. \tag{4}$$

Figure 3(b) shows a picture of the induced charges in the volume surrounding the dielectric. The electroosmotic slip of the perturbed electric field together with the unperturbed zeta potential create an electroosmotic slip as shown by the black arrows, contributing in the same direction as the perturbed zeta potential. Mathematically, the slip velocity due to perturbed zeta potential described as a maximum value  $\mathcal{U}$  scaling with  $\varepsilon \phi_{\text{ther}}^2/a\eta$ , and an angular dependency:  $\mathbf{u}_{\text{slip}} = \mathcal{U} \sin 2\theta \hat{\theta}$ . Here,  $\theta$  is the angle with respect to the applied electric field.

A detailed mathematical description of the CPEO phenomenon can be found in previous publications [5, 6]. A key result that can be extracted from the theory is that as CP drives the phenomenon, typical time is the diffusion time  $t \sim a^2/D$  of the electrolyte (D diffusion constant of the electrolyte ions), i.e. the time the CP takes to build around the dielectric. This limits the frequency of the AC field above which CPEO vanishes. This fact is used to unambiguously differentiate CPEO from ICEO flows, as the diffusion equation further predicts a decay in the velocity

magnitude with  $\sqrt{f}$  above the frequency cut [5].

#### III. EXPERIMENTAL METHODS

We used PDMS microfluidic channels to observe the fluid flow patterns. The fabrication was achieved using common soft-lithography techniques that are reported elsewhere [5, 10]. PDMS pillars and constrictions are embedded in 50  $\mu$ m tall, 200  $\mu$ m wide, 1 cm long channels. In the case of CPEO characterization around micro-spheres, channels are square 50  $\mu$ m cross-section, and spheres are 3 micron in diameter (polystyrene with Carboxylate functionalization,  $\zeta \approx -75$  mV). Flow is traced using 500 nm fluorescent microbeads seeded in the electrolyte. The fluid was a KCl solution diluted to conductivities ranging from 1.5 to 15 mS/m. To avoid particle adhesion to channel walls, channels were treated for 30 minutes prior to experiments using Pluronic F-127, a non-ionic surfactant. Electric field was imposed through metallic needles at channel ends, which served both as fluidic inlets and electric field input. The signal applied had amplitudes up to 1600 Vpp and frequencies from 50 Hz to 100 kHz. Finally, fluid flow field was extracted from particle positioning using PIV [7].

#### IV. RESULTS

#### A. Microfluidic channel features

CPEO flows are first studied around 20  $\mu$ m-diameter pillars in microfluidic channels. Figure 4(a) shows a detail of the array of pillars used for the study. Typical frequencies are  $f \sim 3$  Hz so that a decay with frequency was expected to be observed in the studied frequency regime (50 Hz to 1 kHz). Also, since  $a = 10 \ \mu$ m, Du  $\approx 0.06$  for a KCl conductivity of 1.5 mS/m. A small-Dukhin-number analysis of the electrokinetic equations allowed to obtain analytical expressions for the fluid velocity field which were then compared against experiments. Diffusion equation prediction of  $\sqrt{f}$  velocity decay was verified by experimental observations as shown in Figure 4(b). Same methodology was applied to study the flows around 20  $\mu$ m gap microfluidic constrictions, presented in Figure 4(c).

#### B. Dielectric Micro-spheres

Single 500 nm tracers were tracked around 3  $\mu$ m carboxylate microspheres to infer the CPEO velocity field. Given the change in typical length scales, Dukhin number is significantly higher (Du  $\approx 0.5$ ) and previous analytical studies based on small Dukhin numbers break down. We delivered a weak electric field theoretical analysis for arbitrary Du to account for CPEO flows at smaller scales for comparison with observations around particles. Also, typical frequencies increase to  $f \approx 150$  Hz which allowed observing a velocity plateau experimentally [6]. Figure 4(d) shows an image stack of the tracers describing the CPEO flows around the target particle.



Figure 4: Experimental observations of CPEO flows around various dielectrics. (a) Array of 20 micron pillars in 1.7 mS/m KCl subjected to an AC field of 80 kV/m and 190 Hz. (b) ) Mean CPEO fluid flow velocity around pillars as a function of the AC frequency for three different conductivities. (c) Microfluidic constriction with 20 micron gap in 1.7 mS/m KCl subjected to an AC field of 20 kV/m and 50 Hz. (d) 3  $\mu$ m polystyrene particle in 1.5 mS/m KCl and AC electric field of 80 kV/m amplitude and 290 Hz frequency.

#### V. APPLICATIONS

CPEO around freely moving particles are proved to cause hydrodynamic particle-wall interactions [8, 9]. This is due to the distortion of the velocity field around the particle when in the vicinity of a bounded domain, as represented in Figure 5(a). If the electric field is parallel to the wall, the hydrodynamic force that arises is repulsive which translates into a velocity away from the wall  $u_{\rm rep}$  with a magnitude [8]

$$u_{\rm rep} = \mathcal{U} \frac{3a^2}{8h^2},\tag{5}$$

where h is the separation from the centre of the particle to the wall. The maximum slip velocity  $\mathcal{U}$  depends on particle size and surface charge, allowing different repulsive velocities and thus particle fractionation. This was exploited for separating spherical bacteria (S. Aureus 9144) and polystyrene particles (see Figure 5(b)).

The combination of CPEO flows around constrictions together with particle wall repulsion also allows to explain observed particle trapping in microfluidic constrictions (see Figure 5(c)) [10, 11]. This trapping qualitatively differs from commonly described trapping attributed to electric forces on the particle (dielectrophoresis or DEP), which predicts particle accumulation on or away from the constriction tips.

Recent findings show that CPEO can induce net phoretic motion of dimers composed of particles with different sizes. This motion results from the asymmetry in the CPEO flow intensity generated on each particle. This was termed Concentration Polarization Electrophoresis (CPEP) [13]. The phenomenon was used to capture and carry



Figure 5: Applications of CPEO hydrodynamic flows. (a) Induced wall-particle repulsion when electric field is applied paralel to wall. (b) fractionation achieved between polystyrene particles and bacteria [12]. (c) Trapping of 500 nm particles in microfluidic constrictions (1.7 mS/m KCl, 50 kV/m, 1kHz).

load across micro-scale systems, and dimmers were consequently called microrobots.

## VI. CONCLUSIONS

We summarise a newly-described phenomenon which we called Concentration-Polarization Electroosmosis or CPEO: Hydrodynamic flows arising around charged dielectric objects when subjected to low frequency AC electric fields. We show a mathematical description and experimental observations of such flows around various microscopic elements, e.g. microfluidic channel dielectric features and polystyrene micro-spheres. We use numerical modeling for comparing theory and experiments, and find good experimental agreement.

Scaling laws were deducted from theory, which predicts a scale for velocities with  $\varepsilon \phi_{\rm ther}^2/a\eta$ , and typical frequencies governed by diffusion equation  $f \sim D/2\pi a^2$ , above which flows decay with increasing frequencies following  $\sqrt{f}$ .

Applications are proposed for CPEO particle fractionation and separation in the context of continuous flow microfluidics, where the technique is potentially able to be coupled with existing methods to enhance separation efficiency with no major fabrication complexity added.

#### ACKNOWLEDGMENTS

P.G.S. and A.R. acknowledge the financial support from MCIN/AEI/10.13039/501100011033/FEDER, UE (Grant No. PID2022-138890NB-I00); R.F.M. from MSCA PF (HORIZON-MSCA-2023-PF-01-01 – ID: 101149570).

- [1] R. J. Hunter. Introduction to Modern Colloid Science, Oxford University Press, New York, 1993.
- [2] A. Ramos, H. Morgan, N. G. Green, A. Castellanos. AC electric-field-induced fluid flow in microelectrodes *Journal of colloid and interface science*. vol. 217, 2, 1999.
- [3] T. Squires, M. Z. Bazant. Induced-charge electroosmosis *Journal of Fluid Mechanics*. vol. 509, pp. 217– 252, 2004.
- [4] J. Lyklema. Fundamentals of Interface and Colloid Science, *Academic Press Limited*, London, 1995.
- [5] V. Calero, R. Fernández-Mateo, H. Morgan, P. García-Sánchez, A. Ramos. Stationary Electro-osmotic Flow Driven by ac Fields around Insulators *Physical Review Applied*. vol. 15, 014047, 2021.
- [6] R. Fernández-Mateo, P. García-Sánchez, V. Calero, H. Morgan, A. Ramos. Stationary electro-osmotic flow driven by AC fields around charged dielectric spheres *Journal of Fluid Mechanics*. vol. 924, R2, 2021.
- [7] W. Thielicke, E. J. Stamhuis. PIVlab towards userfriendly, affordable and accurate digital particle image velocimetry in MATLAB, *Journal of Open Research Software*. vol. 2, 30, 2014.
- [8] R. Fernández-Mateo, V. Calero, H. Morgan, P. García-Sánchez, A. Ramos. Wall Repulsion of Charged Colloidal Particles during Electrophoresis in Microfluidic Channels *Physical Review Letters*. vol. 128, 074501, 2022.
- [9] V. Calero, R. Fernández-Mateo, H. Morgan, P. García-Sánchez, A. Ramos. Low-frequency electrokinetics in aperiodic pillar array for particle separation *Journal of Chromatography A*. 1706, 464240, 2023.
- [10] R. Fernández-Mateo, V. Calero, H. Morgan, A. Ramos, P. García-Sánchez. Concentration-Polarization Electroosmosis near Insulating Constrictions within Microfluidic Channels *Analytical Chemistry*. vol. 93, pp. 14667–14674, 2021.
- [11] R. Fernández-Mateo, R. Gannoun, H. Morgan, A. Ramos, P. García-Sánchez. Trapping of micro- and nano-particles within microfluidic constrictions in AC electric fields *in Review*.
- [12] R. Fernández-Mateo, P. García-Sánchez, A. Ramos, H. Morgan. Concentration–polarization electroosmosis for particle fractionation *Lab on a Chip.* vol. 24, 2968, 2024.
- [13] F. Katzmeier, F. C. Simmel. Microrobots powered by concentration polarization electrophoresis (CPEP). *Nature Communications*. vol. 14, no. 1 pp. 14667–14674, 2023.

## Visualization of Singlet Delta Oxygen Produced by Atmospheric Pressure Plasma Jet

S. Kanazawa<sup>1\*</sup>, T. Fukui<sup>1</sup>, T. Furuki<sup>1</sup>, K. Tachibana<sup>1</sup>, R. Ichiki<sup>1</sup>, M. Kocik<sup>2</sup>, J. Mizeraczyk<sup>3</sup>

<sup>1</sup> Faculty of Science and Technology, Oita University, Japan
 <sup>2</sup> Institute of Fluid Flow Machinery, Polish Academy of Sciences, Poland
 <sup>3</sup>Department of Marine Electronics, Gdynia Maritime University, Poland

\*Corresponding author: skana@oita-u.ac.jp

Abstract- Atmospheric pressure plasma jet (APPJ) is widely used for several medical, biological and agricultural applications. This plasma technology supplies highly active species such as reactive oxygen and nitrogen species (ROS & RNS) towards the target surface in the open air. In general, reactive oxygen species include hydroxyl radial (OH), superoxide anion(O<sub>2</sub>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) and singlet delta oxygen (O<sub>2</sub>(a<sup>1</sup> $\Delta_{g}$ )). Among them, singlet delta oxygen (SDO) does not have as much oxidizing power, but it has a longer lifetime. Recently, we have succeeded in the visualization of SDO for the first time by short wave infrared (SWIR) imaging using the InGaAs sensor. The dynamics of SDO against the several targets was studied experimentally.

Keywords- Single delta oxygen, Plasma Jet, Short wave infrared (SWIR) imaging, Visualization.

#### I. INTRODUCTION

Atmospheric pressure plasma jet (APPJ) is utilized in various fields such as industrial process, medicine, and agriculture. This plasma technology delivers highly reactive oxygen and nitrogen species (ROS and RNS) to the target in an external atmosphere. Among them, OH radicals have a higher oxidation potential and have been the subject of much research [1, 2]. While, singlet delta oxygen (SDO,  $O_2(a^1\Delta g)$ ) is known for having low oxidation power but a long lifetime (75 min.) [3]. SDO is being researched as a reactive species with potential applications in cancer treatment [4] and enhancing combustion efficiency [5]. Electron spin resonance (ESR) spectroscopy was performed to measure SDOs in aqueous solution using the spin-trapping agents as an indirect method [6, 7]. SDO measurement has been made by vacuum ultraviolet absorption spectroscopy [8]. Molecular beam mass spectrometry has also been applied to detect SDO [9]. In the optical emission spectroscopy, SDOs may be observed directly because SDOs have an emission spectral peak at about 1270 nm [10, 11]. However, SDO have not been studied much in the field of plasma science due to the detection difficulty. Recently, we succeeded in the visualization of SDO for the first time by short wave infrared (SWIR) imaging using the InGaAs sensor. Here, we present images of the SDO and discuss the dynamics of SDOs generated by the APPJ.

## II. EXPERIMENTAL SETUP AND PROCEDURES

Fig.1 shows a schematic diagram of the experimental setup. A tapered glass tube with a 1 mm inner diameter at the end was used. Two ring electrodes were wound around

the tube. The working gas, either He of He/O<sub>2</sub>, is prepared in a gas mixing tube connected to the mass flow controller. Oxygen concentration was monitored using an oxygen monitor (Daiichi Nekken,  $E_{COA}Z$ ) at the point before entering the glass tube. The low frequency high voltage (output from an inverter type Neon transformer, 20 kHz) was applied to the two ring electrodes, APPJ was generated and a plume was ejected into surrounding air. Various irradiation targets were placed downstream of the plasma jet.

Fig.2 shows the potential-energy curve of O<sub>2</sub> [12]. The SDO is the first excited state of the oxygen molecule with the energy of 0.98 eV. The emission of SDO via the transition  $O_2(X^3\Sigma^-g) \leftarrow O_2(a^1\Delta g)$  at 1270 nm was recorded using an SWIR camera (Raptor photonics, Ninox 640 SU, sensor: InGaAs with 80% quantum efficiency) equipped



Fig. 1. Schematic diagram of experimental setup.



Fig. 2. Potential-energy curve for  $O_2$  lower states [12]. The inset shows the energy positions of states populated in the plasma.

with an optical bandpass filter ( $1270 \pm 10$  nm). The InGaAs sensor was cooled at –  $80^{\circ}$ C. The experiment was carried out at room temperature and under atmospheric pressure.

#### III. RESULTS AND DISCUSSION

#### A. Discharge characteristics

The output of the inverter neon transformer is a sinusoidal high voltage with a frequency of 20 kHz modulated at 60 Hz. Fig.3 shows the voltage-current waveforms at peak output voltage. The discharge current includes a fast component (current pulsed for the generation of plasma jet) and a slow component (displacement current). In this case, helium plasma jet was generated via a dielectric barrier discharge mode between the two ring electrodes.

### B. Plasma jet irradiation in free space

Fig.4 (a) shows the typical image of helium plasma jet



Fig. 4. Helium plasma jet. (a) light emission taken by a digital camera (Nikon D6) and (b) optical emission of 1270 nm under room light captured by an SWIR camera (Ninox 640 SU). The He flow rate is 2 L/min for both.



Fig. 3. Typical applied voltage and current waveforms for helium plasma jet.

captured by the digital camera with exposure time of 1 s. Corresponding image from the emission of 1270 nm under room light captured by the SWIR camera with exposure time of 400 ms is shown in Fig.4 (b). In Fig.4 (b), the emission in the plasma area is mainly the 1270 nm component due to the heat of the plasma, and the clear image of the high-voltage cable area is due to the near-infrared radiation contained in the room lighting. Hence, no singlet delta oxygen, SDOs, production was observed in the helium plasma jet.

Next, when a small amount of oxygen (~2%) was introduced into the helium plasma jet, the plasma plume emitted from the glass tube nozzle observed in Fig.4 (a) was no longer observed, and the emission was mainly limited to between the two ring electrodes. Astonishingly, however, when helium was mixed with oxygen, the SWIR image changed dramatically due to the formation of singlet delta oxygen, as shown in Fig.5 (a). The imaging was carried out in a dark room, and the exposure time of the SWIR camera is 400 ms, which corresponds to 8000 cycles of applied voltage. To our knowledge, this is the



Fig. 5. Helium-oxygen (2%) plasma jet. (a) SWIR imaging of SDOs for free plasma jet and (b) SWIR imaging of SDOs under the influence of 1.4 m/s airflow. The mixture gas flow rate is 2.1 L/min for both.



Fig. 6. Helium-oxygen (2%) plasma jet showing SDOs irradiated to a finger. The mixture gas flow rate is 2.1 L/min.

first 2-D image of SDOs generated by APPJ. The gas velocity at the tip of the nozzle is 42 m/s, from which the gas velocity gradually decreases, and the distribution range is seen to extend in a conical shape. A similar two-dimensional distribution was observed at even lower oxygen concentrations (down to 0.5% in this experiment). The distribution pattern is similar to that observed with the Schlieren method [13]. In addition, when airflow (wind speed 1.4 m/s) is applied from the side, the SDOs are found to be swept sideways as shown in Fig.5 (b).

#### C. Plasma jet irradiation to various targets

Due to the highly non-equilibrium nature of atmospheric pressure plasma jets, it is common practice to apply the plasma plume directly to a finger. Fig.6 shows a case where a finger is inserted away from the plasma jet, but is covered by SDOs. Therefore, it should be noted that SDO, one of the reactive oxygen species, affects even outside the emission region of the plasma.

Fig. 7 shows the interaction between various targets and the plasma jet. Fig.7(a) shows the cone-shaped SDO flow acting on the sphere. There have been many studies on the flow around a sphere [14-16], and a characteristic wake flow behavior was observed for a Reynolds number of about  $10^3$ , which corresponds to this experiment. Fig. 7(b) shows the SDO flow against a disk placed at an oblique angle to the flow. It can be observed that the long-lived SDOs are found flowing along the disk. Furthermore, Fig.7(c) shows that when the mesh plate is used, some SDO flow penetrates through it.

APPJ is widely used for stimulation of biological tissues in aqueous solutions and as a liquid treatment to produce plasma-activated water. Finally, Fig.8 shows SDOs being supplied to water in two petri dishes with different diameters placed out of reach of the plasma jet under room light. It can be clearly seen that SDOs are transported by the plasma-induced gas flow to the surface of the water. Fig.8(a) shows the case where the cone-shaped plasma spread and the inner diameter of the petri dish nearly coincide. On the other hand, the SDOs that reach the water surface spread out over the surface of the water, and when they come to the edge of the petri dish (77 mm inner diameter, 15 mm in height) as shown in Fig.8(b), they wind upward and generate a vortex flow.

In this study, initial results for the visualization of metastable singlet delta oxygen molecules were shown. This was made possible by a state-of-the-art SWIR camera with low thermal noise and high quantum efficiency among many other cameras.

## IV. CONCLUSION

We have succeeded for the first time in the visualization of singlet delta oxygen produced by atmospheric pressure helium-oxygen plasma jet. Singlet delta oxygen, one of the reactive oxygen species, was found to be transported far from the plasma due to the long-lived species. Based on the relationship between the velocity of the airflow and the observed distance, a lifetime of more than one second is expected. Hence, it may contribute to chemical reactions that occur outside the plasma. Further experiments under various conditions such as the effects of gas flow rate, oxygen concentration,



Fig. 7. Helium-oxygen (2%) plasma jet. (a) SWIR imaging of SDOs against for sphere (dia.40 mm), (b) SWIR imaging of SDOs against for a circular plate (dia.80 mm) placed diagonally, and (c) SWIR imaging of SDOs against for a 65 mesh circular plate (dia.50 mm). The mixture gas flow rate is 2.1 L/min for all.



Fig. 8. Helium-oxygen (2%) plasma jet. (a) SWIR imaging of SDOs for a petri dish with 47 mm inner diameter and (b) SWIR imaging of SDOs for a petri dish with 77 mm inner diameter. The mixture gas flow rate is 2.1 L/min for both.

and plasma power are being planned to clarify the dynamics of SDOs.

#### ACKNOWLEDGMENT

This study was partially supported by JSPS KAKENHI Grant Number 24K00872.

#### REFERENCES

- [1] S. Kanazawa H. Kawano, S. Watanabe, T. Furuki, S. Akamine, R. Ichiki, T. Ohkubo, M. Kocik and J. Mizeraczyk, Observation of OH radicals produced by pulsed discharges on the surface of a liquid, Plasma Sources Sci. Technol., 20, 034010, 2011.
- [2] J. Cosimi, F. Marchal, N. Merbahi, O. Eichwald, J. P. Gardou, and M. Yousfi, Laser-induced fluorescence measurements of spatially resolved OH densities in a helium plasma jet interacting with three different targets in the open air, Plasma Sources Sci. Technol., 32, 065012, 2023.
- A. A. Ionin, I. V. Kochetov, A. P. Napartovich, and [3] N. N. Yuryshev, Physics and engineering of singlet delta oxygen production in low-temperature plasma, J. Phys. D. Appl. Phys., 40, R25-R61, 2007.
- [4] P. Singh Maharjan and H. K. Bhattarai, Singlet Oxygen, Photodynamic Therapy, and Mechanisms of Cancer Cell Death, J. Oncology, 2022, 7211485, 2022.
- [5] J. Al.- Nu'airat, I. Oluwoye, N. Zeinali, M. Altarawneh, and B. Z. Dlugogorski, Review of Chemical Reactivity of Singlet Oxygen with Organic Fuels and Contaminants, Chem. Rec., 21, 315-342, 2021.
- T. Takamatsu, K. Uehara, Y. Sasaki, H. Miyahara, Y. [6] Matsumura, A. Iwasawa, N. Ito, T. Azuma, M. Kohnoc, and A. Okino, Investigation of reactive species using various gas plasmas, RSC Adv., 4, 39901-39905, 2014.
- C. Chen, F. Li, H.-L. Chen, and M. G. Kong, [7] Interaction between air plasma-produced aqueous  $^{1}O_{2}$  and the spin trap DMPO in electron spin resonance, Phys. Plasma, 24, 103501, 2017.
- M. Ito, H. Hashizume, J.-S. Oh, K. Ishikawa, T. Ohta, [8] and M. Hori, Inactivation mechanism of fungal

spores through oxygen radicals in atmosphericpressure plasma, Jpn. J. Appl. Phys., 60, 010503, 2021.

- [9] J. Jiang, Y. A. Gonzalvo and P. J. Bruggeman, Spatially resolved density measurements of singlet delta oxygen in a non-equilibrium atmospheric pressure plasma jet by molecular beam mass spectrometry, Plasma Sources Sci. Technol., 29, 045023, 2020.
- [10] J. S. Sousa, G. Bauville, B. Lacour, V. Puech, M. Touzeau, and L.C. Pitchford,  $O_2(a^1\Delta g)$  production at atmospheric pressure by microdischarge, Appl. Phys. Lett., 93, 011502, 2008.
- [11] Y. Inoue, R. Ono, Measurement of singlet delta oxygen in an atmospheric-pressure helium-oxygen
- plasma jet, J. Phys. D. Appl. Phys., 50, 214001, 2017.
  [12] Z. Farooq, D. A. Chestakov, B. Yan, G. C. Groenenboom, W. J. van der Zande, and D. H. Parker, Photodissociation of singlet oxygen in the UV region, Phys. Chem. Chem. Phys., 16, 3305-3316, 2014.
- [13] Y. Zheng, L. Wang, W. Ning, and S. Jia, Schlieren imaging investigation of the hydrodynamics of atmospheric helium plasma jets, J. Appl. Phys, 119, 123301, 2016.
- [14] R. H. Magarvey and C. S. MacLatchy, Vortices in
- [14] R. H. Magarvey and C. S. MacLateny, Voltees in sphere wakes, *Can. J. Phys.*, 43, 1649-1656, 1965.
  [15] E. Achenbach, Vortex shedding from spheres, *J. Fluid Mech*, 62, 209-221, 1974.
- [16] H.-P. Pao and T. W. Kao, Vortex structure in the wake of a sphere, Phys. Fluids, 20, 187-191, 1977.

## Universal Time-Scale Parameter for Describing the Coalescence of Conductive Droplets under Pulsed Electric Fields

P. A. Kostin<sup>1\*</sup>, V. A. Chirkov<sup>1</sup> <sup>1</sup> St. Petersburg State University, St. Petersburg, Russia \*Corresponding author: p.kostin@spbu.ru

Abstract—Electrocoalescence involves merging droplets in immiscible liquids using electric fields, with pulsed voltage possibly enhancing the process. While droplet behavior at very low and high frequencies resembles that under constant voltage, the intermediate range remains less understood. This study employs a numerical model based on the arbitrary Lagrangian—Eulerian method, Gauss's law, and the Navier—Stokes equations to simulate coalescence of conductive droplets in oil. Frequency-dependent thresholds separating coalescence from non-coalescence were identified for different droplet sizes. These results were generalized using a dimensionless time-scale parameter that incorporates pulse frequency, time scales from the governing equations, and the Ohnesorge number. The proposed approach provides a predictive framework for studying electrocoalescence under time-varying electric fields and supports the design and interpretation of future experiments.

Keywords—Numerical Simulation, Arbitrary Lagrangian-Eulerian Method, Electrocoalescence, Two-Phase Liquid.

## I. INTRODUCTION

Electrocoalescence refers to the process of droplet merging under the influence of an external electric field. This physical phenomenon underpins several practical applications, one of which is the electroseparation of emulsions where small droplets of a conductive liquid are suspended in a dielectric medium. A significant example of such electroseparation is the dehydration of crude oil [1,2].

In a number of studies, researchers have sought to enhance the efficiency of electroseparation by applying time-varying rather than constant electric fields [3–8]. These include harmonic signals, unipolar and bipolar pulsed signals, sawtooth waveforms, among others. Experimental investigations in this area yield valuable insights: various signal types are compared, and optimal amplitudes and frequencies are identified. However, these results often fall short of revealing the specific mechanisms responsible for the observed improvements in separation efficiency.

One of the challenges in analyzing experimental data lies in the limited understanding of how the characteristic frequencies of droplets depend on fluid properties and droplet size. As a result, optimal signal frequencies can vary significantly for droplets of different sizes or for liquids with different properties.

For practical applications of electrocoalescence, it is important to identify the threshold field strength beyond which coalescence ceases and either partial coalescence or non-coalescence begins.

Previous work [9] attempted to describe the dependence of the single-drop breakup threshold on the frequency of a pulsed electric field. It was shown that introducing a new time-scale parameter  $t_y$ , and a corresponding dimensionless parameter defined as the product of field frequency f and  $t_y$ , allows the results to be generalized across different droplet radii and oil properties:

$$P_{ty} = f \cdot t_y, \ t_y = \sqrt{\frac{\rho_{oil} r_0^3}{\sigma}} Oh^{0.7}, \ Oh = \frac{\eta_{oil}}{\sqrt{\sigma \rho_{oil} r_0}}.$$
 (1)

Here,  $\rho$  is the density,  $\eta$  is the dynamic viscosity,  $\sigma$  is the interfacial tension,  $r_0$  is the radius of an undeformed droplet.

The next step was to establish a threshold–frequency relationship for the electrocoalescence case [10]. A characteristic curve was obtained for a fixed droplet radius and fluid properties, and its features and asymptotic behavior were analyzed. It was also demonstrated that variability in the threshold arises due to the random phase of the electric signal at the moment of droplet contact.

The present study builds on the aforementioned research. Its aim is to determine, through numerical modeling, how the frequency dependence of the threshold electric field varies with droplet radius and to explore the possibility of generalizing this relationship using the previously introduced parameter  $P_{ty}$ .

## II. NUMERICAL MODEL

The electrocoalescence process is simulated using the Arbitrary Lagrangian–Eulerian (ALE) method. The following assumptions are applied in the construction of the model:

- the droplet is treated as a perfect conductor,
- the oil is treated as a perfect dielectric,
- material properties are homogeneous,
- gravity is neglected,
- both fluids are incompressible,
- droplets are electrically neutral,
- all droplets have the same size,
- droplets are aligned along the direction of the electric field.

The model solves the following set of equations.



Fig. 1. Geometry of the computational model and boundary conditions. \*plane antisymmetry for electric potential.

### Navier-Stokes equations for both phases:

$$\rho\left(\frac{\partial \boldsymbol{\nu}}{\partial t} + (\boldsymbol{\nu} \cdot \boldsymbol{\nabla})\boldsymbol{\nu}\right) = -\boldsymbol{\nabla}p + \eta \Delta \boldsymbol{\nu}, \qquad (2)$$
$$\boldsymbol{\nabla} \cdot \boldsymbol{\nu} = 0, \qquad (3)$$

where v is the velocity, p is the pressure,  $\rho$  is the density, and  $\eta$  is the dynamic viscosity.

Gauss's law for the dielectric (oil):

$$\nabla \cdot (\varepsilon \varepsilon_0 E) = 0, \qquad E = -\nabla \varphi, \tag{4}$$

where  $E, \varphi$  are the electric field intensity and potential,  $\varepsilon$  is the relative permittivity, and  $\varepsilon_0$  is the vacuum permittivity.

#### Interface boundary conditions:

The normal component of the stress tensor experiences a discontinuity due to interfacial forces: the electric force  $f_{el}$  and the surface tension force  $f_{st}$ :

$$f_{el} = \frac{1}{2} \varepsilon \varepsilon_0 E^2, \qquad (5)$$
  
$$f_{st} = 2\sigma \kappa, \qquad (6)$$

where  $\sigma$  is the interfacial tension and  $\kappa$  is the mean curvature of the interface. The tangential component of the stress tensor is continuous across the interface.

The velocity field is continuous, and the geometric interface between the phases moves with the local fluid velocity.

In addition, the electric potential is constant over the entire droplet surface.

Zero charge condition at the droplet interface:

$$\int_{\text{Interface}} \varepsilon \varepsilon_0 E \, dS = 0. \tag{7}$$

The types of **boundary conditions** applied at the edges of the computational domain are illustrated in the Fig. 1. A fixed potential  $\varphi_0$  is applied at the electrode.

The applied potential  $\varphi_0(t)$  is defined through the field intensity as  $\widehat{E_0}(t) = H\varphi_0(t)$ , where  $\widehat{E_0}(t)$  represents a smoothed pulsed waveform with an amplitude of  $E_0$  and a duty cycle  $\beta = 0.5$ . Due to the smoothing of the signal, the effective duty cycle,

$$\beta_{eff} = \frac{\frac{1}{T} \int_0^T \widehat{E_0}(t) dt}{E_0^2} \tag{8}$$

is slightly lower than  $\beta$ , and is equal to  $\beta_{eff} = 0.487$ .

The ALE method used for simulating electrocoalescence requires manual adjustments to the

mesh topology. The simulation process consists of two stages: first, droplet approach is modeled up to a critical distance, followed by the manual insertion of a liquid bridge; second, the deformation dynamics of the merged droplet are analyzed. This approach has been experimentally validated and successfully applied to various problems [11–14].

#### III. RESULTS AND DISSCUSION

In this study, we limited our analysis to a single value of the duty cycle ( $\beta = 0.5$ ,  $\beta_{eff} = 0.487$ ). Additionally, we fixed the properties of the oil as follows: density  $\rho_{oil} = 910$ kg/m<sup>3</sup>, relative permittivity  $\varepsilon_{oil} = 2.85$ , interfacial tension  $\sigma = 16$  mN/m, and dynamic viscosity  $\eta_{oil} = 60$  mPa·s, corresponding to the properties of olive oil [15]. The properties of water were also held constant:  $\rho_{water} = 998$ kg/m<sup>3</sup>,  $\eta_{water} = 1$  mPa·s.

In the baseline case, droplets with an initial radius of  $r_0 = 1$  mm were considered. This radius was then varied in subsequent simulations. For each droplet radius, the threshold electric field strength was evaluated as a function of signal frequency.

# *A. Dependence of Threshold Electric Field on Frequency.*

Let us now consider in more detail how the threshold electric field strength is determined. For all parameter values considered in this study, the physical process follows the same general pattern: under the action of the pulsed electric field, the droplets undergo oscillations and deformation, gradually approaching each other until a critical separation is reached. This moment of approach is interpreted as contact: a liquid bridge is then manually inserted between the droplets, marking the beginning of the second phase of the simulation.

As a result of this interaction, the droplets either merge into a single oscillating droplet—a process we refer to as coalescence—or a new thin bridge appears between them without full merging, which we define as non-coalescence. Examples of droplet shapes observed in non-coalescence outcomes are presented in Fig. 2.

For each field frequency, a series of simulations was performed with varying electric field amplitudes. The threshold field strength is defined as the average of the two extreme values of field intensity at which the outcomes transition between coalescence and non-coalescence. These extreme cases are represented as error bars in the subsequent figures. In the presented results, the difference between these threshold-defining values does not exceed 0.05 kV/cm, while the typical field strength is around 3 kV/cm.

Let us now consider the threshold-vs-frequency curve obtained for the baseline configuration (Fig. 3). A detailed



Fig. 2. Droplet shapes resulting from non-coalescence at various frequencies and field strengths (droplet radius 1 mm).

discussion of this result is provided in [10]; here we briefly highlight its key features:

- 1. At low frequencies, the threshold approaches a steady level where the field amplitude  $E_0$  equals the threshold under a static electric field,  $E_{DC}$ .
- 2. At high frequencies, the threshold also stabilizes, and the root-mean-square (RMS) field value,  $E_{RMS} = E_0 / \sqrt{\beta_{eff}}$  corresponds to  $E_{DC}$ .
- 3. The curve exhibits scatter: points close in frequency may show significant variation in threshold values.
- 4. Overall, the threshold increases with frequency.
- 5. The increase is not monotonic; there exists a frequency range where the threshold is notably elevated.

A detailed discussion of these features is beyond the scope of this study. The primary focus here is to examine how the obtained curve changes with variations in system parameters.

#### B. Effect of Droplet Size.

Let us now consider how the threshold–frequency dependence changes with variations in droplet radius. Before doing so, we introduce a convenient normalization



Fig. 3. Threshold field strength as a function of frequency for the baseline parameter set.



Fig. 4. Frequency dependence of the threshold electric Weber number for varying droplet radii.

approach to ensure the comparability of results. Indeed, as the droplet radius changes, the threshold values vary significantly, making direct comparisons less illustrative. To address this, we move to dimensionless parameters [16,17]: the Ohnesorge number and the electric Weber number:

$$Oh = \frac{\eta_{oil}}{\sqrt{\sigma\rho_{oil}r_0}}, \qquad We = \frac{2\varepsilon_0\varepsilon_{oil}r_0E_0^2}{\sigma}$$
(9)

The latter can be interpreted as a measure of the electric field strength that accounts for droplet size.

The resulting dependencies for different droplet radii are shown in Figure 4. The key finding emphasized in this work is a shift of the threshold curve toward lower frequencies as the droplet radius increases. An additional observation, which deserves separate investigation, is the apparent tendency for the peak of the curve to rise with increasing droplet radius.

The shift of the curve with droplet size is intuitively understandable: a larger droplet requires more time to respond to external excitation, corresponding to a lower characteristic frequency. But how can this shift be described quantitatively?

It was found that a dimensionless parameter (1) previously proposed for a related problem—the breakup of a single droplet—can be successfully applied here as



Fig. 5. Threshold electric Weber number versus the time-scale dimensionless parameter for varying droplet radii.

well. Figure 5 shows the same threshold curves, now plotted against the rescaled frequency using the proposed time-scale-based parameter. A close collapse of the curves is observed (within the expected scatter), indicating that the suggested formulation accurately captures the dependence of characteristic frequency on droplet size.

## V. CONCLUSION

In this study, numerical simulations were used to analyze how the threshold amplitude of the electric field depends on the frequency of pulsed excitation as the droplet size varies. In addition to providing a qualitative explanation for the intuitively expected behavior, a method for quantitative characterization was proposed. At this stage, we have demonstrated that the introduced timescale parameter effectively describes the dependence on droplet radius; its applicability to other system parameters remains to be tested.

The proposed time-scale parameter may serve as a useful tool for planning and interpreting experimental studies. It can help isolate the effects related to frequencydependent threshold variation from other phenomena not included in the current model—for example, those associated with the rupture of asphaltene films.

## ACKNOWLEDGMENT

The study was supported by Russian Science project research 22-79-10078, Foundation, No. https://rscf.ru/en/project/22-79-10078/. The research was performed at the Research Park of St. Petersburg State University "Computing Center," "Center for Nanofabrication of Photoactive Materials (Nanophotonics)," and "Center for Diagnostics of Functional Materials for Medicine, Pharmacology, and Nanoelectronics."

- S.M. Abed, N.H. Abdurahman, R.M. Yunus, H.A. Abdulbari, S. Akbari, Oil emulsions and the different recent demulsification techniques in the petroleum industry - A review, IOP Conf. Ser.: Mater. Sci. Eng. 702 (2019) 012060. https://doi.org/10.1088/1757-899X/702/1/012060.
- [2] M.A. Saad, M. Kamil, N.H. Abdurahman, R.M. Yunus, O.I. Awad, An Overview of Recent Advances in State-of-the-Art Techniques in the Demulsification of Crude Oil Emulsions, Processes 7 (2019) 470. https://doi.org/10.3390/pr7070470.
- [3] Y. Peng, T. Liu, H. Gong, J. Wang, X. Zhang, Effect of pulsed electric field with variable frequency on coalescence of drops in oil, RSC Adv. 5 (2015) 31318–31323. https://doi.org/10.1039/C5RA01357G.
- [4] B. Li, Z. Sun, Z. Wang, Y. Jin, Y. Fan, Effects of highfrequency and high-voltage pulsed electric field parameters on water chain formation, Journal of Electrostatics 80 (2016) 22– 29. https://doi.org/10.1016/j.elstat.2016.01.003.
- [5] R. Hasib, V. Anand, V.M. Naik, V.A. Juvekar, R.M. Thaokar, Mitigating Noncoalescence and Chain Formation in an Electrocoalescer by Electric Field Modulation, Ind. Eng. Chem. Res. 61 (2022) 17145–17155. https://doi.org/10.1021/acs.iecr.2c02202.

- [6] H. Gong, B. Yu, Y. Peng, F. Dai, Promoting coalescence of droplets in oil subjected to pulsed electric fields: changing and matching optimal electric field intensity and frequency for demulsification, Journal of Dispersion Science and Technology 40 (2019) 1236–1245. https://doi.org/10.1080/01932691.2018.1505525.
- [7] T.A. Brasil, E.H. Watanabe, T. Assenheimer, L. Do Carmo, M. Nele, F. Tavares, Microscope analysis and evaluation of the destabilization process of water-in-oil emulsions under application of electric field, IEEE Trans. Dielect. Electr. Insul. 27 (2020) 873–881. https://doi.org/10.1109/TDEI.2020.008494.
- [8] X. Huang, L. He, X. Luo, K. Xu, Y. Lü, D. Yang, Charge-Transfer-Induced Noncoalescence and Chain Formation of Free Droplets under a Pulsed DC Electric Field, Langmuir 36 (2020) 14255–14267. https://doi.org/10.1021/acs.langmuir.0c02371.
- [9] P. Kostin, V. Chirkov, Generalizing Numerical Simulation Results for Droplet Electrodeformation Threshold Under Pulsed DC Voltage, in: 2024 IEEE 5th International Conference on Dielectrics (ICD), IEEE, Toulouse, France, 2024: pp. 1–4. https://doi.org/10.1109/ICD59037.2024.10613309.
- [10] P A Kostin, B.A. Chernykh, A.V. Samusenko, V.A. Chirkov, Similarities and differences in electrocoalescence processes of conducting uncharged droplets at the DC and pulsed voltage, Journal of Electrostatics (2025). https://doi.org/10.1016/j.elstat.2025.104072.
- [11] V. Chirkov, G. Utiugov, P. Kostin, A. Samusenko, Physical correctness of numerical modeling electrohydrodynamic processes in two-phase immiscible liquids basing on the phasefield and arbitrary Lagrangian–Eulerian methods, International Journal of Multiphase Flow (2024). https://doi.org/10.1016/j.ijmultiphaseflow.2024.104881.
- [12] G.O. Utiugov, V.A. Chirkov, I.A. Dobrovolskii, The Experimental Verification of Electrodeformation and Electrocoalescence Numerical Simulation Based on the Arbitrary Lagrangian–Eulerian Method, in: 2020 IEEE 3rd International Conference on Dielectrics (ICD), IEEE, Valencia, Spain, 2020: pp. 529–532. https://doi.org/10.1109/ICD46958.2020.9341816.
- [13] D.D. Saifullin, D.S. Lukin, A.V. Samusenko, V.A. Chirkov, Regime map of non-coalescence between two equal-sized uncharged water droplets suspended in oil: A numerical study, Physics of Fluids 36 (2024) 123310. https://doi.org/10.1063/5.0240476.
- [14] A. Ridel, S. Korobeynikov, M. Lyutikova, V. Chirkov, P. Kostin, Water droplet deformation at alternating electric field action: experiment and numerical simulation, Interfac Phenom Heat Transfer (2023). https://doi.org/10.1615/InterfacPhenomHeatTransfer.20230491 82.
- [15] V. Chirkov, G. Utiugov, I. Blashkov, S. Vasilkov, The effect of changing interfacial tension on electrohydrodynamic processes in two-phase immiscible liquids, International Journal of Plasma Environmental Science and Technology 17 (2023). https://doi.org/10.34343/ijpest.2023.17.e03003.
- V.A. Chirkov, P.A. Kostin, Generalization of numerical simulation results on the electrical coalescence threshold for two conducting droplets based on non-dimensional parameters, J. Phys.: Conf. Ser. 2701 (2024) 012075. https://doi.org/10.1088/1742-6596/2701/1/012075.
- [17] M. Mousavichoubeh, M. Shariaty-Niassar, M. Ghadiri, The effect of interfacial tension on secondary drop formation in electro-coalescence of water droplets in oil, Chemical Engineering Science 66 (2011) 5330–5337. https://doi.org/10.1016/j.ces.2011.07.019.

## The Complex Structure of Electrohydrodynamic Flows Arising in a Twophase Liquid with Weakly Conducting Dispersion Medium and Unequal Ions Mobilities

D. D. Saifullin\*, V. A. Chirkov St. Petersburg State University, Russia \*Corresponding author: d.sayfullin@spbu.ru

Abstract- Dissociation-recombination processes in a leaky dielectric dispersion medium (oil) affect the dynamics of conductive droplets constituting dispersed phase under the influence of an external electric field, which is important for the implementation of industrial electrostatic demulsification or multi-droplet numerical models. In this numerical study an arbitrary Lagrangian-Eulerian method is used to describe the interface between two liquids and consider the case in which mobilities of different types of ions differ. In a wide range of values of the electrical conductivity of the oil, the droplets begin to move in one direction. Also, in a narrow range of values, a trace of charge remains behind the drop, which causes an electrohydrodynamic flow that prevents the droplets from colliding with each other. A higher value of ion mobility corresponds to a lower contribution of the convection transport mechanism, which increases the droplet velocity and decreases the length of the charged trace.

Keywords- arbitrary Lagrangian–Eulerian method, dissociation-recombination charged layers, electrocoalescence, numerical simulation, two-phase immiscible liquid.

## I. INTRODUCTION

In most cases, the external dispersion medium is considered a perfect dielectric when dynamics and interaction of conducting droplets (dispersed phase) suspended in a dielectric oil (dispersion medium) are considered [1]. The large difference in phase conductivities makes it possible to effectively influence the strong electric fields aimed at division of two-phase liquids into components by combining small droplets into larger ones. A number of numerical approaches have been used to describe a two-phase liquid in such cases in attempts to solve the problem of how two droplets interact in various settings. The results obtained in such models of pair interactions can be involved directly in designing purification devices, as well as in multi-droplet approaches, in which the evolution of the entire emulsion (from hundreds to millions of droplets) is studied by describing generalized droplet dynamics data.

Thus, physical effects should be taken into account in models of pair interaction if they have a significant impact on the dynamics of droplets and the result of their interaction. One of the effects is the presence of dissociation-recombination processes in a dispersion medium in case it is leaky dielectric rather than a perfect one. Its degree of influence and the need to account for it may differ occasionally depending on electrical properties of the liquid. Dissociation of impurities results in free ions forming, and their concentration is limited by ion recombination. In most of the liquid volume, the concentrations of ions of both types are equal, while beside the surface of a conductive droplet in an external electric field, under the action of the Coulomb force, ions of one sign migrate away from the surface, and ions of the other sign, on the contrary, concentrate close to the surface. Because of this, charged layers form near the interface, causing a change in the electric field and the appearance of electrohydrodynamic (EHD) flows. The existing studies show that this leads to relatively small quantitative changes in the case when the mobilities of ions of different types are equal [2,3]. However, special attention should be paid to cases where the mobility of ions of different types is unequal, which is often found in practice [4]. It was found that the layers formed in this case lead to qualitative changes—an asymmetric convergence of the two droplets. However, there is still no complete understanding of how the dynamics and the pair interaction of droplets change in such systems.

Thus, the goals of the current work are to study the dynamics of conducting droplets of a dispersed phase and the processes of their interaction under the influence of electric field in case of unequal ion mobilities in the leaky dielectric dispersion medium and to gain understanding of the necessity to account for resulting effects when implementing such systems in "multi-droplet" models.

## II. NUMERICAL MODEL

A sharp interface method based on the arbitrary Lagrangian-Eulerian method was used to describe two-phase immiscible liquid, which makes it possible to account for and consider thin boundary layers near the water-oil interface. The method was used earlier to model similar tasks [2–5].

In this work, the parameters of distilled water ( $\rho_w = 998 \text{ kg/m}^3$ ,  $\mu_w = 0.91 \text{ mPa} \cdot \text{s}$ ,  $\varepsilon_w = 80$ ) and olive oil ( $\rho_o = 910 \text{ kg/m}^3$ ,  $\mu_o = 68 \text{ mPa} \cdot \text{s}$ ,  $\varepsilon_o = 2.85$ ) are used for the dispersed phase and the dispersion medium, respectively, as it was in [2-5].

During the calculations the following equations are solved: the Navier-Stokes (1) and the continuity (2) equations (2) describing liquid dynamics; Poisson's (3) and Gauss's (4) laws describing electric field distribution; system of Nernst-Planck equations (5-7) describing the ion concentration.

$$\rho_{i}\frac{\partial \vec{\upsilon}}{\partial t} + \rho_{i}(\vec{\upsilon},\nabla)\vec{\upsilon} = -\nabla P + \nabla ((\nabla \vec{\upsilon} + \nabla \vec{\upsilon}^{T})\mu_{i}) + q\vec{E} (1)$$

$$\operatorname{div}(\vec{\upsilon}) = 0 \tag{2}$$

$$\operatorname{div}(\vec{E}) = q/\varepsilon\varepsilon_0 \tag{3}$$
$$\vec{E} = -\nabla V \tag{4}$$

$$\vec{E} = -\nabla V \tag{4}$$

$$\int_{\partial t} + \operatorname{div}(\underline{J}_{\pm}) = \mathcal{W} - \mathbf{u}_{\Gamma}n_{\pm}n_{\pm} \qquad (3)$$

$$\int_{\vec{L}} = n_{\pm}\operatorname{sign}(Z_{\pm})b_{\pm}\vec{E} - d\nabla n_{\pm} + n_{\pm}\vec{\upsilon} \qquad (6)$$

$$\frac{1}{2} = n_{\pm} \operatorname{sign}(Z_{\pm}) b_{\pm} L = a \sqrt{n_{\pm}} + n_{\pm} 0 \tag{6}$$

$$q = \sum_{+} Z_{+} e n_{+}. \tag{7}$$

Here,  $\vec{E}$  is the electric field strength, *V* is the electric potential,  $\vec{v}$  is the fluid velocity, *P* is the pressure,  $\varepsilon$  is the relative electric permittivity of oil,  $\varepsilon_0$  is electric permittivity of vacuum, *q* is the space charge density,  $\rho$  is the density of the medium,  $\mu$  is the dynamic viscosity of the medium, *t* is the time, *n* is the ion concentration,  $\vec{j}$  is the ion flux density, *b* is the ion mobility, *Z* is the ion charge number, *e* is the elementary electric charge, *d* is the ion diffusion coefficient, *W* is the dissociation intensity,  $\alpha_r$  is the recombination coefficient. Subscript *i* notify the different phases of liquid, while "plus" and "minus" signs indicate the ion types. The right-hand side of the equation (5) are determined by the following ratios:

$$W = \frac{\sigma^2}{e(|Z_+|b_++|Z_-|b_-)\varepsilon\varepsilon_0}; \tag{8}$$

$$\alpha_{\rm r} = \frac{e(|z_+|b_++|z_-|b_-)}{\epsilon\epsilon_0}.$$
 (9)

Here,  $\sigma$  is the electrical conductivity of the oil (the conductivity of the oil at an equilibrium concentration of ions  $n_0$ ).

In this paper, the case of an asymmetric binary electrolyte containing two types of univalent ions is considered:  $Z_+ = 1$ ,  $Z_- = -1$ . Equations (3–9) are calculated only in a dispersion medium (oil) since water is considered as a perfect conductor.

The finite element method implemented in COMSOL Multiphysics is used to solve the problem. The calculated area is a cylinder, the bases of which are far enough from the drop that the conditions of field uniformity and the equilibrium value of ion concentration are fulfilled. Axial symmetry makes it possible to simplify the model to a two-dimensional formulation. Specified boundary conditions are shown in Fig. 1.

Conditions on the interface (droplet surface) are sophisticated. In addition to the pressure created by the dynamics of the liquid, there is also a pressure drop due to the surface Coulomb force and surface tension:

$$\vec{P}_{\rm C} = \frac{1}{2} \lambda E_{\rm n} \vec{N} = \frac{1}{2} \varepsilon \varepsilon_0 E_{\rm n}^2 \vec{N}; \tag{10}$$

$$\vec{P}_{\rm st} = 2\gamma H \vec{N},\tag{11}$$

where  $\lambda$  is the surface charge density,  $E_n$  is the projection of the electric field to the normal to interface,  $\gamma$  is the interfacial tension, *H* is the mean curvature of the surface,  $\vec{N}$  is the normal to the surface directed from the oil volume.



Fig. 1. Simulated area and boundary conditions of the study.

Due to the presence of these two forces, the pressure/velocity conditions at the interface are formulated as follows:

$$(P_{\text{oil}} - P_{\text{water}}) + \left[ \mu_{\text{water}} (\nabla \vec{\upsilon}_{\text{water}} + (\nabla \vec{\upsilon}_{\text{water}})^{\mathrm{T}}) \vec{N} - \mu_{\text{oil}} (\nabla \vec{\upsilon}_{\text{oil}}) + (\nabla \vec{\upsilon}_{\text{oil}})^{\mathrm{T}}) \vec{N} \right] \vec{N} + \vec{P}_{\text{st}} - \vec{P}_{\text{C}} = 0; \quad (12)$$
$$\left[ \mu_{\text{water}} (\nabla \vec{\upsilon}_{\text{water}} + (\nabla \vec{\upsilon}_{\text{water}})^{\mathrm{T}}) \vec{N} - \mu_{\text{oil}} (\nabla \vec{\upsilon}_{\text{oil}} + (\nabla \vec{\upsilon}_{\text{oil}})^{\mathrm{T}}) \vec{N} \right] \vec{\tau} = 0. \quad (13)$$

The ion concentration conditions at the droplet boundary correspond to the so-called charge loss conditions, presented in [2,4].

$$j_{+} = \begin{cases} n_{+}b_{+}E_{n} - d\nabla n_{+}, \ \vec{E} \uparrow \uparrow \vec{N} \\ 0, \ \vec{E} \uparrow \downarrow \vec{N} \end{cases}$$
(14)

$$j_{-} = \begin{cases} 0, \vec{E} \uparrow \uparrow \vec{N} \\ -n_{-}b_{-}E_{n} - d\nabla n_{-}, \vec{E} \uparrow \downarrow \vec{N}. \end{cases}$$
(15)

Difference of positive and negative ions fluxes forms non-zero charge Q on the surface of the droplet.

$$\frac{dQ}{dt} = \oint e(j_+ - j_-) \mathrm{d}S. \tag{16}$$

Here, *S* is the droplet surface. The initial conditions correspond to the state of the liquid before exposure to an external field—the concentration of ions in the entire volume of oil is  $n_0 = \sigma/e(b_+ + b_-)$ , the charge and velocity are zero in the entire computational area.

#### III. RESULTS AND DISCUSSION

#### A. Single-droplet case

The degree of mobility difference can be determined by introducing parameter k and mobility value b as follows:

$$kb_{-} = b_{+} = b. \tag{17}$$

The paper considers only the case k > 1 ( $b_+ > b_-$ ), because the case  $b_- > b_+$  is symmetrical to this one. The analysis is carried out for V = 2.4 kV/cm and R = 1 mm, which are relevant for such problems [5]. The patterns of droplet dynamics can be considered using the example of  $b = 10^{-9} \text{ m}^2/(\text{V}\cdot\text{s})$ , k = 5 and  $\sigma = 2.4 \cdot 10^{-11}$  S/m, in which the main effects caused by the difference in mobilities are clearly manifested (Fig. 2).

As soon as voltage is applied to the system, the ions begin to migrate along the electric field lines in the direction corresponding to the sign of their charge. Over the whole surface of the drop, ions of one sign move away from the drop, while ions of the other sign accumulate on the drop surface. This forms charged layers around the droplet. At the same time, since the mobility and therefore the velocity of positive ions is greater, the flux of positive charge through the interface prevails and a positive charge accumulates on the drop. Because of this, the droplet begins to accelerate due to the Coulomb force and move to the negative electrode. The finite dissociation time limits the continuous growth of the charged layer, so after some time (estimated by  $\tau_{dis} = \epsilon_{oil} \epsilon_0 / \sigma$ ), the distribution of the space charge around the droplet ceases to change, while the total charge and velocity of the droplet reach an approximately constant value. The size of the formed charged layer can be approximately estimated as the distance migrated by the ions during dissociation time  $(T_{\text{layer}} \approx bE \cdot \tau_{\text{dis}} \approx bE\varepsilon_{\text{oil}}\varepsilon_0/\sigma).$ 

The droplet velocity strongly depends on the charge Q (Fig. 3), which, in turn, is affected by the conductivity (the number of ions formed due to dissociation) and the mobility ratio (determines the imbalance of ion fluxes of different signs). For this reason, all other things being equal, the charge on the droplet is greater at higher k and  $\sigma$ . The conclusion is partly true for velocity, except for a more complex dependence on the  $\sigma$  parameter. The reason for it is space charge.

An increase in conductivity corresponds to an increase in equilibrium ion concentration  $n_0$  and consequently charge density, as well as a decrease in the  $T_{layer}$ . Thus, in the case of large values of  $\sigma$ , high-density negative space charge is concentrated at the front of the moving droplet. The space Coulomb force acting on it is directed against the external field and against the droplet moving direction, which creates increased frontal resistance to the movement of the drop. In the limit of  $\sigma \rightarrow \infty$ ,  $T_{layer} \rightarrow 0$ , while the force acting on the space charge equalizes the Coulomb force acting on the droplet and the drop velocity tends to zero. As a result, it is important to note that the final velocity of the drop cannot be determined by the charge Q, since the space charge in the oil and the space Coulomb force acting on it have a significant effect.

The value of ion mobility *b* also has a direct impact. For different values, all other things being equal, velocity of the droplet is always lower in the case of lower mobility. While lower mobility value corresponds to a higher  $n_0$  and a smaller  $T_{\text{layer}}$ , that is, a greater frontal resistance, even comparing the cases of identical  $n_0$  and  $T_{\text{layer}}$  ( $\sigma/b = \text{const}$ ), the velocity with a larger *b* is still greater. For the case of a larger *b*, the migration rate is an order of magnitude higher than the liquid velocity and, in particular, the droplet velocity. Due to this, the space charge distribution is more determined by dissociation and migration. For the case of a smaller *b*, the migration velocity



Fig. 2. Surface and arrow plots of velocity magnitude (upper part of each image) and space charge density (lower part of each image) at various time points after applying voltage: t = 1 s (a); t = 2 s (b); t = 3 s (c); t = 4 s (d). The magenta circle corresponds to the droplet boundary at t = 0 s.

takes values of the same order as the velocity of the liquid. Thus, among other mechanisms, convection has a strong influence on the space charge distribution. Thus, the charge Q and electric field intensity on the interface are lower, therefore the droplet moves more slowly.

A positively charged trace remains along the path of the drop. A negative charge is also left behind the droplet and prevails in the trace if there is a sufficiently rapid movement of the droplet (or strong convection) and long enough dissociation time. In such cases, the space Coulomb force acting in this trace can lead to the appearance of an EHD flow, directed opposite to the direction of the droplet movement. It should be noted that such an EHD flow is distinct only in a narrow range of  $\sigma$ values, for high k values and is more intense for lower values of b.

As a result, there are a number of the main phenomena observed:

- 1. non-zero charge accumulated on the drop;
- 2. translational motion of a drop under the influence of Coulomb force towards one of the electrodes (wide ranges of parameter values);
- 3. increasing of frontal resistance due to the space Coulomb force acting in the dispersion medium;
- 4. EHD flow in trace of the droplet (narrow ranges of parameter values)

## B. Two-droplet Case

A similar numerical model is used to analyze the interaction of two droplets, but the second drop is added, and the charge Q is calculated separately for each drop. In this case, the effects described in the previous section are also observed. The effects are most pronounced if the distance between the droplets is sufficient for the transient processes of charged layers formation and charging of the droplets to take place before their collision.



Fig. 3. Droplet velocity and maximum velocity in trace (a); droplet charge (b). Results presented as dependencies on  $\sigma$  for different values of *b* and *k*.

The accumulating charge on the droplets causes them to move forward towards the negative electrode. The EHD flow that occurs in the droplet trace has a fundamental effect on their interaction. The case with parameters identical to the results in Fig. 2 is considered since such effect is strongly pronounced in it (Fig. 4).

Firstly, the distance between the droplets decreases rapidly due to their primary deformation in the external field, after which the droplets continue to converge due to the dipole-dipole interaction. They also gradually charge, and both begin to move towards the negative electrode. At the same time, an EHD flow forms in the trace of the drop "1" (Fig. 4) and the other one lies in an oncoming flow, the resistance force of which slows it down and prevents further approach to the drop "1". Thus, droplet collisions do not occur under the following conditions:

- 1. intense EHD flow in the trace of the droplet (narrow range of  $\sigma$ , high *k* value);
- 2. the initial distance between the droplets is sufficient for the formation of layers and the EHD flow to occur before the droplets collide.

## V. CONCLUSION

The numerical model was successfully implemented that makes it possible to study the dynamics of a water droplet in conditions where the mobility of ions of different types in a dispersion medium differs. The results demonstrate fundamental differences both from the case of a perfect dielectric dispersion medium and from the case of equal ion mobilities.

For a wide range of electrical properties of the oil, rapid translational movement of droplets with velocity about 0.5-7 mm/s in the direction of one electrode is observed. The dependence of the droplet velocity on the parameters is complex, due to the influence of both the surface charge on the droplet and the space charge in the dispersion medium. There is also an EHD flow in the droplet trace up to 1.3 mm/s, which may prevent droplet collisions. However, such flows are observed for a narrow range of electrical properties of the oil.

The obtained results can be used both in practice and in multi-droplet models. However, this requires further



Fig. 4. Surface and arrow plots of velocity magnitude (upper part of the image) and space charge density (lower part of the image) for droplet pair interaction (a); time-dependencies of velocities for droplet pair and one-droplet case with identical liquid properties (b).

analysis in order to generalize the obtained results to cases of other droplet sizes and different values of the external field strength.

#### ACKNOWLEDGMENT

This work was supported in part by the Russian Science Foundation, research project №22-79-10078, https://rscf.ru/en/project/22-79-10078/. The research was performed at the Research park of St. Petersburg State University, https://researchpark.spbu.ru/.

- [1] C. Narváez-Muñoz, A. R. Hashemi, M. R. Hashemi, L. J. Segura, and P. B. Ryzhakov, Computational ElectroHydroDynamics in microsystems: A Review of Challenges and Applications, *Archives of Computational Methods in Engineering*, Jun. 2024.
- [2] V. Chirkov, I. Dobrovolskii, and S. Vasilkov, The interaction between two electrohydrodynamics phenomena when an electric field affects a two-phase immiscible liquid, *Physics of Fluids*, vol. 33, no. 4, Apr. 2021.
- [3] D. D. Saifullin, V. A. Chirkov, S. A. Vasilkov, and A. P. Gorbenko, Effect of Dissociation-Recombination Processes in a Leaky Dielectric Dispersion Medium on the Coalescence and Non-coalescence of Conducting Droplets Suspended in It, unpublished.
- [4] I. A. Dobrovolskii, S. A. Vasilkov, and V. A. Chirkov, Electrohydrodynamics of conducting droplets suspended in a low-conducting liquid: The effect of the difference in mobilities of positive and negative ions, *Journal of Electrostatics*, vol. 124, p. 103828, Jul. 2023.
- [5] D. D. Saifullin, D. S. Lukin, A. V. Samusenko, and V. A. Chirkov, Regime map of non-coalescence between two equal-sized uncharged water droplets suspended in oil: A numerical study, *Physics of Fluids*, vol. 36, no. 12, Dec. 2024.

## Effect of Charge on the Coalescence of a Water Droplet Suspended in Oil and a Water Layer

G. S. Yagodin<sup>1\*</sup>, I. A. Elagin<sup>1</sup>, V.A. Chirkov<sup>1</sup>

<sup>1</sup>St. Petersburg State University, St. Petersburg, Russia

\*Corresponding author: g.yagodin@spbu.ru

Abstract—This paper investigates partial coalescence in a drop-layer system for both charged and uncharged drops, using advanced numerical simulations grounded in the moving mesh method. The study aims to comprehensively examine the physical mechanisms governing coalescence behavior under the influence of electric fields, with particular emphasis on the role of surface charge. A detailed regime map is constructed that accounts for multiple influencing factors including electric field strength, drop size, and accumulated charge. The simulations reveal that charge significantly alters drop deformation and approach velocity, with kinetic energy emerging as the dominant determinant in coalescence outcomes. The results hold implications for improving the design and control of electrocoalescers and similar devices.

Keywords—Partial coalescence, electrocoalescence, arbitrary Lagrangian–Eulerian method, charged droplets, numerical modeling.

#### I. INTRODUCTION

Electrocoalescence is a process of vital importance in various industrial applications, particularly in oil-water separation and other multiphase fluid systems [1]. The present study focuses on the behavior of individual drops interacting with a fluid layer in the presence of an electric field. Such scenarios commonly occur in electric devices and dehydration electrocoalescers [2]. Traditionally, these devices are developed through empirical adjustments and trial-and-error methods, owing limited understanding of the complex to electrohydrodynamic processes occurring within [3]. This approach is time-consuming, costly, and often yields suboptimal results.

The current research circumvents these limitations by employing high-fidelity numerical models that simulate two-phase electrohydrodynamic interactions [4]. These simulations offer an efficient and accurate way to explore drop behavior across a wide range of parameters. Our approach is based on the arbitrary Lagrangian–Eulerian method (ALEM) or moving mesh method [5], which more accurately captures interface dynamics than conventional level-set or phase-field techniques. Notably, it prevents unphysical charge dissipation across the interface [6], a flaw that plagues other modeling strategies.

In this work, we investigate the specific "drop-layer" interaction regime, which has been the subject of a number of studies [7-12]. Here, drops often accumulate charge by contacting electrodes or through interactions with other charged entities. This accumulated charge plays a critical role in determining the outcome of a coalescence event, especially at low field strengths where electrostatic forces may be insufficient to drive complete merging in the absence of charge. We aim to construct a detailed regime map that categorizes coalescence behavior under varying conditions of drop size, charge, and electric field intensity.

#### II. METHODOLOGY

#### A. Mathematical and physical model

Computer simulation based on the arbitrary Lagrangian–Eulerian method, Poisson and Navier-Stokes equations for an incompressible liquid were used to study the drop-layer system:

$$\rho \frac{\partial \boldsymbol{\nu}}{\partial t} + \rho(\boldsymbol{\nu}\nabla)\boldsymbol{\nu} = -\nabla P + \mu \Delta \boldsymbol{\nu} + \rho \boldsymbol{g} \qquad (1)$$

$$\operatorname{div} \boldsymbol{\nu} = 0 \tag{2}$$

 $\operatorname{div}(\varepsilon\varepsilon_0 \boldsymbol{E}) = 0 \tag{3}$ 

$$\boldsymbol{E} = -\nabla V. \tag{4}$$

Here  $\rho$  is the liquid density,  $\boldsymbol{v}$  is the velocity vector, t is the time, P is the pressure,  $\mu$  is the dynamic viscosity,  $\boldsymbol{g}$  is the free-fall acceleration,  $\varepsilon$  is the relative permittivity,  $\varepsilon_0$  is the vacuum permittivity,  $\boldsymbol{E}$  is the electric field strength, and V is the electric field potential.

Figure 1 shows the geometry of the model. A drop of water is located in the volume of oil between two electrodes, the upper wall is a high-voltage electrode. Zero potential was set on the surface of the water layer. Under the influence of Coulomb and gravity forces, a drop of water moves towards the layer, then one of the following cases occurs: coalescence (complete union of a drop of water and a layer), partial coalescence (partial union of a drop of water and a layer) or non-coalescence.



Fig. 1. The geometry and boundary conditions.

The study was supported by Russian Science Foundation, research project No. 22-79-10078, https://rscf.ru/en/project/22-79-10078/

A key part of understanding drop behavior under electric fields is quantifying the amount of charge a drop may acquire upon contacting an electrode. Initially, we apply the following analytical relation [13]:  $Q = \frac{2}{3}\pi^{3}\varepsilon\varepsilon_{0}R^{2}E$ , where *R* is the drop radius and *E* is the average field strength. While insightful, this formula assumes ideal conditions and does not account for deformation of the drop or the influence of finite interelectrode distances.

For example, characteristic charges for the larger drops (2 and 2.5 mm) at an applied voltage of 6 kV were determined to be 0.63 nC and 0.98 nC, respectively.

Furthermore, we calculated the maximum stable charge a drop could sustain before destabilization using the classical Rayleigh limit [14]:  $Q_{max} = 4 (\pi \varepsilon \varepsilon_0 \gamma R^3)^{\frac{1}{2}}$ , where  $\gamma$  is the surface tension. These values were then compared with simulation outputs to verify consistency. For a 1 mm drop, the Rayleigh-predicted charge limit aligned closely with the numerically determined threshold.

In preparation for dynamic simulations, the initial release height of the drop above the layer was calibrated to ensure that the drop achieved terminal velocity before interaction. For smaller drops (e.g., R = 1 mm), this distance was approximately 9 mm. For larger drops (R = 2 mm and 2.5 mm), the required height increased significantly to 20 mm and 40 mm, respectively. This adjustment prevented residual oscillations in drop deformation from contaminating the simulation results (Fig. 2).



Fig. 2. Velocity and droplet deformation vs time for R = 2.5 mm, E = 2.5 kV/cm, H = 8 cm, and Q = 0.87 nC.

## B. Liquid properties

The simulation was carried out for olive oil with the following characteristics: density  $\rho_o = 910 \text{ kg/m}^3$ , dynamic viscosity  $\mu_o = 0.065$  Pa s, relative permittivity  $\varepsilon = 2.85$ . The properties of the drop and layer correspond to water:  $\rho_w = 1000 \text{ kg/m}^3$ ,  $\mu_w = 0.001$  Pa s. The interfacial tension for this pair of liquids is set to  $\gamma = 0.016 \text{ N/m}$ .

#### III. RESULTS AND DISCUSSION

Simulations comparing the behavior of charged and uncharged drops under varying electric fields revealed several key insights. First, the presence of non-zero total surface charge consistently increased the electric field threshold required for partial coalescence. This was primarily due to the enhanced kinetic energy imparted by electrostatic acceleration, which enabled the drop to more effectively merge with the underlying layer.

One notable observation was the significant reduction in the volume of the secondary (daughter) drop in charged cases (Fig. 3.). The extra kinetic energy facilitated more rapid and complete transfer of the drop's contents into the layer, limiting the volume available for residual detachment. This effect was more pronounced in drops with higher radii and was less dependent on deformation, highlighting the dominant role of translational motion over geometric distortion.



Fig. 3. Comparison of the relative volume of drops released during partial coalescence vs electric field strength. Blue dots correspond to uncharged droplet, orange dots correspond to characteristically charged droplet, green dots correspond to shifted data for the uncharged case. R = 1 mm.

To further elucidate these effects, we performed parameter sweeps with varying drop charges while tracking both deformation and impact velocity. As charge increased, so did approach speed, leading to faster coalescence. However, deformation also increased (Fig. 4), which in uncharged scenarios would have hindered merging by promoting premature neck thinning. In charged drops, however, the velocity effect outweighed this deformation effect, resulting in improved coalescence efficiency.


Fig. 4. Deformation and relative volume of daughter droplet vs charge. R = 1.5 mm, E = 2.0 kV/cm.

Additional insights were drawn from velocity field visualizations (Fig. 5), which showed that internal fluid circulations were minimal, especially near the point of contact. This validated the assumption that translational kinetic energy dominates the dynamics of coalescence. Flow rate data from Fig. 6 obtained on cut surface with shortest radius near bridge area corroborated this finding. It shows that more highly charged drops completed fluid transfer in shorter timeframes, leading to either full or more efficient coalescence. The reason for this is that the pumping rate through bridge area for more charged droplet higher at least until 15 ms. The graph breaks off after this value because the bridge ceases to exist for the case of complete coalescence.



Fig. 5. Contour graph of the droplet velocity (*z*-component) at the moment before contact. On the left is the total velocity, on the right is the velocity minus the translational motion R = 2.5 mm, E = 2.5 kV/cm.



Fig. 6. Liquid pumping rate as a function of time for a characteristically charged droplet (red) and for a droplet with an increased charge (blue). E = 2 kV/cm, R = 1.5 mm.

The final regime map (Fig. 7) encapsulated all observed trends. Not only did the threshold for partial coalescence increase with drop charge, but the onset of fragmentation (rupture) also shifted. Interestingly, for charged droplets, the breakup occurred below the Rayleigh threshold. This unexpected result was attributed to non-uniform charge redistribution, which altered surface stress patterns. Specifically, charge accumulation at the upper cap of the drop created localized forces sufficient to trigger destabilization which leads to the rupture of the drop at lower voltages than predicted by Rayleigh limit.



Fig. 7. Coalescence regime map for charged and uncharged droplet.

#### V. CONCLUSION

This research presents a numerical study on the impact of surface charge on partial coalescence in a droplayer system. By leveraging the moving mesh method and incorporating both electrostatic and hydrodynamic effects, we have demonstrated that kinetic energy derived from surface charge is a critical determinant in coalescence behavior. Our findings show that while deformation plays a role, it is secondary to the momentum effects induced by electric fields.

The numerical results align well with the experimental findings of Nantanawut [9, 10]. Both studies highlight that charged droplets exhibit faster coalescence due to increased kinetic energy, corroborating the dominance of electrostatic forces over interfacial tension in charged systems. The experiments confirm that higher electric fields lead to greater droplet deformation, which can result in partial coalescence or non-coalescence, as observed in the numerical simulations.

The regime map developed in this study serves as a valuable tool for predicting coalescence outcomes under various conditions. The insights gained here can inform the design of more effective electrocoalescence devices, optimize operational parameters, and reduce reliance on empirical tuning. Future work may include experimental validation with charged droplet, inclusion of multi-drop interactions, and extension to alternating current field scenarios).

#### ACKNOWLEDGMENT

The research was performed at the Research Park of St. Petersburg State University "Computing Center," "Center for Nanofabrication of Photoactive Materials (Nanophotonics)," and "Center for Diagnostics of Functional Materials for Medicine, Pharmacology, and Nanoelectronics."

#### References

- [1] S. Less and R. Vilagines. The electrocoalescers' technology: Advances, strengths and limitations for crude oil separation. Journal of Petroleum Science and Engineering, 81:57–63, 2012.
- [2] I. G. Harpur, N. J. Wayth, A. G. Bailey, M. T. Thew, T. J. Williams, and O. Urdahl. Destabilisation of water-in-oil emulsions under the influence of an AC electric field: Experimental assessment of performance. Journal of Electrostatics, 40-41:135– 140, 1997.
- [3] S. Mhatre, V. Vivacqua, M. Ghadiri, A. M. Abdullah, A. Al-Marri, B. Azzopardi, B. Hewakandamby, and B. Kermani. Electrostatic phase separation: A review. Chemical Engineering Research and Design, 96:177–195, 2015.
- [4] I. A. Elagin, G. S. Yagodin, and V. A. Chirkov. Features of numerical modeling electrical coalescence in a droplet-layer system using the arbitrary Lagrangian-Eulerian method. Journal of Physics: Conference Series, 2701:012078, 2024.
- [5] C. W. Hirt, A. A. Amsden, and J. L. Cook. An arbitrary Lagrangian-Eulerian computing method for all flow speeds. Journal of Computational Physics, 14:227–253, 1974.
- [6] V. A. Chirkov, A. V. Gazaryan, K. I. Kobranov, G. O. Utiugov, and I. A. Dobrovolskii. A modification of the phase-field method to simulate electrohydrodynamic processes in two-phase immiscible liquids and its experimental verification. Journal of Electrostatics, 107:103483, 2020.
- [7] D. Yang, H. Sun, M. Li, Q. Li, X. Gao, C. Chen, and L. He. Effect of electric field strength and droplet diameter on droplet-interface coalescence mechanism. Chemical Engineering Science, 282:119360, 2023.
- [8] N. Li, Y. Pang, Z. Sun, X. Sun, W. Li, Y. Sun, L. Zhu, B. Li, Z. Wang, and H. Zeng. Unraveling partial coalescence between droplet and oil-water interface in water-in-oil emulsions under a direct-current electric field via molecular dynamics simulation. Langmuir, 40(11):5992–6003, 2024.
- [9] W. Nantanawut, B. Techaumnat, and N. Tanthanuch. The coalescence of charged and uncharged drops under electric field. IEEE Transactions on

Dielectrics and Electrical Insulation, PP(99):1-1, 2024.

- [10] W. Nantanawut, B. Techaumnat, and N. Tanthanuch. Experimental study on the breakdown of oil film in the application of water drop electrocoalescence. IEEE Transactions on Dielectrics and Electrical Insulation, PP(99):1–1, 2025.
- [11] B. Li, Y. Wu, X. Dou, W. Xiang, H. Wang, Z. Sun, Z. Wang, and J. Wang. Coalescence dynamics of a nanoparticle-laden droplet at oil-water interface under electric field: A molecular dynamics simulation. International Journal of Multiphase Flow, 184:105129, 2025.
- [12] G. Yagodin, I. Elagin, S. Vasilkov, and V. Chirkov. The numerical analysis of complete and partial electrocoalescence in the droplet-layer system employing the sharp interface technique for multiphase-medium simulation. Computers & Fluids, 286:106478, 2025.
- [13] E. S. Elton, Y. V. Tibrewala, and W. D. Ristenpart. Statistical analysis of droplet charge acquired during contact with electrodes in strong electric fields. Langmuir, 35(10):3937–3948, 2019.
- [14] Lord Rayleigh. On the equilibrium of liquid conducting masses charged with electricity. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 14(87):184–186, 1882.

### Aerosol Jet Printed Surface Dielectric Barrier Discharge (AJP-SDBD) Plasma Actuators: Fabrication And Electromechanical Characteristics

K. Kourtzanidis<sup>1</sup>\*, M. Karani<sup>1</sup>, N. Vlachos<sup>1</sup>, P. Dimitrakellis<sup>1</sup>, N. Hastas<sup>2</sup>, V. Pattanshetti<sup>3</sup>, M. Kotsonis<sup>3</sup>

<sup>1</sup>Advanced Renewable Technologies for Energy & Materials Integrated Systems (ARTEMIS) Laboratory, Chemical

Process & Energy Resources Institute (CPERI), Centre for Research & Technology

Hellas (CERTH), Thessaloniki, Greece

<sup>2</sup>Sector of Condensed Matter and Material Physics, School of Physics, Aristotle University of

Thessaloniki (AUTH), Thessaloniki, Greece

<sup>3</sup>Department of Flow Physics and Technology, Delft University of Technology, Delft, The

Netherlands

\*Corresponding author: kourtzanidis@certh.gr

*Abstract*- We present a novel fabrication technique for SDBD plasma actuators based on Aerosol Jet Printing (AJP) technology of conductive ink and characterize the AJP-SDBDs electromechanical performance. Linear and annular SDBD designs, including custom-shaped patterned edges have been fabricated which when stressed under AC, High Voltage excitation, present stable and quasi-uniform plasma operation. We measure the electromechanical characteristics of the linear and annular designs in terms of ink-related electrical properties (through Van der Pauw-resistivity and Hall measurements), plasma electrical characteristics and perform Particle Image Velocimetry (PIV) measurements of the induced jet comparing with typical designs found in literature based on conventional fabrication techniques.

Keywords- DBD actuators, surface discharge, Aerosol Jet Printing, PIV, atmospheric pressure air plasma.

#### I. INTRODUCTION

Surface Dielectric Barrier Discharges (SDBDs) [1], have gained significant attention in various fields due to their ability to produce relatively strong and localized electrohydrodynamic (EHD) flows while promoting reactive species generation and transport. These induced jet-like flows, often referred to as ionic wind, can help control aerodynamic phenomena [2] [3], promote mixing for combustion applications [4], enable film cooling [5], while the reactivity occurring in SDBDs finds applications in several high-impact fields such as selective anti-cancer [6] and water treatment [7]. However, SDBDs are often limited by fabrication constraints leading to decreased robustness, longevity, repeatability and flexibility in design, hindering their electromechanical performance and applicability. Furthermore, current fabrication techniques are not capable of producing electrodes with fine features and complex geometrical shapes, which could potentially improve the plasma characteristics and EHD flows. In most studies, the fabrication of SDBDs entails the usage of conductive foil/tape (of various thickness), glued (usually with epoxy resin adhesive) on a dielectric surface. This, rather manual, fabrication procedure hampers both the repeatability and the optimization of the SDBD modules, both in terms of electrode shape quality (uniformity, alignment, smoothness), as well as in terms of design flexibility.

Printed electronics and circuit board (PCB) techniques, such as photolithography and wet/chemical etching, have been used to generate more complex electrode designs [8]. These techniques, although very interesting and successfully demonstrated, are costly and require advanced facilities and know-how. Recently,

inkjet-based printed electronics have emerged as a promising technology for SDBD fabrication. [9] [10] [11] [12] Despite its merit, standard inkjet printing (IJP) presents several drawbacks, such as the need for lowerviscosity inks, weak suitability for non-planar thus variable material substrates, typically inferior resolution of printed line width (at least with non-exotic setups i.e. super inkjet technology) and nozzle clogging issues due to the direct, bulk ink flow through the nozzle.

Aerosol Jet Printing (AJP) is a promising alternative to the IJP technique to fabricate SDBDs. While both methods allow non-contact patterning, they differ in their working principles, material compatibility, resolution, and applications. AJP excels in precision applications requiring high resolution and material versatility. It provides high resolution due to its ability to produce fine aerosolized droplets, And the use of a sheath gas, around the aerosol beam, allows for better control over deposition, resulting in more consistent line width and smoother edges compared to IJP [13]. Furthermore, it is less prone to clogging, while achieving higher conductivity when compared to IJP for the same sintering protocols [14]. The resulting process is capable of printing lines on the order of 10-100 µm wide with its "narrow" class of nozzles and printing lines on the order of 800 µm wide with the "wide" nozzle class [15].

In this work, we report for the first time (to the best of our knowledge) the fabrication of Aerosol Jet Printed SDBDs (AJP-SDBD) able to generate stable surface discharges and produce EHD flows. The structure of the remaining part of this article is as follows: In Section II, we present the methods used for the fabrication and the characterization of the SDBDs. In Section III, we present results on electromechanical characteristics. In Section IV, we conclude and provide future directions.

#### II. METHODOLOGY

#### A. Aerosol Jet Printing

All SDBDs were designed and fabricated by CERTH, with an Aerosol Jet Printer (Optomec, AJ200 model) available at CERTH/CPERI and its ARTEMIS laboratory. An aqueous-based silver ink (Metalon JS-A426, NovaCentrix, USA) was used. Ultrasonic atomization (UA) is employed for all prints, with the aerosol carrier gas being pre-saturated, in a bubbler, with water vapor. A narrow circular nozzle (300 µm in diameter) was used for printing the exposed electrode edges (see below for details), while a wider nozzle (0.75 mm in diameter) was used for the bulk areas of the electrode geometries. Both nozzles were delivered by Optomec Inc. (USA). Sintering for all prints was performed at 85 °C for one hour (adequate for the dielectric substrate - see below). The dielectric substrate for all SDBDs is commercially available Plexiglass (PMMA) with a thickness of 3 mm.

# *B. Measurements of electrical transport properties and material structure/properties*

Prior to the SDBD fabrication, Van der Pauw and Hall-effect measurements have been conducted (at AUTH), at room temperature, to evaluate the values of specific resistance, charge carrier density and mobility. A Van der Pauw experimental configuration attaining up to 0.5 T magnetic field strength was used, while measurements were taken for both magnetic field directions and current to eliminate voltage probe contact resistance effects as well as magnetoresistance contributions. Silver paint was used to form Ohmic contacts with a printed rectangular electrode.

# *C. AJP-SDBD* operation and ionic wind flow measurements

The AJP-SDBDs were initially tested in the Plasma Science and Innovations (PlaSci) research team of ARTEMIS laboratory in CERTH/CPERI, with a AC-HV generator delivering max output of 40 kV<sub>p-p</sub> at 20 kHz in an open-air environment. More elaborated tests including discharge power and ionic wind measurements were conducted under quiescent conditions at the Low-Speed Lab of the Department of Flow Physics and Technology, at Delft University of Technology. The actuators were enclosed in a plexiglass box of 1000×500×500 mm, with sufficient optical access all around allowing external placement of the PIV camera and the laser head. LaVision's Imager sCMOS camera captures the PIV images in double frame mode. The region of interest is illuminated by a Quantel Evergreen 200 Nd:YAG laser, used in a double pulse mode. The actuators are powered through Trek's 20/20C-HS high voltage amplifier, which is fed a digitally generated AC waveform from National Instrument's NI9215 card. The electrical parameters used for the ionic wind characterization are shown in Table 2.

Table 2: Electrical parameter combinations

Held Constant	Varied
f = 1  kHz	$V_{AC} = 20, 25, 30, 35 \text{ kV}_{p-p}$
$V_{AC} = 30 \text{ kV}_{p-p}$	f = 1, 2, 3  kHz

#### III. RESULTS

# A. Aerosol Jet Printed SDBDs and printed electrode electrical properties

Three different SDBD designs have been fabricated: 1) a linear AJP-SDBD, with no overlap or gap between the HV (top) and ground (bottom) electrodes. 2) an annular AJP-SDBD consisting of a circular free surface (not covered by conductive ink) on the top (HV electrode) side and a circular ground electrode on the bottom side with no overlap or gap between the two electrodes 3) an AJP-SDBD with same dimensions as in the annular case, but with non-straight internal (to the annular gap) edges, forming a wavy structure. In all designs, conductive paths to allow for proper connection with the HV power source and ground terminals have been included. The designs (including regions printed with fine/wide nozzles) as well as dimensions are shown in Fig. 1 - 4, where W<sub>1</sub>=80 mm,  $L_1=15$  mm,  $L_2=20$  mm,  $D_1=20$  mm.



Figure 1 Linear AJP-SDBD - schematic.



Figure 2 Annular AJP-SDBD – schematic, both top and bottom layers are shown.



Figure 3 Wavy AJP-SDBD – schematic, both top and bottom layers are shown.

The trace width of the JS-A426 silver ink using a 300  $\mu$ m diameter nozzle is approximately 80um, with minimal overspray, while, when using a 0.75 mm diameter circular wide nozzle, it is approximately 400-500  $\mu$ m with ~50  $\mu$ m overspray on each side. The thickness of the deposited layer (printed with the narrow nozzle) is <1  $\mu$ m. Resistivity, charge carrier density and mobility values extracted from Hall measurements are shown in Table 1, for samples that have been printed in x, y, and 45°/135° directions. Considering that the measurements show homogeneous structures, the lower resistivity values are attributed to a high-quality print result. Overall, the three electrodes show a metallic behavior, with their electronic



Figure 4 Photos of the AJP printing process (annular design middle), linear SDBD (left – slightly different design) and wavy SDBD (right). All images by CERTH - plasma ignition achieved with a HV generator delivering max output of 40 kVp-p at 20 kHz.

properties comparing very favorably to other printable materials like PEDOT-PSS  $(1 - 10^{-2} \Omega cm)$  or graphene ink  $(3-8x10^{-3} \Omega cm)$ .

Table 1 Resistivity, charge carrier density and mobility of monoaxial x, y and crisscrossed printed electrodes.

	x-axis	y-axis	х-у
Resistivity (Ωcm)	1.5 10-4	3.4 10-4	1.4 10-4
Charge carrier	1.5 10 <sup>23</sup>	5.5 1022	7.6
density (cm <sup>-3</sup> )			10 <sup>22</sup>
Mobility (cm <sup>2</sup> /Vs)	0.3	3.4	0.6

#### B. Plasma operation and electrohydrodynamic flow

Stable plasma operation was observed for all designs under non-excess applied voltages (< 35 kV<sub>p-p</sub>) at 20 kHz (at CERTH). Images (with a standard camera) of discharge structure in the linear and wavy designs are shown in Fig. 4. At lower frequencies, detailed electrical measurements) (including power and flow characterization were performed at TUD for the linear and annular designs only. The maximum per-unit-length (normalized by  $W_1$  for the linear SDBD and by  $\pi D_1$  for the annular SDBD) average power consumption ranges between 54 - 571 W/m for the linear case and between 29 - 248 W/m for the annular case, which highlights significant lower consumption per unit length in the annular design. Maximum velocities increase with applied voltage and frequency for both designs, ranging from 1.33 to 4.6 m/s for the linear case and 0.56 to 2.32 m/s for the annular case.



Figure 5 Velocity magnitude of the induced flow by the linear actuator.



Figure 6 Velocity magnitude of the induced flow by the annular actuator.

Fig. 5 shows a typical contour plot of the induced jet's velocity magnitude, overlaid with velocity vectors. The plots shown are for the linear actuator operating at  $V_{AC}$  of 30 kV<sub>p-p</sub> and  $f_{AC}$  of 3 kHz, which produced the strongest jet. The top electrode's edge is at x=0 mm, and the ground electrode extends to x=20 mm. Characteristic of a linear DBD actuator, a wall parallel jet is induced by the discharge. Similar plots for the annular actuator are shown in Fig. 6. The axi-symmetric nature of the actuator results in inward jet flows similar to the linear case, coalescing from all sides and turning upwards, forming a wall-normal jet. The normal flow structure is similar to the ones reported in literature for lower AC frequencies [16] but with higher velocity magnitude, while reproduces the numerical results of [17] for large diameter annular SDBDs.

#### V. CONCLUSION

We have successfully demonstrated the applicability of AJP technology for the fabrication and rapid prototyping of custom-shaped SDBD actuators with ultra-fine precision. We successfully ignited the SDBDs in a wide range of operating frequencies (1 - 20 kHz) and applied voltages  $(20 - 40 \text{ kV}_{p-p})$ , which operation showed quite stable plasma formation in all variations. Through PIV measurements, we showed that the resulting EHD flows are similar to ones arising from "conventional" SDBDs. Future work will focus on the detailed plasma characterization of the SDBDs with optical diagnostics, comparison of EHD characteristics with literature results, as well as longevity studies along with an in-depth analysis of electrode characteristics and possible degradation during operation.

#### ACKNOWLEDGMENT

The work of K. Kourtzanidis and P. Dimitrakellis was supported by the European Union Project CAIPIRINH3A, under the GA number 101191768. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

#### REFERENCES

- N. Benard and E. Moreau, "Electrical and mechanical characteristics of surface AC dielectric barrier discharge plasma actuators applied to airflow control," *Exp. Fluids*, vol. 55, no. 11, p. 1846, Nov. 2014, doi: 10.1007/s00348-014-1846x.
- [2] E. Moreau, "Airflow control by non-thermal plasma actuators," *J. Phys. Appl. Phys.*, vol. 40, no. 3, p. 605, Jan. 2007, doi: 10.1088/0022-3727/40/3/S01.
- [3] T. C. Corke, C. L. Enloe, and S. P. Wilkinson, "Dielectric Barrier Discharge Plasma Actuators for Flow Control\*," *Annu. Rev. Fluid Mech.*, vol. 42, no. Volume 42, 2010, pp. 505–529, Jan. 2010, doi: 10.1146/annurev-fluid-121108-145550.
- [4] C.-C. Wang and S. Roy, "Combustion stabilization using serpentine plasma actuators," *Appl. Phys. Lett.*, vol. 99, no. 4, p. 041502, Jul. 2011, doi: 10.1063/1.3615292.
- [5] P. Audier, M. Fénot, N. Bénard, and E. Moreau, "Film cooling effectiveness enhancement using surface dielectric barrier discharge plasma actuator," *Int. J. Heat Fluid Flow*, vol. 62, pp. 247–257, Dec. 2016, doi: 10.1016/j.ijheatfluidflow.2016.10.009.
- [6] L. G. Lima *et al.*, "Comparative effects of direct plasma treatment and plasma-activated media on B16F10 cancer cells using a multipoint surface dielectric barrier discharge system," *J. Phys. Appl. Phys.*, vol. 58, no. 13, p. 135201, Jan. 2025, doi: 10.1088/1361-6463/adac6c.
- [7] S. M. Allabakshi, P. S. N. S. R. Srikar, R. K. Gangwar, and S. M. Maliyekkal, "Feasibility of surface dielectric barrier discharge in wastewater treatment: Spectroscopic modeling, diagnostic, and dye mineralization," *Sep. Purif. Technol.*, vol. 296, p. 121344, Sep. 2022, doi: 10.1016/j.seppur.2022.121344.
- [8] R. J. Durscher and S. Roy, "Three-dimensional flow measurements induced from serpentine plasma actuators in quiescent air," *J. Phys. Appl. Phys.*, vol. 45, no. 3, p. 035202, Jan. 2012, doi: 10.1088/0022-3727/45/3/035202.
- [9] S. Sato, T. Enokido, K. Ashikawa, M. Matsubara, K. Kanie, and N. Ohnishi, "Development of a flexible dielectric-barrier-discharge plasma actuator fabricated by inkjet printing using silver nanoparticles-based ink," *Sens. Actuators Phys.*, vol. 330, p. 112823, Oct. 2021, doi: 10.1016/j.sna.2021.112823.

- [10] S. Yadala *et al.*, "Experimental control of sweptwing transition through base-flow modification by plasma actuators," *J. Fluid Mech.*, vol. 844, p. R2, Jun. 2018, doi: 10.1017/jfm.2018.268.
- J. Kim, S. Park, and W. Choe, "Surface plasma with an inkjet-printed patterned electrode for lowtemperature applications," *Sci. Rep.*, vol. 11, no. 1, p. 12206, Jun. 2021, doi: 10.1038/s41598-021-91720-3.
- [12] S. Sato *et al.*, "Fabrication and performance evaluation of full-inkjet-printed dielectric-barrierdischarge plasma actuators," *Sens. Actuators Phys.*, vol. 344, p. 113751, Sep. 2022, doi: 10.1016/j.sna.2022.113751.
- P. Calvert, "Inkjet Printing for Materials and Devices," *Chem. Mater.*, vol. 13, no. 10, pp. 3299– 3305, Oct. 2001, doi: 10.1021/cm0101632.
- T. Seifert, E. Sowade, F. Roscher, M. Wiemer, T. Gessner, and R. R. Baumann, "Additive Manufacturing Technologies Compared: Morphology of Deposits of Silver Ink Using Inkjet and Aerosol Jet Printing," *Ind. Eng. Chem. Res.*, vol. 54, no. 2, pp. 769–779, Jan. 2015, doi: 10.1021/ie503636c.
- [15] J. D. Rurup and E. B. Secor, "Predicting Deposition Rate and Closing the Loop on Aerosol Jet Printing with In-Line Light Scattering Measurements", doi: 10.1002/adem.202201919.
- [16] B. K. Mishra, "Near-wall characteristics of wallnormal jets generated by an annular dielectricbarrier-discharge plasma actuator," *Phys. Rev. Fluids*, vol. 7, no. 3, 2022, doi: 10.1103/PhysRevFluids.7.033702.
- [17] H. Borradaile, K. Kourtzanidis, F. Rogier, K.-S. Choi, and X. Mao, "Flow reversal in millimetric annular DBD plasma actuator," *J. Phys. Appl. Phys.*, vol. 54, no. 34, p. 345202, Jun. 2021, doi: 10.1088/1361-6463/ac0145.

## Electrohydrodynamic water flow produced by a DC discharge ignited above its surface

Eric Moreau<sup>\*</sup>, F. Dyson, L. Alomari

<sup>1</sup>Institut PPRIME (UPR CNRS 3346), Université de Poitiers, 11 Bd Marie & Pierre Curie, Futuroscope 86962, France \*Corresponding author: eric.moreau@univ-poitiers.fr

Abstract- This study aims at characterizing the water flow induced by a DC discharge ignited between the water surface and a needle located a few millimeters above it. First, we highlighted that two discharge regimes can be observed: a corona-like discharge with current from a few  $\mu$ A to a few dozen of  $\mu$ A, and a normal glow discharge with current of several mA. Second, particle image velocimetry (PIV) measurements allowed us to precisely characterize the flow resulting from the deposition of electrical charges at the water surface by the discharge. These measurements have revealed a flow characterized by the formation of two symmetric and counter-rotating vortices. In the case of a normal-glow discharge, it seems that the water flow is due to two EHD forces: a surface force due to the repulsion of charges at the surface, and an upward force in the liquid due to the migration of opposite charges from the bulk of the liquid. Moreover, we highlighted that the velocity (of a few cm/s) and topology of the flow depend on the voltage polarity, the water conductivity and on its surface tension. In the case of a corona-like discharge, there is still a significant water flow, even for current of a few  $\mu$ A. In this case, a third phenomenon can be at the origin of the liquid flow: the shear stress due to the ionic wind induced in the air, between the needle tip and the water surface.

#### I. INTRODUCTION

The interactions between a cold plasma and a liquid are very complex but very important to study due to various applications in agriculture, biology, nanomaterial synthesis, and water treatment. However, because of the slow diffusion of reactive species in the liquid phase, the flow induced by the discharge in the liquid can play a key role in transporting species into the solution. Therefore, it is imperative to analyse the flow in detail to control the plasma-liquid processes effectively.

In this context, for a few years, we have been investigating the liquid flow induced by three different types of cold plasma in contact with water, and the results are presented in the present ISEHD 2025. The first investigated cold plasma is a helium plasma jet [1]. The second one is a dielectric barrier discharge ignited between a needle placed a few millimetres above the liquid and a grounded electrode below the vessel containing the water [2]. In addition, in [2], a bibliography of studies carried out by other laboratories is presented. Then see [2] for more details. The third type of discharge we have been investigating for a few years is very simple: it is ignited by applying a DC voltage between a needle placed a few millimetres above the surface of the liquid to be treated and a grounded electrode immersed inside the liquid.

In this article, we will see that when the DC voltage is increased, two different discharge regimes can be observed: a corona regime (maximum currents of a few dozen  $\mu$ A) and a normal glow one (current up to 10 mA). Moreover, due to different physical phenomena, several mechanical effects can occur: a gas flow induced by the discharge (ionic wind) [3], a deformation of the liquid surface, and a liquid flow, all these phenomena being currently investigated by our team. In the present experimental study, we will focus on the EHD flow induced inside the liquid with the help of a particle image velocimetry (PIV) system, in the case of the two discharge regimes indicated above.

In this article, we will briefly present the two main discharge regimes occurring in such a geometrical configuration. Secondly, we will present the flow induced in the water in the case of a normal glow discharge (current set at 3.8 mA). We will highlight that the high voltage polarity plays a role in the flow topology. Moreover, the flow velocity decreases when the water conductivity and the superficial tension increase. Third, we will discuss the liquid flow in the case of a corona-like discharge (mean current between 7  $\mu$ A and 30  $\mu$ A). We will show that the flow is faster when the voltage is positive and when the gap between the needle tip and the water surface is increased because the surface forces are stronger.

#### II. METHODOLOGY

In our experimental setup (Fig. 1), the plasma discharge is ignited between the tip of a tungsten needle (curvature radius of 100 µm) and the water surface, which is grounded. The needle is placed a few millimeters above the water surface. The water (20 mL) is contained in an optical glass vessel (30×30×30 mm<sup>3</sup>). Two DC power supplies are used to apply the voltage at the needle: a Technix SR15-P-3000 (+15 kV, 200 mA) for the positive polarity and an Armexel AU-10N30-LC (-10 kV, 30 mA) for the negative polarity. The discharge voltage is measured with a high-voltage probe (LeCroy PPE, 20 kV, 100 MHz) connected to a digital oscilloscope (HDO6054, 500 MHz, 2.5 GS/s). The discharge current is obtained by measuring the voltage across a shunt resistor between the grounded electrode and earth. The PIV system is similar to the one used in [1]. Then see [1] for full PIV details.



Fig. 1. Experimental setup.

#### III. RESULTS AND DISCUSSION

#### A. Discharge regimes

Fig. 2 shows the V-I characteristics of our discharge, for both polarities, and a gap equal to 2 mm. The different regimes are deeply analyzed and discussed in [4]. Briefly, between points A and B, we are in the presence of a corona discharge; the time-averaged discharge current I ranges from a few  $\mu A$  to several dozens of  $\mu A$ . In the case of a negative voltage, the current versus time is composed of a DC component plus Trichel pulses. The current is pulseless for the positive corona discharge, meaning there is no breakdown streamer. The photograph of the discharge reveals a small ionization area extending up to 0.2 mm from the needle tip. Additionally, the liquid surface appears significantly deformed because of the ionic wind flowing from the needle tip toward the water surface [3]. PIV measurements have been carried out in this discharge regime (7  $\mu$ A  $\leq$  I  $\leq$  30  $\mu$ A). From point B, a sudden increase in the time-averaged current and a drop in the DC voltage are observed. Without current limitation, the current can reach several milliamperes (in practice, we control the current values by the current limitation of the power supply). At the same time, the voltage drops to 1-2 kV, depending on the voltage polarity. For the PIV measurements, we fixed the time-averaged current at 3.8 mA, corresponding to voltage values equal to 0.7-1.5 kV in the case of the positive discharge, and 1.4-2.1 kV for the negative one, this voltage value depending on the voltage polarity and also on the water conductivity. Indeed, if the water conductivity changes, the main behavior of I-V characteristics is similar, but the voltage and current values differ. In the current range of several milliamperes, the discharge regime is the normal glow, as illustrated by the right-hand photograph in Fig. 2.

#### B. Normal glow discharge induced-liquid flow

As indicated just above, the time-averaged current was fixed at 3.8 mA for all the PIV measurements, and we investigated the effect of the voltage polarity, the water conductivity and the superficial tension of the water. The water conductivity has been increased in adding KCl in water, and the superficial tension has been decreased in adding ethanol in water (20%). In the present article, we present only the main results.

Fig. 3 presents the velocity fields of the water flow for both polarities and three different values of water conductivity. The background color indicates the velocity modulus (from 0 to 6 cm/s) and the black arrows (uniform length) the flow direction. Several remarks can be made. First, as for a helium plasma jet [1] and a dielectric barrier discharge [2], two main phenomena take place: (1) an upward displacement of the liquid, located directly beneath the point of discharge impact on the liquid surface, and (2) a tangential flow along the water surface, originating from the point of discharge impact on the liquid surface and propagating towards the edges of the vessel. Consequently, this results in the formation of two counter-rotating vortices in the upper half of the liquid. Secondly, we can see that the flow intensity decreases as the liquid conductivity increases. For instance, for the positive polarity, the liquid velocity reaches 6 cm/s for  $\sigma = 3.4 \,\mu$ S/cm when it is limited to about 3.5 cm/s for  $\sigma = 800 \,\mu$ S/cm. Third, the water flow velocity is slightly higher with the positive discharge than with the negative one.



Fig. 2. I-V characteristics of the discharge.

Let us discuss the phenomena at the origin of this water flow. In fact, liquid flows induced by electrical discharges can result from different physical phenomena, such as EHD forces due to the motion of electrical charges, thermal convection, surface tension gradients (Marangoni effect), and shear stress induced by a gas flow along the water surface [2]. Here, we can assume that the liquid flow is mainly due to EHD forces. Indeed, although the discharge power consumption is several watts, the thermal and Marangoni effects are certainly negligeable, and there is no gas flow. In fact, two types of EHD forces can be at the origin of the improvement of the liquid flow, these two forces being due to the deposition of electrical charges at the surface of the liquid, where the discharge impacts the liquid. First, the horizontal flow observed at the gas-water interface (in the x direction) may result from the repulsion of charge carriers at the surface. Indeed, if the charges



Fig. 3. Velocity field for positive and negative normal-glow discharges, and different values of water conductivity.

accumulate in front of the discharge, they repel each other and therefore move from the point of impact of the plasma jet (x = 0) toward the edges of the vessel. This leads to two opposite forces, from x = 0 toward the vessel edges. Secondly, the upward flow is certainly due to the migration of opposite charges from the bulk of the liquid toward the location where the plasma jet impacts the water. For instance, when positive charges are deposited by the plasma jet, negative charges are created inside the liquid. Then, they drift toward the surface due to the electric field, resulting in an upward flow. This theory is consistent with the fact that the flow intensity is stronger when the water conductivity is weaker.

Finally, we investigated the effect of the superficial tension  $\gamma$  of water. For pure water,  $\gamma = 70$  mN/m. In adding



Fig. 4. Velocity field for a positive discharge and with a superficial tension of 40 mN/m (20% ethanol in water). Same velocity range as Fig. 3.

20% of ethanol, the electrical conductivity is unchanged but  $\gamma = 40$  mN/m. Fig. 4 presents the velocity field in the case of positive discharge, when  $\gamma = 40$  mN/m. If we compare this flow with the one observed at  $\gamma = 70$  mN/m (Fig. 3), we can see that a decrease in  $\gamma$  results in an intensification of the flow at the gas-liquid interface.

#### C. Corona discharge induced-liquid flow

A second campaign of PIV measurements has been carried out with corona discharges (between points A and B in Fig. 2). In this case, the electrical power is on the order of 100 mW. The liquid is deionized water with an electrical conductivity varying between 2 and 4  $\mu$ S/cm.

Fig. 4 presents the velocity fields of the water flow for a positive corona discharge, for three different timeaveraged current values (7, 10, and 19  $\mu$ A). The gap equals 2 mm. Three main remarks can be made. First, even for weak discharge current values, the liquid flow is significant as its velocity reaches a few cm/s. Second, the flow velocity increases with the discharge current. Finally, the flow topology is slightly different compared to the one observed previously with the normal glow discharge.

Fig. 5 shows the velocity fields of the water flow for the two polarities, when the gap equals 4 mm and the current 30  $\mu$ A. First, we can see that the flow induced by the positive corona discharge is more intense than the one

produced by the negative one. Furthermore, in the case of the positive corona discharge, the flow velocity is significant as it reaches 6 cm/s at the water surface and 3 cm/s in the vortices.

Let us try to analyse the results and discuss the phenomena at the origin of the water flow. First, as for the normal glow discharge, we can observe an upward displacement of the liquid, located in front of the location where the discharge impacts the liquid surface, and a tangential flow along the water surface. We can then consider that this is due to the same surface and volume EHD forces. However, a third phenomenon can contribute to the formation of the water flow: the shear stress due to the gas flow along the water surface (ionic wind). Indeed, in [3], we recently measured the ionic wind velocity induced by AC corona discharges ignited between the surface of deionized water and a needle. For instance, for a voltage magnitude of 6.5 kV at 1 kHz, the ionic wind jet between the needle tip and the water surface had a width of about 1 mm and a mean velocity of 6 m/s. Then, when it impacts the water surface, the air flows along the water surface.



Fig. 4. Velocity field for a three different positive corona discharge current values (7, 10 and 19  $\mu$ A). Gap = 2 mm.



Fig. 4. Velocity field for positive and negative corona discharges (gap = 4 mm, I = 30  $\mu$ A). same velocity range as Fig. 4.

#### IV. CONCLUSION

This study aimed to characterize the water flow induced by a DC discharge ignited between the water surface and a needle located a few millimeters above it. Particle image velocimetry (PIV) measurements allowed us to characterize the flow resulting from the deposition of electrical charges at the water surface by the discharge. These measurements have revealed a flow characterized by the formation of two counter-rotating vortices, resulting from two EHD forces: a surface force due to the repulsion of charges at the surface, and an upward force in the liquid due to the migration of opposite charges from the bulk of the liquid. Moreover, in the case of a coronalike discharge, a third phenomenon can be at the origin of the liquid flow: the shear stress due to the ionic wind induced between the needle tip and the water surface.

#### ACKNOWLEDGMENT

This project has received financial support from the CNRS through the MITI interdisciplinary programs through its exploratory research program. This work was supported by ANR-11-LABX-0017-01 and ANR-18-EUR-0010.

#### REFERENCES

 Alomari L. Time evolution of the EHD water flow produced by an AC dielectric barrier discharge ignited above its surface, *Proc. ISEHD 2025 (this conference)*.
 Dyson F. Plasma jet impacting the surface of a liquid: electrical analysis and EHD flows, *Proc. ISEHD 2025*.
 Moreau E. Ionic wind produced by a corona-type dielectric barrier discharge between a needle tip and the surface of a liquid, ISPNT 2024, Nov 3-7 2024, Korea.
 Alomari L. Needle-to-liquid DC discharge in atmospheric air: electrical characteristics and impact on potassium halide solutions", *Plasma Chemistry and Plasma Processing*, 45, 677–705, 2025.

## Electrical Discharge Characteristics in a Dielectric Liquid Flow in a Microchannel

K. Russel<sup>1</sup>, P.R. Selvaganapathy<sup>1</sup>, C.Y. Ching<sup>1\*</sup> <sup>1</sup>Department of Mechanical Engineering, McMaster University, Hamilton, ON, CANADA \*Corresponding author: chingcy@mcmaster.ca

Abstract- The effect of fluid flow, both in the co- and counter flow direction with respect to the electric field direction, on discharge characteristics in a dielectric liquid has been studied. A set of 100 interdigitated planar electrode pairs were photolithographically fabricated on a thin glass substrate which acts as the bottom wall of a 100 micron high, 5 mm wide and 50 mm long microchannel. The width of the emitter and collector gold electrodes was 20 and 40  $\mu$ m respectively, with inter-electrode spacing of 120  $\mu$ m. Spacing between each adjacent electrode pairs is 240  $\mu$ m. A syringe pump was used to induce a flow through the microchannel. Current was recorded at different applied DC potential across the emitter and collector electrodes at different flow rates. The results showed an increase in current when flow was induced compared to the no flow case for all applied fields. At low applied electric fields, the current increased as the flow rate increased; while at the higher applied electric fields, there was an optimum flow rate for maximum current.

Keywords- Discharge Characteristics, External Flow, Microchannel, Planar Electrodes.

#### I. INTRODUCTION

Discharge characteristics in dielectric liquids have been studied for different polarities of applied field [1, 2], different flow rates for both AC [3, 4] and DC applied fields [3-7] in gases [7] and liquids [1, 2] with macro-scale inter-electrode spacing (e.g., few mm) and for Reynolds number up to approximately 500. The dielectric fluid flow was either between coaxial cylinder electrodes [3-5] or parallel plate electrodes [2, 6] with the electric field normal to the flow. If the applied electric field is sufficient to overcome the energy barrier set by the cathode emitter electrode and the dielectric liquid, electron(s) will be released from the metal surface into the dielectric liquid to form a negative ion. Momentum interchange between the charged ions and liquid molecules enables the former to be transported through the field free regions. This momentum transfer is typically very efficient as the charged particle and the neutral liquid molecules are of similar mass. The kinetic energy gained by the liquid molecules due to the applied electric field can induce a bulk liquid motion along the path of charge flow [2]. The mobility of the dielectric liquid, when a strong electric field is applied, is thus enhanced [1, 2]. The dielectric mobility increases compared to its true mobility as the ion velocity relative to liquid increases [1] which depends on the applied electric field [2]. Coe et. al. [2] studied the effect of hydrodynamic resistance between the emitter and collector electrodes on the discharge characteristics and found that the current reduced by a factor of 5 when a hydraulic resistance was imposed between the electrodes. They suggested that the current could be significantly increased if a flow was induced from the emitter to the collector electrode by means of a pump, and found an enhancement factor between 5 to 10 in current when the liquid was pumped at 0.5 m/s. For air, Jaworek and Krupa [7] found for a needle-flat plate electrode configuration that the discharge current, for field ionization, increased initially and then decreased as the air velocity increased. The optimum velocity for maximum current depended on the field strength. In case of field emission, the discharge current decreased as the flow velocity increased. The onset voltage to discharge and the breakdown voltage were found to generally increase as the air velocity increased, with a peak at 0.5 and 0.25 m/s respectively. The onset voltage to discharge and breakdown voltage increased by 45 and 25% respectively for air velocity of 4 m/s when compared to still air.

Miyao et al. [3] found for an AC applied field with coaxial cylinder electrode configuration and maximum Reynolds number of 167 that the current decreased with an increase in the flow velocity at lower temperature; but at high temperature the discharge behavior was inconclusive. In the case of a DC applied field, the current increased as the flow velocity increased [3]. The results of Metwally [4], however, showed a decrease in current with an increase in flow for an applied DC field with similar electrode configuration and Re  $\leq$  250. In the case of an AC voltage, the current increased or decreased as the flow velocity increased and was dependent on the electrode material and geometry [4]. Yuan et al. [5], also for coaxial electrode configuration, found that temperature had a great effect on the current-flow velocity relationship and showed that at temperatures less than 40 °C the current decreased as the flow velocity increased; while it increased at temperatures above 80 °C. This was attributed to the disparity in the increase in the mobility of the positive and negative ions caused by the decrease in the viscosity at higher temperature. There are no studies for a planar electrode geometry with dielectric fluid flowing parallel to the electrodes. The planar electrode geometry has a number of practical applications, including electrohydrodynamic (EHD) micropumps. The objective of this study is to investigate the discharge characteristics in dielectric liquid flows with a planar electrode geometry.

#### II. METHODOLOGY

The schematic of the interdigitated electrodes lithographically patterned along the bottom glass wall and bonded to a PDMS microchannel is shown in Fig 1. The module consists of two sets of electrodes: the emitter connected to the high voltage probe of the DC supply and the electrically grounded collector. There was a total of 100 electrode pairs. The dimensions are presented in Fig 1 (b) and details of the microfabrication can be found in [8]. The fluid under test is a commonly used dielectric liquid, HFE 7100 from 3M. The DC field was supplied by connecting a high voltage power supply (Trek 677 with capacity of 2 kV, accuracy  $\leq 0.1\%$  of full scale) to the emitter electrodes while having the collector electrodes grounded. The current was measured using an ammeter (Keithley 2636 SourceMeter, resolution of 1 fA, accuracy better than 0.02% of reading + 25 nA) at different applied voltages. Experiments were performed for field emission mode (negative emitter) as it was found to generate higher discharge current compared to the field ionization mode (positive emitter) [9-11]. Experiments were performed for fluid flowing (i) from the emitter to collector electrode direction and (ii) from the collector to emitter electrode direction. Case (i) will be referred as co-flow as the electric field lines are stretched from the emitter to the collector electrodes, while case (ii) will be referred as counter-flow.

#### **III. RESULTS**

The discharge current as a function of applied DC potential for static (i.e., fluid velocity = 0) and dynamic fluid conditions ( $Re \le 13.1$ ) is presented in Fig 2 (a & b) for co-flow and counter-flow cases. Two regimes of operation are observed: (i) low slope quasi-Ohmic regime. i.e. conduction phenomenon, where current flow is due to the dissociation and recombination of the fluid molecules and the hetero-charges formation at the electrodes; and (ii) high slope injection regime, where charges are injected into the dielectric liquid by electron tunneling. This transition from the low slope quasi-Ohmic region to the high slope injection region has been considered as the onset of charge injection [11]. The voltage at which this transition occurs is considered as the threshold voltage  $(V_{th})$ , which for no fluid flow (e.g. static) condition was found to be 900 V. The threshold voltages for co-flow conditions were smaller than that of the static condition, i.e., < 900 V (Table 1). For the counter-flow condition the threshold voltage was greater than that of the static condition (Table 2). The threshold voltage, in case of coflow, decreased as the Re increased; while for counterflow there was a peak at Re = 1.31. The slopes of the I-V curve for the static condition within the conduction and injection regimes were 0.39 and 30.26 nA/V respectively. The external flow increased the slope of I-V curves for both co- and counter flow conditions within their respective conduction and injection regimes compared to the static condition (Table 1 & 2). This slope within the conduction regime gradually increased as the flow velocity increased, while for the injection regime this



**Fig. 1**: Schematic of (a) interdigitated electrodes and (b) cross sectional view (dimensions not to scale).

slope initially increased and then decreased. For the coflow condition the optimum Re to have maximum slope within the injection regime was 5.23 while for counter flow condition it was 1.31.

The external flow increases the current in both the conduction and injection regime, as found previously [3]. The total current density within the conduction regime can be expressed as [12]

$$j = \sigma E + qw \tag{1}$$

while the total current density within the injection regime, ignoring diffusion, can be expressed as [12]

$$j = q(w + KE) \tag{2}$$

The components  $\sigma E$ , qw and qKE in equation (1) & (2) represent current due to conduction, convection and migration/ionic mobility respectively; where *j* is the total current density,  $\sigma$  the electric conductivity of the bulk liquid, *q* the charge density, *w* the fluid local velocity due to the application of electric field *E* and *K* the true ionic mobility. In this study, there is an additional external flow velocity (*W*) set by the external pump and equation (1) & (2) can be modified for conduction and injection regimes as

$$j = \sigma E + q(w \pm W) \tag{3}$$

$$j = q(w \pm W + KE) \tag{4}$$

As the liquid motion (w) set by the applied electric field (E) flows in the direction of ion motion [1], the external velocity (W) in equation (3) & (4) is positive for the co-



**Fig. 2**: Discharge characteristics in HFE 7100 with applied DC voltage at Re of: (circle) 0, (triangle) 1.31, (square) 2.61, (diamond) 5.19, (cross) 7.85, (down point triangle) 10.43 and (pentagon) 13.1. (a) Open symbols for co-flow and (b) filled symbols for counter-flow direction.



**Fig. 3**:Discharge current at different flow rates within conduction regime. (square) 100V, (circle) 300V and (triangle) 500V. Open symbols represent co-flow, filled symbols represent counter-flow.



**Fig. 4**: Discharge current at different flow rates within injection regime. (square) 1300V, (circle) 1400V and (triangle) 1500V. Open symbols represent co-flow, filled symbols represent counter-flow.

flow case and negative for the counter-flow case. It is evident from Fig 2 that, within the conduction regime the total current at a given Reynolds number increases as the applied electric field increases. This is due to the increase in the conduction current component in equation (1) and (3). The current for the co-flow fluid direction was found to be smaller than the counter-flow direction within the conduction regime and shown for 100, 300 and 500V in Fig 3 as an example (deduced from Fig 2 (a) & (b)). It was expected according to equation (3) that co-flow (+W)would result in a higher magnitude in the convection current compared to the counter flow direction (-W), which was not observed for the conduction regime. Within the conduction regime the total current increases with an increase in *Re* for the co-flow direction and approaches a limiting value. For counter-flow, there is an initial increase in the total current with liquid flow with a subsequent decrease and approaches a limiting value.

For the injection regime  $(V > V_{th})$ : the migration component (qKE in equation (2) & (4)) occurs due to the motion of ions relative to the bulk fluid with velocity KE, under an applied field (E). Under the unipolar charge assumption (i.e., charge injection from one electrode), this component represents the motion of free ions due to charge injection through the metal/dielectric interface [12]. Within the injection regime the discharge current was greater for co-flow (+W) compared to the counterflow (-W) case (Fig 4), as expected according to equation (4). At very high applied voltage (e.g., 1300, 1400 and 1500 V) there exists an optimal flow velocity to generate a maximum current as shown in Fig 4. The presence of optimum flow velocity within the injection regime could be an indication of the hydraulic change in flow regime from laminar to turbulent. It was suggested for unipolar injection that there exists a critical Reynolds number of 10 [13, 14] beyond which EHD instability occurs.

Reynolds number	Threshold voltage (V)	Slope in conduction region (nA/V)	Slope in injection region (nA/V)
0	900	0.39	30.2
1.3	768	0.98	52.2
2.6	830	1.1	77.8
5.2	837	1.75	79.5
7.8	849	4.74	73.0
10.5	816	5.7	57.7
13.1	738	6.34	41.1

**Table 1**: Threshold voltage and slope of I-V curve at different Reynolds number at *co-flow* condition

**Table 2**: Threshold voltage and slope of I-V curve at

 different Reynolds number at *counter-flow* condition

Reynolds number	Threshold voltage (V)	Slope in conduction region (nA/V)	Slope in injection region (nA/V)
0	900	0.39	30.2
1.3	1158	5.9	98.8
2.6	1066	3.66	92.3
5.2	996	4.46	82.5
7.8	1043	5.56	90.2
10.5	943	4.83	58.5
13.1	924	5.74	45.6

#### V. CONCLUSION

Experiments were performed to study the effect of external fluid flow on the discharge characteristics in a dielectric liquid with an interdigitated planar electrode configuration. The experimental cell was 100 µm high, 5 mm wide and 50 mm long microchannel. The interdigitated planar electrodes consist of two sets of electrodes: the emitter and collector electrodes, which were 20 and 40 µm wide respectively, with inter-electrode spacing of 120 µm. HFE 7100 was used as the working fluid. Experiments were performed for a Revnolds number ranging from 0 to 13.1 with the fluid flowing both along and opposite to the electric field. It was found that the total current increased for any applied voltage with an external flow compared to the static case. The threshold voltage for the onset of charge injection decreased for any flow velocity case except for Re = 1.31 at counter-flow direction. In general, the total current increased as an increase in the Re, with an optimum Re to generate a maximum current at very high voltages within the injection regime.

#### REFERENCES

- [1] E. Gray and T. Lewis, The effects of liquid motion on ion mobility measurement in hexane, *British Journal* of Applied Physics, **16**(7): 1049, 1965.
- [2] G. Coe, J. Hughes and P. Secker, High-current injection into liquid hexane using field emitters. *British Journal of Applied Physics*, **17**(7): 885, 1966.
- [3] H. Miyao, M. Higaki and Y. Kamata, Influence of AC and DC fields on streaming electrification of transformer oil, IEEE Trans Electrical Insulation, 23(1): 129-135, 1988.
- [4] I. Metwally, Flow electrification of transformer oil effects of mixed fields, IEEE Trans Dielectrics and Electrical Insulation, **5**(4): 518-526, 1988.
- [5] G. Yuan et al., The effect of DC field on streaming electrification in converter transformer, in *Strategic Technology (IFOST), 2011 6th International Forum on.* 2011: IEEE.
- [6] P. Leblanc et al., Impact of an DC electric field on the charge accumulation at the pressboard/oil interface. in *Dielectric Liquids (ICDL), 2014 IEEE 18th International Conference on.* 2014: IEEE.
- [7] A. Jaworek and A. Krupa, Corona discharge from a multipoint electrode in flowing air, *Journal of Electrostatics*, **38**(3): 187-197, 1996.
- [8] P.Z. Kazemi, P.R. Selvaganapathy and C.Y. Ching, Electrohydrodynamic micropumps with asymmetric electrode geometries for microscale electronics cooling, *IEEE Trans Dielectrics and Electrical Insulation*, 16(2): 483-488, 2009.
- W. Schmidt, Electronic conduction processes in dielectric liquid, *IEEE Trans Electrical Insulation*, 5(EI-19): 389-418, 1984.
- [10] M. Butcher et al., Conduction and breakdown mechanisms in transformer oil, IEEE Trans Plasma Science, 34(2): 467, 2006
- [11] M. Russel, P. Selvaganapathy and C.Y. Ching, Effect of Electrode surface topology oncCharge injection characteristics in dielectric liquids: An experimental study, *Journal of Electrostatics*, **72**(6): 487-492, 2014.
- [12] J.S. Chang, A.J. Kelly, and J.M. Crowley, *Handbook* of electrostatic processes, CRC Press, 1995.
- [13] J. Lacroix, P, Atten and E. Hopfinger, Electroconvection in a dielectric liquid layer subjected to unipolar injection, *Journal of Fluid Mechanics*, 69(03): 539-563, 1975
- [14]F. McCluskey and P. Atten, Modifications to the wake of a wire across Poiseuille flow due to a unipolar space charge, *Journal of Fluid Mechanics*, **197**: p. 81-104, 1988.

### **Traveling-Wave Electrophoresis Of Micro-Particles**

Andrés Rodríguez-Galán<sup>1</sup>, Alberto T. Pérez<sup>1</sup>, Pablo García-Sánchez<sup>1</sup>, Antonio Ramos<sup>1</sup>

<sup>1</sup>Universidad de Sevilla, Depto. de Electrónica y Electromagnetismo, Sevilla, Spain

*Abstract-* We investigate theoretically the electrokinetic motion of microparticles suspended in a liquid subjected to travelingwave electric fields, i.e. Traveling-Wave Electrophoresis (TWE). In our case, the electric fields are generated by oscillating potentials applied on a periodic array of microelectrodes at the bottom of a microfluidic channel. An analytical expression for the traveling-wave electric field is derived by solving the Laplace equation using the Fourier series. This solution is subsequently used in numerical simulations of the particle trajectories. Particle trajectories are simulated within a single wavelength of the traveling wave. A transfer function is built to relate the initial and final positions of a particle within a unit cell. This function enables us to predict the final height and phase of the particle oscillation given its initial conditions. Interestingly, the transfer function reveals regions of apparent chaotic behavior, as well as regions that act as particle attractors.

Keywords- Traveling-Wave, Electrophoresis, Microfluidics.



#### I. INTRODUCTION

Figure 1: Schematic view of the channel studied, with spatial periodicity L. Each electrode is driven by an AC potential. The phase shift between neighboring electrodes is shown.

We study a narrow channel filled with fluid with nonrestricted height and infinite length. At the bottom of the channel, there is a periodic array of electrodes of width a, separated by the same amount. The electrodes are driven by a sinusoidal potential of amplitude  $V_0$  and frequency  $\omega = 2\pi f$ . Each electrode potential has a phase increment  $\pi/2$  with respect to its left neighbor, resulting in a traveling wave electric field with a vertical exponential decay. A schematic view of this configuration can be seen in Fig.1. Using the Fourier series, we derived an analytical expression for the traveling-wave electric field by solving the Laplace's equation. The wavelength of the main mode is given by  $\lambda_0 = 8a = L$ , with subsequent modes having wavelengths  $\lambda_n = \lambda_0/(2n+1)$ . The frequency of every mode is the one of the potential applied to the electrodes [1]. The first order differential equations that describe the motion of a particle with mobility  $\mu$  are

$$\frac{dx}{dt} = \mu E_x(x, y, t),\tag{1}$$

$$\frac{dy}{dt} = \mu E_y(x, y, t). \tag{2}$$

These equations can be nondimensionalized. We make the substitutions  $x \to x/\lambda$ ,  $t \to ft$ ,  $\mathbf{E} \to \mathbf{E}/(kV_0)$ . The resulting equations are

$$\frac{dx}{dt} = RE_x(x, y, t),\tag{3}$$

$$\frac{dy}{dt} = RE_y(x, y, t),\tag{4}$$

where  $R = \mu k^2 V_0 / \omega$  is the nondimensional mobility, the fundamental parameter of our problem.

TWE may be obtained with electrics fields resembling a one-dimensional traveling wave electric field given by

$$E(t,x) = A\cos(x-t),$$
(5)

with nondimensionalized coordinates. The resulting equation of motion is the first-order differential equation

$$\frac{dx}{dt} = R\cos\left(x - t\right),\tag{6}$$

which can be solved with analytical methods [2]. Within this electric field, particles with  $R \leq 1$  undergo oscillations superimposed with a drift velocity given by

$$u = 1 - \sqrt{1 - R^2}$$
(7)

for particles with  $R \leq 1$ . For particles with R > 1, the drift velocity is u = 1 independently of the value of R.

Alternative electrode configurations for TWE, different from the one shown in Fig. 1, have previously been studied [3], where chaotic behavior was observed.

In this work, we study the motion of particles in this electrode configuration via numerical integration of the equations of motion and build the transfer function from these results. Depending on the initial height of the particle above the electrodes, two distinct types of motion are observed, one of which presents chaotic behavior.

#### II. METHODOLOGY

Particle trajectories were obtained via numerical integration of the equations of motion using a second-order Runge-Kutta method. The electric field is calculated using the first 150 modes of the Fourier series solution in the region  $0 \le x < \lambda$ ,  $0 \le y < \lambda$ . Particles that reach the upper boundary are not considered. In order to calculate the value of the electric field at each point (x, y) and time t we built a fine grid from which the value is obtained by linear interpolation. Since the channel is periodic in the horizontal direction, the grid needs to be built only in the first wavelength.

In order to consider the finite radius of the particles r, we impose a minimum separation between the particles and the channel wall. In our simulation, this separation takes the value  $r/L = 1/160 = 6.25 \times 10^{-3}$ , which is the ratio corresponding to a  $0.5\mu$ m particle in a channel of wavelength  $L = 80\mu$ m. We assume a non-elastic hard-wall interaction, which means that when a particle reaches the bottom wall, its vertical velocity becomes zero and it does not penetrate the wall. However, the horizontal motion remains unaffected, allowing the particle to move tangentially along the wall. The particle continues this tangential displacement until the vertical component of the electric field changes sign, at which point the vertical velocity acquires an upward component and the particle detaches from the wall.

#### III. RESULTS

The analysis of the trajectories reveals the existence of different types of motion. For a given mobility value (see Fig. 3), different initial conditions can evolve into completely unrelated trajectories, and similarly for given initial conditions, trajectories can behave strongly differently depending on their mobility.

We calculate trajectories for 300 different values of initial height  $y_0$  in the range  $6.25 \times 10^{-3} \le y_0 \le 0.5$  and for 300 different values of the initial phase  $\phi_0$  in the range  $0 \le \phi_0 < 2\pi$ . The initial conditions for the integration of the equations of motion are the given by

$$x\left(t = \frac{\phi_0}{2\pi}\right) = 0,\tag{8}$$

$$y\left(t = \frac{\phi_0}{2\pi}\right) = y_0. \tag{9}$$

The motion is calculated for 40 wave periods. If for some given initial condition the particle does not exit the first wavelength, the output is set to  $y_{out} = 0$ ,  $\phi_{out} = 0$ , allowing a clear distinction with particles that exit the channel within the simulation time.

From the trajectories data, we can build the transfer function. This function takes the height and wave phase value of a particle at the start of the channel as input and



Figure 2: Height transfer function (a) and phase transfer function (b) of a particle with mobility R=1.885, where two separate regions are clearly distinguished. It should be noted that the top most part appears dark since the velocity of that particles is too low to reach the end of the channel in the running time of the simulation.



Figure 3: Trajectories for particles of mobility R=1.885 starting at x = 0,  $\phi_0 = 0$  for different  $y_0$  values. The difference between trajectories in the top and bottom part are clearly seen. The duration of the simulation is the same for all trajectories.

outputs the height and phase value after the particle travels a wavelength.

Different mobility values result in different transfer functions, but some qualitative characteristics are shared between all functions. Every transfer function can be divided into two regions: a bottom region, where particles mostly exit the channel at height close to the electrodes; and a top region, where particles exit the channel at heights similar to its initial value. The difference is more clearly seen in the height output of the transfer function in contrast to the phase output, but identical patterns can be seen in both.

In theory, interpolation of a fine enough grid should give a good approximation of the transfer function, but we see that the sensitivity to initial conditions of the function, as seen in Fig. 2 makes this approach invalid for some regions.

These quick changes in the values of the transfer function for different initial conditions are probably a reflection of the chaotic behavior of the particles that start close to the electrodes.



Figure 4: Transfer function (a), (b) and velocity in a channel wavelength (c) of a particle with mobility R=0.578, obtained from trajectories with a maximum duration of 80 wave periods. The value of the velocity is obtained as the inverse of the time a particle need to exit a channel wavelength. The bottom part of the diagram presents lower velocity values, with some regions that effectively trap particles

Examples of trajectories used to calculate the transfer function can be seen in Fig. 3. Trajectories in the top part are well behaved, which translates into a smooth transfer function. Meanwhile, the trajectory shown near the electrodes is chaotic, leading to abrupt changes in the corresponding region of the transfer function.

The velocity of the particles in the top region depends directly on the initial height and phase values, decaying exponentially with increasing initial height. In contrast, particles with medium-high mobilities in the bottom region end up with the same average velocity after a few wave periods for any initial conditions. However, for low mobilities, the bottom region may exhibit a different behavior.

The transfer function for sufficiently low mobility values also reveals certain trapping regions, as seen in Fig. 4. Although it cannot be ensured that particles in those regions would not exit the channel after a long enough time, its horizontal motion is much slower than that of particles in other regions of the diagram. However, the zero velocity plateau seen in Fig. 5, longer simulations up to 350 wave periods seem to indicate that some particles, those of mobility R < 0.61, will not exit the first wavelength after any amount of time.



Figure 5: Average velocity of particles with different mobilities starting at x = 0,  $y = 6.25 \times 10^{-3}$ ,  $\phi_0 = 0$ . For low mobilities, R < 0.61, the average velocity goes to zero, which means the particle is trapped in the first wavelength.

#### IV. CONCLUSION

We have simulated the trajectories of microparticles subjected to traveling-wave electric fields generated by microelectrode arrays. The resulting trajectories fall into two distinct categories depending on the initial distance of the particles from the electrode array. Particles initially close to the array exhibit complex, often chaotic trajectories with identifiable accumulation points. In contrast, particles starting farther away follow smoother and more regular paths. These findings are particularly relevant for applications of TWE, such as particle fractionation based on electrophoretic mobility.

#### REFERENCES

[1] Ramos et al. Journal of Applied Physics 97, 084906, 2005

- [2] J. R. Melcher, E. P. Warren, and R. H. Kotwal.*Particles Science and Technology*, vol 7, pp 1-21, 1989.
- [3] Boyd F. Edwards. *Physical Review E*, 80, 036205, 2009

# Improving Collection Efficiency and Energy Saving in a High Electric field type electrostatic precipitator with high gas velocity for diesel exhaust particle

Hayato Ito<sup>1</sup>, Akinori Zukeran<sup>1</sup>, Takumi Kojima<sup>1</sup>, Koji Yasumoto<sup>1</sup> <sup>1</sup>Kanagawa Institute of Technology, Japan \*Corresponding author: zukeran-akinori@ele.kanagawa-it.ac.jp

Abstract- In this study, experiments were carried out to achieve a collection efficiency of 80% at a high gas velocity of 10 m/s in a high electric field electrostatic precipitator (ESP) for diesel exhaust particles. The effects of electrode length and gas velocity were investigated. The experimental system consisted of a diesel engine, a heat exchanger, and the ESP. The exhaust gas temperature was adjusted to 30°C by the heat exchanger and then flowed into the ESP. The gas velocity was adjusted to values between 1 m/s and 10 m/s. The ESP had a coaxial cylindrical structure composed of a high-voltage columnar electrode and a grounded cylindrical electrode. The gap distance was set at either 6.1 mm or 10 mm, and the electrode length ranged from 470 mm to 2000 mm. A negative DC voltage of 19 kV or 11.6 kV was applied to the columnar electrode, depending on the gap distance (10 mm or 6 mm, respectively). As a result, since no discharge current was detected under any conditions, it was revealed that energy was not consumed in the ESP. Furthermore, maximum collection efficiency of 86% was achieved at a gap distance of 6.1 mm, an electrode length of 2000 mm, and a gas velocity of 10 m/s, without energy consumption.

Keywords- electrostatic precipitator, energy saving, high gas velocity

#### I. INTRODUCTION

Electrostatic precipitators (ESPs) have been extensively used for purifying air in houses and road tunnels, or emission gas from power plants, etc. Their power consumption affects  $CO_2$  emission and fossil-fuel consumption, so the energy saving of ESPs becomes more important as its collection efficiency is improved. The energy consumption in an ESP is mainly due to corona discharge.

Therefore, new control systems [1,2], a pulsed energization [3] and an optimum structure of precharger [4], etc. were investigated. Katatani et al. investigated the effect of induction charging on the collection efficiency and the state of collected particles [5, 6]. Their studies are very interesting in that no corona discharge is used for charging particles, while other researchers investigate the energy saving in an ESP using corona discharge. Okuda et al. reported that 75% to 88% of the particles suspended in the air were naturally charged in positive and negative polarity [7, 8].

Thus, it was expected that airborne particles could be removed by a high electric field without corona discharge, and it was shown that the input power decreased to 1/40 or less in comparison to that in a conventional ESP [9]. Furthermore, an experiment was carried out to clarify the effect of the ESP with a high electric field on the collection of diesel exhaust particles at a gas temperature of 130 °C. As a result, it was revealed that the ESP with a high electric field could collect diesel exhaust particles. In addition, it was indicated that the diesel exhaust particles contained both positively and negatively charged particles, so these could also be collected [10]. However, the collection efficiency was low, and it was required to increase the gas velocity.

In this study, experiments were carried out to achieve collection efficiency greater than 80% at a gas velocity of

8 m/s in the ESP with a high electric field for diesel exhaust particles. The effects of the gas temperature, the electrode length, the electrode gap distance and the gas velocity were investigated.

#### II. METHODOLOGY

The schematic of the experimental system is shown in Fig 1. The experimental apparatus mainly consisted of a diesel engine (Denyo, DA-3100SS-IV, water-cooled 4cycle, 400 cc, 3 kW), a heat exchanger, and an ESP with a high-electric field. Residual fuel oil (ENEOS LSA fuel oil) was used for the diesel engine, and the load was set at 3 kW (100%). The exhaust gas temperature was adjusted within the range of 30 to 130°C by the heat exchanger and then flowed into the ESP. The gas velocity was adjusted within a range of 1 m/s to 8 m/s by a separator. The ESP had a coaxial cylindrical structure with an inner columnar electrode for high voltage application and an outer cylindrical electrode for grounding. The gap length was set at 6.1 mm or 10 mm, and the electrode length was set at 470 mm or 2000 mm. By applying a negative DC high voltage of 19 kV to the inner columnar electrode for high voltage application, a high electric field was formed between the electrodes, and the naturally charged diesel exhaust particles were collected. To evaluate the performance of the ESP, the particle mass concentration at the upstream and downstream sides of the ESP were measured. A portion of the exhaust gas was sampled (10 L/min, 15 min) on a filter (Tokyo Dylec in Japan, TX40HI20-WW) using a pump (Tokyo Dylec, NLY-60), and the particle mass was measured with an electronic balance (A&D, HR-202i) to calculate the mass concentration. The filter mass was measured after drying at 50°C for 2 hours. The collection efficiency  $\eta$  was calculated using equation (1).

$$\eta = \left(1 - \frac{N}{N_0}\right) \times 100\% \tag{1}$$

where, N<sub>0</sub> is the particle mass concentration  $[mg/m^3]$  at the upstream side of the ESP or the downstream side when no voltage is applied, and N is the particle mass concentration  $[mg/m^3]$  at the downstream side of the ESP.



Fig.1 Schematic diagram of experimental system

#### **III. RESULTS**

#### A. Effect of gas temperature

The effect of gas temperature was investigated at the electrode length of 470 mm and the gap distance of 10 mm. The collection efficiency was calculated from the ratio of the particle mass concentrations at the downstream side of the ESP before and after voltage application. The collection efficiency as a function of applied voltage at a gas temperature of 130 °C and a gas velocity of 4 m/s is shown in Fig. 2. The collection efficiency was estimated by the particle mass concentration. The collection efficiency increased with increasing applied voltage, and reached 36% at 10.5 kV. Under any of the tested conditions, no discharge current was detected, which was less than the measurement limit of 0.01 mA. Therefore, it is clear that the ESP with a high electric field can remove diesel exhaust particles without power consumption. However, the efficiency was not sufficient, and the efficiency at a voltage of 12 kV was lower than that at 10.5 kV due to a spark discharge.

The relationship between the spark voltage and the gas temperature was investigated to suppress the spark discharge and improve the collection efficiency. The result is shown in Fig. 3. The spark voltage increased as the gas temperature decreased. According to Paschen's law as shown in equation (2) [11], the spark voltage increases, as the mean free pass decreases when the gas pressure increases. A decrease in gas temperature also decreases the mean free path, causing the spark voltage to increase, as in Fig. 3. Therefore, since the applied voltage can be increased at lower temperatures, it is expected that the collection efficiency improves:

$$V_{s} = \frac{Dpd}{ln\frac{Cpd}{ln\left(1+\frac{1}{\gamma_{i}}\right)}}$$
(2)

where  $V_s$  is the spark voltage, p is the gas pressure, d is the gap distance between electrodes,  $\gamma_i$  is the secondary electron emission, C and D are gas constants.

The effect of the gas temperature on the collection efficiency is shown in Fig. 4. The maximum voltage that could be applied was 10.5 kV at the temperature of 130 °C. The collection efficiency at the gas temperature of 130 °C, the voltage of 10.5 kV and the gas velocity of 4 m/s was 36%. When the temperature was cooled to 30 °C, the collection efficiency was 39 %, which was almost the same as that at 130 °C. This indicates that the temperature does not affect the collection efficiency. However, when the gas temperature decreased to 30 °C, the voltage could be increased to 19 kV. Under this condition, the collection efficiency was 58% due to the increase of the coulomb force. Furthermore, the collection efficiency of 82 % was achieved without energy consumption at a gas velocity of



Fig. 2 Collection efficiency as a function of applied DC voltage at a gas temperature of 130 °C and a gas velocity of 4 m/s.



Fig. 3 Relationship between spark voltage and gas temperature.



Fig. 4 Effect of gas temperature on collection efficiency.

1 m/s. This is due to the increased residence time of the charged particles within the ESP.

The time characteristics of the collection efficiency under various conditions at the exhaust gas temperature of 30°C are shown in Fig 5. The initial collection efficiency at the applied voltage of 19 kV and the gas velocity of 1 m/s was approximately 82%, indicating a high value. Although the collection efficiency decreased over time, it remained at 77% after four hours. This decline is considered to be caused by the re-entrainment phenomenon; however, its impact is not significant. Similar tendencies were observed under other conditions. The initial collection efficiency at the applied voltage of 19 kV and the gas velocity of 4 m/s was approximately 53%, while it was approximately 35% at 10.5 kV and 4 m/s. As the gas velocity increases, the residence time of suspended particles in the ESP decreases, and as the voltage decreases, the Coulomb force acting on the particles becomes smaller, resulting in the lower initial collection efficiency.

# *B.* Prediction of collection efficiency under high gas velocity

The collection efficiency was predicted using Deutsch equation shown in equation (3) to achieve a high efficiency of approximately 80% at a high gas velocity of 8 m/s. Since it is known that a portion of suspended particles are naturally charged, it is assumed that 90 % of diesel exhaust particles are charged. Therefore, a coefficient r (0.9) is applied in the equation (3).

$$\eta = r \left\{ 1 - \exp\left(\frac{-W_{th}L}{V_g G}\right) \right\}$$
(3)

where  $W_{th}$  is the effective migration velocity [m/s], L is the electrode length [m],  $V_g$  is the gas velocity [m/s], and G is the electrode gap [m].

To predict the collection efficiency using the Deutsch equation, the effective migration velocity  $W_{th}$  was determined from experimental data. From Fig 4, substituting L = 0.47 m (470 mm),  $V_g = 4$  m/s, and G = 0.01 m (10 mm) into equation (3) with  $\eta = 57\%$  gives a value of  $W_{th} = 0.08539$  m/s. By substituting this value back into equation (3), equation (4) is obtained to predict the collection efficiency for any L,  $V_g$ , and G.

$$\eta = 0.9 \left\{ 1 - \exp\left(\frac{-0.08539L}{V_g G}\right) \right\}$$
(4)

The predicted collection efficiency using equation (4) is shown in Fig 6. For L = 470 mm and G = 10 mm, the collection efficiency is 57% at the gas velocity of 4 m/s and improves to approximately 80% at the gas velocity of 1 m/s. The experimental result is 82%, which agrees well with the prediction. Additionally, the collection efficiency decreases with increasing gas velocity, dropping to 36% at 8 m/s. Therefore, by setting *G* to 6 mm, the collection efficiency becomes 51% at 8 m/s, and by further setting *L* to 1000 mm, it is predicted to be 75%, and 87% at 2000 mm, which nearly meets the target value.



Fig.5 Relationship between collection efficiency and elapsed time.



Fig.6 The predicted Collection Efficiencies using the Deutsch equation.



Fig.7 Relationship between collection efficiency and gas velocity at electrode length of 2000 mm.

#### C. Collection efficiency at electrode length of 2000 mm

Based on the predicted results in Fig 6, the electrode gap G was set to 6.1 mm and the electrode length L to 2000 mm, and the collection efficiency as a function of gas velocity and elapsed time was investigated. The relationship between the collection efficiency and the gas velocity is shown in Fig 7. At all gas velocities, the collection efficiency ranged between 53% and 92%, achieving a high collection efficiency of 75% at a gas velocity of 10 m/s and an electrode length of 2000 mm without energy consumption.

Fig. 8 shows the relationship between collection efficiency and elapsed time at a gas velocity of 10 m/s. The initial efficiency was 77%, and it remained stable for



Fig.8 Relationship between collection efficiency and elapsed time at gas velocity of 10 m/s.

four hours. The average efficiency during this period was as high as 80%.

#### IV. CONCLUSION

In this study, experiments were carried out to improve the collection efficiency in the ESP with a high electric field for diesel exhaust particles. The effects of the gas temperature, the electrode length and the electrode gap distance on the collection efficiency were investigated. Results are follows:

- 1) The collection efficiency initially increased with increasing applied voltage and then decreased due to spark discharge.
- 2) The spark voltage increased with decreasing temperature of the diesel exhaust gas.
- 3) The collection efficiency increased with decreasing gas temperature, since the applied voltage could be increased. The mass collection efficiency achieved 82% without energy consumption at a gas velocity of 1 m/s, a gas temperature of 30 °C, an electrode length of 470 mm and an electrode gap distance of 10 mm.
- 4) The collection efficiency of 75% at a high gas velocity of 10 m/s was achieved without energy consumption at an electrode length of 2000 mm, an electrode gap distance of 6.1 mm and a gas temperature of 30 °C

#### ACKNOWLEDGMENT

This work was supported by a Grant-in-Aid for Scientific Research (B), No. 23K22976 and No. 25K01440, from the Japan Society for the Promotion of Science.

#### References

 MA Jinhui, YANG Yaowen, WANG Ronghua, YAN Keping, Industrial Applications of a New AVC for Upgrading ESP to Save Energy and Improve Efficiency, Proceeding of 11th International Conference on Electrostatic Precipitation, pp. 281-283, 2008

- [2] M. Williamsson, A. Karlsson, N. Dash, P. Ranstad, E. Önnerby Pettersson, Energy optimization in ESP with advanced control system, Proceeding of ICESP 2016, 2016.
- [3] Kjell Porle, Reduced Emission and Energy Consumption with Pulsed Energization of Electrostatic Precipitators, Journal of Electrostatics, Vol. 16, pp. 299-314, 1985.
- [4] Yoshihiro Kawada, Hirotaka Shimizu, Akinori Zukeran, Numerical Study of the Suitable Precharger Grounded Electrode Length in Two-Stage-Type Electrostatic Precipitator, IEEE Transactions on Industry Applications, Vol. 55, No. 1, pp. 833-839, 2019.
- [5] Atsushi Katatani, Hiroshi Hosono, Hikaru Murata, Hiroshi Yahata, Akira Mizuno, Electrostatic Precipitator without Using Corona Discharge - State of Collected Particles on Pole-plates -, International Journal of Plasma Environmental Science & Technology, Vol.10, No.1, pp. 35-40, 2016.
- [6] Atsushi Katatani, Hiroshi Hosono, Hikaru Murata, Hiroshi Yahata, Akira Mizuno, Electrostatic Precipitator Using Induction Charging-, International Journal of Plasma Environmental Science & Technology, Vol 10, No.2, pp. 135-139, 2016.
- [7] Kentaro Fujioka, Keiichi Kurosawa, Takuto Yonemichi, Koji Fukagata, Tomoaki Okuda, "Measurement of the Electrostatic Charging State of Ambient Aerosol Using a Parallel Electrode Plate Plate Device" Abstract of Xth international Aerosol Conference (IAC 2018),4AP.2 2018.
- [8] Iwata, A., Fujioka, K., Yonemichi, T., Fukagata, K., Kurosawa, K., Tabata, R., Kitagawa, M., Takashima, T., Okuda, T., "Seasonal variation in atmospheric particle electrostatic charging states determined using a parallel electrode plate device", Atmospheric Environment, Vol. 203, No. 15, pp. 62-69, 2019.
- [9] Akinori Zukeran, Shogo Inoue, Daiki Ishizuka, Kohei Ito, Takayuki Kaneko, "Energy Saving Effect of High Electric Field on an Electrostatic Precipitator for Air Borne Particle", IEEE Transactions on Industry Applications, Vol. 56, No. 6, pp. 6990-6996, 2020.
- [10] Akinori Zukeran, Daiki Ishizuka, Keisuke Ito, Yuki Tanahashi, Risei Wada, Keisuke Yamashiro, Yoshihiro Sakuma, Takayuki Kaneko, "Effect of electrode length and gas velocity on the collection of diesel exhaust particle in an electrostatic precipitator with a high electric field" Proceeding of the 16<sup>th</sup> International Conference on Electrostatic Precipitator, 2022.
- [11]Yotsuo Toriyama, Takao Sakai, Yoshihiro Murooka, High Voltage Engineering, CORONA PUBLISHING CO. LTD., 1992
- [12]A. Zukeran, Y. Ikeda, Y. Ehara, M. Matsuyama, T. Ito, T. Takahashi, H. Kawakami, T. Takamatsu, Two-Stage Type Electrostatic Precipitator Re-entrainment Phenomena under Diesel Flue Gases, IEEE Trans. Ind. Applicat., Vol35, No.2, pp.346-351, 1999.

### Numerical Study on Dynamics of Falling Drop over Hydrophobic Substrate under the influence of Electric Field

Aaditya Rampal<sup>1</sup>, Yash Agrawal<sup>1</sup>, Absar Lakdawala<sup>1\*</sup> <sup>1</sup>Department of Mechanical Engineering, Nirma University, India \*Corresponding author: absar.lakdawala@nirmauni.ac.in

Abstract- Multiphase Electrohydrodynamics refers to the interaction between two or more immiscible fluids under the action of an electric field. The study of multiphase electrohydrodynamics has applications in microfluidics, biomedical operations, adjustable lenses, microsensors and micro actuators, self-cleaning surfaces, digital displays, lab-on-a-chip devices, etc. The wetting phenomenon is how a liquid behaves after it comes into contact with any solid surface. It is usually quantized by the equilibrium contact angle between the liquids and the surface ( $\theta_e$ ). This phenomenon can be tweaked in many ways, such as by inducing ultrasonic vibrations on the surface, adding surfactants or contaminating the liquid. This paper considers the effects of an external electric field as a tweaking agent.

The simulations have been set up to test for three parametric details: Initial velocity for the values 0.25 m/s and 0.35 m/s; Electric Bond number (Bo<sub>e</sub>) for the values 0.00, 0.05, 0.10, 0.15, 0.20, and 0.25; contact angle for the values 110°, 130° and 150°. The objective of this study is to understand the effects of the various physical parameters, denoted by the non-dimensional numbers (Re, Wb, Bo<sub>e</sub>) and surface contact angle, on the drop dynamics, specifically the spreading ratio. The results have been validated by comparing them against the experimental data obtained by N. Patil (2016). After careful observation and comparisons of available and computed data, a strong direct correlation between an increase in the applied electric field and an increase in the spreading ratio can be shown.

#### Keywords- Multiphase Electrohydrodynamics, OpenFOAM, Wetting Phenomenon, Contact Angle Dynamics.

#### I. INTRODUCTION

Multiphase electrohydrodynamics (MEHD) refers to the study area under which any interaction of two or more fluids occurs under the effect of an electric field. It has remained an area of interest for a long time [1], [2], [3], [4], resulting in multiple practical applications, such as anti-corrosion effects[5], heat transfer mechanisms[6], microfluidics[7], self-coating characteristics[8], lab-on-achip electronics, etc. MEHD flow involves a highly complex interplay of electrostatic, interfacial and fluid dynamic forces. Due to the complications present, such as the charge movement in the fluids and the coupling of various physical parameters, the numerical analysis and simulation of hydrodynamic flows is a time-consuming and imprecise task.

One application of MEHD flow is the behaviour of a water droplet on a hydrophobic surface, while under the influence of an electric field. A variation of this, without the electric field, has been studied extensively [9], [10], [11], but there is a dearth of research in contemporary literature regarding this specific setup, except [12], [13]. Specific practical applications of such research are well known, and this addition to known numerical investigations should prove to be fertile ground for further research.

There are two main concerns during the analysis of this problem: the first is the problem of front-capturing, i.e., how accurately the various fluids involved are resolved, and the second is the calculation of the contact angle between the drop and the surface. For the first concern, the VoF method is chosen as the most appropriate. VoF is implemented based on the Continuum Surface Force (CSF) model, integrating both Weighted Arithmetic Mean (WAM) and Weighted Harmonic Mean (WHM) for calculation of properties at the interface. The control volume will be assumed to be a common fluid, with the physical fluids being denoted using a phase indicator function ( $\phi$ ). The second concern involves the calculation of the contact angle between the drop and the surface, whose accuracy is crucial for capturing the overall behaviour of the drop. Kistler's dynamic contact angle model has been chosen as the best fit for this simulation, providing the best payoff between accuracy and complexity [14].

Thus, the present work is an attempt to show how the motion of a water drop falling on a hydrophobic surface under the effects of an electric field, specifically after it has made contact with the surface, is analogous to the movement of the block in a damped spring mass system, with the inertia being provided by the mass of the drop itself, spring force coming from a combination of surface tension and electric force and the damping being done by the viscous force.

The analysis will be carried out using the in-house solver interEHDFoam. The height and spread of the droplet have been recorded and plotted in all the simulations carried out, and a general equation similar to the equation describing the motion of the mass in the damped spring mass system but based on the variables in the simulation's parametric space (Electric Bond Number ( $B_{oe}$ ), Equilibrium Contact Angle ( $\theta_e$ ) and Ohnesorge Number (Oh)).

#### SUBSCRIPT

1	Fluid 1
2	Fluid 2
m	Mean Value

#### NOMENCLATURE

Boe	Electric bond number	-
$B_{og}$	Gravitational bond number	-
Ε	Electric field	V/m
$F_{ES}$	Volumetric Electric Force	-
$F_{ST}$	Surface tension force	-
g	Acceleration due to gravity	m/s <sup>2</sup>
Te	Electrical Stress Tensor	-
3	Electrical Permittivity	s <sup>4</sup> A <sup>2</sup> /kgm <sup>3</sup>
Θ	Electric Potential	V
μ	Dynamic viscosity	Ns/m <sup>2</sup>
ρ	Density	kg/m <sup>3</sup>
$\rho_e$	Volumetric Charge density	C/m <sup>3</sup>
σ	Electrical Conductivity	s <sup>3</sup> A <sup>2</sup> /kgm <sup>3</sup>
τ	Non-dimensional Time	-
$l_c$	Non-dimensional Length	-
$u_i$	Initial Drop Velcoity	m/s
<i>u</i> <sub>c</sub>	Non-Dimensional Velocity	
m	Mass	kg
с	Damping Factor	Kg/s
k	Spring Factor	N/m

#### II. METHODOLOGY

#### A. Physical Description and Simulation Setup

The physical geometry involves a water droplet with a diameter of  $D_0$  falling onto a hydrophobic surface through air with velocity  $V_{0}$ , as shown in Fig. 1. The water droplet's initial position will be of initial contact. The electric field is created by two electrodes, one present at the top and the hydrophobic surface acting as the second. The calculations will be focused on tracking the height of the water droplet on the axis (H<sub>axis</sub>) and its spread on the surface (R<sub>surface</sub>). Water (fluid 1) is treated as the reference fluid and non-dimensionalising is done by choosing  $D_0$  as characteristic length (l<sub>c</sub>)and  $V_0$  as characteristic velocity (u<sub>c</sub>). The characteristic time ( $\tau$ ) thus becomes  $D_0/V_0$ 

For the non-dimensional computational study of this problem, a 2D axisymmetric computational domain (of size  $3D_0 \times 3D_0$ ) is chosen and the boundary conditions are set as seen in Fig. 1. The interface as seen in the image is defined by the CLSVOF (Combined Level Set Volume of Fluid) method as represented by  $\phi$ , where  $\phi = 0$  for air,  $\phi$ = 1 for water and  $0 < \phi < 1$  being the interface. The top and right walls have been given Far-Field and Outflow boundary conditions to show their spread in the axial and radial directions; the left wall is given axisymmetric boundary conditions due to the cylindrical nature of the problem. Furthermore, for the bottom wall, Kistler's contact angle model has been implemented, which will decide the drop dynamic based on the inputted equilibrium contact angle  $(\theta_0)$  and the calculated contact line velocity (U\_{CL}).

Table 1: Physical	properties	of fluids	involved
-------------------	------------	-----------	----------

Properties	Fluid 1 (Air)	Fluid 2 (Water)	
Density (p)	1.186 kg/m <sup>3</sup>	998 kg/m <sup>3</sup>	
Kinematic Viscosity (v)	1.526x10 <sup>-5</sup> m <sup>2</sup> /s	1x10 <sup>-6</sup> m <sup>2</sup> /s	
Permittivity (E)	8.85x10 <sup>-12</sup> F/m	7.08x10 <sup>-10</sup> F/m	
Conductivity $(\sigma)$	5.49x10 <sup>-12</sup> S/m 5.49x10 <sup>-6</sup> S/		
Surface Tension (y)	0.072 N/m		

The solution algorithm was kept as MULES. MULES means Multi-Dimensional Filter for Explicit Solution, is a very crucial in maintaining the boundedness of scalar fields, in particular for phases of phase fractions in multiphase domain. We have used Semi-Implicit MULES, which eliminates the need for strict CFL number and substantially small time-steps.

This makes sure that an abrupt change in contact angle does not cause unbounded alpha (phase fraction) values and keeps it bounded, preserving the phase interface across sharp curvatures.

To deal with the spurious velocities generated due to artificial compression, nAlphaSmoothCurvature has also been used, this substantially decreases the unphysical velocities around the droplet.

#### B. Mathematical Formulation

The phenomenon under consideration encompasses multiphase flow dynamics with electric potential. Preexisting equations present under the interFoam solver are used with an added term (Volumetric Electric Force), which is used to simulate

multiphase electrohydrodynamics.

Mass - Mass-Conservation Equation:

$$\frac{I}{R}\frac{\partial(RU)}{\partial R} + \frac{\partial V}{\partial Z} = 0$$
 (eq. 1)

Momentum-Conservation equation

$$p_{\rm m} \left( \frac{\partial U}{\partial \tau} + U \frac{\partial U}{\partial R} + V \frac{\partial U}{\partial Z} \right) = -\frac{\partial P}{\partial R} + Oh\mu_{\rm m} \left[ \frac{1}{R} \frac{\partial}{\partial R} \left( R \frac{\partial U}{\partial R} \right) + \frac{\partial^2 U}{\partial Z^2} \right] + B_{\rm og} \mathbf{g} \cdot \mathbf{r} + \kappa \nabla \mathbf{\phi} \cdot \mathbf{r} + B_{\rm oe} \mathbf{F}_{\rm ES} \cdot \mathbf{r}$$
(eq. 2)

$$\rho_{\rm m} \left( \frac{\partial V}{\partial \tau} + U \frac{\partial V}{\partial R} + V \frac{\partial V}{\partial Z} \right) = -\frac{\partial P}{\partial Z} + Oh\mu_{\rm m} \left[ \frac{1}{R} \frac{\partial}{\partial R} \left( R \frac{\partial V}{\partial R} \right) + \frac{\partial^2 V}{\partial Z^2} \right] + B_{\rm og} \mathbf{g} \cdot \mathbf{z} + \kappa \nabla \mathbf{\phi} \cdot \mathbf{z} + B_{\rm oe} \mathbf{F}_{\mathbf{ES}} \cdot \mathbf{z}$$
(eq. 3)

The non-dimensional volumetric electric force can be calculated using Maxwell's Electric Tensor, defined as

$$\mathbf{F}_{\mathbf{ES}} = \begin{cases} \nabla \cdot \mathbf{I}^{e} \\ \nabla \cdot \left[ \epsilon_{m} \left( \mathbf{EE} - \frac{1}{2} \mathbf{E}^{2} \mathbf{I} \right) \right] \\ -\frac{1}{2} \mathbf{E} \cdot \mathbf{E} \nabla \epsilon_{m} + \rho_{e} \mathbf{E} + \nabla \left( \frac{1}{2} \mathbf{E} \cdot \mathbf{E} \frac{\partial \epsilon_{m}}{\partial \rho} \rho \right) \\ (eq. 4)[12] \end{cases}$$

The characteristic scale was decided as follows, and then the non-dimensionalisation was done accordingly

Velocity Scale  $(u_c) = \sqrt{\frac{\gamma}{\rho_1 D}}$ Length Scale  $(l_c) = D$  (Drop Diameter = 1.7 mm) Time Scale  $(\tau) = \frac{l_c}{u_c}$ 

As the solver chosen is a CLSVOF solver, the properties for the interface and fluids throughout the domain are defined as follows.

$$\rho_m = \phi \rho_1 + (1 - \phi) \rho_2$$

$$\mu_m = \phi \mu_1 + (1 - \phi) \mu_2$$

$$\varepsilon_m = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + (\varepsilon_1 - \varepsilon_2) H(\psi)}$$

$$\sigma_m = \frac{\sigma_1 \sigma_2}{\sigma_2 + (\sigma_1 - \sigma_2) H(\psi)}$$

where,

$$H(\psi) \begin{cases} 0 & \text{if } \psi < -\varepsilon \\ \frac{1}{2} \left[ 1 + \frac{\psi}{\varepsilon} + \frac{1}{\pi} \sin\left(\frac{\pi\psi}{\varepsilon}\right) \right], & \text{if } |\psi| \le \varepsilon \\ 1 & \text{if } \psi > \varepsilon \end{cases}$$

Parameter	Value				
Initial Velocity (ui) (m/s)	0.25 0.35			5	
Electric Field $(\Theta_e)$ (kV)	2.5	3.5	4.3	8 5	5.6
Equi. Contact Angle $(\theta_e)$ (°)	110	130		150	

#### **III. RESULTS**

First, the setup and solvers were validated using the experimental and numerical data described in [15]. Then, a general formula representing the family of curves was obtained to represent the height signal obtained from the simulations run.

#### A. Validation

As can be seen from Fig. 2, the best results were achieved at a mesh size of  $400 \times 400$ , with an approximate maximum error of 10%. All further simulations were carried out with mesh size  $400 \times 400$ 



Fig. 2. Comparison of numerical vs experimental results

#### B. Mathematical Derivations

In the beginning, the basic equation describing the motion of a damped spring mass system was taken, and from it, an analogous equation used to describe our system was derived.

That equation was further used, in conjunction with logarithmic decrement, to extract the damping parameters (natural frequency  $(\omega_n)$ , damped frequency  $(\omega_d)$  and damping coefficient  $(\zeta)$ ) of each curve.

The equation  $m\ddot{x} + c\dot{x} + kx = 0$  was converted to  $M\ddot{X} + \overline{C}\dot{X} + \overline{K}X = 0$  using analogous relationships (Cumulative interfacial force for Spring force; Viscosity for Damping) and dimensional scaling

$$\mathbf{M} = \frac{m}{\rho l_c^3}; \qquad \qquad \ddot{X} = \frac{\ddot{x} l_c}{u_c^2}$$

$$\overline{C} = \frac{\mathrm{Oh}c}{\mu l_c} \qquad \qquad \dot{X} = \frac{\dot{x}}{\mu c}$$

$$\overline{K} = \frac{[1 - Boe]k}{\gamma_c} \qquad \qquad X = \frac{x}{l_c}$$

where,  

$$p = p_0 + \gamma_c$$

$$\gamma_c = \gamma - \varepsilon_1 E_{\infty}^2 l_c$$

$$\gamma_c = \gamma - \varepsilon \varepsilon_0 E_{\infty}^2 l_c$$

$$\gamma_c = \gamma \left[ 1 - \frac{\varepsilon \varepsilon_0 E_{\infty}^2 l_c}{\gamma} \right]$$

$$\gamma_c \text{ (Cumulative Interfacial Forces)} = \gamma [1 - Boe]$$
(16)

#### C. Quantitative Comparisons

Fig. 3 shows the relevant physical characteristics being studied. The left side illustrates how the electric field (streamlines) behaves around the drop, as well as how the charge (contour) accumulates at the surface.

On the right side, the movement of the drop can be seen through the velocity streamlines as well as the pressure contour



Fig. 3. Falling droplet

The graphs of how the maximum height reached by a drop is affected if the electrical field is changed, while keeping everything else the same, also provide a lot of information regarding the drop behaviour

At a glance, the nature of these graphs is very similar to a damped curve. Some noteworthy observations are



Fig. 4. Height vs. Time a.  $u_i = 0.25$  m/s and  $\theta_e = 110^\circ$ b.  $u_i = 0.35$  m/s and  $\theta_e = 130^\circ$ 

- 1. Bo<sub>e</sub> is directly proportional to the strength of the electric field
- 2. Larger amplitudes mean more energy and less spread
- 3. Longer wavelengths mean less damping and a longer hysteresis period
- 4. Bubbles with higher Bo<sub>e</sub> have higher energy (larger amplitudes) and lower damping (longer wavelengths)

Similarly, analysing the oscillation factors of the droplets provides interesting data. It can be observed that the frequency has a general decreasing trend as the strength of the electric field increases, with the exception at  $Bo_e = 0.1$ .



a.  $u_i = 0.25 \text{ m/s}, \theta_e = 110^\circ$ 

b.  $u_i = 0.25 \text{ m/s}, \, \theta_e = 130^\circ$ 

c.  $u_i = 0.25 \text{ m/s}, \theta_e = 150^{\circ}$ 

CONTENTS

This behaviour is more pronounced for stronger electric fields and higher equilibrium angles. The overall frequency also decreases as the equilibrium angle increases, indicating a rise in damping.

#### V. CONCLUSION

The following conclusions can be drawn.

- 1. Introduction of an electric field creates a damping effect on the drop
- 2. This effect is also observed at higher equilibrium angles.
- 3. An electric field keeps the drop from bouncing due to the attraction between the drop and the bottom electrode
- 4. Introduction of a DC electric field will cause the drop to stick to the surface, but reduce the area of spread.

Further work can be carried out for studying effects of AC field and son on.

#### ACKNOWLEDGMENT

Authors Aaditya Rampal and Yash Agrawal would like to acknowledge the support and guidance of Nirma University, as well as the computational facilities provided by ParamShavak and Centre of Excellence (CoE)

#### REFERENCES

- Y. Lin, P. Skjetne, and A. Carlson, "A phase field model for multiphase electro-hydrodynamic flow," *International Journal of Multiphase Flow*, vol. 45, pp. 1–11, Oct. 2012, doi: 10.1016/j.ijmultiphaseflow.2012.04.002.
- [2] D. G. K. Aboud and A. M. Kietzig, "Splashing Threshold of Oblique Droplet Impacts on Surfaces of Various Wettability," *Langmuir*, vol. 31, no. 36, pp. 10100–10111, Sep. 2015, doi: 10.1021/acs.langmuir.5b02447.
- [3] F. Almasi, M. S. Shadloo, A. Hadjadj, M. Ozbulut, N. Tofighi, and M. Yildiz, "Numerical simulations of multi-phase electrohydrodynamics flows using a simple incompressible smoothed particle hydrodynamics method," *Computers and Mathematics with Applications*, vol. 81, pp. 772–785, Jan. 2021, doi: 10.1016/j.camwa.2019.10.029.
- [4] D. S. Hathi, P. M. Panchal, A. Sharma, R. Thaokar, and A. M. Lakdawala, "A numerical study on breakup of a liquid jet in an axial electric field," *J Aerosol Sci*, vol. 170, May 2023, doi: 10.1016/j.jaerosci.2023.106142.
- [5] J. Li, Y. Wei, Z. Huang, F. Wang, X. Yan, and Z. Wu, "Electrohydrodynamic behavior of water droplets on a horizontal super hydrophobic surface and its self-cleaning application," *Appl*

*Surf Sci*, vol. 403, pp. 133–140, May 2017, doi: 10.1016/j.apsusc.2017.01.141.

- [6] N. Miljkovic *et al.*, "Jumping-droplet-enhanced condensation on scalable superhydrophobic nanostructured surfaces," *Nano Lett*, vol. 13, no. 1, pp. 179–187, Jan. 2013, doi: 10.1021/nl303835d.
- [7] L. Tian, M. Gao, and L. Gui, "A microfluidic chip for liquid metal droplet generation and sorting," *Micromachines (Basel)*, vol. 8, no. 2, 2017, doi: 10.3390/mi8020039.
- [8] S. T. Thoroddsen, T. G. Etoh, and K. Takehara, "High-speed imaging of drops and bubbles," 2008. doi: 10.1146/annurev.fluid.40.111406.102215.
- [9] A. I. Fedyushkin and A. N. Rozhkov, "NUMERICAL SIMULATION OF A DROP COLLISION WITH AN OBSTACLE."
- C. Antonini, A. Amirfazli, and M. Marengo,
   "Drop impact and wettability: From hydrophilic to superhydrophobic surfaces," *Physics of Fluids*, vol. 24, no. 10, Oct. 2012, doi: 10.1063/1.4757122.
- J. Fukai *et al.*, "Wetting effects on the spreading of a liquid droplet colliding with a flat surface: Experiment and modeling," *Physics of Fluids*, vol. 7, no. 2, pp. 236–247, 1995, doi: 10.1063/1.868622.
- [12] G. Tomar *et al.*, "Two-phase electrohydrodynamic simulations using a volume-of-fluid approach," *J Comput Phys*, vol. 227, no. 2, pp. 1267–1285, Dec. 2007, doi: 10.1016/j.jcp.2007.09.003.
- [13] Q. Yang, B. Q. Li, and Y. Ding, "3D phase field modeling of electrohydrodynamic multiphase flows," *International Journal of Multiphase Flow*, vol. 57, pp. 1–9, Dec. 2013, doi: 10.1016/j.ijmultiphaseflow.2013.06.006.
- J. Göhl, A. Mark, S. Sasic, and F. Edelvik, "An immersed boundary based dynamic contact angle framework for handling complex surfaces of mixed wettabilities," *International Journal of Multiphase Flow*, vol. 109, pp. 164–177, Dec. 2018, doi: 10.1016/j.ijmultiphaseflow.2018.08.001.

[15] N. D. Patil, V. H. Gada, A. Sharma, and R. Bhardwaj, "On dual-grid level-set method for

- contact line modeling during impact of a droplet on hydrophobic and superhydrophobic surfaces," *International Journal of Multiphase Flow*, vol. 81, pp. 54–66, May 2016, doi: 10.1016/j.ijmultiphaseflow.2016.01.005.
- [16] X. Zhang and O. A. Basaran, "Dynamics of Drop Formation in an Electric Field," 1994. [Online]. Available: http://www.idealibrary.com

### Molecular dynamics simulation on electrical conduction of room temperature ionic liquids under strong electric field

Yufeng Cheng<sup>1,2,4</sup>, Weizong Wang<sup>1,3\*</sup>, Yuxiang Chen<sup>1</sup>, Yihua Zhang<sup>1</sup>, Alberto T. Pérez<sup>2\*</sup>, Antonio Ramos<sup>2\*</sup>

<sup>1</sup> Advanced Space Propulsion and Energy Laboratory (ASPEL), School of Astronautics, Beihang University, Beijing 100191, China

<sup>2</sup> Departamento de Electrónica y Electromagnetismo, Facultad de Física, Universidad de Sevilla, Sevilla 41012, Spain
 <sup>3</sup> Aircraft and Propulsion Laboratory, Ningbo Institute of Technology, Beihang University, Ningbo, 315100, China.
 <sup>4</sup> Shen Yuan Honors College, Beihang University, Beijing, 100191, China.

Molecular dynamics simulations of room temperature liquids Abstractionic 1-butyl-3methylimidazoliumbis(trifluoromethylsulfonyl)imide with varying electric field have been done with the reduced all-atom model. As the electric field ranges from 0 V/nm to 1.8 V/nm, the ion current shows a linear (0-0.3 V/nm) and non-linear region (0.3-1.8 V/nm). The ion self-diffusivity barely changed in the linear region whereas increased drastically in the non-linear region. In addition, it was found that the ion current and ion selfdiffusivity of the anion is smaller, which is due to the longer chain structure induced stronger interaction with the surrounding counter-ions. Finally, the conductivities calculated from current and self-diffusivity differ significantly in the non-linear region. To obtain a more reliable estimate of conductivity, it is essential to identify the 'free ions' that solely contribute to conduction, as described by the two-state model.

Keywords- Molecular dynamics, room temperature ionic liquids, electric field, self-diffusivity, conductivity.

#### I. INTRODUCTION

Room temperature ionic liquids (RTILs) are a kind of room temperature molten salt completely composed of ions [1]. With the advantages of high conductivity, nonvolatile, chemical stability, wide electrochemical windows, etc., RTILs have been applied in fuel cells [2], supercapacitors [3], electrospray thrusters [4], etc. In particular, the formation of the electrical double layer in supercapacitors and the ion emission processes in electrospray thrusters are characterized by the presence of a strong electric field. However, the precise mechanisms of how the strong electric field influences the physical properties of RTILs remain inadequately understood. Using the molecular dynamics simulation, several studies have found that the transport properties (such as the diffusivity, mobility, conductivity, etc.) of the RTILs change non-linearly with the strong electric field (107~109 V/m) [5-7]. And Nernst-Einstein equation is claimed to break down for the single ion species (cation or anion) and the entire system due to the strong ion-ion interaction [6]. To better understand these abnormal phenomena, the concept of 'cage' is utilized. The ions are confined by the surrounding counter-ions that act as a cage [8]. Then the nonlinear increase of diffusivity and mobility, and the faster diffusion along the direction of the electric field were reported to be caused by the expansion and anisotropic deformation of the ion cage under a strong electric field [6-7]. However, the reason for the increased diffusion perpendicular to the electric field is still unclear, and the ion cage model is insufficient to quantify the effect of the electric field on the diffusion.

Recently, a two-state model has been proposed in which ions can reside either in a bound state or a free state, with interstate exchanges occurring between the two. In this model, only the free ions weakly interacting with the surrounding ions contribute to the conductivity, thus the Nernst-Einstein equation remains valid. Moreover, the diffusivity and conductivity obtained from the model as a function of temperature were consistent with the experimental results [9]. Although the two-state model appears promising, its applicability under strong electric fields remains uncertain. Furthermore, the high free ion ratios (~15%) predicted by the model contradict the strong underscreening observed in RTILs [10] and the low effective free-ion concentration (~0.003%) revealed by the equilibrium force-distance measurements [11]. In this paper, molecular dynamics simulation was utilized to investigate how the electric field affects the transport properties of 1-butyl-3methylimidazoliumbis(trifluoromethylsulfonyl)imide ([BMIM][TFSI]). The ion current and the ion selfdiffusivity were obtained with varying electric fields. The conductivity was subsequently derived using two methods and compared.

#### II. METHODOLOGY

Fig. 1 shows the schematic diagram of the simulation setting. The simulation domain is a 4 nm cube with periodic boundaries in three directions, and a uniform and static electric field was applied along the Z direction with a constant temperature of 300 K. The initial position of 128 pairs of [BMIM][TFSI] was generated by the PACKMOL package [12]. The classical open-source MD code LAMMPS [13] with GPU acceleration package [14] was utilized to perform the simulation. To make the transportation properties of the ionic liquid more accurate, the reduced charge all-atom model was adopted, and the parameters were obtained from the optimized potential for liquid simulations all-atom (OPLS-AA) model

developed by Doherty B et al. [15]. The OPLS-AA model evaluates the system energy as the sum of the individual energies for each molecule (Eq. (1)), Coulomb and 12-6 Lennard-Jones (L-J) terms for the non-bonded interactions (Eq. (2)). The individual energies include the harmonic bond stretching term, angle bending term, and a cosine series for torsional energy term. In Eq. 1,  $k_b$  and  $k_\theta$  are the force constants for



Fig. 1. The cubic simulation domain with periodic boundaries in three directions and the applied electric field in the Z direction.

thebond and angle energy.  $r_0$  and  $\theta_0$  are the equilibrium bond and angle values.  $V_{1,i}$ ,  $V_{2,i}$ ,  $V_{3,i}$ ,  $V_{4,i}$ , are the four Fourier coefficients. In Eq. 2, q is the partial atomic charge,  $\varepsilon_0$  is the vacuum dielectric constant,  $\sigma$  and  $\varepsilon$ are the Lennard-Jones radii and well-depths respectively.

$$\begin{cases} E_{bonds} = \sum_{i} k_{b,i} (r_{i} - r_{o,i})^{2} \\ E_{angles} = \sum_{i} k_{\theta,i} (\theta_{i} - \theta_{o,i}) \\ E_{torsion} = \sum_{i} \left[ \frac{1}{2} V_{1,i} (1 + \cos \phi) + \frac{1}{2} V_{2,i} (1 - \cos 2\phi) \\ + \frac{1}{2} V_{3,i} (1 + \cos 3\phi) + \frac{1}{2} V_{4,i} (1 - \cos 4\phi) \right] \\ E_{nonbond} = \sum_{i} \sum_{j>i} \left\{ \frac{q_{i}q_{j}}{4\pi\varepsilon_{0}r_{ij}} + \\ 4\varepsilon_{ij} \left[ \left( \frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left( \frac{\sigma_{ij}}{r_{ij}} \right)^{6} \right] \right\}$$
(2)

The simulation domain was first heated to room temperature 300 K using the Nose-Hoover thermostat for 400 ps. The simulation domain was then equilibrated for 10 ns in the isothermal-isobaric (N-P-T) ensemble to maintain a constant pressure of 1 atmosphere and a constant temperature of 300 K. Another 10 ns in the canonical ensemble (N-V-T) was run to further relax the system. Finally, a production run with a uniform electric field applied in the N-V-T ensemble was carried out for trajectory analysis. The time-step was 2 fs for the equilibrium runs and 1 fs for the production runs. The cutoff value for L-J interactions and the Coulomb interactions was 12 Å and 20 Å respectively. The Coulomb potential of the system was calculated using the particle-particle particle-mesh solver [16].

#### **III. RESULTS & DISCUSSION**

Electric fields ranging from 0 V/nm to 1.8 V/nm were applied to the simulation domain. As the electric field was applied, the cations and anions started to drift in the opposite directions along the Z axis and generated a current in the same direction. The current obtained was averaged over all time steps. Fig. 2 shows the total current, cation current, anion current, and their fit data with varying electric fields. A linear region with an electric field smaller than 0.3 V/nm was found. With higher electric fields, the current increased non-linearly. It was also found that a 3<sup>rd</sup>-order power function perfectly fits all the current data, which has not been reported previously. The current of the cations was higher than that of the anions, which should be due to the higher diffusivity of the cation shown in Fig. 3. In addition, Fig. 2 shows that the difference between the current of the cation and the anion increases largely with the electric field.





The self-diffusivity coefficient  $D_i$  of ion type *i* (cation or anion) can be obtained through the trajectories of all ions using:

$$D_{i} = \lim_{t \to \infty} \frac{\left\langle x_{i}^{2}(t) \right\rangle - \left\langle x_{i}(t) \right\rangle^{2}}{2t}$$
(3)

where  $\langle x_i^2(t) \rangle$  is the mean-square displacement of all ion types *i* and  $\langle x_i(t) \rangle$  is the drift displacement of all ion types *i* due to the electric field [6]. In Fig. 3, the diffusivity remains nearly constant with an electric field smaller than 0.3 V/nm and increases non-linearly beyond it. The smaller diffusivity of the anion is due to the fact that the longer chain structure of the anions induces a stronger interaction with more surrounding counter-ions, and hence a higher viscosity drag [17]. However, in comparison to the current, the smaller difference between the cation and anion diffusivities suggests that additional mechanisms may contribute to the cation current.



Fig. 3. The cation diffusivity and anion diffusivity with varying electric fields.

With the current *I* and the diffusivity  $D_i$  obtained, the conductivity can be derived from Ohm's law (Eq. (4)) and the Nernst-Einstein equation (Eq. (5)):

$$\sigma_I = \frac{I}{SE}$$

$$\sigma_{N-E} = \frac{e^2}{k_B T} \sum_i n_i q_i^2 D_i$$
(4)
(5)

where S is the cross-sectional area of the current, e is the electric charge unit,  $k_B$  is the Boltzmann constant, T is the temperature,  $n_i$  is the number density of ion type *i*, and  $q_i$ is the charge of ion type *i*. The conductivities calculated using the two methods are plotted in Fig. 4. Within the linear region (E < 0.3 V/nm), the results are close to each other. However, significant deviations are observed in the non-linear region (E  $\ge$  0.3 V/nm). This discrepancy is probably due to the fact that the number density  $n_i$  used in the calculation included all ions, while, according to the two-state model, only free ions contribute to the conductivity. Also, the self-diffusivity coefficient should be calculated for the free ions and the bound ions, respectively. Nevertheless, the excellent fit observed in Fig. 2 may indicate the existence of an alternative underlying mechanism that governs the current increase with electric field in the non-linear region, beyond the conventional free/bound ion framework.



Fig. 4. Conductivity derived using Ohm's law (symbol line) and the Nernst-Einstein equation (dashed line).

#### V. CONCLUSIONS

In this paper, molecular dynamics simulation was utilized to investigate how a strong electric field

properties influences the transportation of [BMIM][TFSI]. Applying electric fields ranging from 0~1.8 V/nm revealed two distinct regions: a linear region (0~0.3 V/nm) where the current increased linearly, and a non-linear region (0.3 V/nm~1.8 V/nm) where the current increased non-linearly, closely fitting a 3rd-order power function. The ion self-diffusivity barely changed in the linear region and increased drastically in the nonlinear region. The ion current and ion self-diffusivity of the anion were both smaller because of the longer chain structure that induces stronger interaction with the surrounding counter-ions. To better understand the discrepancy in the conductivities obtained from the two methods, the two-state model should be employed to determine the free ions in RTILs under varying electric fields.

#### ACKNOWLEDGMENTS

This research is supported by, the National Natural Science Foundation of China (Grant No. 52277133), the Outstanding Research Project of Shen Yuan Honors College, BUAA (230123101) and the China Scholarship Council (CSC). A.T. Perez and A. Ramos acknowledge financial support by MCIN/AEI/10.13039/501100011033 (Grant No. PID2022-138890NB-I00).

#### REFERENCES

- Z. Lei, B. Chen, Y. M. Koo, and D. R. MacFarlane. Introduction: ionic liquids, *Chemical Reviews*, 117:6633-6635, 2017.
- [2] R. F. De Souza, J. C. Padilha, R. S. Gonçalves, and J. Dupont. Room temperature dialkylimidazolium ionic liquid-based fuel cells, *Electrochemistry Communications*, 5(8):728-731, 2003.
- [3] G. Wang, L. Zhang, and J. Zhang. A review of electrode materials for electrochemical supercapacitors, *Chemical Society Reviews*, 41:797-828, 2012.
- [4] B. D. Prince, B. A. Fritz, and Y. H. Chiu. Ionic liquids in electrospray propulsion systems. In Ionic Liquids: Science and Applications, American Chemical Society, 27-49, 2012.
- [5] N. J. English, D. A. Mooney, and S. O' Brien. Ionic liquids in external electric and electromagnetic fields: a molecular dynamics study, *Molecular Physics*, 109: 625-638, 2011.
- [6] R. Shi, and Y. Wang. Ion-cage interpretation for the structural and dynamic changes of ionic liquids under an external electric field, *The Journal of Physical Chemistry B*, 117(17):5102-5112, 2013.
- [7] R. Clark, M. von Domaros, A. J. McIntosh, A. Luzar, B. Kirchner, and T. Welton. Effect of an external electric field on the dynamics and intramolecular structures of ions in an ionic liquid, *The Journal of chemical physics*, 151(16), 2019.

- [8] M. J. Polissar. A kinetic approach to the theory of conductance of infinitely dilute solutions, based on the "Cage" model of liquids, *The Journal of Chemical Physics*, 6(12):833-844, 1938.
- [9] G. Feng, M. Chen, S. Bi, Z. A. Goodwin, E. B. Postnikov, N. Brilliantov, *et al.* Free and bound states of ions in ionic liquids, conductivity, and underscreening paradox, *Physical Review X*, 9(2):021024, 2019.
- [10]M. A. Gebbie, H. A. Dobbs, M. Valtiner, and J. N. Israelachvili. Long-range electrostatic screening in ionic liquids, *Proceedings of the National Academy* of Sciences, 112(24):7432-7437, 2015.
- [11]M. A. Gebbie, M. Valtiner, X. Banquy, E. T. Fox, W. A. Henderson, and J. N. Israelachvili. Ionic liquids behave as dilute electrolyte solutions, *Proceedings of the National Academy of Sciences*, 110(24):9674-9679, 2015.
- [12]L. Martínez, R. Andrade, E. G. Birgin, and J. M. Martínez. Packmol: A package for building initial configurations for molecular dynamics simulations, *Journal of Computational Chemistry*, 30(13):2157-2164, 2009.
- [13]S. Plimpton. Fast parallel algorithms for short-range molecular dynamics, *Journal of Computational Physics*, 117(1):1-19, 1995.
- [14]W. M. Brown, P. Wang, S. J. Plimpton, and A. N. Tharrington. Implementing molecular dynamics on hybrid high performance computers-short range forces, *Computer Physics Communications*, 182:898-911, 2011.
- [15]B. Doherty, X. Zhong, S. Gathiaka, B. Li, and O. Acevedo. Revisiting opls force field parameters for ionic liquid simulations, *Journal of Chemical Theory* and Computation, 13(12):6131-6145, 2017.
- [16]R. W. Hockney, and J. W. Eastwood. Computer simulation using particles. crc Press, 2021.
- [17]H. Tokuda, K. Hayamizu, K. Ishii, M. A. B. H. Susan, and M. Watanabe. Physicochemical properties and structures of room temperature ionic liquids. 2. Variation of alkyl chain length in imidazolium cation, *The Journal of Physical Chemistry B*, 109(13):6103-6110, 2005.

# Plasma jet impacting the surface of a liquid: electrical analysis and electrohydrodynamic flows

F. Dyson<sup>1\*</sup>, L. Alomari<sup>1</sup>, B. Teychene<sup>1</sup>, E. Moreau<sup>1</sup>

<sup>1</sup>PPRIME, Université de Poitiers, France, 2IC2MP, UMR CNRS 7285, Université de Poitiers, France \*Corresponding author: fredric.dyson@univ-poitiers.fr

*Abstract-* This experimental study aims at studying the water flow induced by a helium plasma jet that impacts the water surface. Particle image velocimetry (PIV) measurements allowed us to characterize the water flow resulting from two main physical phenomena: the shear stress induced by the helium flow along the water surface, and two types of electrohydrodynamic (EHD) forces due to the motion of electrical charges at the liquid surface and in the bulk of the liquid.

#### Keywords- Helium plasma jet, water flow, EHD forces, PIV

#### I. INTRODUCTION

Argon and helium plasma jets are widely studied for their applications in medicine, biology, and chemistry. However, because of the small contact area between the plasma and the liquid and the very slow diffusion of reactive species throughout the liquid, only a limited amount of these species can deeply penetrate the liquid and reach deeper layers. However, a few previous studies have highlighted that the plasma jet results in a flow inside the liquid due to several forces, and that this flow can help chemical species to penetrate the liquid more effectively, as convection is much faster than diffusion.

In the present ISEHD 2025, our research team presents three articles on the flow induced by cold plasmas in contact with a liquid [1, 2]. A detailed introduction and bibliography are presented in [1], so there is no point in repeating it here.

In the present article, we present the results obtained with a helium plasma jet in contact with water, as illustrated by Figure 1. First, we will briefly characterize the electrical properties of the plasma jet. Secondly, we will analyse the flow induced by the plasma jet inside the liquid, with the help of particle image velocimetry (PIV).



Figure 1. Pictures and schematic of the helium plasma jet in contact with a water surface.

#### II. METHODOLOGY

The plasma jet used in our experiments is based on a dielectric barrier discharge plasma jet, as illustrated in Figure 2. The dielectric barrier consists of a glass tube with

inner and outer diameters of 4 mm and 6 mm, respectively. A tungsten welding rod of 1 mm in diameter is used for the high-voltage electrode. It is inserted into the glass tube, leaving a 1 mm gap between the rod and the copper tape wrapped around the outside of the dielectric. The end of the rod has been machined to have a pointed tip, with a radius of curvature of the order of 100  $\mu$ m. The copper tape is 10 mm wide and serves as the ground electrode. The distance between the exit of the plasma jet and the water surface is maintained at 10 mm. Helium 5.0 gas (purity  $\geq$  99.999 %) is supplied from a bottle and the flow rate is measured using a ball float flow meter (FL-2514-V). The flow rate ranges from 3.4 l.min<sup>-1</sup> (gas velocity equal to 7.1 m.s<sup>-1</sup> at the exit of glass tube) to 7.6 l.min<sup>-1</sup> (15.9 m.s<sup>-1</sup>).

A high-voltage sinusoidal wave is applied to the welding rod. This waveform is produced by a function generator connected to a high-voltage amplifier (TREK,  $\pm 30 \text{ kV}$ , 40 mA). The frequencies of the sine wave range from 2 kHz to 12 kHz. The voltage is measured using the voltage monitor on the amplifier. Initially, the signal from this monitor was compared to measurements taken with a high-voltage probe (Tektronix P6015A), and both signals were similar (not shown here for conciseness). A shunt resistor between the grounded copper tape and earth is used to measure the discharge current. The voltage and current are recorded with an oscilloscope (HDO 6054, 12bit, 500MHz, 2.5GS/s) and a numerical low pass filter (-3 dB at 800 kHz) is applied.

Particle image velocimetry (PIV) measurements have been conducted to characterize the liquid flow induced by the plasma jet. For that, the PIV system uses a laserilluminated vertical plane (Terra PIV dual oscillator, 527 nm, Nd:YLF) within the liquid phase. Image pairs are taken with a high-speed camera (Phantom VEO 4K 990L, 4096 x 2304 pixels, Nikon AF Micro-Nikkor 200 mm, f/4D IF - ED). Each pair is taken with a frequency of 101 Hz, with a shorter time interval between each image in a pair. The field of view initially covered all the liquid phase, but the bottom half was excluded for conciseness (see the FOV in Figure 1). The liquid in an optical glass cuvette (30x30x30 mm<sup>3</sup>) is seeded with polyamide tracer particles. These particles have a median diameter of 5 µm and are doped with sulforhodamine B. Davis software (version 10.2.1.90495) is used for all of the PIV calculations. The final interrogation window is set to a 32x32 pixel zone with a 50 % overlap. The mean velocity fields arere computed with 1000 images pairs. In all the experiments, we used deionized water with an electrical conductivity around 2  $\mu$ S/cm. We can then consider that the liquid behaves like an insulating one.



Figure 2. Experimental setup.

#### III. RESULTS

#### A. Electrical results

During our electrical studies, we looked at the influence of the voltage amplitude, its frequency and the helium flow rate, without the presence of water in front of the plasma jet. Figure shows an example of the discharge current for three different frequencies of the applied sinusoidal voltage (2, 7 and 12 kHz). The voltage amplitude is adjusted at 3.2 kV but as the frequency is increased, the measured voltage decreases, due to the slew rate of the TREK amplifier that is limited to 500 V/ $\mu$ s. Consequently, the voltage delivered by the TREK amplifier and applied between the tungsten welding rod and the grounded electrode equals 3 kV at 7 kHz and 2.4 kV at 12 kHz. The current is a half-phase ahead of the voltage wave, characteristic of capacitively coupled

plasma devices, such as dielectric barrier discharges. At 2 kHz, during the rising edge of the voltage, four current pulses with amplitudes between 1.0 mA and 1.6 mA occur. As the voltage frequency increases, the number of current pulses decreases while their amplitude increases. At 12 kHz, only two pulses are present with amplitudes between 2.2 mA and 5 mA. The transition from four current peaks to three happens between 4 kHz and 5 kHz and from three to two peaks between 7 kHz and 8 kHz. In [2], the authors assumed that these current spikes were due to an ionizing wave ("plasma bullet") exiting the reactor. On the one hand, that means that the plasma jet would be due to a phenomenon that looks like a streamer. On the other hand, the characteristics of the current pulses observed in Figure 3 are very different from those of a breakdown streamer observed in the case of DC positive corona discharges, as their width is of several microseconds. Finally, note the electrical power consumption is low; it increases linearly from 0.1 W at 2 kHz up to 0.35 W et 12 kHz.

#### B. Instantaneous PIV results

Figure 4 shows four instantaneous velocity fields from when the high voltage is applied (T0) until about 3 seconds after ignition (T0 + 3010 ms). The voltage amplitude equals 3 kV, the frequency is 7 kHz, the helium flow rate is 3.4 l.min<sup>-1</sup>, and the gap between the end of the tube and the liquid is 10 mm. The velocity magnitude is represented by the background color (between 0 and 6 cm.s<sup>-1</sup>), and the arrows show the direction of the flow. The water depth is shown along the vertical axis, where y = 0 mm represents the bottom of the container. However, only the top half from 10 mm upwards is shown. Along the horizontal axis is the width of the container, where x = 0 mm represents its center as well as the point of impact of the plasma jet.

We can see that at T0 the helium gas impacting the water surface is enough to induce a small flow of up to 2.5 cm.s<sup>-1</sup>. Indeed, the gas velocity at the exit of the glass tube equals 7.1 m.s<sup>-1</sup>. This inducs a water flows tangentially to the surface from the point of impact of the jet outwards towards the edges of the container. This displacement causes a suction effect and then a weak upward flow with a velocity of around 1 cm.s<sup>-1</sup>. Between T0 and T0+9.9 ms, the plasma jet is on; we can see that there is a localized increase of the velocity close to the



Figure 3. DBD current waveforms for a sinusoidal wave of amplitude 3.2 kV at 2, 7 and 12 kHz. (In ambient air with no obstacles)

surface at x = 0 mm, reaching 1.5 cm.s<sup>-1</sup>. Meanwhile, the velocity of the flow tangential to the surface has not increased significantly. At T0+188 ms, the velocity tangential to the surface has increased to 4 cm.s<sup>-1</sup>, and two counter-rotating vortices have begun to form with a radius of about 1 mm. Finally, at T0+3010 ms, the flow has fully developed and is confined by the walls of the container. The flow tangential to the surface reaches 5 cm.s<sup>-1</sup>, the upwards flow underneath the point of impact of the jet reaches 2.5 cm.s<sup>-1</sup> and the vortices have a radius of about 3 mm.



Figure 4. Instantaneous velocity fields of the flow generated in the liquid by the plasma jet for 3 kV, 7 kHz and 3.4 l.min<sup>-1</sup>.

#### C. Effect of frequency on the induced flow

To investigate the effect of the discharge frequency on the induced liquid flow, the voltage between both electrodes equals 3 kV, the flow rate of helium is  $3.4 \text{ l.min}^{-1}$  and the gap is still 10 mm. The frequency varies from 4 kHz to 10 kHz. An optimal frequency with the strongest induced flow was found at 7 kHz. The resulting velocity field averaged over a 10-second period is shown in Figure 5. As with the instantaneous velocity fields of Figure 4, we can see two counter-rotating vortices on both sides of the location where the plasma jet impacts the water surface.

To highlight the influence of the voltage frequency, Figure 6 shows the velocity magnitude plotted along a vertical line in the center (x = 0 mm) of the container, as illustrated by the red dot line in Figure 5. In the absence of discharge (there is only the helium jet without discharge, black curve), the maximum velocity reaches about 0.9 cm/s<sup>-1</sup>. When the high voltage is applied, the presence of the plasma jet results in a strong increase in the water velocity. At 6 kHz, the maximum velocity reaches 1.8 cm.s<sup>-1</sup>. Increasing the frequency to 7 kHz, the flow reaches a maximum velocity of 2.5 cm.s<sup>-1</sup> before dropping to 2.1 cm.s<sup>-1</sup> for 8 kHz. This behavior will be discussed later in this article.



Velocity |V| [m/s]: 0.00 0.01 0.02 0.03 0.04 0.05 0.06

Figure 5. Averaged velocity field of the flow for 3.2 kV, 7 kHz, 3.4 l.min<sup>-1</sup> and a gap of 10 mm.



Figure 6. Velocity profile along a vertical line in the center of the velocity field (x = 0 mm), for 3 kV, 7 kHz, 3.4 l.min<sup>-1</sup>, and a gap of 10 mm.

#### C. Effect of the gas flow rate

Finally, we looked at the effect of the helium flow rate on the induced liquid flow. Figure 7 shows the velocity fields averaged over 10 seconds for three flow rate values,  $3.4 \text{ l.min}^{-1}$ ,  $5.4 \text{ l.min}^{-1}$  and  $7.6 \text{ l.min}^{-1}$ . The discharge voltage is 3 kV, and the frequency is 7 kHz. We can see that when the flow rate of helium is increased, the flow induced inside the liquid is also increased. This is to be expected as the shear force due to the helium gas on the water surface increases with the velocity of the helium flowing along the water surface.

Finally, Figure 8 presents the velocity magnitude of the liquid flow along a vertical line in the center of the field (x = 0 mm), as in Figure 6. In this Figure, the dotted curves represent the water velocity when there is only the helium flow (without plasma jet), and the solid curves show the velocity when the plasma jet is present. We can

see that the effect of the plasma jet is decreased as the gas flow rate increases. Indeed, at  $3.4 \text{ l.min}^{-1}$ , the maximum velocity (measured at y  $\approx 20 \text{ mm}$ ) increases from about 0.9 cm.s<sup>-1</sup> up to 2.2 cm.s<sup>-1</sup> (red curves). At 7.4 l.min<sup>-1</sup> (blue curves), the plasma has a weak effect at the water surface, but it has a greater effect deeper in the water, resulting in a velocity increase from 0.6 cm.s<sup>-1</sup> to 0.8 cm.s<sup>-1</sup> at 10 mm from the bottom of the cuvette.



Figure 7. Averaged velocity field of the flow for different helium flow rates (3 kV, 7 kHz, gap of 10 mm).

#### V. DISCUSSION AND CONCLUSION

A PIV system has been used to study the flow induced by the plasma jet in a liquid. The velocity fields reveal a flow characterized by a suction in front of the plasma jet, resulting in an upward flow and two counter-rotating vortices.

As indicated in the introduction of this article, the liquid flow induced by electrical discharges can result from different physical phenomena, such as the shear stress caused by the helium flow along the water surface, electrohydrodynamic (EHD) forces due to the motion of electrical charges, thermal convection, and surface tension gradients (Marangoni effect). In our case, we can assume that the liquid flow is only due to the two first phenomena.

In the absence of electrical discharge, Figure 4 at T0 has showed that the helium flow alone could result in a flow inside the liquid, due to shear stress at the gas-liquid interface. This has been confirmed by Figure 8, which highlights that the velocity of the liquid flow increases with the helium flow rate, *i.e.* the helium velocity at the gas-liquid interface.

In the presence of the plasma jet, two types of EHD force can be at the origin of the improvement of the liquid flow, these two forces being due to the deposition of electrical charges at the surface of the liquid, where the plasma jet impacts the liquid. First, the horizontal flow observed at the interface (in the x direction) may result from the repulsion of charge carriers at the surface. Indeed, if the charges accumulate in front of the plasma jet, they repel each other and therefore move from the point of impact of the plasma jet (x = 0) toward the edges of the cuvette. This leads to two opposite forces, from x = 0toward the cuvette edges. Secondly, the upward flow is certainly due to the migration of opposite charges from the bulk of the liquid toward the location where the plasma jet impacts the water. For instance, when positive charges are deposited by the plasma jet, negative charges are created inside the liquid. Then, they drift toward the surface due to the electric field, resulting in an upward flow.

Finally, the reason for the optimal frequency of 7 kHz (see Figure 6) is unclear. However, it could be because from a threshold frequency (between 7 and 8 kHz in our case), the positive and negative charges deposited at the water surface by the plasma jet begin to neutralize from one voltage half-period to the next.



Figure 8. Velocity profile along a vertical line at x = 0 for 3 kV, 7 kHz, with and without the presence of plasma.

#### ACKNOWLEDGMENT

This project has received financial support from the CNRS through the MITI interdisciplinary programs through its exploratory research program. This work was supported by ANR-11-LABX-0017-01 and ANR-18-EUR-0010.

#### REFERENCES

[1] Alomari L. Time evolution of the EHD water flow produced by an AC dielectric barrier discharge ignited above its surface, *Proc. ISEHD 2025 (this conference)*.

[2] Moreau E. Electrohydrodynamic flow produced by a DC discharge ignited above its surface, *Proc. ISEHD* 2025.

[3] Ryan CT. Electrical properties determine the liquid flow direction in plasma–liquid interactions, *Scientific Report*, 14, 2024.
# Time evolution of the electrohydrodynamic water flow produced by an AC dielectric barrier discharge ignited above its surface

L. Alomari<sup>1,2\*</sup>, Thomas Orriere<sup>1</sup>, Romain Bellanger<sup>1</sup>, Benoit Teychene<sup>2</sup> and Eric Moreau<sup>1</sup>

<sup>1</sup>Institut PPRIME (UPR CNRS 3346), Université de Poitiers, ISAE-ENSMA, 11 Bd Marie & Pierre Curie, Futuroscope 86962, France

<sup>2</sup> Institut de Chimie des Milieux et des Matériaux de Poitiers (UMR CNRS 7285), Ecole Nationale Supérieure d'Ingénieurs de Poitiers (ENSIP), Université de Poitiers, 1 rue Marcel Doré, Poitiers Cedex 86022, France \*Corresponding author: lara.alomari@univ-poitiers.fr

*Abstract-* This study investigates the flow induced in water by an AC dielectric barrier discharge (DBD) ignited above its surface. Using Particle Image Velocimetry (PIV), the velocity fields reveal a symmetric pattern featuring a central suction and two counter-rotating vortices. The influence of the discharge frequency and the liquid conductivity on the flow dynamics is analyzed. An optimal frequency near 0.5 kHz is identified, balancing injected power and conductivity evolution. Results indicate that electrohydrodynamic (EHD) forces are primarily responsible for flow generation, with interfacial charge repulsion and bulk charge migration playing key roles.

Keywords- Electrohydrodynamic forces, plasma–liquid interaction, dielectric barrier discharge, flow visualization, Particle Image Velocimetry.

## I. INTRODUCTION

Plasma treatment is essentially a surface process that occurs at the plasma–liquid interface. Due to the limited contact area between the plasma and the liquid, as well as the very slow diffusive transport of reactive species within the liquid volume, the amount of reactive species effectively transferred to a substrate in solution remains limited. This phenomenon becomes particularly restrictive as the volume of the liquid to be treated increases [1]. Various strategies have been explored to optimize the transfer of reactive species. Among them, the use of falling film plasma reactors or the application of multiple electrical discharges in contact with thin layers of water help increase the contact surface-to-volume ratio [2–4]. However, these approaches are naturally limited in terms of flow rate and the volume of liquid that can be treated.

Recently, several reports have highlighted the importance of plasma-induced liquid flow in the transport of reactive species towards target molecules dissolved in the water. Two main flows have been observed in the liquid: (1) a flow moving away from the plasma impact point [5], and the formation of vortices with velocities reaching up to several centimeters per second, depending on the type of the discharge [6].

To date, the mechanism behind the flow generation and its driving force are not clearly understood. Four main mechanisms are commonly identified as potential contributors to the flow: (1) electrohydrodynamic (EHD) forces, (2) shear stress induced by the gas flow, (3) thermal convection, and (4) surface tension gradients (Marangoni effect).

In the study conducted by Dickenson *et al.* [7], a twodimensional numerical model, validated experimentally, was developed to identify the dominant mechanism in the case of two liquids with different conductivities: deionized water with a conductivity of 2  $\mu$ S/cm and tap water with a conductivity of 300  $\mu$ S/cm. Their results show that electric stresses at the interface are the dominant mechanism for the flow of a dielectric liquid, while flow induced by EHD forces in the gas phase dominates in the case of a conductive liquid.

Stancampiano et al. [6] studied a pulsed-voltage helium-based plasma jet and found that no well-defined flow appeared with the helium jet alone, regardless of the gas flow rate tested. In contrast, an upward vortex flow developed when the plasma was activated. The flow showed no polarity dependence. The hypothesis that this flow was driven by a temperature gradient was excluded following thermal mapping of the liquid surface using an infrared camera. The hypotheses proposed by the authors to explain this phenomenon include the modification of the gas flow through the introduction of tangential velocity components caused by the plasma (swirl), as well as EHD effects. In contrast to Stancampiano's assumptions, Yang et al. [8] suggest that the upward flow results from local evaporation of the liquid, while the vortices are formed due to viscous stress.

Marangoni stresses are another possible origin of the observed flow. These stresses are induced by surface tension gradients, leading to flow from regions of low surface tension toward those of high surface tension. When a surfactant is added, a Marangoni flow occurs due to the modification or removal of the surfactant by plasmainduced chemical reactions. This phenomenon has been extensively studied by Kawasaki's research group. In one of their studies [9], PIV measurements were performed on a surfactant solution (lauryl betaine). The frequency was gradually increased from 1 to 12 kHz, with a settling time of 20 s for each frequency value. At low frequencies, the flow is directed downward along the discharge axis, with no vortex structure. However, around 5 kHz, the flow direction reverses upward, accompanied by the formation of two counter-rotating vortices.

Despite these recent insights, the respective contributions of the different mechanisms remain very difficult to determine. Understanding how these forces govern the topology and intensity of the flow is essential to improve the transport efficiency of reactive species. EHD forces are increasingly recognized as key contributors to the generation of plasma-induced liquid flow, especially in weakly conductive solutions. In this context, the present study aims to investigate in detail the plasma-induced flow dynamics in water under an AC glow-like Dielectric Barrier Discharge (DBD). Using the Particle Image Velocimetry (PIV) technique, we characterize the spatio-temporal evolution of the flow under various discharge frequencies and liquid conductivities. Particular attention is given to identifying the dominant flow structures and trying to link them to EHD effects.

## II. METHODOLOGY

In our experimental setup (Fig. 1), the plasma discharge is ignited at the tip of a tungsten needle with a curvature radius of 100 µm. The needle is placed above an optical glass tank, filled with 20 mL of the liquid to be treated. The distance between the tip and the liquid surface (the electrode gap) is kept constant at 2 mm. The tank is placed symmetrically on a piece of copper tape  $(90 \times 50 \text{ mm}^2)$ , which serves as the grounded electrode. The needle is connected to a high voltage amplifier (Trek, 20 kV, 20 mA), which amplifies a low sinusoidal voltage produced by a function generator. The voltage between the needle and ground (discharge voltage) is measured with a high voltage probe (Tektronix P6015A, 20 kV, 75 MHz). Note that this voltage is the sum of the voltages across the electrode gap, the liquid phase and the dielectric (the reactor bottom). The current is obtained by measuring the voltage across a shunt resistor. All signals are recorded with a digital oscilloscope (HDO6054, 500 MHz, 5 GS/s).

PIV measurements were conducted during the discharge process to obtain the velocity vector fields in the liquid. Several parameters were varied, mainly the discharge frequency (from 0.05 to 4 kHz) and the initial liquid conductivity (from 2 to 800 µS/cm). For this purpose, 5-µm polyamide particles doped with rhodamine B were used as tracers. A 32-mJ pulsed Nd:YAG laser, operating at 532 nm with a pulse duration of 7 ns, was employed to create two successive laser sheets with an adjustable time delay. Concurrently, a high-resolution camera (Imager pro X 4M, 2048 × 2048 pixels) was utilized to record a single laser pulse in each frame. For each test case, the image pairs of the plasma-induced liquid flow were captured over a duration of 5 min at a frequency of 7 Hz, resulting in 2100 images per test. The 2D velocity vector field for each pair of camera frames was then computed through a cross-correlation procedure.



Fig.1. Experimental setup.

## III. RESULTS AND DISCUSSION

A. Mean velocity field



Fig. 2. Flow topology induced by the plasma in pure water, with a discharge frequency of 2 kHz, an applied voltage amplitude of 8 kV and an electrode gap of 2 mm.

Fig. 2 shows a typical time-averaged velocity field obtained after 5 minutes of treatment in the case of pure water (initial conductivity =  $2 \mu S/cm$ ), with a discharge frequency of 2 kHz and an applied voltage amplitude of 8 kV. The origin of the coordinate system is located at the intersection between the liquid surface and the vertical axis of the needle. The background color represents the mean velocity magnitude, while the arrows indicate its average direction. The flow field is symmetrical with respect to the discharge axis and can be divided into two main parts: on one hand, an upward suction along the discharge axis, and on the other, the formation of two symmetrical counter-rotating vortices on either side of this axis. The upward flow associated with the suction accelerates as it approaches the interface, reaching a maximum velocity of approximately 50 mm/s. The two vortices have a toroidal 3D structure, characterized by a circular cross-section where the velocity increases radially from the vortex center. The vortex centers are located at Y = -4 mm and  $X = \pm 11 \text{ mm}$ , giving the vortices an outer radius of approximately 4 mm.

## B. Effect of discharge frequency



Fig. 3. Time-averaged velocity profiles in pure water along the discharge axis (X = 0 mm), under a discharge voltage amplitude of 8 kV, an electrode gap of 2 mm, and a discharge frequency ranging from 0.05 to 4 kHz.

To examine the effect of frequency, Fig. 3 shows the vertical velocity profiles  $V_y$  along the vertical discharge axis (X = 0 mm), extracted from time-averaged velocity fields in pure water. The discharge frequency was varied between 0.05 and 4 kHz, while the voltage amplitude was kept at 8 kV for all cases. When the electrical frequency changes, we observe that the maximum velocity at the interface does not vary significantly. However, between -5 and -20 mm in depth, the differences become more pronounced and noticeable. There is a significant increase in flow velocity between 0.05 and 0.5 kHz, followed by a decrease beyond 0.5 kHz.

To better understand the effect of frequency and clarify why an optimal frequency appears to be around 0.5 kHz, we now examine the time evolution of the velocity at a specific point located at X = 0 and Y = -1 mm, as shown in Fig. 4. It should be noted that instantaneous velocities at the measurement point were considered only after 70 s of plasma treatment to avoid erroneous vectors caused by strong interface disturbances and the formation of a cavity deeper than 1 mm beneath the plasma during the initial phase. We observe that at 0.05 and 0.25 kHz, the velocity remains relatively stable at approximately 20 and 40 mm/s, respectively. In contrast, at higher frequencies, the velocity initially ranges between 40 and 50 mm/s at the onset of the discharge but gradually decreases over time, reaching values between 20 and 30 mm/s by the end of treatment. According to the results on temporal evolution, an earlier and more pronounced deceleration phase at higher frequencies appears to be the main reason behind the optimal frequency observed at 0.5 kHz.

These findings suggest that changes in liquid properties over time significantly affect both the achieved flow velocities and the overall flow characteristics. In fact, as the frequency increases, the electrical power, the heat power dissipated and the liquid conductivity increase



Fig. 4. Temporal evolution of the velocity in pure water at the point (0, -1 mm), under a discharge voltage amplitude of 8 kV, an electrode gap of 2 mm, and a discharge frequency ranging from 0.05 to 4 kHz.

(Table 1). If the liquid flow is driven by the thermal convection, we would expect the flow velocity to increase with frequency, which is not the case.

Let us now look to the liquid conductivity (Table 1). For frequencies where the velocity remains relatively stable over time (0.05 and 0.25 kHz), the final conductivity stays below 10  $\mu$ S/cm, indicating that the liquid properties remain close to those of pure water. In contrast, for frequencies between 0.5 and 4 kHz, where strong velocity variations are observed over time, the conductivity increases significantly, reaching up to 160  $\mu$ S/cm at 4 kHz.

 Table 1: Evolution of electrical power, heat power dissipated and final liquid conductivity with discharge frequency.

Frequency (kHz)	P <sub>elec</sub> (W)	P <sub>heat</sub> (W)	σ <sub>initial</sub> (μS/cm)	σ <sub>final</sub> (µS/cm)
0.05	0.4	0.0	2	5.2
0.25	0.5	0.1	2	7.4
0.5	0.7	0.2	2	15.6
1	1.7	0.6	2	54.6
2	2.8	0.9	2	86
4	4.6	1.4	2	161

## C. Effect of initial liquid conductivity

To go a step further, liquids with different initial conductivities were subjected to 5 minutes of plasma treatment under identical discharge conditions (2 kHz frequency, 2 mm gap, and 8 kV voltage amplitude). The variation in initial conductivity was achieved by adding potassium chloride (KCl) at different concentrations. Fig. 5 shows the mean profile of V<sub>y</sub> (vertical component of the velocity) along the discharge axis (X = 0 mm), highlighting a reduction in the maximum velocity from 43 mm/s to 24 mm/s (approximately half) as the initial conductivity increases from 14 to 787  $\mu$ S/cm. At 14  $\mu$ S/cm, the upward flow along the discharge axis extends to the bottom of the cuvette, whereas at 52  $\mu$ S/cm,



Fig. 5. Time-averaged velocity profiles in KCl solutions along the discharge axis (X = 0 mm), under a discharge voltage amplitude of 8 kV, a discharge frequency of 2 kHz, and an electrode gap of 2 mm.

 $V_y$  drops to zero by Y = -17 mm. For initial conductivities of 199 and 787  $\mu$ S/cm,  $V_y$  nearly vanishes by Y = -10 mm.

These results highlight the key role of EHD phenomena in the establishment of the flow. With a nonconductive solution, charges tend to accumulate at the interface, which strengthens the electric field and enhances the volumetric EHD force, leading to stronger suction of the liquid along the vertical discharge axis. In addition, charge repulsion at the interface drives the horizontal interfacial flow and also causes disturbances, which are more prominent in low-conductivity solutions.

## IV. CONCLUSION

The flow induced by a sinusoidal AC DBD in a liquid was investigated using the PIV technique. The velocity fields reveal a flow characterized by a central suction and the formation of two symmetric, counter-rotating vortices. These structures are strongly influenced by various parameters related to the plasma and the liquid. This paper focuses primarily on the effect of two key parameters: the discharge frequency and the liquid conductivity. In all cases, the discharge operates in the glow regime, with an applied voltage of 8 kV and a 2 mm gap between the electrode tip and the liquid surface.

The analysis of flow velocities in pure water at different discharge frequencies reveals the existence of an optimal frequency around 0.5 kHz. This value represents a compromise between the electrical power injected into the liquid and the dissipation of electric charges due to the progressive increase in liquid conductivity versus time. This phenomenon becomes more significant as the frequency increases, as illustrated by the measurements of instantaneous velocities of the flow. Indeed, for frequencies equal to or below 0.5 kHz, the relative variation in conductivity over time remains limited, resulting in relatively stable flow velocities. In contrast, when the frequency becomes too high and conductivity evolves significantly over time, the flow velocities decrease markedly.

These observations support the hypothesis that EHD forces play a significant role in the establishment of the

flow. Specifically, the horizontal flow observed at the interface may result from the repulsion of charge carriers at the surface, while the central suction is likely driven by the migration of opposite charge carriers from the bulk of the liquid toward the plasma-liquid interaction zone.

## ACKNOWLEDGMENT

This work was supported by the French government program "Investissements d'Avenir" (EUR IntREE: reference ANR-18-EURE-0010; LABEX INTERACTIFS: reference ANR-11- LABX-0017).

- [1] Walker RZ, Foster JE. Understanding the influence of fluid flow regime on plasma morphology and dose delivery at the plasma–liquid interface. *Journal of Applied Physics* 133:093301, 2023.
- [2] Ajo P, Preis S, Vornamo T, Mänttäri M, Kallioinen M, Louhi-Kultanen M. Hospital wastewater treatment with pilot-scale pulsed corona discharge for removal of pharmaceutical residues. *Journal of Environmental Chemical Engineering*, 6:1569–77, 2018.
- [3] Foster JE, Mujovic S, Groele J, Blankson IM. Towards high throughput plasma based water purifiers: design considerations and the pathway towards practical application. *J Phys D*: Appl Phys, 51:293001, 2018.
- [4] Malik MA, Ghaffar A, Malik SA. Water purification by electrical discharges. *Plasma Sources Sci Technol* 10:82–91, 2001.
- [5] Kawasaki T, Kusumegi S, Kudo A, Sakanoshita T, Tsurumaru T, Sato A. Effects of Gas Flow Rate on Supply of Reactive Oxygen Species Into a Target Through Liquid Layer in Cold Plasma Jet. *IEEE Trans Plasma Sci* 44:3223–9, 2016.
- [6] Stancampiano A, Bocanegra PE, Dozias S, Pouvesle J-M, Robert E. Evidence, origin and impact of liquid flows in plasma medicine in vitro treatments with APPJs. *Plasma Sources Sci Technol* 30:015002, 2021.
- [7] Dickenson A, Walsh JL, Hasan MI. Electromechanical coupling mechanisms at a plasma–liquid interface. Journal of Applied Physics 129:213301, 2021.
- [8] Yang Z, Kovach Y, Foster J. Visualization and analysis of coupling between plasmas selforganization and plasma-induced fluid circulation in 1 atm DC glows with liquid anode. *Journal of Applied Physics* 129:163303, 2021.
- [9] Kawasaki T, Shen K, Shi H, Koga K, Shiratani M. Instant switching control between two types of plasma-driven liquid flows. *Jpn J Appl Phys* 62:060904, 2023.

## Effect of Voltage Slope on Electrohydrodynamic Force Generation in Pulsed Corona Discharges

M. Shimizu<sup>1\*</sup>, E. Moreau<sup>2</sup>, H. Nishida<sup>1</sup>

<sup>1</sup>Department of Mechanical System Engineering, Tokyo University of Agriculture and Technology, Japan <sup>2</sup>Department of Electrical Engineering, University of Poitiers, France

\*Corresponding author: hnishida@cc.tuat.ac.jp

*Abstract-* We investigated the electrohydrodynamic (EHD) force generation characteristics of corona discharges occurring between a plate electrode and a needle electrode with a dielectric barrier. Plasma and fluid simulations were performed to investigate the plasma distribution, EHD force, and flow field formed in pulsed streamer corona discharges that occur when a steep voltage is applied. We also compared the experiment and simulation. Focusing on a typical case in which a streamer discharge occurs, we clarified that when the streamer reaches the dielectric, a strong EHD force is generated at the head of the streamer due to the high charge density and steep potential gradient formed near the dielectric surface. This phenomenon is attributed to the formation of a sheath between the plasma and the solid wall.

Keywords- EHD force, corona discharge, streamer discharge.

## I. INTRODUCTION

Corona discharge is the phenomenon that occurs between electrodes with significantly different radii of curvature. Electrohydrodynamic (EHD) force, generated in corona discharges under atmospheric pressure, has long attracted attention and has been actively studied. The principle of EHD force generation is illustrated in Fig. 1. Plasma particles generated by the discharge are accelerated by the electric field and transfer momentum through collisions with neutral particles in the surrounding air, resulting in a flow called ionic wind. The EHD force corresponds to the sum of all the Coulomb forces acting on the ions.

The phenomenon in which this force induces a fluid jet is referred to as the EHD effect. To realize engineering applications utilizing this effect, improving the thrustto-power ratio remains a major challenge [1]. In corona discharges, the flow is typically induced from the electrode with a smaller radius of curvature toward the one with a larger radius, as depicted in Fig. 1.

Reference[2] demonstrated that in a repetitive breakdown and streamer discharge mode, the ionic wind is pulsed at the same frequency that the breakdown streamer one, highlighting the key role of streamers in the EHD force. This type of discharge occurs when a high positive voltage is applied between the electrodes and differs significantly from glow discharges or Trichel pulses, which occur under lower voltage or negative polarity conditions, respectively. The jets induced by streamer discharges are



Figure 1: EHD Force Generation of Corona Discharge

markedly stronger compared to those caused by glow discharges or Trichel pulses [2].

While streamers in corona discharge contribute to EHD force generation, streamers in surface dielectric barrier discharges have been reported to have minimal contribution in [2]. Thus, the characteristics of EHD force generation associated with streamer discharges remain not fully understood.

If the mechanism by which streamers induce a pulsed ionic wind can be clarified, it may offer valuable insights toward enhancing the performance of corona-discharge-based EHD actuators.

In this study, we aim to enhance the generation of EHD force in corona discharges by numerically investigating the effect of applied voltage gradient on the characteristics of EHD force generated by a single streamer in pulsed corona discharges. We performed plasma and fluid simulations, and the results are compared with experiment in terms of current. Furthermore, the temporal evolution and spatial distribution of the EHD force are analyzed in detail.

#### II. METHODOLOGY

We performed plasma simulation and fluid simulation and the discharge characteristics, the EHD force generated by the plasma, and the flow field created by it were investigated. Also, the validity of the simulation was verified by comparing with the experimental results.

### A. Plasma Simulation

The plasma was treated as an electromagnetic fluid, and two-dimensional axisymmetric simulations were conducted. The governing equations were the drift-diffusion equations for electrons and ions and Poisson's equation for the electric potential. These equations were solved using the finite volume method. Numerical fluxes were evaluated using the Scharfetter–Gummel scheme, and time inte-



Figure 2: Simulation setting

gration was carried out with the second-order Runge-Kutta method.

The computational domain for the plasma simulation is illustrated in Fig. 2. The electrode configuration consists of a needle electrode and a flat plate electrode with a dielectric layer mounted on its upper surface. Note that since we performed axisymmetric simulation, the calculation space is cylindrical. The mesh was designed with a minimum grid spacing of  $\Delta x = 3 \ \mu m$  in the x-direction and  $\Delta z = 5 \ \mu m$  in the z-direction.

Two types of grids were prepared. The first grid was designed to reduce computational cost, with 200 grid points in the x-direction and 520 in the z-direction. In this case, uniform spacing is applied in the x-axis direction from the cylinder axis at x=0mm to x=0.3mm, while grid stretching is used in other areas. The second grid maintained the same resolution in the x-direction (200 points) but increased the number of grid points in the z-direction to 980, applying uniform spacing between the electrodes.

A pulsed voltage was applied to the high-voltage needle electrode according to (1).

$$V = V_p \tanh(0.0305 t) \tag{1}$$

 $V_p$  [V] represents the peak voltage and t [ns] represents time. In the simulation, the rise time  $t_r = 60$  ns, and calculations were carried out for conditions with  $V_p =$ 2-9 kV. The initial conditions assumed air at 1 atm and 300 K, with uniform charge densities of  $n_p = 10^7 \text{ m}^{-3}$ for positive ions,  $n_n = 10^7 \text{ m}^{-3}$  for negative ions, and  $n_e = 10^7 \text{ m}^{-3}$  for electrons. The EHD force is generated as a result of Coulomb forces accelerating ions in the plasma. The accelerated ions then transfer their momentum to neutral particles in the surrounding air through collisions.

## B. Fluid Simulation

To investigate the flow field induced by corona discharge, two-dimensional axisymmetric simulations were conducted using the SMAC (Simplified Marker and Cell)

method. The governing equations were the continuity equation and the two-dimensional incompressible Navier–Stokes equations, with the EHD force obtained from the plasma simulation introduced as a external force term.

Fig. 2 shows computational domain. the region excluding the dielectric was used. The computational grid had 200 grid points in the x direction and 500 grid points in the z direction, with equal spacing. The density of the fluid (air) was set to  $\rho = 1.205 \text{ kg/m}^3$  and the dynamic viscosity was set to  $\nu = 1.51210^{-5} \text{ m}^2/\text{s}$ . An embedded boundary method was used for the treatment of grid conditions.

## C. Experiment

As in the simulation, we performed experimental measurements using a needle electrode and a plate electrode with a dielectric on it. However, unlike the simulation, we used a 0.35 mm thick kapton for the dielectric. The distance between the electrodes was 5 mm, the same as in the simulation. Therefore, the distance from the tip of the needle electrode to the surface of the dielectric was 4.65 mm. In these experiments, the slope of the voltage versus time equals 6 ns/kV.

#### III. RESULTS AND DISCUSSIONS

#### A. Simulation results and comparison with experiments

Fig. 3 shows the simulation results of time history of current and Fig. 4 shows the experiment results of time history of current. (t = 0 corresponds to the time at which the)voltage starts to be applied). Here, the current in the simulation is the displacement current calculated from the the time variation of the spatial electric field. This displacement current contains components of capacitive current and plasma current that flows toward the ground. As can be seen from Fig. 4, a significantly higher current peak is observed for  $V_p = 6-9$  kV compared to  $V_p = 2-5$  kV. At this time, it is considered to be due to whether or not discharge is occurring. From Fig. 3, for  $V_p = 6-9$  kV, the currents observed in the simulation exhibits the distinct peak. The current peak become larger as  $V_p$  increases. Similarly, Fig. 4 shows that the currents observed in the experiment also has the peak under high voltage conditions. However, the magnitude of the current in the experiment is approximately fifty times greater than that in the simulation. Although there are quantitative differences between the experiment and simulation, it is possible to qualitatively reproduce the plasma phenomenon.

Next, Fig. 5, 6 and 7 show the time history of the current and space-integrated value of z-directional EHD force at 3, 6 and 9 kV, respectively. Here, the EHD force in the z-axis direction is the integral value over the entire space. It is also important to note that the EHD force is negative, as it is generated from the needle electrode toward the plate electrode. From Fig. 5, Fig. 6 and Fig. 7, we can see that the tendency is different in current and EHD force between  $V_p = 3$ kV and  $V_p = 6$  and 9 kV. This difference results from whether discharge occurs. As shown in Fig. 5 in the case of  $V_p = 3$  kV, there is almost no discharge and only capacitive current flows. As shown in the figures 6 and 7, in the case of  $V_p = 6$  kV and 9 kV, a discharge current flows. Comparing Fig. 6 and 7, it is found that as the voltage increases, the timing at which the current reaches its maximum become faster, but in both cases, the maximum EHD force is reached at the time when the current is at its maximum.

#### B. Discussion

In order to analyze the EHD phenomena occurring in pulsed discharges in detail, we focus on the model case of  $V_p = 6$  kV. From Fig. 6, the current and EHD force reach their maximum values at t = 71.94 ns.

Fig. 8 and 9 show the distribution of positive ions, zdirectional EHD force and z-directional flow velocity at different times in the  $V_p = 6$  kV case. Fig. 8 and 9 correspond to  $t_1 = 37.68$  ns and  $t_2 = 71.94$  ns, respectively. They show that a streamer discharge occurs, in which a plasma column (streamer) propagates from the needle electrode toward the plate electrode.  $t_2$  is the time when the z-directional EHD force reaches its maximum value and Fig. 9 shows that this time  $t_2$  corresponds also to the time for which the streamer reaches the dielectric. This is due to the fact that the main contributing component of the EHD force generation is positive ions in positive corona discharges. In addition, both figures show that the streamer head with the larger EHD force has more plasma and charge density is high. This indicates that a strong flow acceleration is formed at the streamer head. Note that changes in the flow field are limited, since the time scale is on the order of  $10^{-7}$  s and the fluid response is slower than the discharge response. To investigate why the EHD force is maximum when the streamer reaches the dielectric, we dhow the distribution of the EHD force before and after the reaching. Fig. 10 shows an enlarged view of the head of the streamer before (t = 71.78 ns), at (t = 71.94 ns) and after(t = 71.93 ns) it reaches the dielectric. Fig. 10 shows that the region of strong EHD forces at the streamer head spreads only at the moment when the streamer impacts the dielectric surface. In order to analyze in detail, we focus on the z-directional profile of charge density and electrical potential near the dielectric surface. The EHD force is gener-



Figure 3: Total current (simulation).



Figure 4: Total current (experiment).



Figure 5: Current and EHD force in z direction ( $V_p = 3kV$ ).



Figure 6: Current and EHD force in z direction ( $V_p = 6kV$ ).



Figure 7: Current and EHD force in z direction ( $V_p = 9kV$ ).

ated by the Coulomb force acting on the plasma. Therefore, it is calculated from the charge density and the electric field that is the gradient of the electric potential. Fig. 11 shows the charge density and potential profiles before (blue line) and after (green line) the time (red time) when the EHD force reaches its maximum value.

Fig. 11a shows that the charge density at the streamer head is small at t = 71.44 ns (blue line), but at t = 71.94 ns (red line), the streamer head reaches the dielectric surface and the charge density becomes high. Fig. 11b also shows that electric the potential at the streamer head exhibits a steep spatial variation at t = 71.44 ns (blue line)



Figure 8: Distribution of positive ion, EHD force and velocity in z direction (t = 37.68 ns).



Figure 9: Distribution of positive ion, EHD force and velocity in z direction (t = 71.94 ns).

and t = 75.00 ns (green line). In contrast at t = 71.94ns (red line) when the streamer reaches the dielectric surface, there is an even steeper potential gradient at the dielectric surface. Furthermore, the potential inside the streamer changes spatially gradually.

## IV. CONCLUSION

A numerical analysis was performed on the EHD force induced by a single streamer in a pulsed corona discharge in a needle-to-plate corona configuration. A comparison of the experiment and simulation revealed that the results were qualitatively reproducible. As a simulation result, it was found that a strong EHD force was generated by the sheath



Figure 10: Comparison of EHD force distribution before, at and after the streamer reaches the dielectric.





Figure 11: One-dimensional profile along the axis below the needle electrode.

generated near the solid wall when the streamer reached the dielectric. This phenomenon is considered to be the mechanism of the strong induced jet generation by the streamer.

#### **ACKNOWLEDGMENTS**

This work was supported by The ANRI Fellowship.

- [1] S. Grosse, E. Moreau, and N. Binder, Modeling of the Flight Performance of a Plasma-Propelled Drone: Limitations and Prospects, Drones, vol. 8, no. 3, p. 114, 2024.
- [2] E. Moreau and N. Benard, Ionic wind produced by volume corona discharges and surface dielectric barrier discharges: What role do streamers play?, J. Electrostat., vol. 132, p. 103988, 2024.

## Influence of Co-existing Ions on Plasma–induced Chemical Reactions at Gas–Liquid Interface: Investigation through Halogen Generation

K. Tachibana<sup>1\*</sup>, Y. Hayasaki<sup>1</sup>, R. Kimoto<sup>1</sup>, Y. Takahashi<sup>1</sup>, H. Tasaka<sup>1</sup>,

S. Kanazawa<sup>1</sup>, S. Uchida<sup>2</sup>

<sup>1</sup>Faculty of Science and Technology, Oita University, Japan

<sup>2</sup>Department of Electrical Engineering and Computer Science, Tokyo Metropolitan University, Japan

\*Corresponding author: tachibana-kosuke@oita-u.ac.jp

Abstract- Plasma in contact with liquid is widely investigated aiming for various applications, such as water purification, material synthesis, medical and agricultural applications. However, the mechanisms of such plasma applications have not been fully understood. In this study, to explore a possibility that short-lived active species generated by plasma could react with solutes only at the topmost layer of the water surface, we investigated how generation characteristics of halogen (chlorine, bromine, and iodine) after the plasma irradiation were changed depending on co-existing ions with halide (chloride ( $CI^-$ ), bromide ( $Br^-$ ), and iodide ( $I^-$ )) ions. A DC argon plasma was irradiated to a solution containing the halide ion, and then concentrations of halogen and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) were measured. It was found that chlorine and bromine concentrations increased when co-existing ions with the halide ions were changed from sodium (Na<sup>+</sup>) to ammonium (NH<sub>4</sub><sup>+</sup>) ions. Furthermore, bromine and iodine concentrations decreased when co-existing ions of perchlorate ( $CIO_4^-$ ) were added to sodium halide solutions. To explain these experimental results, we have proposed that the co-existing ions change the surface concentration of the halide ions, which lead to the increase and decrease in the halogen and H<sub>2</sub>O<sub>2</sub> concentrations.

Keywords- Plasma-liquid interactions, Gas-liquid interface, Halide ions, Co-existing ions.

## I. INTRODUCTION

Plasma in contact with liquid is widely investigated aiming for various applications, such as water purification [1], material synthesis [2], medical and agricultural applications [3, 4]. However, the mechanisms of such plasma applications have not been fully understood. To reveal their mechanisms, it is important to better understand plasma–liquid interactions, which are physical and chemical phenomena occurring at gas–liquid interface.

In our previous study, we suggested a possibility that short-lived active species generated by plasma could react with solutes only at the topmost layer of the water surface [5]. We found that, when a DC argon plasma was irradiated to 2.1 M sodium halide (NaX (X=Cl, Br, or I) solutions, average production rates of bromine and iodine were 0.30  $\mu$ M/s and 0.71  $\mu$ M/s, respectively, which were 500–1000 higher than that of chlorine. However, there is a paper reporting that chloride (Cl<sup>-</sup>), bromide (Br<sup>-</sup>), and iodide (I<sup>-</sup>) ions have similar reaction coefficients for OH radicals, which are 4.2×10<sup>9</sup> L/mol/s, 1.1×10<sup>10</sup> L/mol/s, 1.5×10<sup>10</sup> L/mol/s, respectively [6]. To explain our experimental results, we suggested that the halide ion's concentrations at the gas-liquid interface, which were generally different from those in bulk liquid, play an important role in the halogen generation. This suggestion is consistent with simulation results reported in papers, where the halide ion's concentrations at the gas-liquid interface were higher in the order of I<sup>-</sup>, Br<sup>-</sup>, and Cl<sup>-</sup> [7, 8].

In this study, to explore the possibility suggested in our previous work, we investigated how halogen concentrations after plasma irradiation were changed depending on co-existing ions with the halide ions. This is because we expect that the co-existing ions can alter the concentrations of the halide ions at the topmost layer of the water surface, which probably changes the halogen concentrations generated by plasma in contact with liquid. In addition to the halogen concentrations, we also measured hydrogen peroxide  $(H_2O_2)$  concentrations to consider how OH radicals generated by plasma are consumed through plasma-induced chemical reactions.

## II. METHODOLOGY

Fig. 2 shows an experimental setup of a plasma reactor. The reactor consisted of acrylic plates and a pipe, and its inner diameter and height were 40 mm and 30 mm, respectively. Solutions were prepared by dissolving chemicals into ultrapure water (Direct-O UV3, Merck Millipore), and the solution's volume was 20 mL. A high voltage (H.V.) electrode was a screw made of stainless steel (SUS304) and located approximately 2 mm above the solution's surface. A grounded electrode, which was a platinum-coated titanium electrode, was partly immersed in the solution and connected to the ground through a current measurement resistor (1 k $\Omega$ ). A voltage was applied to the H.V. electrode through a ballast resistor  $(1 \text{ M}\Omega)$  by using a H.V. power supply (HAR-50R6, Matsusada Precision), and then the plasma was generated between the H.V. electrode and the water surface. A regulated current and a plasma irradiation time were set to 2 mA and 60 s, respectively, in every experiment. Argon gas was provided from a gas tank to the plasma reactor through a mass flow controller (model 3660, KOFLOC) with a flow rate of 200 mL/min. A magnetic stirrer was used to mix the solution during the experiments.



Fig. 1 Experimental setup of a plasma reactor.

Voltage and current waveforms were recorded with an oscilloscope (DHO924S, RIGOL). The voltage at the H.V. electrode was measured with a H.V. probe (HV-P30, Iwatsu), and a plasma current was calculated by dividing the voltage across the current measurement resistor by its resistance.

Halogen concentrations in solution were measured by a DPD (N, N-diethyl-p-phenylenediamine) method. A chemical reagent including DPD was added to the solution, and then its absorbance was measured with a photometer (HI97101, HANNA Instruments).

 $H_2O_2$  concentrations in solution were measured by a method using a Ti-PAR solution [9–11]. This method has better sensitivity than a titanium sulfate method and enabled us to measure the  $H_2O_2$  concentrations on the order of 1  $\mu$ M [9]. In our experiments, a 0.2 mL Ti-PAR (0.3 mM) solution was mixed with a 1 mL solution sample, and the solution was stirred enough. Then, a 0.8 mL alkaline phosphate buffer (75 mM) with a pH of 11.5 was added to the solution. This solution was allowed to stand for 5 min at 45°C, and, after cooling to room temperature, the absorbance at a wavelength of 508 nm was measured with an UV-Vis spectrometer (UV-2550, SHIMADZU).

## III. RESULTS AND DISCUSSION

## A. Discharge characteristics of DC argon plasma

Fig. 2 shows typical voltage and current waveforms when the DC argon plasma was irradiated to a 2.1 M sodium chloride (NaCl) solution. A voltage across the electrodes and a plasma current were approximately 400 V and 2.0 mA on average, respectively. An average plasma power, which was calculated by multiplication of the average volage and current, was approximately 0.8 W. In the calculation of the plasma power, we assumed that the power consumption in the solution was negligible because its conductivity was high enough.

Although the DC argon plasma was irradiated to various types of aqueous solutions in our experiments, it was considered that plasma characteristics were consistent irrespective of the types of the solutions. This is because the plasma current was regulated at 2 mA for every solution. In addition, the power consumption in the



Fig. 2 Typical voltage and current waveforms when a DC argon plasma was irradiated to a 2.1 M sodium chloride (NaCl) solution.

solution would be negligible because every solution used in our experiments had very high conductivity.

## B. Generation characteristics of Halogen and $H_2O_2$ for DC argon plasma irradiated to sodium halide solutions

Fig. 3 shows halogen (chlorine, bromine, and iodine) and  $H_2O_2$  concentrations after the DC argon plasma was irradiated to 2.1 M NaCl, NaBr, and NaI solutions, respectively, for 60 s. As shown in fig. 3(a), the halogen concentrations were higher in the order of the iodine, bromine, and chlorine. This tendency corresponds to the surface propensity of the halide ions for the gas–liquid interface as explained in the introduction section. On other hand, according to Fig. 3(b), the  $H_2O_2$  concentrations were higher as the halogen concentrations became lower. This is probably because the more OH radicals react with the halide ions, the less OH radicals are used for their recombination reaction.

Please note that, although the chlorine concentration was almost zero after the plasma irradiation, there is a possibility that some OH radicals reacted with Cl<sup>-</sup> ions. In our experiments, it is considered that the plasma characteristics are not changed depending on the types of the solution. Therefore, the H<sub>2</sub>O<sub>2</sub> concentrations should be maximum and constant when the OH radicals do not react with solutes, which corresponds to the case of Na<sub>2</sub>SO<sub>4</sub> solution. As shown in fig. 3(b), after the argon plasma irradiation, the H<sub>2</sub>O<sub>2</sub> concentration in the 2.1 M NaCl solution was lower than that in a 0.5 M Na<sub>2</sub>SO<sub>4</sub> solution, which indicates that some OH radicals are used for chemical reactions related to Cl<sup>-</sup> ions.

## C. Influence of co-existing ions on generation characteristics of halogen and $H_2O_2$

Fig. 4 shows halogen (chlorine and bromine) and  $H_2O_2$  concentrations after the plasma irradiation for 60 s when the halide ions existed with sodium (Na<sup>+</sup>) or ammonium (NH<sub>4</sub><sup>+</sup>) ions. As shown in figs. 4(a) and 4(b), when the co-existing ions with the halide ions were changed from Na<sup>+</sup> to NH<sub>4</sub><sup>+</sup> ions, the halogen concentrations increased while the  $H_2O_2$  concentrations decreased.





Fig. 5 shows halogen (bromine and iodine) and  $H_2O_2$  concentrations after the plasma irradiation for 60 s when co-existing ions with the halide ions were perchlorate (ClO<sub>4</sub><sup>-</sup>) ions in addition to Na<sup>+</sup> ions. From fig. 5(a), we observed that the halogen concentrations decreased with the increase in the sodium perchlorate (NaClO<sub>4</sub>) concentrations. Meanwhile, the  $H_2O_2$  concentrations were almost the same or decreased a little when the NaClO<sub>4</sub> solution was added to the NaX solutions.

One of the possible reasons for the above results is that the co-existing ions of  $NH_4^+$  and  $ClO_4^-$  change the halide ion's concentrations at the gas-liquid interface. According to the literature related to atmospheric and molecular chemistry, some chemical reactions primarily proceed at gas-interface rather than in bulk liquid, and the mechanisms of such reactions at gas-liquid interface can be different from those in bulk solution [12-14]. For example, I<sup>-</sup> ions could primarily react with ozone at gasinterface of aerosols [12], and the reaction between them could generate surface-specific intermediates [13]. Furthermore, there is a paper reporting that  $ClO_4^-$  ions exclude I<sup>-</sup> ions from the gas-liquid interface when these ions co-exist in solution [15]. Therefore, the



Fig. 4 Halogen and  $H_2O_2$  concentrations after the argon plasma irradiation for 60 s when halide ions existed with sodium (Na<sup>+</sup>) or ammonium (NH4<sup>+</sup>) ions.

concentrations of the halide ions at gas–liquid interface probably decrease when  $ClO_4^-$  ions are added to the NaX solutions, which lead to the decrease in the halogen concentrations as shown in fig. 5(a). Due to the similar reason, the concentrations of the halide ions at gas–liquid interface probably increase when the NH<sub>4</sub><sup>+</sup> ions co-exist with the halide ions, leading to the increase in the halogen concentrations as shown in fig. 4(a).

We would like to note that it is difficult to remove the possibility that the co-existing ions of  $NH_4^+$  and  $ClO_4^-$  are involved with oxidation reactions of the halide ions to the halogens. According to the literature, we found that  $NH_4^+$  ions are unlikely to react with OH radicals [16]. In addition, it is known that  $ClO_4^-$  ions are not likely to react with OH radicals, either. However, there is a possibility that intermediates of the chemical reactions from halide ions to the halogens might react with the co-existing ions. Therefore, in addition to the influence of the co-existing ions on the surface concentrations of the halide ions react with the intermediates of the halogen generation or not.



Fig. 5 Halogen and  $H_2O_2$  concentrations after the argon plasma irradiation for 60 s when halide ions existed with perchlorate (ClO<sub>4</sub><sup>-</sup>) ions in addition to Na<sup>+</sup> ions.

## IV. CONCLUSION

To explore a possibility that short-lived active species generated by plasma could react with solutes only at the topmost layer of the water surface, we investigated how halogen (chlorine, bromine, and iodine) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) concentrations after plasma irradiation are changed depending on co-existing ions. It was found that halogen concentrations increased after the argon plasma irradiation when co-existing ions were changed from sodium (Na<sup>+</sup>) to ammonium (NH<sub>4</sub><sup>+</sup>) ions. In addition, we observed that the halogen concentrations decreased when co-existing ions of perchlorate (ClO<sub>4</sub><sup>-</sup>) ions were added to sodium halide (NaX (X=Cl, Br, or I)) solutions. To explain these experimental results, we have proposed that the co-existing ions change the surface concentrations of the halide ions, which lead to the increase and decrease in the halogen and H<sub>2</sub>O<sub>2</sub> concentrations.

#### ACKNOWLEDGMENT

This work was partially supported by JSPS KAKENHI Grant Number JP22K14244.

- [1] H. Nishiyama, K. Niinuma, S. Shinoki, and H. Takana, Decomposition of Acetic Acid Using Multiple Bubble Jets with Pulsed Electrical Discharge, *Plasma Chem. Plasma Process*, 35, 339–354, 2015.
- [2] J. Kang, O.L. Li, and N. Saito, Synthesis of structurecontrolled carbon nano spheres by solution plasma process *Carbon*, 60, 292–298, 2013.
- [3] M. Laroussi, Plasma Medicine: A Brief Introduction, *Plasma*, 1, 47–60, 2018.
- [4] P. Attri, K. Ishikawa, T. Okumura, K. Koga, and M. Shiratani, Plasma Agriculture from Laboratory to Farm: A Review, *Processes*, 8, 1002, 2020.
- [5] K. Tachibana and K. Yasuoka, Understanding of chemical reactions induced by argon plasma in contact with sodium halide solutions: importance of surface properties for plasma–liquid interactions, J. Phys. D: Appl. Phys., 53, 125203, 2020.
- [6] G.V. Buxton, C.L. Greenstock, W.P. Helman, and A.B. Ross, Critical Review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals (·OH/·O<sup>−</sup>) in Aqueous Solution, J. Phys. Chem. Ref. Data, 17, 513–886, 1988.
- [7] P. Jungwirth and D.J. Tobias, Molecular Structure of Salt Solutions: A New View of the Interface with Implications for Heterogeneous Atmospheric Chemistry, J. Phys. Chem. B, 105, 10468–10472, 2001.
- [8] T. Ishiyama and A. Morita, Molecular Dynamics Study of Gas-Liquid Aqueous Sodium Halide Interfaces. I. Flexible and Polarizable Molecular Modeling and Interfacial Properties, J. *Phys. Chem. C*, 111, 721–737, 2007.
- [9] C. Matsubara, Y. Nishikawa, Y. Yoshida, and K. Takamura, A spectrophotometric method for the determination of free fatty acid in serum using acyl-coenzyme A synthetase and acyl-coenzyme A oxidase, *Anal. Biochem.*, 130 128–133, 1983.
- [10] Y. Komazaki, T. Inoue, S. Tanaka, Automated measurement system for H<sub>2</sub>O<sub>2</sub> in the atmosphere by diffusion scrubber sampling and HPLC analysis of Ti(IV)-PAR-H<sub>2</sub>O<sub>2</sub> complex, *Analyst*, 126, 587–593, 2001.
- [11] K. Takamura and T. Matsumoto, UV-visible spectral analysis for the characterization of the titanium(iv)-4-(2pyridylazo) resorcinol complex as a reagent for determining hydrogen peroxide, *Dalton Trans.*, 49 690– 696, 2020.
- [12] S. Enami, C.D. Vecitis, J. Cheng, M.R. Hoffmann, and A.J. Colussi, Mass spectrometry of interfacial layers during fast aqueous aerosol/ozone gas reactions of atmospheric interest, *Chem. Phys. Lett.*, 455, 316–320, 2008.
- [13] Y. Sakamoto, A. Yabushita, M. Kawasak, and S. Enami, Direct Emission of I<sub>2</sub> Molecule and IO Radical from the Heterogeneous Reactions of Gaseous Ozone with Aqueous Potassium Iodide Solution, *J. Phys. Chem. A*, 113, 7707– 7713, 2009.
- [14] R. Kusaka, S. Nihonyanagi, and T. Tahara, The photochemical reaction of phenol becomes ultrafast at the air–water interface, *Nature Chemistry*, 13, 306–311, 2021.
- [15] S. Enami and A.J. Colussi, Long-range specific ion-ion interactions in hydrogen-bonded liquid films, J. Chem. Phys., 138, 184706, 2013.
- [16] L. Huang, L. Li, W. Dong, Y. Liu, and H. Hou, Removal of Ammonia by OH Radical in Aqueous Phase, *Environ. Sci. Technol.*, 42, 8070–8075, 2008.

## The Method of Determining Ion Mobilities in a Liquid Dielectric in a Wirecylinder Electrode System Based on Current Characteristics

D. V. Zhuravlev<sup>\*</sup>, S. A. Vasilkov St. Petersburg State University, St. Petersburg, Russia \*Corresponding author: d.zhuravlev@spbu.ru

Abstract- A novel method for determining ion mobility in dielectric liquids is proposed that is based on the analysis of current signals under applied voltage. The approach relies on observing current decay caused by heterocharge layers forming near electrodes, where charge transport is dominated by ions of opposite polarity. Two electrode geometries are studied—planar and coaxial (wire-cylinder). While the planar configuration offers simplicity and higher currents, the coaxial setup enables selective measurement of ion mobilities depending on electrode polarity. A numerical model simulates the time evolution of ion depletion and current drop, demonstrating that ion mobility can be unambiguously extracted from the current shape in the coaxial system without ion injection. Preliminary experimental results for transformer oil validate the method's potential as a tool for characterizing ion mobility in dielectric fluids.

## Keywords- Dielectric liquid, ion mobility, heterocharge layers, current characteristics, numerical modeling

## I. INTRODUCTION

One of the current challenges in the study of electrodynamic processes is the limited knowledge of the values of ion mobilities and their ratio for different ion species. Those values are essential for the development of electrohydrodynamic conduction pumping technologies [1].

A common approach for determining ion mobility in dielectric liquids involves time-of-flight measurements, in which ions traverse an interelectrode gap under the influence of an electric field [2], [3], [4]. However, this method requires a directed ion flux originating from one of the electrodes. Such a flux is typically generated either by electrochemical injection or by ionization of the medium under external irradiation. In both cases, the measured mobility corresponds to ions introduced by artificial means rather than those naturally present in the liquid. It is often assumed that ions accumulate at the electrode-liquid interface under the influence of an electric field and subsequently move toward the opposite electrode when the polarity is reversed. However, the formation and stability of such interfacial charge accumulations are not well understood.

Some studies employ frequency domain spectroscopy to estimate ion mobilities [5], [6], [4]. The principle is based on the observation that, at a certain critical frequency f, ions are no longer able to reach the electrodes within half a voltage cycle, which manifests as a distinct feature in the spectral response. Nevertheless, this method faces difficulties in accurately determining the frequency f, and different authors propose different equations relating f to ion mobility.

Ion mobility can also be estimated from the dynamic viscosity of the liquid using Walden's rule [7]. However, this approach only provides an approximate value, as it

requires prior knowledge of the equivalent hydrodynamic radius of the ion.

In this work, we propose a novel method for determining ion mobility based on the analysis of current signals induced by an applied voltage. When current flows through the system, heterocharge layers form near the electrodes, in which charge transport is dominated by particles of opposite sign. This localized imbalance of charge carriers causes a noticeable drop in current, providing valuable insight into the mobility of the ions.

Two electrode configurations are considered: the parallel plate and coaxial (wire-cylinder) ones. The parallel plate geometry is simpler and allows precise control of the interelectrode distance while also supporting higher currents due to a larger electrode area. However, its symmetry limits the measurement to an averaged mobility of positive and negative ions. In contrast, the wirecylinder geometry provides access to more selective information: variations in total conductivity are primarily governed by processes occurring near the wire electrode, where the stronger electric field induces thicker heterocharge layers, further amplified by the initially small cross-sectional area. By selecting the polarity of the wire electrode, it becomes possible to isolate the contribution of ions of a specific charge sign to the overall conductivity, thereby allowing differential mobility analysis.

## II. METHODOLOGY

## A. Numerical Modeling

To assess the feasibility of extracting ion mobilities from heterocharge-layer formation, and to facilitate comparison with experimental data, we constructed a onedimensional numerical model using the finite-element method in COMSOL Multiphysics. Boundary conditions (positive polarity)

$$\varphi = U \qquad \varphi = 0$$
  

$$j_{c,pos} = 0 \qquad j_{c,pos} = b_{pos} c_{pos} E$$
  

$$j_{c,neg} = -b_{neg} c_{neg} E \qquad j_{c,neg} = 0$$
  

$$r = R_0 \text{ or } x = 0 \qquad r = R_1 \text{ or } x = d$$

#### Fig. 1. Boundary conditions.

The model couples electrostatics and ion transport by solving Gauss's law (1) for the electric field and the Nernst–Planck equation (3) for conservation of positive and negative ions:

$$\nabla \cdot (\varepsilon \varepsilon_0 E) = F_{const} (c_{pos} - c_{neg}) \tag{1}$$
$$\mathbf{F} = -\nabla \omega \tag{2}$$

$$\mathbf{E} = -\nabla\varphi \tag{2}$$

$$\frac{\partial t}{\partial t} + \nabla \cdot (\mathbf{j}_{c,i}) = W - F_{rec} \tag{3}$$

$$\boldsymbol{j}_{\boldsymbol{c},\boldsymbol{i}} = -D_i \nabla \boldsymbol{c}_{\boldsymbol{i}} \pm b_i \boldsymbol{c}_{\boldsymbol{i}} \boldsymbol{E}$$
(4)

Here E is the electric field strength,  $\varphi$  is the electric potential,  $\varepsilon$  is the relative electric permittivity,  $\varepsilon_0$  is the vacuum permittivity,  $c_i$  is the concentration of species i (*pos* = positive, *neg* = negative),  $j_{c,i}$  is its flux,  $D_i$  is the diffusion coefficient,  $b_i$  is the ionic mobility,  $F_{const}$  is the Faraday constant, W is the dissociation rate,  $F_{rec}$  is the recombination rate. The charge numbers of ions are assumed to be +1 for positive and -1 for negative ions.

The diffusion coefficient  $D_i$  is linked to mobility  $b_i$  via the Einstein relation:

$$D_i = \frac{k_B T}{e} b_i \tag{5}$$

where  $k_B$  is the Boltzmann constant, *T* the absolute temperature and *e* is the elementary charge.

The equilibrium (initial) ion concentration  $c_0$  is determined from the low-field conductivity  $\sigma_0$  of the liquid:

$$c_0 = \frac{\sigma_0}{F_{const}(b_{pos} + b_{neg})} \tag{6}$$

Recombination is described by a modified Langevin expression:

$$F_{rec} = k_{rec} \frac{(b_{pos} + b_{neg})F_{const}}{\varepsilon\varepsilon_0} c_{pos} c_{neg}$$
(7)

where  $k_{rec}$  is the empirical correction factor introduced to better fit experimental behavior.

Dissociation is assumed to balance recombination at equilibrium:

$$W = k_{rec} \frac{\sigma_0^2}{F_{const} \varepsilon \varepsilon_0 (b_{pos} + b_{neg})}$$
(8)

In this work, we introduce the notion of effective conductivity  $\sigma_{eff}$ , which is calculated from the measured current *I*, applied voltage *U*, and the cell geometry, as if the conductivity were uniformly distributed throughout the medium. For the two electrode configurations considered,  $\sigma_{eff}$  is given by:

$$\sigma_{eff} = \frac{l}{U}\frac{d}{S} \tag{9a}$$

for the parallel-plate cell, where d is the interelectrode distance and S is the area of each planar electrode;

Table 1: Numerical simulation parameters

Property	Value	Unit		
З	2.2	1		
<b>b</b> <sub>neg</sub>	1e-9	$m^2 V^{-1} s^{-1}$		
$b_{pos}$	5e-10	$m^2 V^{-1} s^{-1}$		
<i>k</i> <sub>rec</sub>	1	S m <sup>-1</sup>		
$\sigma_{\scriptscriptstyle 0}$	4.2e-11	1		
U	200	V		
$R_0$	2.5e-5	m		
$R_1$	1.03e-2	m		
L	0.101	m		

$$\sigma_{eff} = \frac{I}{U} \frac{\ln(R_1/R_0)}{2\pi L} \tag{9b}$$

for the coaxial (wire–cylinder) geometry, where  $R_0$  is the radius of the central wire electrode,  $R_1$  is the inner radius of the cylindrical electrode and *L* is the active length of both electrodes.

All equations are solved simultaneously over the chosen electrode geometry (either parallel - plate or wire-cylinder), with appropriate boundary conditions (Fig. 1). The model assumes that there is no electrochemical injection of ions from the electrodes.

The fluid parameters used in the numerical simulations were chosen to approximate the properties of GK-1700 transformer oil. The specific values are summarized in Table 1. The mobility of negative ions was set to be twice that of positive ions in order to investigate whether this asymmetry could be revealed through the formation and evolution of heterocharge layers near the electrodes. This artificial imbalance allows us to assess the method's sensitivity to differences in ion mobility.

#### B. Experimental Setup (Planar Electrode System)

Preliminary experiments were carried out using a planar electrode cell, which comprises two polished molybdenum mirrors acting as the electrodes. The interelectrode spacing is set by inserting small plastic spacers between the mirrors, allowing precise control of the gap.

Voltage across the cell is monitored via a resistive voltage divider, while the current is sensed through a measurement resistor; both signals are routed into an analogue–to–digital converter (ADC) for acquisition.

A challenge in these measurements is the presence of capacitive currents due to the parasitic capacitance of the electrode system. To suppress these unwanted transients, the cell is equipped with a dedicated pre-charge circuit: immediately upon application of the voltage step, the electromagnetic relay bypasses all resistors for an initial  $10-100 \mu$ s, rapidly charging the parasitic capacitances. Only after this brief pre-charge interval does the circuit switch to the normal measurement path, ensuring that the recorded current reflects true conductive behavior rather than capacitive currents.

#### III. RESULTS AND DISCUSSION

## A. Numerical Results (Coaxial Electrode System)

Fig. 2 presents the steady-state concentration distributions for positive and negative ions. Near the wire electrode (when it is positively biased), a pronounced positive-ion depletion layer forms, with  $c_{pos}$  dropping nearly to zero at the surface. Concurrently,  $c_{neg}$  increases slightly because the reduced local concentration of positive ions diminishes the recombination rate. Around the cylindrical electrode, a similar—but much thinner—depletion layer appears, owing to the relatively weaker field strength.

During the development of heterocharge layers, the effective conductivity  $\sigma_{eff}$  falls from its low-field value  $\sigma_0$  as illustrated in Fig. 3. Once the heterocharge layers reach equilibrium thickness,  $\sigma_{eff}$  stabilizes at a new, lower level. Crucially, when ion mobilities differ, the conductivity decay curves for positive and negative polarities diverge: the species with higher mobility forms a thicker depletion layer, causing a greater drop in  $\sigma_{eff}$ . Hence, in the wire–cylinder geometry, one can discriminate between ions of differing mobility based on the time course of conductivity reduction.

The simulated current–voltage (I–V) curve (Fig. 4) remains approximately linear, with a slight downward deviation from the line corresponding to  $\sigma_0$ . In experiments, I–V measurements are especially practical because they do not require resolving fast transients; deviations below linearity indicate heterocharge layer formation, whereas upward deviations signal the onset of ion injection overcoming depletion.

## B. Reconstruction of Ion Mobilities from Current–Time Responses

The model contains three unknown parameters positive mobility  $b_{pos}$ , negative mobility  $b_{neg}$ , and recombination coefficient  $k_{rec}$ —that shape the current– time curves  $I_{pos}(t)$  and  $I_{neg}(t)$ . To test parameter recoverability, we first generated "reference" currents  $I_{pos0}(t)$  and  $I_{neg0}(t)$  using a trial set:

 $b_{pos}^0 = 0.646b, \ b_{neg}^0 = 1.320b, \ k_{rec}^0 = 0.237$ Starting from different initial guesses for  $b_{pos}, b_{neg}$ 

Starting from different initial guesses for  $b_{pos}$ ,  $b_{neg}$ and  $k_{rec}$  we implemented an optimization algorithm that



Fig. 2. Distribution of ion concentrations (positive polarity).



Fig. 3. Dependence of effective electrical conductivity on time.



Fig. 4. Volt-ampere characteristic.

minimize the objective functional (10), thereby adjusting the model parameters to reduce the discrepancy between the reference data and the simulation results:

$$f = \int (I_{pos} - I_{pos}^0)^2 + (I_{neg} - I_{neg}^0)^2 dt$$
(10)  
The following optimization values were obtained:

 $b_{pos}^1 = 0.649b, \ b_{neg}^1 = 1.325b, \ k_{rec}^1 = 0.237$ 

These results demonstrate that, within the assumptions of the model (absence of injection and other unmodeled effects), it is indeed possible to unambiguously retrieve both ion mobilities (and the recombination coefficient) from experimentally accessible current–time oscillograms.

## C. Experimental Results

Fig. 5 shows the time-dependent decay of the effective conductivity measured in the GK-1700 transformer oil under a planar electrode geometry. At low applied voltage (U = 10 V), we fitted experimental data by assuming equal mobilities for positive and negative ions. The best-fit mobility magnitude was found to be one to two orders of magnitude lower than typical literature values for transformer oil. Nonetheless, the simulated conductivity decay closely matches the experimental curve (Fig. 6), and the simulated I–V characteristic reproduces the overall shape observed in the experiment, albeit with a slightly more pronounced curvature.

At higher voltage (U = 30 V) with the same simulation parameters, however, the model predictions deviate more noticeably from the experimental data (Fig. 7). In the simulations, the heterocharge layer fills the entire interelectrode gap, yielding an abrupt stabilization of  $\sigma_{eff}$ once the initial ions have traversed the gap. In contrast, the experimental decay remains smooth at all times, even



Fig. 5. Dependence of effective electrical conductivity  $\sigma_{eff}$  on time *t* at voltage U = 10 V and gap distance  $d = 19 \mu m$ .



Fig. 6. Volt-ampere characteristic

under high field. Possibly, this discrepancy is explained by the existence of a distribution of ion mobility in real oil, which could smooth out the abrupt transition predicted by the single-mobility model and provide a more gradual approach to stationary conductivity.

## IV. CONCLUSION

In this work, we have introduced and validated a novel method for determining ion mobilities in weakly conducting dielectric liquids by analyzing transient current responses associated with heterocharge layer formation. A coupled finite-element model—solving Gauss's law and the Nernst–Planck equations with generation–recombination kinetics—demonstrates that differences in positive and negative ion mobilities manifest as distinct conductivity decay profiles. In particular, the coaxial (wire–cylinder) geometry allows unambiguous discrimination of ion mobilities through polarity - dependent transient behavior.

Simulation for transformer oil confirms that both ion mobilities and the recombination coefficient can be retrieved by fitting dual polarity current-time curves, provided that parasitic effects such as injection are negligible.

Preliminary experimental measurements in GK-1700 transformer oil, conducted in a planar electrode cell, qualitatively corroborate the model predictions at low applied voltage (10 V), with the fitted mobilities yielding a conductivity decay consistent with simulations. At higher voltages (30 V), the smoother experimental decay indicates that the current numerical model does not



Fig. 7. Dependence of effective electrical conductivity  $\sigma_{eff}$  on time *t* at voltage U = 30 V and gap distance  $d = 19 \mu m$ .

describe all the effects that occur in the liquid.

In general, combined modeling and experimental research confirm the possibility of determining ion mobility based on the formation of heterocharge layers. In future studies, it will be necessary to determine the cause of the discrepancy between the experimental data and the modulations at relatively large fields. Experimental verification of the coaxial geometry is also necessary in order to determine the possibility of determining the ratio of mobilities of positive and negative ions.

- M. Yazdani and J. Seyed-Yagoobi, "Effect of Charge Mobility on Electric Conduction Driven Dielectric Liquid Flow," *J. Electrostat.*, vol. 72, no. 4, pp. 285– 294, 2014.
- [2] F. Vahidi, M. Jovalekic, S. Tenbohlen, M. Rösner, C. Perrier, and H. Fink, "Electrical Conductivity Measurement and Determination of Ion Mobility in Insulating Oil," *IEEE Electr. Insul. Conf.*, pp. 313– 317, 2013.
- [3] Q. Xue, I. Timoshkin, M. P. Wilson, M. Given, and S. J. MacGregor, "Mobility of charge carriers in mineral oil and ester fluids," *High Volt.*, vol. 6, no. 6, pp. 1040–1050, 2021.
- [4] L. Yang and M. S. Zadeh, "Measurement of Ion Mobility in Transformer Oils for HVDC Applications," 2012 Int. Conf. High Volt. Eng. Appl., pp. 464–467, 2012.
- [5] X. Sidambarompoulé, P. Notingher, T. Paillat, J. C. Laurentie, and P. Leblanc, "Study of electrical properties and estimation of average mobility and diffusion coefficients in several insulating liquids by dielectric spectroscopy," *Int. J. Plasma Environ. Sci. Technol.*, vol. 14, no. 3, pp. e03006, 2020.
- [6] A. Cremasco, E. Logakis, P. A. A. F. Wouters, J. Van Duivenbode, M. Curti, and E. A. Lomonova, "Temperature Dependency of Ion Mobility in Synthetic Ester by Dielectric Response Analysis in Time and Frequency Domain," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 4, pp. 1451–1459, 2023.
- [7] I. Adamchevskiy. Electric Conductivity of Liquid Dielectrics. Leningrad: Energiya, 1972.

## Experimental Investigation of Electrocoalescer Unit Prototype for Numerical Models Verification

Ilia Elagin\*, Aleksandr Kozlov, Andrei Sitnikov, Vladimir Chirkov St. Petersburg State University, Russia \*Corresponding author: i.elagin@spbu.ru

Abstract—The study is devoted to a collection of experimental data on emulsion evolution, which can be appropriate for thorough checking the correctness of various numerical models and conclusions made on their base. We created a lab scale electrocoalescer unit prototype with moderately uniform electric field distribution that simplifies creation and application of various computational models. The electrostatic oil cleaner was filled with transparent two-phase liquid—a water-in-oil emulsion with grape-seed oil being used for the continuous phase. A number of video recordings were made for various values of input parameters. The observed experimental data can be used for the verification of computer models describing emulsion behavior under the effect of the electric field.

Keywords—Electrocoalescence, water-in-oil emulsion, separation rate, droplet size distribution.

## I. INTRODUCTION

In recent years, numerous models have been developed to describe electrocoalescence [1,2]. Some of these models focus on the interaction between individual droplets, while others consider the behavior of the emulsion as a whole. However, the applicability of such models is limited by their accuracy and assumptions related to inter-droplet interactions.

A key challenge remains the quantitative validation of these models (especially, the multi-droplet ones) based on the experimental data. Though there are many experimental study in the literature (e.g., [3–7]), they are mostly devoted to enhancing the efficiency of dehydration in complicated systems that are inconvenient to quantitative validation of computations.

This study presents experimental investigations of emulsion evolution under an electric field. A laboratoryscale prototype of an electrocoalescer was developed with a moderately uniform electric field distribution, enabling consistent comparison between simulations and experiments. The experimental data obtained under different values of the electric field strength can be used to validate numerical models and assess their predictive capabilities.

## II. METHODOLOGY

The experimental cuvette is a rectangular cell made of acrylic glass with dimensions of  $210 \times 60 \times 60$  mm<sup>3</sup>. A pair of rectangular aluminum electrodes is embedded into the side walls. The experimental setup (Fig. 1) includes the following main components: the cell, a light source, a high-voltage power supply, a CCD camera, an analog-to-digital converter (ADC), a computer, and an optical microscope. Additionally, a light diffuser was placed between the light source and the cell to ensure more uniform illumination during the experiment.



Fig. 1 Schematic diagram of the experimental setup.

A water-in-oil emulsion with 1:10 ratio between water and grape-seed oil was used in the experiments. The components were mixed using a blender. After preparation, the emulsion was transferred to a small container with a tightly sealed lid and allowed to settle for 16–24 hours. This step was necessary to ensure the removal of air bubbles introduced during mixing.

The properties of the liquids are as follows: density of oil 920 kg/m<sup>3</sup> and that of water 998 kg/m<sup>3</sup>, dynamic viscosity of oil 54 mPa·s and that of water 0.9 mPa·s, relative permittivity of oil 3.09, and interfacial tension between oil and water 25.2 mN/m [8].

The following parameters were investigated: emulsion transparency and droplet size distribution. To evaluate transparency, a reference image was taken prior to each experiment with pure oil in the cell. This image is referred to as the baseline image. The emulsion was then poured into the cell, and an electric field was applied. A camera recorded the emulsion clarification process.

Using in-house video processing software, the average brightness in the regions of interest within the cell was normalized by the corresponding brightness values from the baseline image. It can be confidently stated that the clearer the emulsion, the higher its transparency and thus its image brightness. When the relative brightness approached unity, the emulsion was considered clarified.

To analyze the droplet size distribution, samples were extracted from the cell and imaged under a microscope. For imaging, the sample was placed between microscope slides separated by spacers. The optimal spacer thickness was at least twice the maximum droplet radius. However, droplet collapse was still observed at spacer thicknesses of 90–100  $\mu$ m, so it was increased to 120–130  $\mu$ m. Size distributions were constructed using specialized software.

Before each experiment, the cell was rinsed with water, cleaned with a degreasing agent, dried, and filled with clean oil. Camera settings were then adjusted: focusing, light source brightness, and camera exposure were tuned to ensure pixel brightness did not reach the maximum value (255). The frame rate was set to 1 frame per second. After adjustments, the baseline image was captured. The cell was then cleaned again and filled with emulsion.

The power supply outputs were connected to the ADC through a resistive voltage divider. The ADC sampling rate was set to 25 Hz. After equipment setup, video recording began, followed by the oscilloscope trace acquisition and voltage application.

During the experiments, samples were periodically collected from the center of the inter-electrode region. The power supply was briefly turned off, the emulsion was drawn with a syringe, and placed between microscope slides for imaging. Five to seven images were taken from different areas of each probe (Figs. 2 and 4).

After the experiment, the images were binarized, and equivalent circles preserving the original area were fitted to the droplets. Droplet radius distributions were constructed (Figs. 3 and 5), and the temporal evolution of emulsion parameters was analyzed.

## III. RESULTS AND DISSCUSION

The performance of the electrocoalescer unit was evaluated based on several parameters: emulsion transparency and changes in droplet size distributions.



Fig. 2 Example of a microscope photo at the beginning of the experiment.



Fig. 3 Example of droplet size distribution at the beginning of the experiment.



Fig. 4 Example of a microscope photo at the end of the experiment.



Fig. 5 Example of droplet size distribution at the end of the experiment.

Plots were obtained showing the time evolution of relative brightness, as well as the average and maximum droplet sizes in the inter-electrode gap (IEG). Experiments were conducted at the electric field strengths of 1.5 kV/cm and 2.5 kV/cm. The primary clarification process occurs within the IEG, whereas the emulsion layer above it clarifies more slowly, reducing the overall efficiency of the cell. Reducing the emulsion volume from 150 mL (liquid layer above the IEG: 4.7 cm) to approximately 121 mL (layer above the IEG: 1.5 cm) eliminated this issue while maintaining full coverage of the active zone.

Structural shortcomings of the cell were also identified. Gaps between the electrode edges and the

acrylic walls led to the formation of protrusions that locally intensified the electric field, triggering an electrohydrodynamic vortex. This vortex transported contaminated emulsion from the bottom of the cell back into the IEG. To suppress this effect, an insert was introduced to block vortex formation. Final experiments were conducted after implementing this design modification.

Relative brightness was evaluated in four regions of the image (Fig. 6): (1) upper part of the IEG, (2) central part of the IEG, (3) lower part of the IEG, and (4) the combined area covering regions 1 through 3.

Comparative plots for experiments at different voltages are presented below (Fig. 7). The relative brightness plots are shown for region 1, as it clarifies faster than the other regions. The plots demonstrate that increasing the electric field strength results in faster emulsion clarification.

Now, we proceed to the analysis of the statistical characteristics of the emulsion. Below are the plots showing the time evolution of the maximum droplet radius, average droplet radius, and the number of droplets per image (Figs. 8–10).

The relative brightness plots tend to reach a steadystate value, indicating that the emulsion is no longer clarifying. However, some values do not reach the theoretical maximum of 1. This can be attributed to small droplets adhering to the transparent cell walls during the experiment, slightly reducing the final relative brightness.

It can also be observed that, regardless of the applied field strength, both the maximum and average droplet radii remain approximately constant throughout the experiment.



Fig. 6 Areas for brightness calculation.



Fig. 7 Relative brightness in area 1.



Fig. 8 Time dependence of the maximum droplet radius on the photo.



Fig. 9 Time dependence of the average droplet radius on the photo.



Fig. 10 Time dependence of the number of drops on the photo.

#### IV. CONCLUSION

In this study, an experimental prototype of an electrocoalescer unit was developed to obtain quantitative data necessary for the validation of numerical models. A set of parameters characterizing the efficiency of emulsion clarification was selected and measured, including the relative brightness in the interelectrode zone and statistical properties of the emulsion such as the number of droplets per sample, and the maximum and average droplet radii.

Methods were developed for acquiring these parameters, including video recording of the processes in the cell and microscopic analysis of extracted samples. The cell was also modified by adding an insert that eliminates undesired vortices caused by edge effects near the electrodes. Additionally, the volume of emulsion poured into the cell was adjusted to prevent slow settling of the emulsion from the upper region of the cell.

An analysis of the influence of electric field strength on the clarification process was carried out. It was shown that large droplets capable of undergoing electrospraying did not form under the tested field strengths and for the chosen electrode size.

The experimental results showed that the average and maximum droplet radii remained approximately constant during the process, while the number of droplets in the sample decreased more rapidly with increasing applied voltage.

## ACKNOWLEDGMENT

The study was supported by Russian Science research 22-79-10078, Foundation, project No. https://rscf.ru/en/project/22-79-10078/. The research was performed at the Research Park of St. Petersburg State University "Computing Center," "Center for Nanofabrication of Photoactive Materials (Nanophotonics)," and "Center for Diagnostics of Functional Materials for Medicine, Pharmacology, and Nanoelectronics."

## REFERENCES

- [1] C. Narváez-Muñoz, A. R. Hashemi, M. R. Hashemi, L. J. Segura, and P. B. Ryzhakov, "Computational ElectroHydroDynamics in microsystems: A Review of Challenges and Applications," *Arch. Comput. Methods Eng.*, no. June, Jun. 2024, doi: 10.1007/s11831-024-10147-x.
- [2] V.A. Chirkov, S.A. Vasilkov, P.A. Kostin, and I.A. Elagin, Numerical models of two-phase electrohydrodynamics for simulating key processes

in electrostatic coalescers: a review (invited paper), Journal of Electrostatics, 104085 (2025), *in press*.

- J. Xu, B. Li, Z. Sun, Z. Wang, B. Liu, and M. Zhang, "Effects of electrode geometry on emulsion dehydration efficiency," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 567, no. December 2018, pp. 260–270, 2019, doi: 10.1016/j.colsurfa.2019.01.069.
- [4] H. Gong, B. Yu, Y. Peng, and F. Dai, "Promoting coalescence of droplets in oil subjected to pulsed electric fields: changing and matching optimal intensity and frequency electric field for demulsification," J. Dispers. Sci. Technol., vol. 40, 1236-1245, 2019, no. 9. pp. doi: 10.1080/01932691.2018.1505525.
- [5] P. P. Kothmire, Y. J. Bhalerao, V. M. Naik, R. M. Thaokar, and V. A. Juvekar, "Experimental studies on the performance and analysis of an electrostatic coalescer under different electrostatic boundary conditions," *Chem. Eng. Res. Des.*, vol. 154, pp. 273–282, 2020, doi: 10.1016/j.cherd.2019.12.012.
- [6] R. Hasib, V. Anand, V. M. Naik, V. A. Juvekar, and R. M. Thaokar, "Mitigating Noncoalescence and Chain Formation in an Electrocoalescer by Electric Field Modulation," *Ind. Eng. Chem. Res.*, vol. 61, no. 46, pp. 17145–17155, Nov. 2022, doi: 10.1021/acs.iecr.2c02202.
- [7] R. Painuly and V. Anand, "Bottle test technique for separating water-in-sunflower oil emulsion under an application of electric field stabilised by surfactant and hydrolysed polyacrylamide," *Fuel*, vol. 377, no. March, p. 132734, Dec. 2024, doi: 10.1016/j.fuel.2024.132734.
- [8] V. Chirkov, G. Utiugov, I. Blashkov, and S. Vasilkov, "The effect of changing interfacial tension on electrohydrodynamic processes in two-phase immiscible liquids," *Int. J. Plasma Environ. Sci. Technol*, vol. 17, no. 3, p. e03003, 2023, doi: 10.34343/ijpest.2023.17.e03003.

## Effect of Polarity Change on Asymmetric Cylinder-To-Cylinder EHD Device

Ihssan Matar<sup>1\*</sup>, Michel Daaboul<sup>2</sup>, Christophe Louste<sup>1</sup> <sup>1</sup>Team EFD, Pprime, University of Poitiers, France <sup>2</sup>Department of Mechanical Engineering, University of Balamand, Lebanon \*Corresponding author: ihssan.matar@univ-poitiers.fr

Abstract-Since the 1960s, electrohydrodynamics (EHD) has attracted significant research interest, particularly for its potential in developing EHD micro-pumps. These pumps offer advantages such as low power consumption, absence of mechanical vibrations, and straightforward fabrication, making them ideal for space applications and other environments requiring thermal management of electronic devices. Despite these benefits, EHD pumps often exhibit lower efficiency compared to other fluid transport technologies, limiting their broader application. A crucial factor influencing EHD pump performance is the geometry and placement of electrodes, which significantly affect electric force distribution and fluid motion. Various electrode configurations, such as bladeblade and point-blade arrangements, have been studied, each demonstrating unique impacts on current distribution, fluid velocity, and overall pump efficiency. These studies highlight the importance of optimizing electrode design to enhance pump performance. Previous research focused on a symmetric cylinder-to-cylinder EHD configuration to ensure a conduction-dominated electric force regime, avoiding charge injection for a more controlled environment. Under these symmetric conditions, it was observed that polarity had little effect on fluid velocity and vortex size, although it mirrored vortex shape and position relative to the vertical axis. This study extends previous findings by experimentally analyzing the effects of polarity manipulation in an asymmetric cylinder-to-cylinder system with a fixed electrode gap. The results indicate that varying polarity between asymmetric electrodes significantly alters fluid dynamics, impacting vortex morphology, location, and fluid velocity. These changes are attributed to ionic mobility ratios within the fluid and the electric field intensity between asymmetric cylinders. By demonstrating how polarity changes in asymmetric systems influence EHD pump behavior, this work provides valuable insights for optimizing EHD pump configurations. The findings contribute to a deeper understanding of EHD systems and offer potential improvements in thermal management applications where precise fluid control is essential.

## Keywords- Electrohydrodynamics, Hydrofluoroether-7100, Micro-Pump, Particle Image Velocimetry.

## I. INTRODUCTION

The efficiency of industrial systems that involve liquid flow can be improved through the integration of control mechanisms. Electrohydrodynamic (EHD) techniques offer a promising approach for regulating liquid motion due to their several advantages, including high reliability, rapid response times compared to conventional methods, and minimal energy consumption.

There are three major EHD phenomena that can be utilized to induce liquid movement. The first, which is the focus of this study, is the conduction phenomenon [1]. This mechanism occurs under relatively low electric field intensities and is governed by the dissociationrecombination process, along with the formation of heterocharge layers near the electrode surfaces. The second phenomenon involves the injection of ions into a dielectric liquid [2], which takes place when the applied electric field surpasses a critical threshold. The third mechanism, induction [3], arises in the presence of a thermal gradient.

In the presence of an electric field, three distinct types of electric forces can act upon a liquid:

• Coulomb Force: This force is directly proportional to the electric charge of a particle and governs its motion.

•Dielectrophoretic Force: This force depends on the gradient of the particle's permittivity, influencing its movement in non-uniform electric fields.

•Electrostriction Force: This force is associated with the particle's polarity and the resulting deformation in its shape under the influence of the electric field.

A key determinant of EHD pump performance is the geometry and spatial arrangement of the electrodes, as these factors play a crucial role in shaping the distribution of electric forces and, consequently, the resulting fluid motion. The electrode configuration directly influences charge transport, field intensity, and the formation of heterocharge layers, all of which are critical to the efficiency of the pumping mechanism.

Various electrode arrangements have been extensively investigated to assess their impact on the overall effectiveness of EHD pumps. Among these, bladeblade [4] and point-blade [5] configurations have been studied, each exhibiting distinct effects on current distribution, induced fluid velocity, and energy efficiency. The blade-blade setup ensures a more uniform electric



Fig. 1. Front view of the cell. a) Symmetrical cylinders, b) Asymmetrical cylinders.

Table 1: Material Properties				
Material	Density $(kg/m^3)$	Conductivity (S/m)	Permittivity	
HFE7100	1480	10 <sup>-8</sup>	7.4	
PMMA	1180	10 <sup>-17</sup>	2.9	

field distribution, promoting steady fluid motion, whereas the point-blade configuration generates localized highintensity electric fields, enhancing charge injection but also introducing complexities in flow stability.

These findings underscore the necessity of optimizing electrode design to improve pump performance. Finetuning parameters such as electrode spacing, shape, and alignment can lead to enhanced charge mobility, reduced energy losses, and greater control of the fluid flow. As a result, ongoing research aims to refine electrode geometries to achieve higher efficiency, reduced power consumption, and improved operational stability.

Previous studies have primarily investigated a symmetric cylinder-to-cylinder [6] EHD configuration to establish a conduction-dominated electric force regime while minimizing the effects of charge injection. This approach was adopted to maintain a controlled and predictable environment, ensuring that the primary mechanism influencing fluid motion was conduction rather than ion injection.

## II. EXPERIMENTAL SETUP

## A. Experimental Configuration

Fig. 1 presents the schematic diagrams of two experimental setups. The first configuration, shown in Fig. 1(a), consists of two symmetric copper cylindrical electrodes, each with a diameter of 22 mm and a length of 55 mm, separated by a 10 mm gap. The second setup, depicted in Fig. 1(b), features two asymmetric cylindrical electrodes with the same gap; the electrode on the left has a diameter of 39 mm, while the one on the right has a diameter of 5 mm. In both cases, the electrodes are connected to a high-voltage power supply, with one electrode being grounded in some configurations. Both electrode pairs are enclosed within a PMMA cavity cell with dimensions of 10cm×8cm×5cm. This specific geometry was chosen to minimize ion injection at the edges of the electrodes. The cavity is filled with HFE 7100 through two openings on its upper surface. To ensure consistency throughout the experiments, PMMA tracer particles were utilized, as previous studies [7] have shown their suitability for this type of measurement. The tracer particles were dried at 50°C for one hour to eliminate moisture content before being introduced into the system. Material properties are shown in Table 1 [8].



Fig. 2. PIV Measurement Apparatus



## B. PIV Measurement Technique

Flow velocity fields were measured using Particle Image Velocimetry (PIV) [9], a well-established technique for capturing time-resolved, full-field velocity distributions in both single-phase and multiphase flows. This method involves seeding the flow with tracer particles, whose characteristics are critical to the accuracy of the measurements. In this study, a LaVision acquisition system (LaVision GmbH, Göttingen, Germany) was employed for PIV measurements. Tracer particles were illuminated by a thin sheet of light generated by a pulsed laser. Two successive laser pulses illuminated the measurement plane, and particle displacements were captured by a CCD digital camera. The apparatus is shown in Fig. 2. The particle velocity fields were computed by cross-correlating the particle positions in the two images, with a known time interval between pulses allowing the calculation of the velocity vector fields. For each experimental trial, 2000 frames were captured to ensure statistically converged time-averaged velocity fields.

## III. RESULTS

Experiments were conducted using a direct current (DC) power supply with both positive and negative voltage polarity. In the first setup, the voltage polarity did not significantly affect the quantitative outcomes. However, in the second configuration, the polarity played a crucial role in both qualitative and quantitative results. Consequently, it is essential to report the polarity when discussing the findings. For each configuration, 2000 instantaneous flow fields were captured using the PIV technique, and the corresponding time-averaged velocity fields were subsequently computed.

Following each experimental run, the experimental cell was disassembled and thoroughly cleaned to prevent contamination between tests. The cleaning procedure involved washing the cell components with soap and water, followed by a complete rinse with distilled water. The components were then dried using compressed air and placed in a drying oven at  $50^{\circ}$ C to ensure complete moisture removal before subsequent tests.

## A. Normality

A critical aspect of any experimental investigation is the reliability and statistical viability of the acquired data. In the present study, the raw velocity data obtained from



2000 PIV samples were analyzed to ensure that the inherent noise did not compromise the quality of the measurements. To validate this, it was essential to demonstrate that the velocity data followed a normal (Gaussian) distribution. A quantile–quantile (Q–Q) plot [10], presented in Fig. 3, confirms the normality of the data distribution, with a distribution coefficient ranging from 96.8% to 99.4% across all test runs. Furthermore, the distribution of the global average velocity is illustrated in Fig. 4. These findings, when combined with what is discussed in the repeatability section, justify the use of the ensemble-averaged velocity field computed over the 2000 samples as a statistically robust representative for comparing different experimental conditions.

### B. Repeatability

То evaluate the repeatability of the PIV measurements, a series of experiments was conducted under identical operating conditions. A direct current (DC) voltage of 2 kV was applied between the electrodes. For each experimental run, 2000 instantaneous velocity fields were acquired using the PIV system. As described in subsection A, the variation of the temporally averaged velocity field with respect to the acquisition sequence (i.e., sample number) is illustrated in Fig. 4. The results indicate that the average velocity consistently fluctuates within a narrow range when at  $\Delta V = 2 \text{ kV}$ . Additionally, timeaveraged velocity fields were computed and compared across independent experiments. Both the global mean velocity and the peak velocity remained nearly constant across all runs. In the configuration, when the larger electrode was set to positive polarity. The maximum observed deviation did not exceed 0.03 mm/s, which falls within acceptable uncertainty bounds.



Fig. 5. Time-averaged Velocity field for  $\Delta V = 2 \text{ kV}$  When Positive Polarity is on The Large Electrodes.

These findings demonstrate the high repeatability of PIV measurements under the specified experimental conditions. Minor discrepancies between runs are primarily attributed to slight fluctuations in seeding particle density and ambient environmental conditions. Overall, the experimental uncertainty remained within acceptable limits for reliable quantitative flow characterization. Given the observed consistency in both symmetric and asymmetric configurations, it was deemed appropriate to proceed with varying the applied voltage to investigate its influence on the flow behavior.

#### C. Voltage Dependence

During the experiments, the applied voltage  $\Delta V$  was systematically varied across a range of 1, 2, 4, 6, 8, and 10 kV for both polarity configurations. When the positive polarity was applied to the larger electrode, it was possible to extend the voltage range further, reaching up to 20 and 30 kV. The subsequent analysis will examine the evolution of both the average and maximum fluid velocity as a function of the applied voltage for each polarity configuration. Additionally, the vorticity distribution around the electrodes will be investigated to assess the influence of polarity inversion on the flow structure. For clarity and convenience, the larger electrode is denoted as 'B' and the smaller electrode as 'S' during the discussion.

## D. Positive Polarity on the Large Electrode

In this configuration, a positive voltage was applied to 'B', while 'S' was held at negative potential. Fig. 5 displays the velocity field for an applied voltage of  $\Delta V = 2$  kV. A prominent vortex structure is observed along the length of the 'B', originating near the edge adjacent to the smaller electrode. The flow pattern exhibits symmetry above and below 'B', suggesting a balanced distribution of induced motion. Notably, a near-zero velocity region appears at the edge of the large electrode within the inter-electrode gap, which is likely associated with a zone of neutral electrical charge. The maximum fluid velocity is observed at the edge of 'B', coinciding with the region of flow separation.

As the applied voltage was varied, both the maximum and global average velocities were found to increase linearly. Fig. 6 illustrates this relationship, showing a clear linear trend with a predicted slope of approximately  $2.5 \text{ mm} \text{s}^{-1} \text{kV}^{-1}$ . This indicates a proportional response of the flow velocity to the strength of the applied electric field under the given configuration.



Fig. 6. Time-averaged Velocity field for  $\Delta V = 2 \text{ kV}$  When Positive Polarity is on The Large Electrodes.



Fig. 7. Time-averaged Velocity field for  $\Delta V = 2$  kV When Positive Polarity is on The Small Electrodes.

## E. Positive Polarity on the Small Electrode

In this configuration, a positive voltage was applied to 'S', while 'B' was held at negative potential. Fig. 7 illustrates the resulting velocity field at  $\Delta V = 2$  kV. Compared to the previous configuration, the flow exhibits increased unsteadiness, particularly beneath the electrodes, suggesting more complex and possibly turbulent behavior. The main vortices appear closer to the inter-electrode gap and are smaller in size. A distinct streamline is observed between the two vortices, extending from the 'S' toward 'B', which may indicate the presence of charge injection occurring across the gap. Overall, the dominant flow direction is oriented from 'S' to 'B'. The maximum velocity is recorded on the upper side of 'S', near the region of highest flow separation.

Upon varying the applied voltage, a linear relationship between velocity and voltage was again observed, similar to the previous case. However, the slope of this trend was significantly lower, measured at approximately  $1.15 \text{ mm} \cdot \text{s}^{-1} \cdot \text{kV}^{-1}$ , as presented in Fig. 6.

## IV. DISCUSSION AND CONCLUSION

The results obtained from both polarity configurations reveal distinct differences in flow behavior, spatial velocity distribution, and response to the applied voltage. When the positive voltage was applied to 'B', the flow exhibited a relatively stable and symmetric vortex structure extending along the surface of the electrode. The velocity field was well-organized, with a linear increase in global average and maximum velocity as the applied voltage increased. This trend suggests a strong and uniform EHD driving mechanism under this polarity, with a predicted velocity-voltage slope of 2.5 mm·s<sup>-1</sup>·kV<sup>-1</sup>.

In contrast, when the polarity was reversed, applying a positive voltage to 'S', the flow became more irregular and complex. The vortices were smaller, more chaotic, and shifted closer to the electrode gap, indicating increased local instabilities or the onset of turbulence. The presence of a direct flow channel from 'S' to 'B' and a global flow direction aligned accordingly suggests the possibility of charge injection, which could alter the electric field distribution and, consequently, the flow dynamics. Notably, although the velocity still exhibited a linear response to voltage, the slope decreased significantly to  $1.15 \text{ mm} \cdot \text{s}^{-1} \cdot \text{kV}^{-1}$ , reflecting a less efficient momentum transfer under this configuration. These observations highlight the critical influence of electrode geometry and polarity on the structure and intensity of EHD flows. The larger electrode under positive potential creates a more favorable configuration for inducing strong and stable flow patterns. Conversely, reversing polarity results in weaker and more disordered flow, possibly due to enhanced charge injection effects and field non-uniformity. Such insights are essential for optimizing electrode design and operating conditions in applications involving EHD flow control, such as cooling systems or fluid transport.

- [1] C. Louste, H. Romat, P. Traoré, M. Daaboul, P. Vázquez, and R. Sosa. Electroconvective Cavity Flow Patterns Created by Asymmetric Electrode Configuration, *IEEE Transactions on Industry Applications*, 54(5):4851-4856, Sept.-Oct. 2018.
- [2] S. Zhihao, D. Sun, J. Hu, P. Traoré, H.-L. Yi, and J. Wu. Experimental study on electrohydrodynamic flows of a dielectric liquid in a needle-plate configuration under direct/alternating current electric field, *Journal of Electrostatics*, 106: 103454, 2020.
- [3] S.A. Vasilkov, V.A. Chirkov, and Y.K. Stishkov. Study on high- voltage conductivity provided solely by field-enhanced dissociation in liquid dielectrics, *Journal of Electrostatics*, 88:81-87, 2017.
- [4] M. Daaboul, C. Louste, and H. Romat. PIV Measurements of the Influence of Seeding Particles Concentration on the Velocity of an EHD Flow, *ESA/IEEE-IAS/IEJ/SFE Joint Conference on Electrostatics*, Boston, USA, June 2009.
- [5] P. Atten and J. Seyed-Yagoobi. Electrohydrodynamically induced dielectric liquid flow through pure conduction in point/plane geometry, *IEEE Transactions on Dielectrics and Electrical Insulation*, 10:27-36, Feb. 2003.
- [6] I. Matar, C. Louste and M. Daaboul. Numerical Estimation of the Electric Force Induced by a Cylinderto-Cylinder EHD Device, *International Conference on Dielectric Liquids*, Worcester, USA, 2023.
- [7] M. Daaboul, I. Matar, M. Nassar, and C. Louste. Testing Different Tracer Types in Particle Image Velocimetry Measurements in Electrohydrodynamics, *International Conference on Dielectric Liquids*, Worcester, USA, 2023.
- [8] M. Nassar, P. A. Vázquez, N. Chauris, M. Daaboul, A. Michel, and C. Louste. Experimental Models of the Variation of HFE-7100 and HFE-7000 Electric Properties with Temperature, *IEEE Transactions on Industry Applications*, 56:4193-4199, 2020.
- [9] A. E. Perri, A. Sankaran, C. Staszel, R. J. Schick, F. Mashayek, and A. L. Yarin. The particle image velocimetry of vortical electrohydrodynamic flows of oil near a high-voltage electrode tip, *Experiments in Fluids*, 62:1-13, 2021.
- [10] M. Kratz, and S.I. Resnick, The QQ-estimator and heavy tails. *Communications in Statistics. Stochastic Models*, 12:699–724, 1996.

## Application of the Arbitrary Lagrangian–Eulerian Approach to Simulate Two-phase Electrohydrodynamics of Low-conducting Droplets in Low-Conducting Dispersion Medium

V.A. Chirkov\*, E.O. Chervinskaia, P.A. Kostin, D.A. Kudinov, S.A. Vasilkov, I.A. Elagin St. Petersburg State University, St. Petersburg, Russia \*Corresponding author: v.chirkov@spbu.ru

Abstract—The present study is devoted to the modification of numerical model basing on the arbitrary Lagrangian—Eulerian method in COMSOL Multiphysics software to simulate electrohydrodynamics of low-conducting droplets in a low-conducting dispersion medium. The new models consider both normal and tangential projection of the electrostatics forces and droplet-surface charging owing to emerging ion fluxes after the electric field change or volume alteration (e.g., due to droplet electrodeformation). The modified model was applied to simulate several specific tasks to check its correctness, in particular, to model air bubble shape change under the AC electric field. The model can be applied for computation of low-conducting droplets and bubbles behavior under the electric field.

Keywords—Leaky dielectric model, numerical simulation, air bubble, electrodeformation.

## I. INTRODUCTION

Presently, there are a lot of models available for computations of electrohydrodynamic (EHD) processes in two-phase immiscible liquids [1,2]. One of the very promising approaches-the arbitrary Lagrangian–Eulerian (ALE) method-has been successfully applied recently to simulate electrical coalescence of two electrically conducting droplets suspended in a dielectric fluid [3-5]. However, the case of electrically conducting droplets is much simpler than the case of less conducting suspended medium due to the following. In the former case, electrostatic forces act only along the normal direction and the surface-charge relaxation time is negligible. The late case is not new and has been studied for several decades [6-9]. It is known that the direction of deformation of a droplet of one oil in another is determined by the ratio of the dielectric permittivity, electrical conductivity, and viscosity values, and the droplet can either elongate or contract. A number of studies have been devoted to numerical modeling and analytical analysis of the corresponding problem [10-12]. However, fully reproducing experimental data on the electrohydrodynamics of a droplet of one oil suspended in another oil, as in [13], remains a challenging task.

The present study is devoted to corresponding modification of the ALE model and its implementation in COMSOL Multiphysics software. The new models consider the following:

- both normal and tangential projection of the electrostatics forces;

- droplet-surface charging owing to emerging ion fluxes after the electric field change or volume alteration (e.g., due to droplet electrodeformation).

Particular attention is given to modeling transient (non-stationary) processes associated with the accumulation (variation) of surface charge on the droplet interface. If successfully implemented, this model can be further extended to account for:

- charge convection along the surface (e.g., due to droplet rotation);

- dissociation-recombination charge layers in both media;

- and bubble compressibility.

Moreover, following the approach used in modeling electrocoalescence of conducting droplets, a model for bubble coalescence could also be developed.

## II. NUMERICAL MODEL

Numerical modeling was performed using the COMSOL Multiphysics software package. Two modeling approaches were considered: one based on the steady-state current continuity set of equations, and another based on a novel approach described in [14], where the differential form of Gauss's law is solved in the bulk domain while an additional ordinary differential equation for surface charge density is solved at the interface.

In the first approach (hereafter referred to as Model #1), the following system of equations was solved in the bulk domain:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla P + \nabla \cdot (\eta (\nabla \vec{u} + \nabla \vec{u}^{\mathrm{T}})) \quad (1)$$

 $\nabla \cdot \vec{u} = 0 \tag{2}$ 

$$\nabla \cdot \vec{j} = 0 \tag{3}$$

$$\dot{j} = \sigma \vec{E} \tag{4}$$

$$\vec{E} = -\nabla V. \tag{5}$$

Here  $\rho$  is the mechanical density,  $\vec{u}$  is the velocity, P is the pressure,  $\eta$  is the dynamic viscosity,  $\vec{j}$  is the electric current density,  $\vec{E}$  is the electric field, V is the electric potential,  $\sigma$  is the electrical conductivity, t is the time.

In the second approach (hereafter referred to as Model #2), the following equation was solved in the bulk domain instead of Equations (3)–(4):

$$\nabla \cdot (\varepsilon \varepsilon_0 \vec{E}) = 0 \tag{6}$$

and at the interface:

$$\frac{d\lambda}{dt} = j_{\rm diff} + j_{\rm geom} \tag{7}$$

$$j_{\text{geom}} = -\frac{\lambda}{\xi} \frac{d\xi}{dt} \tag{8}$$

$$j_{\text{diff}} = \text{up}(\sigma E_{\text{n}}) - \text{down}(\sigma E_{\text{n}})$$
 (9)

Here  $\lambda$  is the surface charge density, "up" and "down" represent the values of the function "above" and "below" the boundary,  $j_{\text{diff}}$  is the density of the electric current due to the charge conservation,  $j_{\text{geom}}$  is the change in the surface charge due to the movement of the surface,  $\xi$  is the expansion coefficient of the surface element.

In the case of the ALE approach, the interface between the two phases is represented as a geometry line. The line moves in accordance with the calculated fluid velocity throughout the solution of the problem. So, the velocities of contacting liquids—the dispersed phase  $\vec{u}_d$  and continuous media  $\vec{u}_m$ —are equal to each other at the boundary and equal to that of the interface  $\vec{u}_{interface}$ :

$$\vec{u}_{\rm d} = \vec{u}_{\rm m} = \vec{u}_{\rm interface}.$$
 (10)

The normal and tangent components of the Coulomb surface force  $\vec{P}_{c}$  acting on the surface charge can be represented by expressions (11) and (12), respectively [8]:

$$P_{C_n} = \frac{1}{2} \left( \varepsilon_m E_{c_n}^2 - \varepsilon_d E_{d_n}^2 - (\varepsilon_m - \varepsilon_d) E_{\tau}^2) \right)$$
(11)

$$P_{C_{\tau}} = \left(\varepsilon_{\rm m} E_{\rm c_n} - \varepsilon_{\rm d} E_{\rm d_n}\right) E_{\tau}.$$
 (12)

Here  $E_{c_n}$  and  $E_{d_n}$  are the normal components of electric field strengths on the droplet boundary at the corresponding sides,  $E_{\tau}$  is the tangent component of electric field strength; subscript "m" means medium and "d"—droplet.

The following properties of liquids were used (if another values are not specified in figure captions):  $\eta_m = 0.06 \text{ Pa} * \text{s}$ ,  $\rho_m = 910 \text{ kg/m}^3$ ,  $\varepsilon_m = 2$ ,  $\sigma_m = 1e - 10 \text{ S/}$ m,  $\eta_d = 0.001 \text{ Pa} * \text{s}$ ,  $\rho_d = 1000 \text{ kg/m}^3$ ,  $\varepsilon_d = 4$ ,  $\sigma_d = 1e - 10 \text{ S/m}$ , interfacial tension  $\gamma = 16 \text{ mN/m}$ . For the simulation of bubble electrodeformation, the following properties were used:  $\eta_b = 1e - 5 \text{ Pa} * \text{s}$ ,  $\rho_b = 1.25 \text{ kg/m}^3$ ,  $\varepsilon_b = 1$ .

The geometry of the computer model and the boundary conditions for the two approaches are shown in Fig. 1.



Fig. 1. A schematic representation of the model geometry.

#### III. RESULTS AND DISSCUSION

First and foremost, Model #1 was employed to compute droplet deformation values for various ratios of dielectric permittivity and electrical conductivity between the droplet and surrounding medium. In Fig. 2, the simulation results are depicted as red markers, while the blue curves represent the analytical solution for deformation degree according to Taylor's formula [6,12]:

$$D = \frac{a-b}{a+b}$$
(13)  
$$D = \frac{9We}{ce} \frac{1}{c^{\sigma_{m}} 2_{-1}} \left( \left(\frac{\sigma_{m}}{c}\right)^{2} + 1 - 2\frac{\varepsilon_{d}}{c} \right)^{2} + 1 - 2\frac{\varepsilon_{d}}{c}$$

$$+3\left(\frac{\sigma_{\rm m}}{\sigma_{\rm d}}-\frac{\varepsilon_{\rm d}}{\varepsilon_{\rm d}}\right)*\frac{5\frac{\eta_{\rm d}}{\eta_{\rm m}}+3}{1-2}$$
(14)

$$F3\left(\frac{1}{\sigma_{d}} - \frac{1}{\varepsilon_{m}}\right) * \frac{5\eta_{d}}{5\eta_{m}+5}$$
(14)

$$We = \frac{\varepsilon_0 \varepsilon_m R_d E_0}{\gamma}.$$
 (15)

Here D is the degree of the deformation, a is the major semi-axis, b is the minor semi-axis of an ellipse, We is the electric Weber number,  $R_d$  is the droplet radius, and  $E_0$  is the average electric field strength.



Fig. 2. Numerical results and the theoretical prediction of small deformations for: a)  $\sigma_d/\sigma_m = 5$  and We = 0.1; b)  $\epsilon_d/\epsilon_m = 2$  and We = 0.1; the blue line is the theoretical curve and the green one is the case of perfectly conducting droplet.

The direct application of Model #1 to solve the transient problem yields incorrect results. Therefore, Model #2 was employed to calculate the deformation of an air bubble in an AC electric field. Initially, the bubble deformation following pulsed voltage application was computed. For the selected properties of the bubble and surrounding medium, the steady-state deformation value according to Taylor's formula should correspond to the compression, which was indeed obtained in the numerical solution. However, during the transient process, the bubble initially exhibited elongation, and only subsequently (after sufficient accumulation of free charge at the interface) began to compress.



Fig. 3. Time-dependence of air bubble deformation after pulsed turn-on of the DC voltage (We = 0.1).

Subsequently, the problem of bubble deformation in a 50 Hz alternating electric field was solved. In this case, the surface charge failed to accumulate sufficiently at the interface during each half-cycle of the voltage, resulting in sustained bubble elongation rather than compression. These numerical results demonstrate good qualitative agreement with established experimental data, e.g., as reported in [15].



Fig. 4. Time-dependence of air bubble deformation under AC voltage (We = 0.1).

#### IV. CONCLUSION

In this paper, we implement and qualitatively verify a model of electrical deformation of a drop of a lowconducting liquid and a bubble in another lowconducting liquid using the arbitrary Lagrangian–Eulerian approach. The modified model was applied to simulate several specific tasks to check its correctness. In particular, the modeling of air bubble shape change under AC electric field was done. The model can be applied for computation of low-conducting droplets and bubbles behavior under the electric field.

#### ACKNOWLEDGMENT

The research was performed at the Research Park of St. Petersburg State University "Computing Center."

- [1] C. Narváez-Muñoz, A. R. Hashemi, M. R. Hashemi, L. J. Segura, and P. B. Ryzhakov, "Computational ElectroHydroDynamics in microsystems: A Review of Challenges and Applications," *Arch. Comput. Methods Eng.*, no. June, Jun. 2024, doi: 10.1007/s11831-024-10147-x.
- [2] V.A. Chirkov, S.A. Vasilkov, P.A. Kostin, and I.A. Elagin, Numerical models of two-phase electrohydrodynamics for simulating key processes in electrostatic coalescers: a review (invited paper), Journal of Electrostatics, 104085 (2025), *in press*.
- [3] G. Utiugov, V. Chirkov, and M. Reznikova, "Application of the arbitrary Lagrangian-Eulerian method to simulate electrical coalescence and its experimental verification," *Int. J. Plasma Environ. Sci. Technol.*, vol. 15, no. 2, p. e02009, 2021, doi: 10.34343/ijpest.2021.15.e02009.
- [4] V. Chirkov, G. Utiugov, P. Kostin, and A. Samusenko, "Physical correctness of numerical

modeling electrohydrodynamic processes in twophase immiscible liquids basing on the phase-field and arbitrary Lagrangian–Eulerian methods," *Int. J. Multiph. Flow*, vol. 177, no. April, p. 104881, Jul. 2024, doi: 10.1016/j.ijmultiphaseflow.2024.104881.

- [5] D. D. Saifullin, D. S. Lukin, A. V Samusenko, and V. A. Chirkov, "Regime map of non-coalescence between two equal-sized uncharged water droplets suspended in oil: A numerical study," *Phys. Fluids*, vol. 36, no. 12, p. 123310, Dec. 2024, doi: 10.1063/5.0240476.
- [6] G. Taylor and P. R. S. L. A, "Studies in electrohydrodynamics. I. The circulation produced in a drop by an electric field," *Proc. R. Soc. London. Ser. A. Math. Phys. Sci.*, vol. 291, no. 1425, pp. 159–166, 1966, doi: 10.1098/rspa.1966.0086.
- [7] D. A. Saville, "Electrohydrodynamics: The Taylor-Melcher Leaky Dielectric Model," *Annu. Rev. Fluid Mech.*, vol. 29, no. 1, pp. 27–64, Jan. 1997, doi: 10.1146/annurev.fluid.29.1.27.
- [8] J. M. López-Herrera, S. Popinet, and M. A. Herrada, "A charge-conservative approach for simulating electrohydrodynamic two-phase flows using volume-of-fluid," *J. Comput. Phys.*, vol. 230, no. 5, pp. 1939–1955, Mar. 2011, doi: 10.1016/j.jcp.2010.11.042.
- [9] P. M. Vlahovska, "Electrohydrodynamics of drops and vesicles," *Annu. Rev. Fluid Mech.*, vol. 51, pp. 305–330, 2019, doi: 10.1146/annurev-fluid-122316-050120.

- [10] A. Esmaeeli, "Transient electrohydrodynamics of a liquid drop in AC electric fields," *Eur. Phys. J. E*, vol. 41, no. 11, p. 135, Nov. 2018, doi: 10.1140/epje/i2018-11745-1.
- [11] Q. Dong and A. Sau, "Electrohydrodynamic interaction, deformation, and coalescence of suspended drop pairs at varied angle of incidence," *Phys. Rev. Fluids*, vol. 7, no. 3, pp. 1–38, 2018, doi: 10.1103/PhysRevFluids.3.073701.
- [12] Y. Lin, "Two-phase electro-hydrodynamic flow modeling by a conservative level set model," *Electrophoresis*, vol. 34, no. 5, pp. 736–744, Mar. 2013, doi: 10.1002/elps.201200300.
- [13] J. R. Karp, B. Lecordier, and M. S. Shadloo, "Electrohydrodynamic flows inside a neutrally buoyant leaky dielectric drop," *Phys. Fluids*, vol. 36, no. 5, pp. 1–12, May 2024, doi: 10.1063/5.0204569.
- [14] D.A. Kudinov, V.A. Chirkov, S.A. Vasilkov, I.A. Elagin, "Features of numerical simulation of unsteady-state electric current passage processes in COMSOL Multiphysics in relation to the capacitive energy storage simulation," *Journal of Physics: Conference Series, in press.*
- [15] S. M. Korobeynikov, A. V. Ridel, and D. A. Medvedev, "Deformation of bubbles in transformer oil at the action of alternating electric field," *Eur. J. Mech. - B/Fluids*, vol. 75, pp. 105–109, May 2019.

## Impact of Seeding Particle Properties on PIV Accuracy in Electrohydrodynamic Systems

Michel Daaboul<sup>1\*</sup>, Ihssan Matar<sup>2</sup>, Christophe Louste<sup>2</sup> <sup>1</sup>University of Balamand, Tripoli, Lebanon <sup>2</sup>University of Poitiers, Poitiers, France \*Corresponding author: michel.daaboul@balamand.edu.lb

Abstract- Particle Image Velocimetry (PIV) is a widely utilized technique for visualizing fluid flows, enabling the capture of instantaneous velocity fields with a single measurement. This method requires introducing fine tracer particles into the fluid, which are illuminated by a laser source, and their motion is recorded to determine the velocity distribution. However, in electrohydrodynamic (EHD) systems, the use of these particles introduces additional challenges due to their interaction with the applied electric field. One key concern is the accumulation of electric charges on the particles' surfaces, which can alter the electric field distribution. Additionally, charged particles may travel at velocities different from the surrounding fluid, violating the fundamental assumption of PIV that the particles accurately track fluid motion. Further issues include particle clumping, filament formation, or adhesion to solid surfaces, which can hinder charge transfer in the dielectric liquid. In extreme cases, the particles may absorb all available charges, neutralizing the fluid and reducing its motion. These phenomena depend strongly on the type of fluid and tracer particles used.

In this study, five types of particles were examined: PMMA (polymethyl methacrylate), POM (polyoxymethylene), PTFE (polytetrafluoroethylene), SiO<sub>2</sub> (silicon dioxide), and Vestosint. Experiments were conducted on a hydrofluoroether dielectric liquid (HFE-7100) in a symmetric cylinder-to-cylinder configuration, with a DC voltage applied between the electrodes. To ensure consistent results, the repeatability of PIV measurements was evaluated across multiple experimental runs. In addition, the migration velocity of tracer particles relative to the fluid was analyzed for various particle types to understand their influence on measurement accuracy. The results demonstrated that fluid behavior varied significantly with the particle type. This indicates that the properties of the seeding particles affect the performance of the EHD apparatus. These findings emphasize the importance of selecting appropriate tracer particles to ensure accurate PIV measurements, particularly in the presence of electric fields where particle-fluid interactions can rigorously affect experimental outcomes.

## Keywords- Dielectric Liquid, Electrohydrodynamics, Particle Image Velocimetry, Seeding Particle.

#### I. INTRODUCTION

Dielectric liquids are widely used in various industrial applications due to their electrical insulation and thermal stability. One important area where they are commonly applied is electrohydrodynamic (EHD) systems [1], where an electric field is used to generate fluid motion [2]. These systems are found in technologies such as electrostatic pumps [3], heating and cooling systems [4], and spraying devices [5]. As the demand for compact and energy-efficient flow control increases, interest in EHD-based designs continues to grow.

The motion in EHD systems is driven by different mechanisms depending on the applied field and fluid properties. Three main regimes are typically identified: conduction, injection, and induction. Conduction happens at low electric field strengths and is associated with charge dissociation and recombination near electrodes [6]. Injection requires a threshold voltage and involves the release of charges from the electrode, which then repel each other and move the fluid [7]. Induction occurs when there is a conductivity gradient in the fluid, often due to a temperature difference, causing fluid motion [8].

To measure flow behavior in such systems, optical techniques like Particle Image Velocimetry (PIV) and

Laser Doppler Anemometry (LDA) are often used [9]. These methods rely on seeding the liquid with small tracer particles and tracking their motion using highspeed imaging. In typical flow conditions like in classical fluid mechanics, these particles follow the fluid accurately. However, under electric fields, this assumption becomes less reliable. The particles may accumulate surface charge, causing them to move differently from the surrounding fluid. In some cases, they can even interfere with the flow by distorting the electric field or even agglomerating together. Density and permittivity differences between the particles and the fluid can also lead to sinking, floating, or other unwanted behaviors [10].





Table 1: Properties of HFE-7100 at a temperature of 25°C [12].

Operating	Density	Electric	Relative
Fluid	(kg/m <sup>3</sup> )	Conductivity (S/m)	Permittivity
HFE-7100	1480	10 <sup>-8</sup>	7.4

This study constitutes a continuity of a previous work which tested PIV method using several tracer particles [11]. The current work focuses on the influence of tracer particle properties on the accuracy and reliability of PIV measurements in EHD systems. Several types of particles with different physical characteristics were tested under a moderate electric field to assess their behavior and their impact on flow visualization. In particular, attention was given to the ability of each particle type to follow the fluid motion without introducing significant disturbances. Special emphasis was also placed on the repeatability of the experiments and on identifying the main causes of measurement degradation when improper seeding particles are used. The goal is to provide practical recommendations for selecting suitable tracer particles for PIV measurements in dielectric liquids subjected to electric fields. This will help improve measurement reliability and support the development of more effective EHD applications.

#### II. EXPERIMENTAL SETUP

## A. Experimental Apparatus

The experimental setup is shown in Fig. 1. It consists of two identical copper cylinders, labeled (1) and (2), mounted in a parallel configuration. A cylinder-tocylinder geometry was chosen to ensure a lower electric field intensity on the electrode surfaces. This is important for facilitating EHD conduction while avoiding EHD injection, which occurs when the electric field exceeds a threshold, often triggered by sharp-edged electrodes. The test cell, (3), is made of PMMA and has internal dimensions of 10 cm  $\times$  8 cm  $\times$  5 cm. It is sealed using anti-leakage joints on sidewalls (4) and (5) to prevent fluid loss. The cell is filled with hydrofluoroether dielectric liquid (HFE-7100) before adding the tracer particles. To eliminate any trapped air, bubbles are vented through the upper openings, (6) and (7).

The operating fluid used in the experiments is HFE-7100, whose properties at 25 °C are listed in Table 1 [12], and previously studied in [13].

PIV measurements are conducted using a LaVision GmbH system, as shown in Fig. 2 [14]. The system is equipped with a double-pulsed laser for illumination and a high-resolution camera for image capture. For each test run, up to 2000 instantaneous images are recorded at a frequency of 5 Hz. This approach allows for consistent

Table 2: Properties of Tested Seeding Particles [16].

Seeding Particle	Density (kg/m <sup>3</sup> )	Electric Conductivity (S/m)	Relative Permittivity
PMMA	1180	10 <sup>-17</sup>	2.9
POM	1400	10 <sup>-15</sup>	3.8
PTFE	2150	10 <sup>-16</sup>	2.1
SiO <sub>2</sub>	2500	10 <sup>-14</sup>	4.6
Vestosint	1020	$10^{-12}$	N/A



Fig. 2. PIV measurement apparatus (© LaVision GmbH) [14].

observation of flow patterns over the test duration.

The captured images are processed using DaVis 8.0 software, where cross-correlation techniques are applied to determine particle displacement between successive frames. Then, the average velocity field is calculated, providing a detailed view of the fluid motion under the influence of the applied electric field. Care was taken to maintain consistent lighting and alignment throughout all measurements to ensure accuracy and repeatability.

## **B.** Experimental Procedure

After each experiment, the test cell was thoroughly cleaned, dried, and reassembled. It was then refilled with the dielectric liquid, sealed, and checked for any leakage before the seeding particles were added. The concentration of tracer particles was kept below 20 mg/L, which is within the acceptable range to ensure minimal interference with the dielectric liquid when subjected to an electric field [15].

Five different types of particles were tested: PMMA (PolyMethyl Methacrylate), POM (PolyOxyMethylene), PTFE (PolyTetraFluoroEthylene or Teflon), SiO<sub>2</sub> (Silicon Dioxyde or Silica), and Vestosint 2070 (Polyamide 12 fine powder). These particles were selected based on differences in density, permittivity, and surface characteristics. Their relevant physical properties are summarized in Table 2 [16].

From these values, it is observed that all tested particles have lower electrical conductivity and permittivity than the operating fluid. On another hand, their densities vary, with some being lower and others higher than that of the liquid.



Fig. 3. Sample PIV image at the start of a test with Vestosint.

The high voltage required for the experiments was supplied by two Spellman SL-100 DC power supplies. One electrode (left) was connected to the high-voltage output, while the opposite electrode (right) was grounded. To verify the symmetry of the setup, the polarity was also reversed between the cylinders in separate tests. The results confirmed symmetrical behavior of the system but these findings are not presented in this paper.

## III. RESULTS AND DISCUSSION

## A. Particle Behavior Under Electric Field

Because the number of tests conducted within the current study is enormous, only sample results are presented for the various tested particles. The purpose is to show a specific behavior observed for a specific tracer type. For example, Fig. 3 shows a sample PIV image at the start of a test with Vestosint. The tracer particles can be clearly seen illuminated by the laser. However, after a certain time, these particles disappeared from the test zone. They were either captured by the charged cylinders or collected at the walls of the PMMA cell. A quick conclusion is that Vestosint particles are not suitable for the HFE liquid in these experiments. Similarly, SiO<sub>2</sub> particles exhibited a random behavior and are also eliminated because their results were inconsistent.

The conclusion section summarizes the most important guidelines that must be taken into consideration when selecting an appropriate tracer type that can provide reliable PIV results with a working fluid.

#### B. Quality of PIV Measurements

Fig. 4 illustrates the velocity field obtained using PTFE tracer particles under an applied voltage of 2 kV. The flow is primarily driven by the conduction mechanism, as evidenced by the development of strong velocity gradients near the high-voltage electrode (left cylinder here). A distinct recirculation pattern emerges between and above the electrodes, consistent with typical EHD conduction flow behavior. The velocity magnitudes are highest near the electrode surfaces and progressively decay toward the boundaries of the test cell. Minor



Fig. 4. Sample velocity vectors and contours with PTFE tracers. image with POM tracer particles.



Fig. 5. Temporal variation of the average velocity measured with POM seeding particles at 2 kV.

irregularities observed close to the side walls can be attributed to a lower seeding density or to optical distortions near the PMMA walls. Importantly, the use of PTFE tracers enabled stable and consistent measurements throughout the test duration, without significant particle agglomeration or deposition, confirming their effectiveness as tracers for PIV in the HFE-7100 dielectric liquid subjected to moderate electric fields.

#### C. Repeatability and Reliability Analysis

Fig. 5 presents the temporal evolution of the average velocity obtained using POM seeding particles at an applied voltage of 2 kV. Four independent tests were conducted under identical conditions to assess the repeatability of the experimental setup. Across all runs, the average velocity remains within a narrow range of approximately 0.004 to 0.006 m/s, with no significant drift or instability observed over the 500 recorded images. The slight difference may be attributed to minor variations in the initial seeding density and particle distribution. The data demonstrate a high level of repeatability, as the velocity trends remain consistent in both amplitude and temporal behavior. The low deviation between tests highlights the reliability of POM particles for PIV applications in EHD flows. These findings support the conclusion that POM tracers do not significantly disturb the liquid behavior and are capable of accurately tracking the flow without undergoing significant charge accumulation or migration toward the electrodes. However, one must be careful when analyzing their results because this behavior can be affected with time (possibly test 4 in the same figure).



Fig. 6. Variations of the number of validated correlations per image with POM tracer particles.

Fig. 6 illustrates the number of validated correlations per image during the PIV processing of for POM tracer particles at 2 kV. Two behaviors can be identified: one corresponding to the beginning of the experiment where the curve looks to be horizontal, and the other after 500 images. It can be observed that after that point, the number of validated vectors gradually decreases with time, indicating a progressive loss of tracer particles from the fluid domain. This is consistent with the earlier observations where particles were seen to deposit onto the electrodes and cell walls. One quick conclusion with POM particles is that a stabilized run can be done within the first 500 images before the images lose a significant amount of tracers which allow for more reliable velocity measurements. This confirms that the particle behavior must be carefully monitored throughout the experiment to ensure accurate PIV results. Note that PMMA and PTFE results remained constant over the entire set of measurements and they are not shown in this section.

## IV. CONCLUSION

The results obtained in this study highlight the critical importance of careful tracer particle selection in PIV measurements conducted under electric fields. While all tested particles were initially considered suitable based on size and density, their behavior under highvoltage conditions varied significantly. PTFE and PMMA tracers showed better overall performance, maintaining good dispersion and producing stable, repeatable velocity fields with minimal deposition on the electrodes or cell walls. POM particles also performed reasonably well, producing clear velocity fields with good dispersion, although they exhibited a slightly higher tendency to accumulate near the electrodes over time. On the other hand, SiO<sub>2</sub> and Vestosint particles tended to accumulate quickly on solid surfaces, degrading the quality of the PIV data and limiting the duration of usable measurements. These observations suggest that, beyond physical compatibility with the fluid, electrical properties such as permittivity and conductivity must also be taken into account. For conduction-dominated EHD flows in dielectric liquids, it is recommended to select particles with low electrical conductivity, moderate density close to that of the liquid, and minimal tendency to become highly charged. Following these criteria helps ensure accurate flow tracking and reliable measurement results over extended test durations.

- M. Tanski, M. Kocik, M. Oleksy, J. Krasniewski, A. Hapka, and W. Janke. A system for liquid cooling of electronic elements with EHD pumping mechanism, *International Journal of Plasma Environmental Science and Technology*, 10(1):47-50, 2016.
- [2] C. Louste, M. Daaboul, and H. Romat. Experimental study of a plane turbulent wall jet induced by a dielectric barrier injection in dielectric liquid, 16<sup>th</sup> IEEE International Conference on Dielectric Liquids (ICDL 2008), Chasseneuil, France, 2008.

- [3] K. Adamiak, A. Mizuno, and M. Nakano. Electrohydrodynamic Flow in Optoelectrostatic Micropump: Experiment Versus Numerical Simulation, *IEEE Transactions on Industry Applications*, 45(2):615-622, 2009.
- [4] D. Nakhla, E. Thompson, B. Lacroix, and J. Cotton. Measurement of heat transfer enhancement in melting of n-Octadecane under gravitational and electrohydrodynamics (EHD) forces, *Journal of Electrostatics*, 92:31-37, 2018.
- [5] M. Daaboul, N. Saba, J. Rishmany, and C. Louste. Properties of Fuel Spray Obtained by Electrohydrodynamic Atomization, 28<sup>th</sup> European Conference on Liquid Atomization and Spray Systems (ILASS-Europe 2017), Valencia, Spain, Sep 2017.
- [6] P. Vázquez, M. Talmor, J. Seyed-Yagoobi, P. Traoré, and M. Yazdani. In-depth description of Electrohydrodynamic conduction pumping of dielectric liquids: physical model and regime analysis, *Physics of Fluids*, 31(11):113601, 2019.
- [7] J. Shrimpton and A. Kourmatzis. Direct numerical simulation of forced flow dielectric EHD within charge injection atomizers, *IEEE Transactions on Dielectrics and Electrical Insulation*, 17(6):1838-1845, 2010.
- [8] S.A. Vasilkov, V.A. Chirkov, and Yu K. Stishkov. Study on high-voltage conductivity provided solely by field-enhanced dissociation in liquid dielectrics, *Journal of Electrostatics*, 88:81-87, 2017.
- [9] A. E. Perri, A. Sankaran, C. Staszel, R. J. Schick, F. Mashayek, and A. L. Yarin. The particle image velocimetry of vortical electrohydrodynamic flows of oil near a high-voltage electrode tip, *Experiments in Fluids*, 62:1-13, 2021.
- [10]M. Daaboul and C. Louste. Validity of particle image velocimetry measurements in electrohydrodynamic flows, *Experimental Techniques*, in press.
- [11]M. Daaboul, I. Matar, M. Nassar, and C. Louste. Testing Different Tracer Types in Particle Image Velocimetry Measurements in Electrohydrodynamics, 22<sup>nd</sup> IEEE International Conference on Dielectric Liquids (ICDL 2023), Worcester, MA, USA, 2023.
- [12]3M, Novec<sup>™</sup> Engineered Fluid HFE-7100, Product Information, 3M Electronics Markets Materials Division, 2009.
- [13]M. Nassar, P. A. Vázquez, N. Chauris, M. Daaboul, A. Michel, and C. Louste. Experimental Models of the Variation of HFE-7100 and HFE-7000 Electric Properties with Temperature, *IEEE Transactions on Industry Applications*, 56(4):4193-4199, 2020.
- [14]LaVision GmbH, Germany, http://www.lavision.de.
- [15]M. Daaboul, C. Louste, and H. Romat. PIV Measurements of the Influence of Seeding Particles Concentration on the Velocity of an EHD Flow, *ESA/IEEE-IAS/IEJ/SFE Joint Conference on Electrostatics 2009*, Boston, USA, June 2009.
- [16]Matweb, Material Properties Data Sheets, http://www.matweb.com.

## **Finite Taylor Cone: the impact of the electrospray**

J. Rivero-Rodríguez<sup>1\*</sup>, A. Hijano<sup>1</sup>, Francisco Higuera<sup>2</sup>, I. González-Loscertales<sup>1</sup>

<sup>1</sup>Department of fluid mechanics, University of Malaga, Spain

<sup>2</sup>Department of fluid mechanics and aerospace propulsion, Universidad Politécnica de Madrid, Spain \*Corresponding author: jrivrod@uma.es

*Abstract-* Electrospray technology is a process that uses an electric field to produce a fine spray of charged droplets from a liquid with applications such as mass-spectrometry, drug encapsulation, propulsion or surface coating. The parametric range in flow rates and electric field for which the the electrospray regime is stable is still not well understood. In this work, the spray and meniscus interaction is studied by numerical means to shed light on this intricate and complex phenomena that involves numerical singularities and deformable interphases of both the meniscus and the envelope of the spray. It serves as a first step towards the understanding of the stability of the electrospray regime.

Keywords- Electrospray, Taylor cone, electrohydrodynamics

## I. INTRODUCTION

When a conductive liquid flows out of a needle under the effect of an electric field, a conical shape may be exhibited for a certain range of the strength of the electric field and a jet or a spray is ejected from its appex. The first attempt to model this situation was carried out by G.I. Taylor (1964), who simplified the geometry to an infinite cone and stablished the given value of the strength of the electric field that is in equilibrium with the surface tension and the semiangle of the cone, known as the Taylor cone angle  $\alpha$ . Later, Fernandez de la Mora (1992) included in the analysis the influence of the emitted electrospray that modifies both the strength of the electric field and the cone angle, and Pantano et al. (1994) took into account the shape of the electrodes and finite value of the cone volume without the spray.

## II. METHODOLOGY

In this work, we perform numerical simulations on the Taylor cone, taking into consideration both (1) the influence of the finiteness of the cone and geometry of the device, and (2) the mutual impact of the electrospray.

To do so, we have solved the Poisson equation for the electric potential, the conservation of charge for the inertialess-electrospray and the Young-Laplace stress balance for the deformable interphase in spherical coordinates formulated using the Arbitrary- Lagrangian-Eulerian (ALE) method to account for the deformation of the meniscus and spray envelope, with the help of the weak form module of Comsol Multiphysics and analytical manipulation of the singularity.

## III. RESULTS

In figure 1, we can observe the electrode and needle (on the left) connected to a high voltage, the grounded counterelectrode (on the right) and the computed shape of the cone as a result of the balance between surface tension and

electrostatic stresses. The electrospray volumetric charge is also considered, although not shown.



Figure 1: Numerical solution with electric potential, Taylor cone and electrospray envelope. Isopotential in colour. Streamlines in grey. Electrodes, needle, axis and Taylor cone and envelope in black.

As part of the results, we have obtained the range of feasible electric Bond number,  $Bo_E = \epsilon \Phi^2 / \gamma R$ , based on the applied voltage  $\Phi$  and geometry of the device characterised by the radius of the needle R, while locally reproducing the one obtained by Taylor at the apex. It has been done for several values of the electric current carried by the electrospray, hence shedding light on how the electrospray influences the cone. More specifically, in figure 2, we can observe that as the current increases, the repulsion of the electric charge exerted on the meniscus requires an increase of the electric Bond number for the same volume of the meniscus.

#### IV. CONCLUSIONS

The Taylor cone interaction with the electrospray is studied in a finite configuration, locally recovering the solution by de la Mora [2]. It allows to elucidate the impact on the spray electric current on the shape of the meniscus, which becomes larger in volume as the current increases for the same configuration of the electrode voltages.



Figure 2: Electric Bond number as a function of the dimensionless volume of the meniscus for varying electric current of the spray.

## ACKNOWLEDGMENTS

This work has been supported by the Spanish Ministerio de Ciencia, Innovación y Universidades through grants PID2023-150329NB-C21 and PID2023-150329NB-C22.

- Taylor, G. Disintegration of water drops in an electric field. *Proceedings Of The Royal Society Of London. Series A. Mathematical And Physical Sciences.* 280, 383-397 (1964)
- [2] De La Mora, J. The effect of charge emission from electrified liquid cones. *Journal Of Fluid Mechanics*. 243 pp. 561-574 (1992)
- [3] Pantano, C., Ganan-Calvo, A. & Barrero, A. Zerothorder, electrohydrostatic solution for electrospraying in cone-jet mode. *Journal Of Aerosol Science*. 25, 1065-1077 (1994)

## Electrokinetic Effects in Cone-Jet Electrospraying: Ion Size and Solvent dependence

J. M. López-Herrera<sup>1\*</sup>, M. A. Herrada<sup>1</sup>, A. M. Gañán-Calvo<sup>1</sup>

<sup>1</sup>Departamento de Ing. Aerospacial y Mec. de Fluidos, ETSI, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092,

Sevilla, Spain.

\*Corresponding author: jmlopez@us.es

*Abstract-* This work explores the often-neglected electrokinetic phenomena in cone-jet electrospraying. While the successful Taylor-Melcher leaky dielectric (LD) model describes macroscopic features, it typically ignores the underlying ion dynamics. Recent studies [9, 11] have initiated electrokinetic modeling. This paper specifically investigates the cone-jet transition region, crucial for determining current and jet size. Using a numerical model based on the Poisson-Nernst-Planck (PNP) equations coupled with fluid dynamics and reaction terms, we analyze the impact of liquid viscosity and ion size on the ion composition and stresses within this zone. The objective is to clarify the conditions under which electrokinetic effects become significant in this electrospraying mode.

Keywords- Cone-jet electrospraying, electrokinetics

## I. INTRODUCTION

Electrospraying, particularly the cone-jet mode, is widely used for generating fine liquid sprays. The Taylor-Melcher leaky dielectric (LD) model, validated by theory [3] and simulation [6, 7, 2], effectively predicts macroscopic aspects like current and jet diameter by treating charge as accumulated on the surface [10, 13]. However, it simplifies the complex underlying electrokinetics involving multiple ionic species.

Key dimensionless parameters in this system are  $\Gamma$  and  $\Lambda_D$ .  $\Gamma$  represents the ratio between the macroscopic applied voltage and the thermal voltage ( $\Phi_T = K_B T/e$ ), indicating that the electrical stresses are of the order of the capillary stresses. On the other hand,  $\Lambda_D$  is the ratio between a characteristic macroscopic length (the needle radius  $R_n$ ) and the Debye length  $\lambda_D$ , where  $\lambda_D$  is the characteristic length scale over which electric charge in the solution is screened.

Recent efforts [1, 14, 12] have attempted to derive the LD model rigorously from the Poisson-Nernst-Planck (PNP) equations, establishing specific validity conditions related to length scales ( $\Lambda_D \gg 1$ ) and voltage scales ( $\Gamma \gg 1$ ). Crucially, numerical studies [9, 11] suggest that one key condition ( $\Gamma/\Lambda_D \gg 1$ , related to external field not disturbing the Debye layer) is often not met in typical electrospray, despite LD predictions holding true, indicating a need for detailed electrokinetic analysis.

Existing electrokinetic simulations of electrospray show differences. [9] uses a PNP model with reaction terms, valid for dilute solutions treating ions as point particles. [11] employs a variant including steric effects but omitting reactions, focusing on the cone-jet transition with different characteristic scales. This work focuses on the electrokinetic effects at the cone-jet transition, similar to [11]. We use a numerical model based on the PNP equations including reaction terms to study how viscosity and ion size affect the ion composition and stresses in this critical region, aiming to identify the significance of electrokinetic phenomena.



Figure 1: Sketch of the problem

#### II. FORMULATION OF THE PROBLEM

The system is a steady TCJ from a capillary (Fig. 1) ejecting an ionic solution with a symmetric binary compound undergoing reversible dissociation (S  $\implies$  A + C). Axisymmetric geometry is assumed, neglecting gas dynamics and treating liquid density and permittivity as constant.

## A. Governing Equations

The dimensionless bulk equations governing the system are:

a) The Navier-Stokes equations,

$$v\partial_r w + w\partial_x w = -\partial_x p + Oh \nabla^2 w + \rho_e E_x$$
$$v\partial_r v + w\partial_x v = -\partial_r p + Oh \left(\nabla^2 v - \frac{v}{r^2}\right) + \rho_e E_r$$
$$\partial_x w + \partial_r v + \frac{v}{r} = 0$$
(1)

where v and w are, respectively, the (dimensionless) radial and axial components of the velocity vector  $\mathbf{u}$ , and Oh is the Ohnesorge number.  $\rho_e$  is the dimensionless net bulk charge and  $E_r$  and  $E_x$  are, respectively, the radial and axial component of the dimensionless electric field  $\mathbf{E}$ ; the Laplacian operator is  $\nabla^2() = \partial_{xx}() + \partial_{rr}() + \frac{\partial_r()}{r}$ .



Figure 2: (a) Interface position and liquid streamlines in the cone-jet transition region, including the theoretical Taylor cone slope [15]. (b-e) Axial profiles of volumetric charge density  $(\rho_e)$  and concentrations  $(n_o, n_-, n_+)$  along the interface. Profiles for four ion sizes (0.1, 0.6, 7.3, and 20.8 Å) are shown, plotted relative to the transition origin  $x_o$ .

b) The Maxwell electrostatic equations,

$$\nabla^2 \phi_o = 0, \quad \nabla^2 \phi = -\frac{\rho_e}{\beta} = -\frac{\Lambda_D^2 z_v}{\Gamma} (n_+ - n_-)$$
 (2)

where  $\phi(\mathbf{x})$  is the dimensionless electric potential distribution and  $\beta$  is the relative permittivity. The subscript 'o' denotes the gas phase and  $\mathbf{E} = -\nabla \phi$ . The dimensionless parameters  $\Gamma$  and  $\Lambda_D$  are defined in the text. c) Concentration conservation equations,

$$\mathbf{u} \cdot \nabla n_{\pm} - D_{\pm} \nabla^2 n_{\pm} \mp (z_v \Gamma D_{\pm}) \nabla \cdot (n_{\pm} \mathbf{E}) - \zeta (n_o - n_{+} n_{-}) =$$

$$\mathbf{u} \cdot \nabla n_o - D_o \nabla^2 n_o \zeta_o (n_o - n_{+} n_{-}) = 0 \qquad (4)$$

Above,  $n_{\pm}$  and  $n_o$  are dimensionless concentrations of cations, anions, and neutral species, respectively;  $D_+$ and  $D_{\rho}$  are dimensionless diffusivities; and  $\zeta$  and  $\zeta_{\rho}$  are Damköhler numbers. The complex, coupled system of Navier-Stokes and Poisson-Nernst-Planck equations with reaction terms governing the cone-jet dynamics is solved numerically using the JAM method, developed by [8]. This highly accurate numerical scheme is specifically designed to tackle complex problems involving fluid interfaces, allowing for precise tracking of the liquid-gas boundary and accurate resolution of the coupled fluid flow, electric field, and species transport equations, particularly in regions with sharp gradients such as the Debye layer and the cone-jet transition region.

#### III. RESULTS

Numerical simulations were performed for 1-octanol doped with a 1:1 salt, maintaining a fixed bulk conductivity  $(\kappa = 10^{-6}S/m)$  while varying the ion size  $(a_{ion})$ . Operational parameters match typical electrospray conditions. While the macroscopic LD model predicts a unique operating point for current and jet size based solely on bulk conductivity [7, 5, 4], the full PNP model reveals a dependency on the specific ionic species.



Figure 3: Radial profiles of species concentrations  $(n_o, n_+, n_-)$  and relative conductivity  $(\kappa/\kappa_o)$  across different axial sections of the cone-jet transition region. Profiles are shown for four characteristic ion sizes (0.1, 0.6, 7.3, and 20.8 Å).



Figure 4: (a) Dimensionless electrical current  $I/I_o$  and (b) (emitted jet size as a function of symmetric ion size  $(a_{ion})$ ). Numerical results are compared to the Leaky Dielectric Model (dashed lines) [7]. A threshold value from [11] is marked by a vertical line. Selected ion sizes for detailed profiles are indicated by markers.

Simulations show that for ion sizes above approximately 1 Å, the predicted electrical current and jet diameter are in good agreement with the LD model and existing scaling laws (Fig. 4). However, a significant deviation occurs for smaller ion sizes ( $a_{ion} \ll 1$  Å). In this regime, the total electrical current increases sharply as the ion size decreases, while the jet size simultaneously decreases (Fig. 4).

This deviation arises from the detailed electrokinetic structure at the cone-jet transition (Figs. 2, 3). For small ions, characterized by higher diffusivities and a tendency towards weak electrolyte behavior, there is a significant accumulation of charge carriers within the Debye layer near the interface. This leads to a local conductivity that is orders of magnitude higher than the bulk conductivity ( $\kappa/\kappa_o \gg 1$ , Fig. 3).

Analysis of the current contributions (Fig. 5) reveals that the increased total current for small ions is primarily driven by a large conduction current component established within this region of enhanced local conductivity. This excess conduction is substantially counterbalanced by a diffusion-driven current component  $(I_d)$ . For larger ions,


Figure 5: Axial profiles showing the decomposition of the total electric current  $(I_{full})$  into convection  $(I_a)$ , conduction  $(I_c)$ , and diffusion  $(I_d)$  components for four ion sizes (0.1, 0.6, 7.3, and 20.8 Å). Results are compared with the conduction current for uniform bulk conductivity  $(I_c^B)$  and Leaky Dielectric Model predictions.

where the local conductivity remains relatively uniform, the current contributions are consistent with the simplified picture assumed by the LD model. These results highlight that, contrary to the assumptions of macroscopic models, the specific nature of the ions (particularly their size impacting diffusivity and local concentration distributions) can significantly alter the electrokinetic behavior and macroscopic characteristics (current, jet size) of cone-jet electrosprays, especially for solutions containing small ions. The findings underscore the importance of a detailed electrokinetic description for a complete understanding of the electrospraying process in certain regimes.

# REFERENCES

- J. C. Baygents and D. A. Saville. The circulation produced in a drop by an electric field: A high field strength electrokinetic model. *AIP Conference Proceedings*, 197(1):7–17, 1990.
- [2] M. Gamero-Castaño and M. Magnani. Numerical simulation of electrospraying in the cone-jet mode. J. *Fluid Mech.*, 859:247–267, 2019.
- [3] Alfonso M. Gañán-Calvo. Cone-Jet Analytical Extension of Taylor's Electrostatic Solution and the Asymptotic Universal Scaling Laws in Electrospraying. *Phys. Rev. Lett.*, 79(2):217–220, 1997.
- [4] A.M. Gañán-Calvo, J. Dávila, and A. Barrero. Current and droplet size in the electrospraying of liquids. Scaling laws. J. Aerosol Sci., 28(2):249–275, 1997.
- [5] A.M. Gañán-Calvo, J.M. López-Herrera, M.A. Herrada, A. Ramos, and J.M. Montanero. Review on the physics of electrospray: From electrokinetics to the operating conditions of single and coaxial Taylor cone-jets, and AC electrospray. *J. Aerosol Sci.*, 125:32–56, 2018.

- [6] R. P. A. Hartman, D. J. Brunner, D. M. A. Camelot, J. C. M. Marijnissen, and B. Scarlett. Electrohydrodynamic atomization in the cone-jet mode physical modeling of the liquid cone and jet. *J. Aerosol Sci.*, 30:823–849, 1999.
- [7] M. A. Herrada, J. M. Lopez-Herrera, A. M. Gañan-Calvo, E. J. Vega, J. M. Montanero, and S. Popinet. Numerical simulation of electrospray in the cone-jet mode. *Phys. Rev. E*, 86(2):026305, 2012.
- [8] M A Herrada and J M Montanero. A numerical method to study the dynamics of capillary fluid systems. J. Comput. Phys., 306:137–147, 2016.
- [9] J. M. López-Herrera, M. A. Herrada, and A. M. Gañán-Calvo. Electrokinetic modelling of cone-jet electrosprays. *Journal of Fluid Mechanics*, 964:A19, 2023.
- [10] J R Melcher and G I Taylor. Electrohydrodynamics: A review of the role of interfacial shear stresses. *Annual Review of Fluid Mechanics*, 1(1):111–146, 1969.
- [11] K. Misra, M. Magnani, and M. Gamero-Castano. Electrokinetic versus leaky-dielectric modeling of electrosprays operating in the cone-jet mode. *J. Fluid Mech.*, submitted, 2025.
- [12] Yoichiro Mori and Y.-N. Young. From electrodiffusion theory to the electrohydrodynamics of leaky dielectrics through the weak electrolyte limit. *J. Fluid Mech.*, 855:67–130, 2018.
- [13] D. A. Saville. Electrohydrodynamics: The Taylor-Melcher leaky dielectric model. Annu. Rev. Fluid Mech., 29:27–64, 1997.
- [14] Ory Schnitzer and Ehud Yariv. The taylor-melcher leaky dielectric model as a macroscale electrokinetic description. J. Fluid Mech., 773:1–33, 2015.
- [15] G. Taylor. Disintegration of water drops in electric field. *Proc. R. Soc. Lond. A*, 280:383–397, 1964.

# Effective Control Method of High Reynolds Number Flow around Airfoil Using Plasma Actuator

Y. Nakamura<sup>1</sup>, T. Oka<sup>2</sup>, T. Fujino<sup>3\*</sup>

<sup>1</sup>Graduate School of Science and Technology, University of Tsukuba, Tsukuba, Japan <sup>2</sup>School of Science and Engineering, University of Tsukuba, Tsukuba, Japan <sup>3</sup>Institute of Systems and Information Engineering, University of Tsukuba, Tsukuba, Japan \*Corresponding author: tfujino@kz.tsukuba.ac.jp

*Abstract-* We conducted two-dimensional numerical simulations to explore the effective flow control method around an airfoil in high Reynolds number air flow using a series-connected dielectric barrier discharge plasma actuator. In the numerical simulations, compressible gas-dynamic equations with electrohydrodynamic effects were discretized with a cell-centered finite volume method, where a large-eddy simulation model was employed. The numerical results indicated that a flow induced in the opposite direction against the mainstream near the airfoil surface wall by a series-connected dielectric barrier discharge plasma actuator generates periodic and clockwise vortices, contributing to a slight increase in the time-averaged lift coefficient, compared to that in no plasma actuator case.

Keywords- Dielectric barrier discharge plasma actuator, Flow control, High Reynolds number flow.

#### I. INTRODUCTION

Dielectric barrier discharge plasma actuators (DBD-PAs) [1] have gained attention as active flow control devices around fluid machinery. Fig. 1 illustrates the basic configuration of a DBD-PA. It consists of a dielectric and a pair of electrodes. The authors aim to develop DBD-PA devices for large-scale airfoils under high Reynolds number (Re) conditions such as  $Re=O(10^6)$ . Herein, the dimensionless number Re is defined as

$$\operatorname{Re} = \frac{\rho_{\infty} u_{\infty} c}{\mu},\tag{1}$$

where  $\rho_{\infty}$  is the mainstream mass density,  $u_{\infty}$  the mainstream velocity, *c* the chord length, and  $\mu$  the viscosity coefficient, respectively. Aono et al. [2] numerically showed that a DBD-PA operated in a high burst frequency mode could promote the transition from laminar to turbulent state in a separated shear layer around a leading edge of an airfoil under relatively low Reynolds number air flow conditions of Re= $O(10^5)$ , consequently disappearing a separated shear layer. In contrast, the numerical study of a DBD-PA for an airfoil at Re= $O(10^6)$  by Sato et al. [3], where a separated turbulent shear layer was formed around the leading edge under no control, showed that the DBD-PA with

a high burst frequency was ineffective in suppressing the separated shear layer. Moreover, their numerical study suggested that merging a large-scale vortex originating from a separated shear layer with a vortex induced by the DBD-PA effectively improved the lift force of the airfoil through the formation of a high-energy vortex.

Based on the effects of DBD-PA shown by Sato et al. [3], in this paper, we present the idea of generating a strong clockwise vortex near the leading edge of an airfoil by a DBD-PA inducing the flow in the direction opposite to the mainstream, and we also examine the effectiveness of this idea for the aerodynamic characteristics of airfoil in high Reynolds number air flow of  $Re=O(10^6)$ . In our previous paper[4], we proposed and developed a series-connected type DBD-PA device with multiple DBD-PA elements and also experimentally demonstrated that the series-connected type DBD-PA device can effectively enhance the velocity of induced flow, compared to conventional, single-type DBD-PA devices (Fig. 1). In the series-connected type DBD-PA device, the encapsulated and exposed electrodes between adjacent units of the multiple DBD-PA elements are interconnected and share the same potential. Consequently, each DBD stage in the series-connected type DBD-PA induces and powers the flow in the same direction. This paper proposes using a series-connected type DBD-PA de-



Figure 1: Basic configuration of DBD-PAs



Figure 2: Schematic of series-connected DBD-PA device with two DBD-PA elements on airfoil surface

Cases	Total number of DBD-PA elements	$D_c$ (-)	DT (-)	$f_{base}$ (kHz)	$F^{+}(-)$
Counter-1	1	10.0	30.0	100.0	1.0
Counter-2	2	10.0	30.0	100.0	1.0
Counter-3	3	10.0	30.0	100.0	1.0





Figure 3: Temporal variations of lift coefficient  $C_L$  for the no-control case, and the cases: Counter-1, Counter-2, and Counter-3

vice with multiple DBD-PA elements to induce the counterflow against the mainstream direction. We expect that the counterflow induced by the series-connected DBD-PA would contribute to form large-scale vortices over an airfoil, improving the aerodynamic characteristics of the airfoil in high Reynolds number air flow.

The objective of this study, therefore, is to examine the effect of a series-connected DBD-PA device inducing a counterflow against the mainstream on the flow filed around an airfoil in high Reynolds number air flow and its aerodynamic characteristics by two-dimensional, electrohydrodynamic (EHD) numerical simulation.

#### II. METHODOLOGY

In our numerical simulations, the conservation equations of mass, momentum, and total energy conservation equations for air flow around an airfoil were employed as the governing equations, where the electrohydrodynamic (EHD) effects were considered using Suzen-Huang's model [5]. Turbulent effects were treated with the coherentstructure Smagorinsky model (CSM) for LES developed by Kobayashi [6]. The governing equations were expressed in two-dimensional (x - y) approximation. A standard cellcentered finite volume method was adopted for discretizing the governing equations in space. The numerical fluxes of the convection terms in the governing equations were evaluated using SLAU2 scheme [8] coupled with the fourthorder, compact monotone upstream-centered schemes for



Figure 4: Distributions of pressure coefficient  $C_p$  along the surface of the airfoil for the no-control case, and the cases: Counter-1, Counter-2, and Counter-3

conservation laws (MUSCL) TVD scheme [9]. The diffusion terms were calculated using the Green-Gauss theorem (G-G) gradient scheme [10].

For this study, NACA0015 was adopted as the shape of the airfoil. As the air flow condition, the dimensionless number Re and an angle of attack (AoA) were set to  $1.2 \times 10^6$  and 20 degrees, respectively, where a boundary layer separation occurs after the flow in the shear layer over the airfoil transitions from laminar to turbulent state. Table 1 lists the number of DBD-PA elements of the series-connected DBD-PA devices and the operating cases specified for this study, where  $f_{base}$  is the base frequency of a sinusoidal wave applied to the DBD-PA device, and  $F^+$  is the dimensionless burst frequency, which is defined as

$$F^+ = \frac{f^+c}{u_\infty},\tag{2}$$

where  $f^+$  is the burst frequency. Furthermore, in Table 1, DT is the duty ratio defined as the ratio of the on-time to off-time of the DBD-PA as  $1/f^+$ ;  $D_c$  [11] is the dimensionless parameter of Suzen-Huang's model describing the effect of the EHD body force  $f_{EHD}$  induced by the DBD-PA relative to the dynamic pressure of mainstream, which is defined as

$$D_c = \frac{\rho_{c,max} E_{max} c}{\rho_\infty u_\infty^2},\tag{3}$$

where  $\rho_{c,max}$  is the maximum charge density generated around the DBD-PA and  $E_{ref}$  is the maximum electric field strength. In the cases "Counter-1", "Counter-2", and "Counter-3", the series-connected DBD-PA was assumed to



Figure 5: Distributions of spanwise vorticity  $\omega_z$  at dimensionless time  $t^*$ =4.0, 4.8, 5.6, and 6.4 for the no-control case, Counter-1, and Counter-3

have one (single), two, or three DBD-PA elements implemented to induce the flow by each DBD-PA element in the opposite direction to the mainstream. For all of the cases, the exposed electrode edge of the final element of the seriesconnected DBD-PA in the downstream direction of the induced flow was positioned at 2% of the chord length, as indicated by the blue circle in Fig. 2 which approximately corresponds to the laminar separation bubble over the airfoil.

#### III. RESULTS

Fig. 3 represents the temporal variations of the lift coefficient  $C_L$  for the no-control case, and the cases: Counter-1, Counter-2, and Counter-3. Herein, the coefficient  $C_L$  is defined as

$$C_L = \frac{2L}{\rho u_\infty^2 c},\tag{4}$$

where L is lift force acting on the entire airfoil. Note that the horizontal axis in Fig. 3 shows the dimensionless time

 $t^* = tu_{\infty}/c$ . Compared to the no-control case, the timeaveraged  $C_L$  from  $t^* = 3$  to 8 decreases by approximately 9.7% in Counter-1, but it increases as the number of DBD-PA elements increases. The averaged  $C_L$  in Counter-3 is 4.3% higher than the no-control case. Furthermore, the amplitude of  $C_L$  is hardly affected by the flow control.

Fig. 4 shows the distributions of pressure coefficient  $C_p$  along the airfoil for the no-control case, Counter-1, Counter-2, and Counter-3. The coefficient  $C_p$  is defined as

$$C_p = \frac{2(p - p_\infty)}{\rho u_\infty^2},\tag{5}$$

where p is the static pressure at each point on the airfoil and  $p_{\infty}$  is the mainstream static pressure. Note that the values  $C_p$  in Fig. 4 correspond to the time-averaged values from  $t^* = 3$  to 8 in Fig. 3. In Counter-1 inducing the flow in the opposite direction to the mainstream by the single DBD-PA device, the coefficient  $C_p$  increases at the upper side of the airfoil in x/c = 0.0 to 0.4, while it decreases at the trailing edge of the airfoil. In Counter-2 and Counter-3, the coefficient  $C_p$  slightly decreases in x/c = 0.2 to 0.7 around

the center of the airfoil. The increase in the time-averaged  $C_L$  in Counter-2 and Counter-3 shown in Fig. 3 is due to the decrease in  $C_p$  at the center of the airfoil.

## IV. DISCUSSION

In Sec. III., compared to the no-control case, the timeaveraged  $C_L$  slightly increased in Counter-2 and Counter-3, while decreased in Counter-1. To consider this reason, we focus on the effect of DBD-PA driving on the temporal vortical structures. The distributions of spanwise vorticity  $\omega_z$ at dimensionless times  $t^*$ =4.0, 4.8, 5.6, and 6.4 for the nocontrol case, Counter-1, and Counter-3 are given in Fig. 5. Positive vorticity observed in Fig. 5 indicates counterclockwise vortices, while negative vorticity indicates clockwise vortices, respectively.

In the no-control case, clockwise vortices generated from the separated shear layer are carried downstream by the mainstream. Additionally, counterclockwise vortices periodically generated from the trailing edge interact with the clockwise vortices, forming a complex flow field.

In both of Counter-1 and Counter-3, a flow induced by the DBD-PA device in the opposite direction against the mainstream generates periodic and clockwise vortices over the upper airfoil surface in the region of  $0 \le x \le 0.4$  m. But, in terms of the magnitude of vorticity  $\omega_z$ , Counter-3 shows a larger magnitude of negative vorticity  $\omega_z$  near the leading edge of the airfoil (x = 0.15 m) compared to Counter-1, indicating the formation of stronger clockwise vortices in Counter-3 than in Counter-1.

# V. CONCLUSION

In this study, two-dimensional electrohydrodynamic simulations were conducted to seek an effective control method of high Reynolds number flow around an airfoil equipped with series-connected dielectric barrier discharge plasma actuator (DBD-PA) device. In the numerical simulations, the series-connected DBD-PA device was assumed to have one (single), two, or three DBD-PA elements. Regardless of the element numbers, the DBD-PA device was installed near the leading edge of the airfoil. Furthermore, the series-connected DBD-PA device was driven to induce the flow in the opposite direction against the mainstream.

Compared to the no-control case, the time-averaged lift coefficient was decreased by the DBD-PA with a single element, while it was slightly increased by the series-connected DBD-PA with two and three elements. The series-connected DBD-PA periodically induced strong clockwise vortices over the upper airfoil, slightly increasing the time-averaged lift coefficient.

This study suggests that the flow control method using series-connected DBD-PAs to generate a high-velocity counter-flow against mainstream is effective for improving the aerodynamic characteristics of high Reynolds number flow around an airfoil.

- [1] J. Roth, D. Sherman, and S. Wilkinson. Boundary layer flow control with a one atmosphere uniform glow discharge surface plasma, *AIAA paper*, 1998-328, 1998.
- [2] H. Aono, S. Kawai, T. Nonomura, M. Sato, and K. Fujii and K. Okada. Plasma-actuator burst-mode frequency effects on leading-edge flow-separation control at Reynolds number 2.6×10<sup>5</sup>, *AIAA journal*, Vol. 55, pp. 3789-3806, 2017.
- [3] M. Sato, K. Asada, T. Nonomura, H. Aono, A. Yakeno and K. Fujii. Mechanisms for turbulent separation control using plasma actuator at Reynolds number of  $1.6 \times 10^6$ , *Physics of Fluids*, Vol. 31, 095107, 2019.
- [4] Y. Nakamura, T. Fujino, and T. Segawa. Method to avoid crosstalk for induced flow acceleration in multistage dielectric barrier discharge plasma actuators, *Applied Physics Letters*, Vol. 126, 014102, 2025.
- [5] Y. B. Suzen and P. G. Huang. Simulations of Flow Separation Control using Plasma Actuators, *AIAA paper*, 2006-877, 2006.
- [6] H. Kobayashi. The subgrid-scale models based on coherent structures for rotating homogeneous turbulence and turbulent channel flow, *Physics of Fluids*, Vol. 17, 045104, 2005.
- [7] S. Gottlieb and C.-W. Shu. Total Variation Diminishing Runge-Kutta Schemes, *Mathematics of Computation*, Vol. 67, pp. 73–85, 1998.
- [8] K. Kitamura and E. Shima. Towards shock-stable and accurate hypersonic heating computations: A new pressure flux for AUSM-family schemes, *Journal of Computational Physics*, Vol. 245, pp. 62–83, 2013.
- [9] S. Yamamoto and H. Daiguji. Higher-order-accurate upwind schemes for solving the compressible Euler and Navier-Stokes equations, *Computers & Fluids*, Vol. 22, pp. 259–270, 1993.
- [10] J. Blazek. Computational Fluid Dynamics: Principles and Applications, *Butterworth-Heinemann*, p. 116, 2005.
- [11] D. Tsubakino, Y. Tanaka, and K. Fujii. Effective Layout of Plasma Actuators for a Flow Separation Control on a Wing, *AIAA paper*, 2007-474, 2007.

# Experimental study of particle removal by dielectric barrier discharge

F. Pontiga<sup>1</sup>, H. Moreno<sup>1</sup>, C. Soria-Hoyo<sup>2</sup>, F. J. Durán-Olivencia<sup>2</sup>, M. A. Martín-Alfonso<sup>1</sup>, J. M. Valverde<sup>2</sup>
<sup>1</sup>Dpt. Física Aplicada II, Universidad de Sevilla, Spain
<sup>2</sup>Dpt. Electrónica y Electromagnetismo, Universidad de Sevilla, Spain
\*Corresponding author: pontiga@us.es

Abstract- This study investigates the removal of calcium carbonate particles deposited on a substrate using a dielectric barrier discharge (DBD). The reactor consisted of a glass epoxy board with an array of copper electrodes energized by a sinusoidal voltage. Particles of different sizes (15  $\mu$ m to 80  $\mu$ m) were tested, and the particle removal efficiency was monitored by measuring the ejected mass over time. Particle removal occurs through concurrent mechanisms involving Coulomb force and ionic wind. Results showed that the time required for complete particle removal decreases with increasing particle size up to 45  $\mu$ m. However, for larger particles, sweeping time slightly increases, likely due to the growing influence of gravity. These findings provide insights into the interplay of forces involved in DBD-based particle removal processes.

Keywords- Dielectric Barrier Discharge (DBD), particle removal, particle size effect.

# I. INTRODUCTION

Avoiding the adhesion and accumulation of particles on surfaces is extremely important in numerous technological and industrial applications. For example, fine powdery materials are usually pneumatically conveyed through pipes in the pharmaceutical, chemical, cement and food sectors. In all these industries, pipeline blockage is one of the most common and troublesome problems that can affect pneumatic conveyor systems [1]. In photovoltaic power plants, dust accumulation on solar panels causes drastic losses of efficiency [2], and great effort has been made in implementing cost-effective systems for cleaning solar panels.

Accumulated particles on surfaces can be removed using the electrostatic and electrodynamic forces that arise in electrical discharges, particularly in corona and dielectric barrier discharges [3]. During the development of the discharge, particles become electrostatically charged and, moreover, they are subjected to the effect of the ionic wind generated by the discharge itself. Both factors decisively contribute to the rapid elimination of particles from the surface.

This work will investigate the removal of fine  $CaCO_3$  particles deposited on a surface using dielectric barrier discharge (DBD). Since particle adhesion is strongly dependent on particle size, special attention will be paid to the influence of particle size on the time required to remove them from the surface.

# II. MATERIALS AND METHODS

The dielectric substrate of the DBD reactor consisted of a FR-4 glass epoxy board, 60 mm long and 30 mm wide, which was cut as shown in Fig. 1. On the top of glass epoxy board, an array of 14 copper strips, 1 mm wide, were arranged in parallel separated by 3 mm (red lines in Fig. 1). Similarly, on the lower side, 15 parallel copper strips were also distributed (blue lines in Fig. 1). Each strip on the upper side was equidistant from two strips on the lower side. The lower side of the reactor was covered with a second FR-4 board, with identical geometry, but without copper strips.

The copper strips on the upper side of the board were connected to a high-voltage amplifier (20/20C-HS, Trek Inc.) that amplifies the signal produced by an arbitrary waveform generator. Conversely, the copper strips on the lower side of the board were grounded, with a 1  $\mu$ F capacitor inserted in the path to ground. Therefore, the intensity of the electrical discharge can be determined by measuring the voltage drop across the capacitor.

The particles used in this investigation were made of natural calcium carbonate (99.10 % CaCO<sub>3</sub>). Four different sets of particles were used in the experiments, with predominant particle size of 15  $\mu$ m, 30  $\mu$ m, 45  $\mu$ m and 80  $\mu$ m. In each experiment, one gram of CaCO<sub>3</sub> particles was deposited on the glass epoxy board, covering a rectangular area 53 mm × 22 mm corresponding to the array of electrodes on the board.

When the DBD reactor is energized, the CaCO<sub>3</sub> particles are progressively swept from the surface of the dielectric by the effect of Coulomb force and the ionic wind. To measure the efficiency of the DBD in removing the CaCO<sub>3</sub> powder, the mass of particles ejected over time was measured using an analytical balance (AB204-S/FACT, Mettler Toledo), with a resolution of 0.1 mg.

# III. RESULTS

In the present study, the DBD was generated using a sinusoidal waveform, with frequency 50 Hz and amplitude 18 kV peak-to-peak. The removal of particles deposited on the dielectric occurs through several concurrent mechanisms. On one hand, during the electrical discharge, the particles acquire an electric charge and can be repelled by the electrodes when they have the same polarity as the particles. On the other hand, the ions generated during the discharge transfer momentum to the gas molecules



Figure 1. Schematic picture of the dielectric barrier discharge reactor used in the experiments. Copper electrodes on the upper (lower) side of the dielectric substrate are shown in red (blue) colour.

through collisions, leading to the generation of an electric wind capable of dragging the particles deposited on the dielectric.

The photograph in Fig. 2 shows the light emitted by the discharge (ISO 6400, f/3.5, 2.5 s) in the absence of particles. This image provides relevant information about the intensity of the electrical discharge. As expected, the discharge is more intense at the tips of the electrodes, while it is practically absent in the concave corners located along the central axis of the electrode array. For this reason, the removal of CaCO<sub>3</sub> particles deposited on the dielectric begins at the outer regions and then progresses inward. Additionally, current intensity measurements show that the microdischarges of the DBD exhibit different intensities during the positive and negative voltage half-cycles, being much greater during the negative voltage half-cycle.

As is customary, the electrical energy E consumed in each discharge cycle can be determined as

$$E = C \int_0^T V dV_C, \tag{1}$$

where *V* is the voltage applied to the reactor and  $V_C$  is the voltage drop across the capacitor connected in series with the reactor, with a capacitance of  $C = 1 \mu F$ . Since  $CV_C$  corresponds to the charge *Q* stored in the capacitor, the result of (1) is equal to the area enclosed by the Lissajous figure that plots *Q* as a function of *V*. Fig. 3 shows this curve, which takes the usual form of a parallelogram. The value of  $V_C$  was averaged over multiple cycles to eliminate high-frequency oscillations associated with the micro-discharges. The average energy consumed by the DBD obtained in this manner was 1.8 mJ/cycle, or equivalently, 90 mW.

Fig. 4 shows, for different CaCO<sub>3</sub> particle sizes, the time evolution of the mass *m* that remains on the dielectric substrate after the discharge is activated. This mass was determined based on the mass collected on the balance, considering that the initial mass deposited on the dielectric was  $m_0 = 1$  g. A small fraction of the expelled particles adheres to nearby surfaces and is not recorded by the balance. For this reason, and to facilitate comparison between different experiments, the mass measured by the balance was normalized to  $m_0$ .

As can be observed, the time required to completely remove the layer of  $CaCO_3$  deposited on the dielectric depends on the particle size, and decreases as the particle size increases. This behavior is consistent with the fact that the Van der Waals adhesion force between particles



Figure 2. Photograph of the visible light emitted by the DBD for a frequency of 50 Hz and applied voltage of 18 kV peak-to-peak, when the dielectric substrate is not cover with CaCO<sub>3</sub> particles. Film speed: ISO 6400, f-number: 3.5, exposure time: 2.5 s.

(assumed spherical) scales with the particle radius R, while the maximum electrical charge they can acquire is proportional to  $R^2$ , and their weight increases as  $R^3$ . Therefore, the Van der Waals force is particularly significant for the finest particles (15 µm). Of course, the problem is certainly more complex, because in addition to Van der Waals force, Coulomb force and gravitational force, the drag force due to the electric wind can also be present.

The effect of particle size on the time required to sweep the particles from the surface can perhaps be seen more directly in Fig. 5, which shows the average time, calculated as

$$\langle t \rangle = \frac{1}{m_0} \int_0^{m_0} t \, dm = \frac{1}{m_0} \int_0^\infty m \, dt.$$
 (2)

It is interesting to note that, for particle sizes above  $45 \,\mu\text{m}$ , the sweeping time of the particles does not decrease with increasing size, but instead slightly increases from  $45 \,\mu\text{m}$  to  $80 \,\mu\text{m}$ . This behavior may be due



Figure 3. Lissajous curve of electric charge as a function applied voltage for a DBD of frequency of 50 Hz and applied voltage of 18 kV peak-to-peak.



Figure 4. Time evolution of the mass of  $CaCO_3$  particles remaining on the dielectric substrate after the activation of the DBD for different particles size.

to the growth of the relative importance of gravitational force as the particle radius becomes larger.

Taking the mean particle sweep time as a reference, the energy consumed by the discharge to remove particles from the dielectric substrate varies from 0.45 J/g for the finest particles (~15  $\mu$ m), to 0.12 J/g for 45  $\mu$ m particles.

#### V. CONCLUSION

Dielectric barrier discharge (DBDs) is an effective means for removing fine CaCO<sub>3</sub> particles from dielectric surfaces. However, the efficiency of particle removal strongly depends on particle size. Smaller particles (~ 15  $\mu$ m) are more difficult to remove because of Van der Waals adhesion forces. As particle size increases up to 45  $\mu$ m, removal becomes faster, as the electrostatic and aerodynamic forces overcome adhesion forces more effectively. Finally, for particle sizes larger than 45  $\mu$ m, the removal time slightly increases, likely due to the increasing influence of gravitational force,

The removal process starts at the edges of the electrode array—where the discharge is most intense and progresses inward, correlating with observed nonuniformity in discharge intensity across the surface. The energy consumption of the DBD system was measured to be approximately 0.45 J/g for the finest particles (~15  $\mu$ m), making the method relatively energy efficient.

#### ACKNOWLEDGMENT

This work was supported by the Spanish State Research Agency (contracts TED2021-132676A-I00, funded by MCIN/AEI/10.13039/501100011033 and by NextGenerationEU/PRTR, EU; and PID2022-138943OB-I00, funded by MICIU/AEI/10.13039/501100011033 and by FEDER, EU).



Figure 5. Mean sweep time of particles from the dielectric substrate as a function of the characteristic particle size of the  $CaCO_3$  powder.

#### REFERENCES

- [1] G.E. Klinzing. Pneumatic conveying: transport solutions, pitfalls, and measurements, *Handbook of Powder Technology*, **10**: 291-301, 2001.
- [2] H. A. Kazem, M. T. Chaichan, A. H. A. Al-Waeli, and K. Sopian. A review of dust accumulation and cleaning methods for solar photovoltaic systems, *Journal of Cleaner Production*, 276:123187, 2020.
- [3] A. Tilmatine, N. Kadous, K. Yanallah, Y. Bellebna, Z. Bendaoudi, and A. Zouaghi. Experimental investigation of a new solar panels cleaning system using ionic wind produced by corona discharge, *Journal of Electrostatics*, **124**:103827, 2023.

# Characteristics of single-phase gliding arc equipment with twisted electrodes and radial gas injection

Shin-ichi Aoqui<sup>1\*</sup>, Kouji Yamauchi<sup>1</sup>, Akihiro Ikeda<sup>1</sup>, Eiji Sakai<sup>1</sup>, Tetsuro Baba<sup>2</sup>, Hiroharu Kawasaki<sup>3</sup>, Oleksandr Boiko<sup>4</sup>, Henryka Danuta Stryczewska<sup>4</sup> <sup>1</sup>Department of Computer and Information Sciences, Sojo Univ., Japan <sup>2</sup>HyBridge Co., Ltd., Japan <sup>3</sup>Department of Electrical and Electronics Engineering, Sasebo National College of Technology, Japan

<sup>4</sup>Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Poland \*Corresponding author: aoqui@cis.sojo-u.ac.jp

Abstract- Gliding arc discharge is one of the newer types of atmospheric pressure discharge. It is currently developing important applications in exhaust gas treatment, water treatment and carbon dioxide fixation. However, the non-steady state of discharge mechanism has led to a number of difficulties. In this study, twisted electrodes were proposed in classical single-phase gliding arc structure to reduce the problem of non-steady state. The structure of the twisted electrodes with gas introduction into the radial direction of discharge tube was a classical single-phase gliding arc, it was found to be capable of providing a plasma volume equivalent to that of multi-electrode type.

Key words- gliding arc discharge, environmental protection, nonthermal equilibrium, twisted electrodes, atmospheric pressure discharge, non-steady state discharge

# I. INTRODUCTION

In recent years, Gliding Arc Discharge (GAD) has taken on a very important position as a new mechanism for atmospheric discharge, with application in areas such as exhaust gas treatment, water treatment and even carbon capture from carbon dioxide. GAD was discovered by A. Czernichowski in 1989 [1-3]. The working gas flow for this GAD is strongly related to the discharge phenomenon. The relationship between the working gas of GAD and plasma phenomena is shown below in relation to the discharge research of many previous researchers.

Discharge phenomena are unlikely to occur in atmospheric pressure environment, so in earlier times there was little of interest to researchers except for direct current arc discharge. However, atmospheric pressure discharges have already been known in the field of electrical and high voltage engineering since 1950s, and experiments on atmospheric pressure high frequency inductively coupled plasma (ICP) were reported by T.B. Leed and colleagues in 1960s, followed by a physical model proposed by Eckert and others [4]. T.B. Leed and colleagues used a large flow of working gas inside a discharge tube wound with a working coil as the device to generate ICP. A pump with a high exhaust velocity was equipped downstream due to the large gas flow from the upstream of the discharge tube. They observed that the position of the ICP plasma emission changed in the axial direction of the discharge tube when the gas flow velocity was changed when a high-frequency induced discharge was maintained. This showed that the gas flow velocity, which is a relatively slow phenomenon, is strongly related to the fast response of the plasma. Plasma generation by atmospheric pressure discharges has so far been largely divided into two categories in terms of electrical power. DC arc and ICP are high power discharge and are driven by low voltage and high current. dielectric barrier discharge, corona discharge and streamer, on the other hand, are high-voltage, low current discharge and the total power is not large. GAD is in the middle part of the power range and is seen as an extremely important phenomenon. In other words, ICP has extremely high thermal equilibrium temperature and big power consumption, which limits its application. On the other hand, dielectric barrier discharge and corona discharge have low power consumption per electrode area, and require a large area for large-scale treatment for objects. In contrast, GAD can consume a reasonable amount of power depending on the equipment configuration, and there are high expectations for large-scale processing. However, number of fundamental challenges exist in principle for GAD. The characteristics of GAD can be summarized in the following points.

(1) Simple structure constructed with only high-voltage transformer using a commercial power supply

- (2) Non-steady state discharge plasma
- (3) Difficult to maintain a stable continuous discharge

Firstly, (1), because atmospheric pressure discharge does not require a vacuum exhaust system and a power supply consists only of a commercial power supply and high-voltage transformer, it has advantages in terms of cost and fault-tolerance. On the other hand, (2), with regard to non-steady state, GAD have a considerably long period of time during which the discharge is stopped. In other words, there is a time when the arc is arc extinction. The arc extinction strongly depends on the electrode configuration and gas flow rate, but during the time when the discharge is stopped, the working gas passes directly through the electrodes. In other words, the working gas passes through without being plasma. In addition, a stable AC arc is required for the start of the discharge, as the arc discharge between the electrodes is the start of the discharge. However, as the start of the arc is strongly dependent on the electrode configuration, it can be difficult to adjust the power consumption of GAD and the control of current and voltage characteristics. For these reasons, despite the attractive and promising prospects of GAD, there are some characteristics that make them difficult to use. However, despite the strong dependence of GAD on electrode geometry, there are few research reports on that geometry.

This paper presented a proposal for electrode development that reduces the problem of non-steady state discharge by reviewing the rod and plate electrode geometries that have been used empirically by many researchers.

#### A. Basic configuration of single-phase GAD

The basic GAD is single-phase GAD. The configuration of a single-phase GAD with knife-edge electrodes is shown in Fig. 1. This electrode structure generates a two-dimensional discharge surface. This means that, in principle, the plasma space is sheet shaped.



The same applies to rod electrodes. In Fig.1, the electrode spread is shown as a straight line, but in many research cases, the opening is larger towards the top of the electrode. d<sub>0</sub> indicates the shortest distance between electrodes at gas inlet. The discharge starts from AC arc in this area and the discharge path progresses downstream of the gas flow, terminating in the middle or at the top of the electrode spread, thus extinguishing arc. When the arc is extinguished, the next discharge is repeated, starting again from the lowest point. At this point, the gas flow from the bottom end significantly contributes to the characteristics of the discharge. GAD does not start without gas introduction. If the gas is stopped during the discharge, the discharge also stops. In many research papers, protective resistor (R<sub>L</sub> and R<sub>H</sub>) is inserted on the primary or secondary side of the power supply, as shown in Fig.1 (a) and (b). These are inserted to prevent damage to the highvoltage transformer in case of AC arc, as the transformer is close to short-circuiting. However, this protective resistor consumes power and loses the power input to the plasma. Discharge path exist in the space between the electrodes, and in single-phase GAD configuration, the discharge path has a strong two-dimensionality. In other words, when the discharge tube housing the electrodes is

cylindrical, both the problem of non-steady state and the two-dimensionality of the discharge path are related to the untreated working gas. Easiest way to avoid this problem of two-dimensionality is to make it multi-phase, and we had developed GAD equipment such as 3-phases 3-electrodes, 6-phases 6-electrodes and prototype 12-phases 12-electrodes model. The electrode configuration is shown in Fig. 2 (a) and a photograph of the discharge state is shown in Fig. 2 (b) [5-7].



Fig. 2. 3 and 6 phases GAD system

However, multi-electrode configuration complicates the equipment configuration, especially 6 and 12 phases types require a special power supply sysytem, which moves away from GAD characterized for their simple structure. But, in the case of a 6-electrodes, there would be two or three discharge paths, covering the entire discharge tube, as shown in Fig.3, and the untreated rate of working gas would be significantly reduced.



High-speed camera image of a 6-electrode discharge seen from the top. Fig. 3. High-speed camera image taken at 10000 fps from the top

Therefore, it was considered whether it would be possible to fill the discharge tube with discharge path in a simple single-phase GAD. The method can be divided into two parts. One is to change the two-dimensionality of the discharge path to three-dimensional by twisted electrodes as shown in Fig. 4.



Fig. 4. Rod Electrodes with 180° twist angle

The other is radial gas introduction, which is carried out in a tornado type GAD (gliding arc in tornado, GAT) [8,9]. GAT is a very good idea and can significantly reduce the amount of unprocessed gas due to non-steady state. However, GAT is very different from classical GAD and is not suitable for comparison here, nor will it be discussed. The introduction of gas in the radial direction is expected to increase the residence time of the gas in the discharge space.

#### II. EXPERIMENT

Two types of twisted GAD electrodes were prepared in this study. They were rod electrode and plate electrode. Discharge phenomena were measured using a high-speed camera (Nobby Tech, Phantom V1210) and an oscilloscope (Lecroy WaveRunner, 204Xi-A) for I-V measurements synchronized with it, a current probe (Tektronix, TCP2020), a high-voltage probe (Tektronix, P6015A) and a pulse generator (Hamamatsu, C10149) were used. The measurement system is shown in Fig. 5. Ar, CO<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub> and He were used as the working gases, with flow rates varying from 5  $\ell$ /min to 50  $\ell$ /min respectively.



Fig. 5. Experimental setup of synchronized high-speed CAM & I-V measurement system

## III. RESULTS

# A. Rod electrode

Experiments were carried out at  $90^{\circ}$  and  $180^{\circ}$  twisted angles at rod electrode. The results with regard to gas type dependence at  $90^{\circ}$  twist are shown in Fig.6.



twisted rod electrodes by gas type

The image position of the discharge path for each gas shows the same number of frames after ignition, that means same time after ignition. High-speed camera images showed no significant dependence on gas species, and the discharge path raised after the initial ignition at the lower end of the electrode. However, there were differences in the position of the electrode depending on the gas species. In Ar, it sometimes reached up to the top, but in N<sub>2</sub> and CO<sub>2</sub>, it remained in the middle position. A low-speed image in Ar is shown in Fig 7. Only one discharge path was existent, but due to the long exposure time, ignition at the lower end was visible after the arc was extinguished at the upper end.



Fig. 7. Long exposure image at  $180^{\circ}$  twisted rod electrodes by Ar 50  $\ell$ /min

# B. Plate electrode

Experiments were also carried out on plate electrode at twist angles,  $90^{\circ}$  and  $180^{\circ}$ . In the plate electrode, the gas introduction part at the bottom was equipped with gas introduction ports at an angle of  $45^{\circ}$  to the bottom plane from 4 different directions, in addition to the bottom end of the electrode, where the flow rate can be controlled individually from 4 different directions. The configuration of the twisting electrode and gas inlet port is shown in Fig. 8.



Fig. 8. Twisting electrode and gas inlet port configuration

Typical high-speed camera images of Ar gas flow rates of 50  $\ell$ /min from the bottom end and 10  $\ell$ /min from the bottom and 40  $\ell$ /min from one 45° port (total 50  $\ell$ /min) are shown in Fig. 9.



Fig. 9 High-speed camera image at 10000 fps
(a) Ar 50 ℓ/min from bottom, (b) Ar 10 ℓ/min from bottom, 40 ℓ/min from one 45° port

In the case where the gas introduction was only at the bottom, the discharge path extended almost directly above the gas introduction direction. In the case where gas was introduced from one 45° direction, as shown in the Fig. 9., the discharge path moved in the direction of gas diffusion. Furthermore, the discharge path itself was more twisted and the discharge path itself was three-dimensional.

A low-speed image at 300 fps is also shown in Fig. 10. The discharge path almost reached the top of the electrode, confirming that the discharge path was rotating and rising since the ignition. It was also confirmed that the discharge path was flowing in the direction of gas diffusion due to gas injection from the  $45^{\circ}$  port.



wer part only Ar 50 l/min gas inlet low and one 45° location Fig. 10. low-speed images at lower end and 45° gas injection at Ar 50 ℓ /min

#### IV. DISCUSSION

It was confirmed that the twisted electrode structure causes the discharge path to rise along the twist of the electrode. In other words, it was confirmed that the strongly two-dimensional discharge path in a plate electrode configuration inside the discharge tube becomes three-dimensional by twisted electrode. It is important to consider the relationship between the rate of rise of the discharge and the gas diffusion speed. Evaluation of the high-speed camera images confirmed that the discharge path rises average rate of 25 m/sec at 30  $\ell$ /min by Ar, which was by faster than the diffusion speed of the gas supplied by the 1/4-inch pipe. The speed of movement of the discharge path determined from the image analysis of the high-speed camera is shown in Fig. 11.



Fig. 11. Dependence of the speed of movement of the discharge path by Ar gas flow rate

Because at 30  $\ell$ /min, the gas velocity inside 1/4-inch pipe where the gas was introduced was about 35 m/sec, but because the inner diameter of the discharge tube was 76 mm, the gas diffused after being released into the discharge tube and the flow velocity slowed down rapidly. However, the relationship between the arc extinction time of the discharge and the survival time of the plasma has to be considered. The rate of rise of discharge path and arc extinction time were strongly related to the gas flow rate and applied voltage between the electrodes, so efforts must be made to find the optimum values. Also, although the graph is not shown here, with regard to I-V characteristic in the discharge, it depends not only on gas flow rate and applied voltage between the electrodes, but also on the gas flow rate from the 45° incidence port. Therefore, if the axial gas diffusion velocity can be suppressed by reducing the gas flow rate from the lower

end and increasing the gas in the radial direction, this will have a positive effect on the gas treatment leakage during the arc extinction time.

It is unclear why gas introduction with a radial component causes the discharge path to move. The direction of movement of the discharge path was in the direction of gas injection from the gas introduction pipe and was almost perpendicular to the discharge path. The introduced gas was at about room temperature, but the temperature of the resident gas particle density decreases because power was consumed by plasma inside the discharge tube. Because of the temperature and the density difference between the resident gas and the gas immediately after introduction, they will not mix easily and will propagate into the discharge path. This difference in particle density and temperature is considered to be strongly related to the movement of the discharge path.

#### V. CONCLUSION

The simplest classical single-phase GAD is a very good atmospheric discharge configuration. However, because it is single-phase, the electrode configuration is plane and the discharge path is highly two-dimensional. This poses a challenge for atmospheric pressure plasma generation for gas processing purposes. In this study, the discharge path was turned three-dimensional by preparing the single-phase electrode from a planar structure to a twist into an electrode. It was also confirmed that the position of the discharge path can be moved by adding gas injection with radial component. The axial component of the radial gas diffusion velocity was smaller than the axial injection, which was advantageous for gas treatment. In conclusion, it was shown that single-phase GAD has the potential to generate three-dimensional plasma space equivalent to that of multi-electrode GAD.

- Czernichowski A., Oil & Gas Science and Technol. Rev. IFP, Vol. 56, No. 2, pp. 181-198, 2001
- [2] Czernichowski A., Gliding Arc Applications to Engineering and Environment Control. Pure and Applied Chemistry, 66, 6, 1301-1310, 1994
- [3] Czernichowski A., Electrically Assisted Conversion of Natural Gas into Syngas. Karbo-Energochem. Ekol., 43, 11,359-369, 1998
- [4] Reed T.B., J. Appl. Phys. 32 821, 1961
- [5] Bata T., Przeglad Elektrotechniczny, 88(6) 86-88, 2012
- [6] Mitsugi, F., Eur. Phys. J. Appl. Phys. Volume 61, Number 2, 2013
- [7] Mitsugi, F., Przeglad Elektrotechniczny, 92(6), 119-122, 2016
- [8] Rufael T. S., REVIEW OF SCIENTIFIC INSTRUMENTS 76, 025110, 2005
- [9] Fridman A, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 43, NO. 5, 2015

# Fully 3D Numerical Computations of the Unipolar Injection between an Hyperbolic Blade and a Plane Electrode.

P. Traoré<sup>1</sup>, P.A. Vazquez<sup>2</sup>, A.T. Pérez<sup>3</sup>, Z. Yan<sup>4</sup>, U. Seth<sup>5</sup>.

<sup>1</sup> Département Fluide-Thermique-Combustion, Institut PPRIME, Université de Poitiers, France.

<sup>2</sup>Departamento de Física Aplicada III, Universidad de Sevilla, ESI, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain.

<sup>3</sup>Departamento de Electrónica y Electromagnetismo. Facultad de Física. Universidad de Sevilla. 41012 Sevilla. Spain <sup>4</sup> Logistics Engineering College, Shanghai Maritime University, Shanghai, China.

<sup>5</sup> Qubit Pharmaceuticals, Dept. HPQC, 29 rue du Faubourg Saint Jacques, 75014 Paris, France.

\*Corresponding author: Philippe.traore@univ-poitiers.fr

Abstract- This study investigates the electrohydrodynamic (EHD) flow phenomena induced by unipolar charge injection in a blade-plane electrode configuration within a dielectric liquid in a threedimensional framework. Numerical simulations have been conducted using the Oracle3D finite volume code on a refined computational grid to analyze the behavior of EHD plumes, which are jet-like flows generated by the interaction of injected charges with the surrounding fluid. The blade electrode acts as a high-voltage emitter, while the plane electrode serves as a grounded collector. The study focuses on the transition from steady to unsteady flow regimes, influenced by the blade geometry, injection laws, and electric Reynolds number. Results reveal that the injection mechanism significantly impacts flow structures, including the formation of Kelvin-Helmholtz instabilities and turbulent mixing. The study also highlights the role of injection laws in determining charge distribution patterns and flow dynamics, with stronger coupling between charge density, electric field, and velocity observed in non-autonomous injection cases. These findings provide valuable insights into the design and optimization of EHD systems for applications such as heat transfer enhancement, fluid mixing, and flow control.

Keywords- 3D numerical simulation, Unipolar charge injection, Blade-plane electrode, Kelvin-Helmoltz instability.

# I. INTRODUCTION

Flow phenomena induced by electrohydrodynamics in dielectric liquids, particularly in the context of a bladeplane electrode configuration, have been extensively studied both numerically and experimentally. The EHD flow that occurs in this configuration can result from either injection or conduction mechanisms of charge transport within the dielectric liquid. This study primarily focuses on the injection mechanism, which is triggered when the electric field at the electrode tip surpasses a certain threshold. In the injection phenomena, the blade serves as a charge particle emitter, while the plane electrode acts as a collector. The injected charged particles induce motion in the surrounding fluid by transferring their momentum to neutral fluid particles, setting the fluid in motion towards the plane electrode in a jet-like manner. This jetflow is commonly referred to as like an electrohydrodynamic plume. A distinctive feature of EHD plumes is that the resulting jet flow occurs without any mass transfer in the bulk, offering a significant energy advantage over other fluid movement methods such as blowing or suction. This type of jet flow has been investigated for various applications, including enhancing heat transfer to cool hot walls, mixing different miscible fluids, and controlling flow, among others (Wu et al [1]). Therefore, just like thermal plumes, an in-depth study of EHD plumes is crucial from an industrial perspective. Vazquez et al [2] conducted a comparative study of thermal and EHD plumes, analyzing axisymmetric plumes

across various Prandtl numbers. Subsequent numerical studies by Vazquez et al. utilized finite element-based numerical approaches to accurately describe the EHD plumes and their characteristics. Pérez et al [3] conducted studies to analyse the dynamics and linear stability of charged jets in dielectric liquid and in [4] Pérez et al. examined the EHD plumes in a blade-plane setting, using a Finite Volume method with a TVD scheme (SMART), and discussed different flow regimes. Traoré et al. [5] numerically analyzed EHD plume flows with different blade configurations, incorporating various injection laws. They found that the blade shape and injection laws significantly impact the flow structure, particularly the transition of flow from steady to unsteady regimes.

To date, most, if not all, studies on this subject have been conducted in 2D. However, in our ongoing study, we are conducting purely 3D numerical simulations. These simulations conclusively demonstrate that the flow is strongly 3D, even for moderate values of the electrical Reynolds number. This confirms the necessity of considering the flow as three-dimensional for this type of study.

The reminder of this paper is organized as follows:

In the following section the formulation of the problem will be stated in terms of governing equations and numerical methods. Then in the section III we will discuss the main results obtained. Finally, a conclusion is drawn up in section IV.

#### II. FORMULATION OF THE PROBLEM

#### A. Governing equations

This study examines the 3D electroconvective flow generated by Coulomb's force within a dielectric liquid containing electrical charges, positioned between two metallic electrodes under constant voltage. The electrode configuration consists of a blade electrode with a small tip curvature radius *r* that injects electrical charge into the liquid following a specific relationship  $q = f(\|\vec{E}\|)$ . This

injection relationship determines the charge density at every point along the blade electrode's surface. The second electrode is a plate positioned at a distance d from the blade (as illustrated in Fig 1).



Fig. 1. Sketch of the blade-plane configuration

The electric charge moves toward the collecting electrode under the combined influence of the electric field and fluid velocity. In formulating this problem, we employ standard assumptions of a newtonian incompressible fluid characterized by kinematic viscosity  $\nu$  and density  $\rho$ . The fundamental scaling parameters include the distance d, the injected charge density  $q_0$ , and the velocity  $U_0 = K_H (V_0 - V_1)/d$ , where  $V_0$  and  $V_I$  represent the respective electrode potentials and  $K_H = \sqrt{\varepsilon / \rho}$  denotes the hydrodynamic velocity.  $\varepsilon$  represents here the permittivity. The governing equations in dimensionless form are as follows:

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}.\nabla)\vec{u} = -\nabla \tilde{P} + \frac{1}{R_{ev}}\nabla^2 \vec{u} + q\vec{E}$$
(2)

$$\frac{\partial q}{\partial t} + \nabla \cdot \left[ \left( \vec{u} + \frac{\vec{E}}{M} \right) q \right] = 0$$
(3)

$$\nabla^2 V = -q \tag{4}$$

$$\vec{E} = -\nabla V \tag{5}$$

where  $\vec{u}$  is the fluid velocity,  $\tilde{p}$  is the modified pressure which is the sum of the static pressure p and the scalar from which the electrostriction force derives [10]. As the fluid is homogeneous and isothermal the dielectric force vanishes and only the Coulomb force  $q\vec{E}$  acts on the fluid. q is the charge density. V is the electric potential,  $\vec{E}$  is the electric field. The non dimensional numbers involved in this problem are the Reynolds number  $R_{ey} = \frac{(V_0 - V_1)}{v} \sqrt{\frac{\varepsilon}{\rho}}$ 

 $M = \frac{K_H}{K}$  is the ratio between the so-called hydrodynamic mobility and the true mobility of ions. It gives an order of the magnitude of the velocity of the fluid while K stands for the ionic mobility.  $C = \frac{q_0 d^2}{\varepsilon (V_0 - V_1)}$  is a dimensionless measure of the injection strength, d being the distance between the two électrodes.

#### B. Numerical method

The study utilizes the Oracle3D finite volume code to solve the governing equations on a non-orthogonal mesh. The computational domain consists of 1.96 million control volumes, with refined grid near the blade tip to capture sharp charge gradients. Second-order temporal and spatial discretization schemes are employed, with particular attention to preserving charge density gradients through TVD schemes. 3D numerical simulations are intractable without using parallel computations. Oracle3D has been parallelized based on MPI library and shows a very good scalability up to 1200 cores [8].



Fig. 2. Blade-plane computational grid.

# C. Injection laws

In this study we considered the two following injection laws:

**Injection law 1°**: q = C, where  $\|\vec{E}\| \ge \alpha E_{\max}$ ;  $\alpha$  is a value between 0 and 1. The case  $\alpha = 0$  corresponds actually to the autonomous injection case from all the blade.  $E_{\max}$  is the maximum value of the electric field, located at the tip of the blade those value is computed during the simulation.

**Injection law 2°**:  $q = \frac{\|\vec{E}\|}{E_c} C$  where  $E_c$  is the threshold

# electric field taken as 60 % of the $E_{max}$ .

#### D. Boundary conditions

Boundary conditions regarding electric potential, charge density and velocity field are depicted of Fig 6.



Fig. 3. Computational domain with boundary condition and mesh in cross-section.

## III. RESULTS AND DISCUSSION

*A. 3 dimensionality of the flow* 



Fig. 4 2D Charge density contours in three different planes in Z direction at  $t=1.2 \ 10^{-3}$  with  $2^{nd}$  injection law. Rey=5.000.

From Fig 4 and 5, it can be observed that the flow quickly loses its two-dimensionality. In Fig 4, we display the structure of the charge density distribution across three different z-slices, clearly indicating that the charge density varies from one slice to another. Fig 5 presents the distribution of the isocontours of the z-component of velocity in the middle slice. In the early stages of the simulation, the flow is indeed two-dimensional (w=0); however, it rapidly transitions to a three-dimensional structure.



Fig. 5. Instantaneous iso-contour of the w velocity component in x-y plane Rey=5.000.



Fig. 6. Instantaneous iso-contour of z Vorticity in x-y plane. Rey=5.000.



Fig. 7 2D iso- contours of the magnitude vorticity at  $t=1.2 \ 10^{-3}$ with  $3^{nd}$  injection law. Rey=5.000.

Fig7 illustrates the distribution of vorticity magnitude across three different z-slices. The pattern of charge distribution shown in Fig 4 is largely influenced by the structure of the vorticity field.



B. Comparison of the two injection laws

Fig. 8. 3D charge density iso-surfaces (q = 0.1 (blue) and q = 0.5 (green)) at non-dimensional time 0.0017, Rey=10.000.



Fig. 9. Two-dimensional charge density iso-surfaces (q = 0.1 (blue) and q = 0.5 (green)) at non-dimensional time 0.0017and 0.002. Rey=10.000.

Fig 8 and 9 display the isosurfaces for charge distribution at q = 0.1 and q = 0.5 for the two injection laws at two dimensionless times: 0.0017 and 0.002. The complexity of the flow is reflected in the volumic charge density distribution. It can be observed that the 2<sup>nd</sup> injection law, injects much more charge in the bulk than the first one.

# IV. CONCLUSION

This study provides new insights into three-dimensional EHD flows in blade-plane configurations. The results demonstrate the importance of considering threedimensional effects and the significant impact of injection laws on flow characteristics. These findings have important implications for applications in heat transfer enhancement and fluid mixing technologies.

# ACKNOWLEDGMENT

This research was funded by the France 2030 program (LABEX INTERACTIFS, reference ANR-11-LABX-0017-01).

Authors P.A. Vázquez and A. T Pérez acknowledge the grant PID2022-138890NB-I00 funded by MCIN/AEI/10.13039/501100011033

We extend our heartfelt gratitude to Professor Adamiak for generously providing us with the mesh for this computational domain.

- [1] J. Wu, P. Traoré, C. Louste, A. T. Peéez, P. A. Vazquez "Heat transfer enhancement by an electrohydrodynamic plume induced by ion injection from a hyperbolic blade", IEEE Int Conference on Liquid Dielectrics (2004).
- [2] P. A. Vazquez, A. Pérez, A Castellanos, "Thermal and electrohydrodynamic plumes. A comparative study," Phys. Fluids 8, 2091 (1996).
- [3] A. T. Pérez, P. A. Vazquez, A. Castellanos, "Dynamics and linear stability of charged jets in dielectric liquids," IEEE Trans. Industry Appl. 31, 761 (1995).
- [4] A. Pérez, P. Traoré, D. Koulova-Nenova, H. Romat "Numerical Study of an Electrohydrodynamic Plume between a Blade Injector and a Flat Plate", IEEE Transactions on Dielectrics and Electrical Insulation, Volume 16, pp 448–455, 2009.
- [5] P. Traore, J. Wu, C. Louste, Q. Pelletier, L. Dascalescu, "Electro-Hydro-Dynamic plumes due to autonomous and non-autonomous charge injection by a sharp blade electrode in a dielectric liquid," IEEE Transc. Industry Applications, (2013).
- [6] Z. Yan, C. Louste, P. Traoré, J. Wu, J. Fang « Structural characteristics of electrohydrodynamic jets induced by a bladeplane actuator subjected to highly non-uniform electric fields: Parametric investigation through the particle image velocimetry techniques» High Voltage, pp 1-13, 2022.
- [7] Wu J., Traoré P., Louste C., Koulova D., Romat H., Direct numerical simulation of electrohydrodynamic plumes generated by a hyperbolic blade electrode. Journal of Electrostatics, Volume 71, Issue 3, Pages 326-331, June 2013
- [8] U. Seth "Message passing Interface parallelization of a multi-block structured numerical solver. Application to the numerical simulation of various typical Electrodynamics flows" PhD thesis University of Poitiers (2019).

# Numerical Investigation of Flow Reversal in Electrohydrodynamic Conduction: An Analysis of Blade-Plane Configuration

P. Traoré<sup>1,\*</sup>, P. A. Vazquez<sup>2</sup>, A.T. Pérez<sup>3</sup>, U. Seth<sup>4</sup>.

<sup>1</sup> Département Fluide-Thermique-Combustion, Institut PPRIME, Université de Poitiers, France.

<sup>2</sup>Departamento de Física Aplicada III, Universidad de Sevilla, ESI, Camino de los Descubrimientos s/n, 41092 Sevilla,

Spain.

<sup>3</sup>Departamento de Electrónica y Electromagnetismo. Facultad de Física. Universidad de Sevilla. 41012 Sevilla. Spain <sup>4</sup> Qubit Pharmaceuticals, Dept. HPQC, 29 rue du Faubourg Saint Jacques, 75014 Paris, France.

\*Corresponding author: Philippe.traore@univ-poitiers.fr

Abstract- A dielectric liquid with low conductivity can be set into motion through the application of an external electric field. The primary driving mechanism is the volumetric Coulomb force, which acts on free charge carriers in the presence of the electric field. This study focuses on low-conductivity liquids where dissociation of ionic pairs in the bulk driven by the Coulomb force is the dominant process. We present an efficient numerical algorithm based on the finite volume method to solve a dissociation model. This numerical approach is employed to simulate electrically induced flows between a hyperbolic blade and a vertical plane electrode configuration. Our numerical results demonstrate that the conduction mechanism leads to the formation of a hetero-charge layer around the blade electrode, generating fluid motion directed from the plate toward the blade, as predicted by theory. However, an intriguing phenomenon emerges for small values of the dimensionless parameter  $C_0$  representing the ratio between ionic transit time and positive ion relaxation time. Initially, the flow follows the expected direction toward the blade. Subsequently, after a critical time, the flow unexpectedly reverses direction, moving from the blade toward the opposite plate electrode, manifesting as a jet-like or plume-like motion. We analyze and identify the specific conditions that trigger this transition from conduction to injection-like behavior within the same flow field. This transition is both numerically simulated and physically interpreted within a single computational framework.

Keywords : Numerical simulation, dissociation and conduction mechanism, blade-plane configuration, plume like motion.

# I. INTRODUCTION

Electrohydrodynamics (EHD) is a multidisciplinary field that studies the interaction between electric fields and fluid motion 0. This interaction is relevant to numerous industrial processes and natural phenomena, as it can induce fluid flow, enabling applications such as EHD pumping or mixing 0. EHD offers several advantages for flow control, including rapid and precise adjustments via electric potential, the absence of mechanical parts, simplicity in design, low power consumption, minimal vibration, and low acoustic noise. In incompressible and isothermal dielectric liquids, the Coulomb force is the primary driver of EHD motion. Two main mechanisms for charge generation are commonly studied: injection and conduction. Conduction occurs when neutral electrolyte molecules AB dissociate into positive and negative ions  $A^+$ and  $B^{-}$ . These ions can also recombine back into ABmolecule.

 $AB \xleftarrow{k_D}{k_R} A^+ + B^-$  where  $k_D$  and  $k_R$  are the

constant rate of dissociation and recombination respectively.

When an electric field is applied ions that are present in the bulk due to the dissociation process of the neutral species will be drawn along electric field lines and attracted to counter-polarized electrode surface, forming "heterocharge layers" near the electrodes. If the electrodes are asymmetrically shaped, the electric field is stronger near the sharper electrode, creating a net fluid flow toward it due to the localized Coulomb force.

However, this study demonstrates that under specific conditions, this expected flow direction can reverse, with the fluid moving from the sharper electrode to the flatter one.

The paper is structured as follows: Section II outlines the problem formulation, Section III presents the theoretical model and governing equations, Section IV describes the numerical methods, Section V discusses the results, and Section VI concludes the study.

# II. FORMULATION OF THE PROBLEM

The system analyzed in this study consists of a weakly conducting liquid contained within a cavity, where two electrodes are immersed: one shaped like a blade and the other a vertical plane. The two electrodes are separated by a distance d, and an electric potential difference  $V_0-V_1$  is applied between them, generating an electric field directed toward the plane electrode. See Figure 1. The study assumes a conduction mechanism involving dissociation and recombination processes.



Fig. 1. Sketch of the blade-plane configuration

## III. THEORETICAL MODEL

*A. Conduction model with fluid motion* The simplest conduction model (see [3]), describes the reversible dissociation and recombination of neutral molecules *AB*.

$$AB \xrightarrow[k_R]{k_D} A^+ + B^-$$

The concentration of neutral species c and the charge densities of positive p and negative n ions evolve according to specific transport equations.

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \left[ (\vec{u} + K_+ \vec{E}) N_p \right] = k_D c - k_R N_p N_n \tag{1}$$

$$\frac{\partial N_n}{\partial t} + \nabla \cdot \left[ (\vec{u} - K_{-}\vec{E})N_n \right] = k_D c - k_R N_p N_n$$
(2)

Where  $K_+, K_-$  are the mobility coefficient for each species respectively.  $\vec{E}$  is the electric field and  $\vec{u}$  stands for the fluid velocity.

According to Langevin's theory [4], the recombination rate depends on the fluid's permittivity  $\varepsilon$  and is expressed as:  $k_R = \frac{K_+ + K_-}{\varepsilon}$ . At thermodynamic equilibrium, the dissociation and recombination rates balance, leading to

equilibrium values for the ion concentrations  $N_{p_0} = N_{n_0}$ 

and one can write:

$$k_D c = k_R N_{p_0} N_{n_0} = k_R N_{p_0}^2 = k_R N_{n_0}^2$$
(3)

Here subscript "0" refers to equilibrium values. As a result, it follows that:  $N_{n_0} = \sqrt{k_D c / k_R}$ 

The electric field is governed by Gauss's law :

$$\nabla \cdot \left( \varepsilon \vec{E} \right) = N_p - N_n \tag{4}$$

while the Navier-Stokes equation, modified to include the Coulomb force, describes the fluid motion.

$$\rho \left( \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right) = -\nabla \tilde{P} + \mu \Delta \vec{u} + (p - n) \vec{E} \tag{5}$$

The fluid is assumed to be Newtonian, incompressible, and characterized by its viscosity  $\mu$  and density  $\rho$ .  $\tilde{P}$  is the modified pressure including the classical pressure P and the scalar from which the electrostriction force derives. For universality in description of the problem, dimensionless variables are introduced. The reference

dimensionless variables are introduced. The reference scales for dimensionless variables denoted with a star are introduced as follow:

$$\begin{bmatrix} x^* \end{bmatrix} \propto d \quad ; \quad \begin{bmatrix} t^* \end{bmatrix} \propto \frac{d^2}{K(V_0 - V_1)} = \text{ ionic transit time}$$
$$\begin{bmatrix} V^* \end{bmatrix} \propto (V_0 - V_1) \quad ; \quad \begin{bmatrix} \vec{E}^* \end{bmatrix} \propto \frac{(V_0 - V_1)}{d} \quad ; \quad \begin{bmatrix} p^*, n^* \end{bmatrix} \propto n_0$$
$$\begin{bmatrix} \vec{u}^* \end{bmatrix} \propto u_{ref} = \frac{K(V_0 - V_1)}{d} \quad ; \quad \begin{bmatrix} \tilde{p}^* \end{bmatrix} \propto \rho_0 u_{ref}^2$$

where d is the inter-electrode spacing,  $V_0 - V_1$  is the electric potential difference between the two electrodes. This introduces a set of dimensionless parameters characterizing the problem:

The electrical Reynolds number:  $R_{el} = \frac{\rho K_+ (V_0 - V_1)}{\mu}$ 

The mobility parameter  $M = \frac{1}{K_+} \left(\frac{\varepsilon}{\rho_0}\right)^{1/2}$  which is the ratio

between the so-called hydrodynamic mobility and the ionic mobility.

 $C_0 = \frac{n_0 d^2}{\varepsilon (V_0 - V_1)}$  is the ratio between the ionic transit time:

 $d^2 / K_+ (V_0 - V_1)$  and the relaxation time of the positive ions:  $\varepsilon / \sigma$  where  $\sigma$  is the fluid conductivity.

 $\gamma = \frac{K_{-}}{K_{+}}$  the ratio of the two ionic mobilities.

This leads to the following set of dimensionless equations for the ion species where for sake of simplicity the (\*) have been dropped:

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \left( (\vec{u} + \vec{E}) N_p \right) = C_0 \left( \gamma + 1 \right) \left( 1 - N_p N_n \right) \tag{6}$$

$$\frac{\partial N_n}{\partial t} + \nabla \cdot \left( \left( \vec{u} - \gamma \vec{E} \right) N_n \right) = C_0 \left( \gamma + 1 \right) \left( 1 - N_p N_n \right)$$
(7)

$$\nabla^2 V = -C_0 \left( N_p - N_n \right) \tag{8}$$

$$\vec{E} = -\nabla V \tag{9}$$

$$\nabla \cdot \vec{u} = 0 \tag{10}$$

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = -\nabla \tilde{P} + \frac{1}{R_{el}}\nabla^2 \vec{u} + C_0 M^2 (N_p - N_n)\vec{E}$$
(11)

# C. Boundary conditions

The boundary conditions associated to this model are as follow:

On the blade: 
$$V_0 = 1, N_p = 0, \frac{\partial N_p}{\partial n} = 0, u = v = 0$$

On the vertical opposite electrode:

$$V_1 = 0, \frac{\partial N_p}{\partial x} = 0, N_n = 0, \ u = v = 0$$

On all the other walls:  $\frac{\partial V}{\partial n} = \frac{\partial N_p}{\partial n} = \frac{\partial N_n}{\partial n} = u = v = 0$ 

## D. Initial conditions

For the conduction simulations all the variables are initialized to zero except the ionic densities  $N_p = N_n = 1 \ \forall \vec{x} \in D$  where D is the computational domain.

#### IV. NUMERICAL METHOD

The numerical simulations are performed using the inhouse code Oracle3D, which is based on the finite volume method [5], [6]. This approach allows for accurate integration of the governing equations on a nonorthogonal mesh, ensuring precise representation of the blade geometry (see Fig 2). The equations are discretized using second-order schemes in both time and space. For further details on the numerical implementation, readers are referred to previous studies [7], [8].

# V. RESULTS

#### A. Regime 1

In the first numerical experiment, the electric Reynolds number is set to 2.5. M=10 and  $C_0=6.5$ .

In Figure 3, the velocity field is shown, clearly illustrating that the flow moves from the plane electrode toward the blade electrode, which aligns with theoretical expectations. This behavior is explained by the fact that the electric field is more concentrated near the tip of the blade electrode due to its smaller radius of curvature. Consequently, the Coulomb force is stronger in the vicinity of the sharp blade electrode compared to the vertical plane electrode on the opposite side of the domain. This results in a greater drift of negative ions toward the blade electrode, while the positive ions exhibit a weaker drift toward the plane electrode.



Fig. 3. Velocity field at steady state for  $R_{el}$ =2.5. M=10 and  $C_0$ =6.5

# B. Regime 2

In the second numerical experiment with have set the electric Reynolds number to 2.5, M = 10 and  $C_0 = 0.1$  On Fig 4. we have displayed the velocity field at four different non-dimensional time a = 0.35), b=1.4), c=2.15), d=3.3)





Fig. 4. Four instantaneous display of the velocity field for  $R_{el}=2.5, M=10, C_{0}=0.1$ 

#### VI. DISCUSSION

Unexpectedly and in a completely unforeseen manner, a highly intriguing phenomenon was observed. In Figure 4, we present four instantaneous and consecutive velocity fields under the same flow conditions (Rel = 2.5, M = 10, C0 = 0.1): time a) < time b) < time c) < time d). Initially, the flow is clearly directed from the plane electrode to the blade electrode, as expected under these conditions (see time a, b, and c). However, at time d, the flow direction suddenly reverses, moving from the blade to the plane. This surprising behavior can be explained by analyzing the electric charge distribution  $q = N_p - N_n$ , as shown in Figure 5. In this figure, we also display the components of

Figure 5. In this figure, we also display the components of the electric field and the induced electric force, depending on the sign of the electric charge. At the early stage, the heterocharge layer near the blade electrode is predominantly negative (see case 1). Based on the components of the electric field, this results in a negative Coulomb force in the x-direction  $F_x = qE_x$ , causing the flow to move toward the blade, as initially expected. Over time, due to the convection of ion species by the flow, the charge distribution changes, and a significant amount of positive charge accumulates near the blade's tip, where the electric field is most intense (see case 2). This leads to a positive Coulomb force component in the x-direction, reversing the flow direction from the blade to the plane.



Fig. 5. Electric charge density distribution and electric field and Coulomb force components.

#### VI. CONCLUSION

In this study, we observed a highly intriguing phenomenon where the flow behavior deviates from what is typically expected in conductive flows, where the dissociation of neutral molecules serves as the primary mechanism for generating electric charges. Under certain conditions, deeply linked to the value of  $C_0$ , the flow direction can unexpectedly reverse, moving from the blade to the plane, contrary to theoretical predictions for such scenarios. It was demonstrated that, in specific circumstances, the distribution of electric charges can undergo significant changes, which in turn alters the distribution of the Coulomb force, ultimately leading to a reversal in the flow direction like in pure injection flow.

#### ACKNOWLEDGMENT

This research was funded by the France 2030 program (LABEX INTERACTIFS, reference ANR-11-LABX-0017-01).

Authors P.A. Vázquez and A. T Pérez acknowledge the grant PID2022-138890NB-I00 funded by MCIN/AEI/10.13039/501100011033.

We extend our heartfelt gratitude to Professor Adamiak for generously providing us with the mesh for this computational domain.

- [1] A. Castellanos, "Electrohydrodynamics", *Springer, New York*, 1998.
- [2] J.M. Cowley, "Fundamentals of Applied Electrostatics", Wiley, New York, 1986.
- [3] J.J Thomson. "Conduction of electricity through gazes" Merchant Books, 2006.
- [4] P. Langevin, "Recombinaison et mobilités des ions dans les gaz" Annales de Chimie et de Physique, 28(7)b(1903), 433.
- [5] S.V. Patankar, "Numerical Heat Transfer and Fluid Flow", Stockholm, Washington, DC, (1980)
- [6] P. Traoré, Y. Ahipo, C. Louste, "A robust and efficient finite volume scheme for the discretization of diffusive flux on extremely skewed meshes in complex geometries". *Journal of Computational Physics*, 228, pp. 5148-5159, 2009.
- [7] P. Traoré P, A.T. Pérez, "Two-dimensional numerical analysis of electroconvection in a dielectric liquid subjected to strong unipolar injection", *Physics of Fluid* 24, (2012) 037102.
- [8] J. Wu, P. Traoré, C. Louste, "An efficient finite volume method for electric field–space charge coupled problems", *Journal of Electrostatics*, (2013), pp 319-325.
- [9] U. Seth « Message Passing Interface parallelization of a multi-block structured numerical solver. Application to the numerical simulation of various typical Electro-hydrodynamic flows." PhD Thesis 2019. University of Poitiers.

# Numerical Study of Electro-Thermo-Hydrodynamic Conduction in Dielectric Liquids: Impact of Temperature-Dependent Properties and Dielectric Forces on Rayleigh-Bénard Instability.

P. Traoré<sup>1,\*</sup>, P. A. Vazquez<sup>2</sup>, A.T. Pérez<sup>3</sup>, J. Wu<sup>4</sup>.

<sup>1</sup> Département Fluide-Thermique-Combustion, Institut PPRIME, Université de Poitiers, France.

<sup>2</sup>Departamento de Física Aplicada III, Universidad de Sevilla, ESI, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain.

<sup>3</sup>Departamento de Electrónica y Electromagnetismo. Facultad de Física. Universidad de Sevilla. 41012 Sevilla. Spain

<sup>4</sup> Key Laboratory of Aerospace Thermophysics, School of Energy Science and Engineering, Harbin Institute of

Technology, China.

\*Corresponding author: Philippe.traore@univ-poitiers.fr

Abstract- This study focuses on the numerical investigation of electro-thermal-convection phenomena driven by the combined effects of electrohydrodynamic (EHD) conduction and a thermal gradient between two parallel plates, specifically in the context of Rayleigh-Bénard instability. The governing equations, which include the Navier-Stokes equations, the heat equation, transport equations for ionic densities, and the Poisson equation for the electric potential, are solved using the finite-volume homecode Oracle. These equations are coupled to account for the complex interactions between the electric field, ionic transport, and thermal gradients. Previous research has shown that the flow dynamics in such systems are significantly influenced by the ionic mobility of each ionic species and the liquid's permittivity. However, in most studies, the ionic mobility is often assumed to be identical for all species and independent of temperature, which limits the accuracy of the results. In this work, we address this limitation by incorporating temperature-dependent variations of both the liquid permittivity and the ionic mobility of each species into the model. This allows for a more realistic representation of the physical properties of the dielectric liquid under varying thermal conditions. Furthermore, the study examines the impact of the dielectric force and the Onsager effect on thermal convection and heat transfer. The Onsager effect, which increases the dissociation of ionic species with the electric field seems to play a critical role in modifying the flow structure and stability. By analyzing these effects, we aim to better understand how the interplay between electrical and thermal forces influences the onset and development of convection patterns. The stability of the flow is also investigated by exploring the influence of these parameters, which are closely linked to the temperature field. Our findings highlight the importance of considering temperature-dependent properties and their impact on flow behavior, particularly in systems where precise control of heat transfer and fluid motion is required. This study provides new insights into the complex dynamics of electro-thermal-convection phenomena and lays the groundwork for future research in this field.

**Keywords :** Rayleigh-Bénard instability, heat-transfer, numerical simulation, finite-volume method, conduction phenomenon, electro-convection, dielectric force, Onsager effect.

#### I. INTRODUCTION

Electrohydrodynamics (EHD) is a multidisciplinary field that studies the interaction between electric fields and fluid motion [1]. This interaction is relevant to numerous industrial processes and natural phenomena, as it can induce fluid flow, enabling applications such as EHD pumping or mixing [2]. EHD offers several advantages for flow control as well as for heat transfer enhancement [3], [4]. Two main mechanisms for charge generation are commonly studied: injection and conduction. Conduction occurs when neutral electrolyte molecules *AB* dissociate into positive and negative ions  $A^+$  and  $B^-$ . When the electrostatic energy of Coulombic attraction exceeds the thermal energy, these ions can also recombine back into *AB* molecule.

$$AB \xleftarrow{k_D}{k_R} A^+ + B^-$$
 where  $k_D$  and  $k_R$  are the constant

rate of dissociation and recombination respectively [5]. Ions that are present in the bulk due to the dissociation process of the neutral species will be drawn along electric field lines and attracted to counter-polarized electrode surface, forming "heterocharge layers" near the electrodes. In incompressible flows of dielectric or weakly conductive liquids subjected to heat transfer, the temperature dependance of several physicochemical properties of the liquid is of primary importance for a detailed and accurate flow description.

If the electrodes are symmetrically shaped, no flow will occur, as the Coulomb forces developing near the heterocharge layers are equal in magnitude and opposite in direction. In the presence of a thermal gradient that opposes gravity, Rayleigh-Bénard instability will develop, leading to thermoconvection once the Rayleigh number exceeds 1708. The purpose of this paper is to analyze how conduction may influence the stability of the flow and the efficiency of heat transfer.

The paper is structured as follows: Section II outlines the problem formulation, Section III presents the theoretical model and governing equations, Section IV describes the numerical methods, Section V discusses the results, and Section VI concludes the study.

#### II. FORMULATION OF THE PROBLEM

The system analyzed in this study consists of a weakly conducting liquid contained within a rectangular cavity of aspect ratio 2, where two electrodes are immersed: The two electrodes are separated by a distance H and an electric potential difference  $V_1-V_0$  is applied between them, generating an electric field directed upwards. The high-voltage electrode is heated at temperature  $\theta_1$  while the counter electrode is maintained at a lower temperature  $\theta_0$  thus generating the development of Rayleigh-Bénard instability (see Figure 1). The study assumes a conduction mechanism involving dissociation and recombination processes.



Fig. 1. Sketch of physical domain configuration

# A. Theoretical model with fluid motion

The simplest conduction model, describes the reversible dissociation and recombination of neutral molecules (see [5]). The concentration of neutral species c and the charge densities of positive  $N_p$  and negative  $N_n$  ions evolve according to specific transport equations.

$$\frac{\partial N_p}{\partial t} + \nabla \left[ (\vec{u} + K_+ \vec{E}) N_p \right] = k_D c - k_R N_p N_n \tag{1}$$

$$\frac{\partial N_n}{\partial t} + \nabla \left[ (\vec{u} - K_{-}\vec{E})N_n \right] = k_D c - k_R N_p N_n$$
(2)

Where  $K_+, K_-$  are the mobility for each species respectively.  $\vec{E}$  is the electric field and  $\vec{u}$  stands for the fluid velocity. According to Onsager [6], when an external electric field  $\vec{E}$  is applied, the dissociation process is enhanced. Thus the dissociation rate  $k_D$  is dependent on the magnitude of the electric field:  $k_D = F(w)k_D^0$ , where F is the Onsager function, w is the enhanced dissociation rate coefficient and  $k_D^0$  refers to the dissociation constant at the thermodynamic equilibrium without external electric field. The enhanced dissociation rate coefficient w depends on the magnitude of the electric field as well as the temperature and permittivity distribution:

$$w = \sqrt{\frac{e^3 \|\vec{E}\|}{16\pi\varepsilon k_B^2 \theta^2}}$$
 where is the electron charge,  $\varepsilon$  the fluid's

permittivity and  $k_B$  the Boltzman's constant.

The Onsager function  $F(w) = \frac{I_1(4w)}{2w}$  where  $I_1$  is the modified Bessel function of the 1<sup>st</sup> kind and order one.

According to Langevin's theory [7], the recombination rate  $k_R$  depends on the  $\varepsilon$  and is expressed as:  $k_R = \frac{K_+ + K_-}{\varepsilon}$ .

At thermodynamic equilibrium, the dissociation and recombination rates balance, leading to equilibrium values for the ion concentrations  $N_{p_0} = N_{p_0}$ 

and one can write: 
$$k_D c = k_R N_{p_0} N_{n_0} = k_R N_{p_0}^2 = k_R N_{n_0}^2$$
(3)

Here subscript "0" refers to equilibrium values. As a result, it follows that:  $N_{n_0} = \sqrt{k_D c / k_R}$ 

Finally, the transport equations for ionic species can be written as:

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \left[ (\vec{u} + K_+ \vec{E}) N_p \right] = \left( \frac{K_+ + K_-}{\varepsilon} \right) \left( F(w) N_{n_0}^2 - N_p N_n \right)$$
(4)

$$\frac{\partial N_n}{\partial t} + \nabla \cdot \left[ (\vec{u} - K_- \vec{E}) N_n \right] = \left( \frac{K_+ + K_-}{\varepsilon} \right) \left( F(w) N_{n_0}^2 - N_p N_n \right)$$
(5)

The electric field is governed by Gauss's law :

$$\nabla \cdot \left( \varepsilon \vec{E} \right) = N_p - N_n \tag{6}$$

The fluid is assumed to be Newtonian, incompressible, and characterized by its viscosity  $\mu$  and density  $\rho$ . The fluid motion is governed by the Navier-Stokes equations under the Boussinesq assumption, incorporating three body forces: the Coulomb force due to the electric field acting on free charges, the dielectric force arising from polarization effects, and the buoyancy force due to density variations.

$$\rho_{0}\left(\frac{\partial \vec{u}}{\partial t} + (\vec{u}.\nabla)\vec{u}\right) = -\nabla \tilde{p} + \nabla \cdot \left(\mu\left(\overline{\nabla \vec{u}} + \overline{\nabla \vec{u}}^{T}\right)\right) + (p-n)\vec{E} - \frac{\left\|\vec{E}\right\|^{2}}{2}\nabla(\varepsilon) + \rho\vec{g}$$

$$(7)$$

The energy equation is solved to determine the temperature distribution throughout the domain.

$$\rho_0 C_p \left( \frac{\partial \theta}{\partial t} + \vec{u} \cdot \nabla \theta \right) = \nabla \cdot \left( \lambda \nabla \theta \right)$$
(8)

The physical properties of the fluid, including ionic mobilities of both species, electrical permittivity, density, and viscosity, exhibit temperature dependence.

$$K_{+} = K_{0+} \left( 1 + k_{1} (\theta - \theta_{0}) \right)$$
(9)

$$K_{-} = K_{0-} \left( 1 + k_1 (\theta - \theta_0) \right)$$
(10)

$$\varepsilon = \varepsilon_0 \left( 1 - e_1(\theta - \theta_0) \right) \tag{11}$$

$$\rho = \rho_0 \left( 1 - \beta(\theta - \theta_0) \right) \tag{12}$$

$$\mu = \mu_0 \left( 1 - k_1 (\theta - \theta_0) \right) \tag{13}$$

Both  $\lambda$  and  $C_p$  may vary with temperature; however, within the temperature range where the Boussinesq assumption is valid,  $\lambda$  and  $C_p$  can be treated as constants. For the same reason, Joule heating can be safely disregarded.  $\tilde{p}$  is the modified pressure including the classical pressure p and the scalar from which the electrostriction force derives.

For universality in description of the problem, dimensionless variables are introduced. The reference scales for dimensionless variables denoted with a star are introduced as follows:

$$\begin{aligned} x^* &= x/H \quad ; \quad y^* &= y/H \quad ; \quad t^* &= t/\frac{H^2}{K_{0+}(V_1 - V_0)} \\ V^* &= V/(V_0 - V_1) \quad ; \quad \vec{E}^* &= \vec{E}/\frac{(V_1 - V_0)}{H} \\ p^* &= p/n_0 \quad ; \quad n^* &= n/n_0 \\ K^*_+ &= K_+/K_{0+} \quad ; \quad K^*_- &= K_-/K_{0+} \\ \varepsilon^* &= \varepsilon/\varepsilon_0 \quad ; \quad \rho^* &= \rho/\rho_0 \quad ; \quad \mu^* &= \mu/\mu_0 \\ \vec{u}^* &= \vec{u}^*/\frac{K(V_1 - V_0)}{H} \quad ; \quad \vec{p}^* &= \vec{p}/\rho_0 u_{ref}^2 \quad ; \quad \theta^* &= \frac{\theta - \theta_0}{\theta_1 - \theta_0} \end{aligned}$$

where *H* is the inter-electrode spacing,  $V_1 - V_0$  is the electric potential difference between the two electrodes. This leads to the following set of dimensionless equations where for sake of simplicity the (\*) have been dropped:

$$\frac{\partial N_p}{\partial t} + \nabla \cdot \left( (\vec{u} + K_+ \vec{E}) N_p \right) = C_0 \left( \frac{K_+ + K_-}{\varepsilon} \right) \left( F(w) - N_p N_n \right)$$
(14)

$$\frac{\partial N_n}{\partial t} + \nabla \cdot \left( (\vec{u} - K_- \vec{E}) N_n \right) = C_0 \left( \frac{K_+ + K_-}{\varepsilon^*} \right) \left( F(w) - N_p N_n \right)$$
(15)

$$\nabla \cdot \left( \mathcal{E} \nabla V \right) = -C_0 \left( N_p - N_n \right) \tag{16}$$

$$\vec{E} = -\nabla V \tag{17}$$
$$\nabla \cdot \vec{u} = 0 \tag{18}$$

$$\begin{aligned} \frac{\partial \vec{u}}{\partial t} + (\vec{u}.\nabla)\vec{u} &= -\nabla \tilde{p} + \frac{1}{R_{el}}\nabla \cdot \left(\mu \left(\overline{\nabla \vec{u}} + \overline{\nabla \vec{u}}^T\right)\right) \\ &+ C_0 M^2 (N_p - N_n)\vec{E} - M^2 \frac{\left\|\vec{E}\right\|^2}{2}\nabla(\varepsilon) + \frac{Ra}{PrR_{el}^2}\theta \tilde{y} \end{aligned}$$
(19)

$$\frac{\partial \theta}{\partial t} + \vec{u} \cdot \nabla \theta = \frac{1}{PrR_{el}} \nabla^2 \theta \tag{20}$$

$$K_{+} = 1 + NRa\theta \tag{21}$$

$$K_{-} = \gamma \left( 1 + NRa\theta \right) \tag{22}$$

$$\varepsilon = 1 - LRa\theta \tag{23}$$

$$\mu = 1 - NRa\theta \tag{24}$$

This introduces a set of dimensionless parameters characterizing the problem:

The electric Reynolds number:  $R_{el} = \frac{\rho_0 K_{0+} (V_1 - V_0)}{\mu_0}$ 

The mobility parameter 
$$M = \frac{1}{K_{0+}} \left(\frac{\varepsilon_0}{\rho_0}\right)^{1/2}$$
 which is the

ratio between the so-called hydrodynamic mobility and the ionic mobility.

$$C_0 = \frac{n_0 H^2}{\varepsilon_0 (V_1 - V_0)}$$
 is the ratio between the ionic transit time:  
$$H^2 / K_{0,1} (V_1 - V_0)$$
 and the relaxation time of the positive

ions:  $\varepsilon_0 / \sigma$  where  $\sigma$  is the fluid conductivity.

The Rayleigh number: 
$$Ra = \frac{\rho_0 \beta \Delta \theta H^3 g}{\mu_0 \kappa}$$

The Prandt number: 
$$Pr = \frac{\mu_0}{\rho_0 \kappa}$$

$$L = \frac{e_1 \mu_0 \kappa}{\beta \rho_0 g H^3}$$
 and  $N = \frac{k_1 \mu_0 \kappa}{\beta \rho_0 g H^3}$  are dimensionless

numbers that account for the temperature dependence of permittivity and ion mobilities respectively.  $\kappa = \lambda / \rho_0 C_p$  is the fluid thermal diffusivity.  $\gamma = K_{0-} / K_{0+}$  is the ratio of ion mobility at reference temperature  $\theta_0$ .

The enhanced dissociation rate coefficient w will be

expressed as: 
$$W = \sqrt{\frac{O\|\vec{E}\|}{\varepsilon(\theta^2 + 2\theta\Gamma_a + T_a^2)}}$$
 where

$$O = \frac{e_0^3 E_{ref}}{16\pi\varepsilon_{ref} \kappa_B^2 \theta_{ref}^2}$$
 is the Onsager number and

 $T_a = \frac{\theta_0}{\theta_{ref}}$  is also a new dimensionless number occurring

in this study.

$$\varepsilon_{ref} = \varepsilon_0 \varepsilon_R; \theta_{ref} = \theta_1 - \theta_0; E_{ref} = \frac{V_1 - V_0}{H}$$

# C. Boundary conditions

The boundary conditions associated to this model are depicted on figure 2.

# D. Initial conditions

For the conduction simulations all the variables are initialized to zero except the ionic densities  $N_p = N_n = 1 \ \forall \vec{x} \in D$  where D is the computational domain.



#### IV. NUMERICAL METHOD

The numerical simulations are performed using the inhouse code Oracle, which is based on the finite volume method. The equations are discretized using second-order schemes in both time and space. For further details on the numerical implementation, readers are referred to previous studies [8].

#### V. RESULTS AND DISCUSSION

Various regimes emerge based on the values of specific dimensional parameters within the problem. As an example, Figure 3, depicts an overstability regime.

# VI. CONCLUSION

This study investigates electro-thermal-convection phenomena driven by electrohydrodynamic (EHD) conduction and thermal gradients between two parallel plates, focusing on Rayleigh-Bénard instability. A key innovation of this work is the incorporation of temperature-dependent variations in liquid permittivity and ionic mobility, addressing limitations in previous studies that assumed uniform ionic mobility. The study also explores the effect of the Onsager effect on thermal convection and heat transfer, revealing their significant influence on flow structure and stability



Fig. 3. Time evolution of the maximum velocity. Ra=5000, R<sub>el</sub>=2, C0=6.5, M=10, O=200,  $\gamma = 0.75$ 

#### ACKNOWLEDGMENT

This research was funded by the France 2030 program (LABEX INTERACTIFS, reference ANR-11-LABX-0017-01).

Authors P.A. Vázquez and A. T Pérez acknowledge the grant PID2022-138890NB-I00 funded by MCIN/AEI/10.13039/501100011033"

- [1] A. Castellanos, "Electrohydrodynamics", *Springer, New York*, 1998.
- [2] J.M. Cowley, "Fundamentals of Applied Electrostatics", Wiley, New York, 1986.
- [3] P. Atten, F. M. J. McCluskey and A. T. Perez, « Electroconvection and its Effect on Heat Transfer » IEEE transactions on Electrical Insulation Vol. 23 No. 4, August 1888.
- [4] P. Traoré P, A.T. Pérez, "Two-dimensional numerical analysis of electroconvection in a dielectric liquid subjected to strong unipolar injection", *Physics of Fluid* 24, (2012) 037102.
- [5] J.J Thomson. "Conduction of electricity through gazes" Merchant Books, 2006.
- [6] L. Onsager, Deviations from ohm's law in weak electrolytes, Journal of Chemical Physics, 2(9) (2004).
- [7] P. Langevin, "Recombinaison et mobilités des ions dans les gaz" Annales de Chimie et de Physique, 28(7)b(1903), 433.
- [8] J. Wu, P. Traoré, C. Louste, "An efficient finite volume method for electric field–space charge coupled problems", Journal of Electrostatics, (2013), pp 319-325.

# Numerical Simulation of Electrohydrodynamic Deformation of a Leaky Dielectric Droplet employing Arbitrary Eulerian Lagrangian (ALE) Approach using COMSOL Multiphysics

Sandesh More<sup>1</sup>, Rochish Thaokar<sup>1\*</sup>

<sup>1\*</sup>, <sup>1</sup>Department of Chemical Engineering, Indian Institute of Technology Bombay, Powai 400076 \*Corresponding author : rochish@che.iitb.ac.in

*Abstract-* Electrohydrodynamics (EHD) drop deformation refers to the study that how a fluid responds (deformation) when subjected to an external electric field. This phenomenon occurs due to the interaction between electric field and the electric charge distribution on the droplet surface, which induces electric stress at interface thereby leads to deformation. The drop may undergo stretching, elongation, or even breakup depending on factors such as the field strength, fluid properties and drop size. Understanding EHD drop deformation has its application in such as electrowetting, inkjet printing, microfluidics and electrospinning where precise manipulation of droplet deformation is required. This study aims to explore the governing principles of drop deformation employing ALE approach using COMSOL Multiphysics software, providing insights into the role of electrostatic forces which plays a role in deformation of fluid droplets in electric field. The droplet is considered to be leaky dielectric so the electric current inside and outside induces the surface charge distribution which creates the normal and tangential stresses on interface leads to prolate and oblate deformation as shown in figures below for the parameters R, Q and , where R is conductivity ratio Q is dielectric constant ratio and is viscosity ratio respectively. Taking this formulation we can model different physical electrohydrodynamic phenomenon like drops deformation in an emulsion, electrowetting of droplets, as well as electrospinning and electrospraying application.

Keywords- Electrohydrodynamic, Droplet, Deformation, Voltage.

## I. INTRODUCTION

The electrohydrodynamic (EHD) deformation of droplets refers to the changes in shape and behavior of liquid droplets under the influence of an applied electric field. When a droplet is subjected to an electric field, electrical forces act on the interface between the two fluids and bulk fluid inside the droplet, leading to complex interplays between electrical, hydrodynamic, and surface tension forces[1,2,3,8]. Depending on factors such as the field strength, fluid properties (electrical conductivity, permittivity, viscosity) and surrounding medium, the droplet can stretch, elongate into a prolate (elongated) or oblate (flattened) shape.

In the systems devoid of free charge, where the fluids behave as ideal insulating dielectrics or when a perfectly conducting droplet is immersed in an insulating medium the interfacial electric stress is purely normal to the surface. This normal Maxwell stress is counteracted by the interfacial tension, resulting in an equilibrium shape where the droplet elongates along the direction of the applied electric field, forming a prolate spheroid[11]. In realistic scenarios, droplets are treated as leaky dielectrics, meaning they possess finite electrical conductivity. Under an applied electric field conduction currents within and outside the droplet lead to the accumulation of interfacial surface charges. These surface charges generate not only a normal electric stress but also a tangential (shear) electric stress at the droplet interface. Recognizing this, G.I.[4,5] Taylor incorporated the effect of tangential electric stress into the force balance, which is resisted by the viscous stresses in the surrounding fluids. This framework led to the development of the leaky dielectric model in elec-

trohydrodynamics. Depending on the relative electrical and viscous properties of the inner and outer fluids, the droplet may undergo oblate (flattened) deformation instead of the prolate shape predicted in ideal insulating systems. Haisheng Fang et.al[12] has used ALE moving mesh formulation to explore the process of emission of charged droplet from a nozzle. Here they explore the regime by constructing a phase diagram of transition of dripping to spray mode depending upon the initial volume of the liquid (contact angle of fluid with nozzle), Electric field Vhaloska(2019)[3] summarizes recent strength  $Ca_E$ . experimental and theoretical studies in the area of fluid particles (drops and vesicles) in electric fields, focusing on transient dynamics and extreme deformations. It provides a theoretical framework for the time evolution of nearly spherical shapes, highlighting the broader applicability of the leaky dielectric approach. Zhang et al[7] investigates experimental EHD deformation of droplets subjected to a combined DC electric field and shear flow, providing insights into the interplay between electric and flow fields on droplet behavior. Chirkov et al[8] has shown the possible outcomes of the interaction of a conductive droplet pair suspended in oil under the action of high voltage with an amplitude above the threshold value when electrocoalescence is replaced with non-coalescence.

The present study investigates the deformation behavior of a leaky dielectric droplet subjected to a uniform electric field under creeping flow conditions. The deformation patterns are obtained using the Arbitrary Lagrangian-Eulerian (ALE) framework implemented in COMSOL Multiphysics. By varying the ratios of electric conductivity and dielectric permittivity between the droplet and the surrounding medium, both prolate and oblate deformations



Figure 1: (a)Geometry of droplet with its Physical properties (b)Boundary conditions implementation

are observed. This investigation provides a fundamental understanding of how topological changes at the droplet interface arise due to electric stresses. The insights gained are broadly applicable to electrohydrodynamic systems, including electrocoalescers, electrowetting, electrospray technologies, and inkjet printing.

#### II. NUMERICAL MODEL

The Arbitrary Lagrangian-Eulerian(ALE) method[9,10] also known as the moving mesh method, is employed to numerically simulate the electrohydrodynamic (EHD) deformation of a droplet in a two-phase fluid system. An axisymmetric cylindrical geometry is considered, as illustrated in Fig 1(a), where a small droplet of radius a (denoted as F1, Fluid 1) is suspended in another immiscible fluid (denoted as F2, Fluid 2). Both fluids are assumed to be Newtonian, with densities  $\rho$ , and dynamic viscosities  $\overline{\mu}$  (overbar inside the droplet) and  $\mu$  (without overbar outside the droplet).

Furthermore, both fluids are modeled as leaky dielectrics, characterized by their dielectric constants  $\overline{\epsilon}$  and  $\epsilon$ , and electrical conductivities  $\overline{\sigma}$  and  $\sigma$ . To analyze the system, the following dimensionless ratios of physical properties are defined

- 1. Conductivity ratio  $R = \frac{\sigma}{\overline{\sigma}}$
- 2. Dielectric constanty ratio  $Q = \frac{\overline{\epsilon}}{\epsilon}$
- 3. Viscosity ratio  $\lambda = \frac{\overline{\mu}}{\mu}$
- 4. Deformation  $(D = \frac{l_1 l_2}{l_1 + l_2})$
- 5. Electrocapillary number  $Ca_E = \frac{\epsilon\epsilon_0 a E_{\infty}^2}{\gamma}$

We employ the laminar flow module which is coupled with electric currents module using COMSOL multiphysics software to obtain the deformation $(D = \frac{l_1 - l_2}{l_1 + l_2})$ . The fluid

flow governing equations are given by

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \vec{\nabla} \vec{u}) = \vec{\nabla} \cdot \mathbf{T} + \rho g_z \tag{1}$$

where **T** is the fluid stress Tensor **T** =  $-p\mathbf{I} + \mu[(\vec{\nabla}\vec{u}) + (\vec{\nabla}\vec{u})^T]$ 

$$\rho[\vec{\nabla} \cdot \vec{u}] = 0 \tag{2}$$

The Electric field governing equations are given as

$$\vec{\nabla}.\vec{J} = 0 \tag{3}$$

where  $\vec{J} = \sigma \vec{E} + \frac{\partial \vec{D}}{\partial t}$  and  $\vec{D} = \epsilon \epsilon_0 \vec{E} \& \vec{E} = -\nabla V$ The difference in the dielectric constant creates the surface charge distribution at the interface. And the discontinuity of the electric field creates a jump of stress known as the Maxwell electric stress  $\mathbf{T}^e = \epsilon \epsilon_0 \left( \vec{E} \vec{E} - \frac{1}{2} E^2 \mathbf{I} \right)$ , which is summed with hydrodynamic stress at the droplet interface as shown in Fig 1(b). No slip boundary condition is applied at the outermost boundries.Uniform electric field is maintained by applying electric potential at upper plate while

lower plate is grounded. Considering the dimensional analysis of the problem. The Electric field is scaled as  $E_{\infty}$ .Since the drop is suspended in an unbounded medium so the characterstic length scale is the initial radius a of the droplet.The characterstic velocity viscous and electric stresses are scaled as  $\frac{\mu U}{a}$  and  $\epsilon\epsilon_0 E_{\infty}^2$ . The relative comparison of electric to surface tension is given by Electrocapillary number  $Ca_E = \frac{\epsilon\epsilon_0 a E_{\infty}^2}{\gamma}$ . Under the limit of small perturbation taylor[4,5] has solved the drop deformation problem the followed by Ajayi[2] to the first and second order correction to  $Ca_E$ . The axisymmetric deformation is defined as  $D = \frac{l_1 - l_2}{l_1 + l_2}$  where  $1_1$  and  $l_2$  are drop length and drop breadth respectively.

#### III. RESULTS AND DISCUSSION

Firstly we overview the droplet behavior at  $\lambda = 1$ . The results are systematically compared with the the first order theory, second order correction and the BEM(Boundary Element Method) simulations performed by Lac and Homsy.

#### A. Prolate drops

Fig 2 presents the variation of the deformation parameter D with the electric capillary number  $Ca_E$  for a conductivity ratio for R = 0.1 and perimitvitty ratio Q = 0.1. The results clearly demonstrate that the numerical simulations performed using COMSOL Multiphysics capture the deformation trend with second-order accuracy, consistent with theoretical predictions. Droplet breakup is not observed within the simulated range of  $Ca_E$ , as excessive deformation leads to significant mesh distortion, which can result in numerical instability or failure in the ALE framework.

The velocity streamlines indicate that the flow converges



Figure 2: Prolate droplet deformation for  $\lambda = 1 C a_E$  for R = 0.1and Q = 0.1



Figure 3: Initial Normal and Tangential Stress at the droplet surface

along the axial (z) direction and diverges radially outward, thereby exerting a stretching effect that elongates the droplet along the z-axis. The initial time normal and tangential electric stress distributions along the droplet interface are shown in Fig 3. These profiles indicate that the system is normal stress dominant. The normal stress is found to be positive value near the poles, acting along the surface normal, which drives the droplet to deform into a prolate shape aligned with the applied electric field.

#### B. Oblate Drops

Fig 4 shows the variation of the deformation parameter D with the electric capillary number  $Ca_E$  for a conductivity ratio for R = 10 and permitvitty ratio Q = 2. The corresponding electric stress distribution along the droplet interface is depicted in Fig 5. In this case, the system is observed to be tangential stress dominant, in contrast to the previous scenario. The normal stress at the poles is negative and directed inward along the surface normal of the droplet. This inward-directed force opposes elongation and instead drives the droplet to deform into an oblate shape, compressed along the direction of the applied electric field.



Figure 4: Oblate droplet deformation for  $\lambda = 1 \ Ca_E$  for R = 10and Q = 2



Figure 5: Initial Normal and Tangential Stress at the droplet surface

#### IV. CONCLUSION

We have numerically investigated the deformation of a suspended droplet subjected to a steady DC uniform electric field under the creeping flow approximation, using the Arbitrary Lagrangian-Eulerian (ALE) moving mesh method implemented in COMSOL Multiphysics. For the case where the inner and outer fluids have equal viscosity  $\lambda = 1$  the droplet exhibits distinctly different deformation behaviors depending on the electric conductivity ratio R and permittivity ratio Q. At low electric capillary number  $Ca_E$  the droplet deformation closely follows the predictions of Taylor's small deformation theory. However, droplet breakup could not be captured due to the limitations of the ALE method in handling severe mesh distortions at high deformations. Consequently, deviations are observed between the current results and boundary element method (BEM) simulations, as shown in Fig 2 and Fig 4 for prolate and oblate cases, respectively. The analysis reveals that when the droplet is more conducting than the surrounding medium (i.e., low R), the system is normal stress dominated, leading to prolate deformation. Conversely, when the droplet is less conducting (i.e., high R), tangential electric stresses dominate, resulting in oblate deformation. These findings highlight the critical role of electrical property ratios in governing the electrohydrodynamic response

of leaky dielectric droplets.

## ACKNOWLEDGMENTS

Author thanks Prof V A Juvekar for his guidance and suggestion on completeness of work.

- [1] LAC E, HOMSY GM. Axisymmetric deformation and stability of a viscous drop in a steady electric field, *Journal of Fluid Mechanics.*,2007;590:239-264.
- [2] O. O. Ajayi. A note on Taylor's electrohydrodynamic theory*Proc. R. Soc. Lond. A*, 364(1978), pp. 499–507.
- [3] Petia M. Vlahovska. Electrohydrodynamics of Drops and Vesicles *Annual Review of Fluid Mechanics*, 2019.
- [4] Taylor, G. I. 1964 Disintegration of water drops in an electric field.*Proc. R. Soc. Lond. A 291, 159–166*
- [5] Taylor, G. I. 1966 Studies in electrohydrodynamics.
   I. The circulation produced in a drop by an electric field*Proc. R. Soc. Lond. A 280, 383–397.*
- [6] Saville, D. A. 1997 Electrohydrodynamics: the Taylor-Melcher leaky dielectric model.*Annu. Rev. Fluid Mech.* 29, 27–64.
- [7] Zhang, Y., et al.Experimental Study on the Electrohydrodynamic Deformation of Droplets in a Combined DC Electric Field and Shear Flow Field*Results in Engineering*, 2021
- [8] G. Utiugov, V. Chirkov, and M. Reznikova, "Application of the arbitrary Lagrangian-Eulerian method to simulate electrical coalescence and its experimental verification*Int. J. Plasma Environ.Sci. Technol.*, vol. 15, no. 2, p. e02009, 2021
- [9] C. W. Hirt, A. A. Amsden, and J. L. Cook, "An arbitrary Lagrangian- Eulerian computing method for all flow speeds", *J. Comput. Phys.*, vol.14, no. 3, pp. 227–253, Mar. 1974.
- [10] G. Supeene, C. R. Koch, and S. Bhattacharjee, "Deformation of a droplet in an electric field: Nonlinear transient response in perfect and leaky dielectric media,"*J. Colloid Interface Sci., vol. 318, no. 2, pp.463–476, Feb.* 2008
- [11] Allan, R. S. & Mason, S. G. 1962 Particle behaviour in shear and electric fields. i. deformation and burst of fluid drops., *Proc. R. Soc. Lond. A 267, 45–6*
- [12] Hao Chen, Wei Chen, Zhouping Yin and Haisheng Fang,Electrohydrodynamic-induced partial coalescence between a droplet and a liquid–air interfaceJ. *Fluid Mech. (2023), vol. 963, A39*