



# Dynamics of sessile droplet over hydrophobic surfaces under external electric field

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**Dynamics of sessile droplet over hydrophobic surfaces under external electric field**

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## **STATEMENT OF ORIGINALITY**

It should be noted that the research work in this article is based on my own ideas and research work. Contributions and ideas of others are welcome and included in the article. This article was written by us.

[Abdul Mannan Qamar

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**“Colloids and Surfaces A”**

### **Abstract**

The manipulation of sessile droplets on hydrophobic surfaces using external electric fields has gained significant attention due to its potential for controlling droplet behavior. In the field of microfluidics, precise control of droplet behavior is very important leading to improved drug delivery systems, lab-on-a-chip technologies, and chemical synthesis. Our research's goal is to identify the optimal range of conditions where the sessile droplets on a hydrophobic surface undergo motion under the action of electrohydrodynamic forces. Experimental investigations involved the development of hydrophobic surfaces using different hydrophobic liquids and the evaluation of dielectric liquid films for controlled droplet motion. The sides of the hydrophobic surface were attached to rectangular electrodes. The range of electric field strength ( $E_0$ ) applied varied from  $\sim 28$  to  $\sim 500$  kV/m. We found three different modes wherein the sessile droplet composed of water only elongates without motion, elongates with motion, or disperses into tiny daughter droplets under different range of electro-physical conditions. We also conducted experiments on sessile droplet composed of surfactant solutions. It was found that the aforementioned modes were replicated when the surfactant concentrations were less than the critical micelle concentration ( $C_{CMC}$ ), however, different behavior in the form of arrested elongation of sessile droplet occurred above  $C_{CMC}$ . Finally, the sessile droplet modes were mapped in the  $E_0$  vs. non-dimensional surfactant concentration ( $C^* = C_s/C_{CMC}$ ) parametric space where  $C_s$  is the surfactant concentration. We believe that the research conducted in this thesis contributes to advancing the knowledge of droplet dynamics and the control of droplet behavior on hydrophobic surfaces using external electric fields which is useful in different areas of science and technology.

**Keywords:** Hydrophobic surface, Sessile droplet, Electric field, Modes of dynamics

## Chapter No. 1

### Introduction

In recent years, the use of external electric fields to manipulate sessile droplets on hydrophobic surfaces has garnered considerable attention due to its potential for controlling droplet behavior. This includes influencing droplet spreading, evaporation, and motion,[1] which has wide-ranging implications across various fields such as microfluidics, surface tension measurement, contact angle analysis, chemical reactions, microelectromechanical systems, medicine, and biomedical engineering[2][3]– [8].

The dynamics of sessile droplets on hydrophobic surfaces under external electric fields are influenced by several factors. These factors encompass the surface properties of the substrate, the nature and strength of the electric field applied, and the physical and chemical properties of the droplet itself [9]. Understanding these dynamics and the underlying physical mechanisms governing them contributes to the fundamental knowledge of droplet behavior. The research on manipulating sessile droplets on hydrophobic surfaces using external electric fields has numerous applications across various fields. Here, we discuss some of these applications along with relevant references:

**1.1 Microfluidics:** The precise control of droplet behavior on hydrophobic surfaces offers significant opportunities in microfluidic devices. These devices can be utilized for drug delivery systems, lab-on-a-chip technologies, and chemical synthesis [9].

**1.2 Surface tension measurement:** Accurate measurement of surface tension is crucial in fields such as materials science, pharmaceuticals, and industrial processes. The understanding of droplet

dynamics on hydrophobic surfaces under external electric fields can lead to improved techniques for measuring surface tension[10].

**1.3 Surface engineering and coatings:** Manipulating the contact angle through the use of different dielectric films provides insights into interfacial interactions between droplets and hydrophobic surfaces [11]. This knowledge can be applied in industries dealing with coatings, adhesives, and surface engineering to optimize surface properties and enhance performance.

**1.4 Chemical reactions:** Studying droplet behavior on hydrophobic surfaces under external electric fields provides insights into reaction kinetics and control [12]. This has implications in catalysis, electrochemistry, and analytical chemistry, where precise control over droplet behavior can significantly impact reaction outcomes and efficiency.

**1.5 Biomedical engineering:** The ability to manipulate sessile droplets on hydrophobic surfaces using external electric fields find applications in microfluidic diagnostics, tissue engineering, and drug screening [13].

**1.6 Lab-on-a-chip devices:** The precise control of droplet behavior on hydrophobic surfaces enables the development of lab-on-a-chip devices for various applications, including biomedical diagnostics, environmental monitoring, and chemical analysis [14].

**1.7 Drug delivery systems:** External electric fields can be utilized to manipulate droplet motion and release drugs from hydrophobic surfaces [15]. This technology offers precise control over drug dosage and release kinetics, which is crucial for targeted drug delivery and personalized medicine.

**1.8 Surface cleaning and self-cleaning coatings:** By manipulating droplet behavior on hydrophobic surfaces using external electric fields, it is possible to enhance surface cleaning

processes and develop self-cleaning coatings [16]. This has applications in industries such as automotive, aerospace, and building materials, where the removal of contaminants and easy maintenance are desired [10]

**1.9 Optoelectronics:** Manipulating droplets on hydrophobic surfaces using external electric fields can be employed in the fabrication of optoelectronic devices, such as flexible displays, lenses, and sensors [17].

**1.10 Energy harvesting:** The manipulation of droplets on hydrophobic surfaces using external electric fields can be utilized in energy harvesting systems [18].

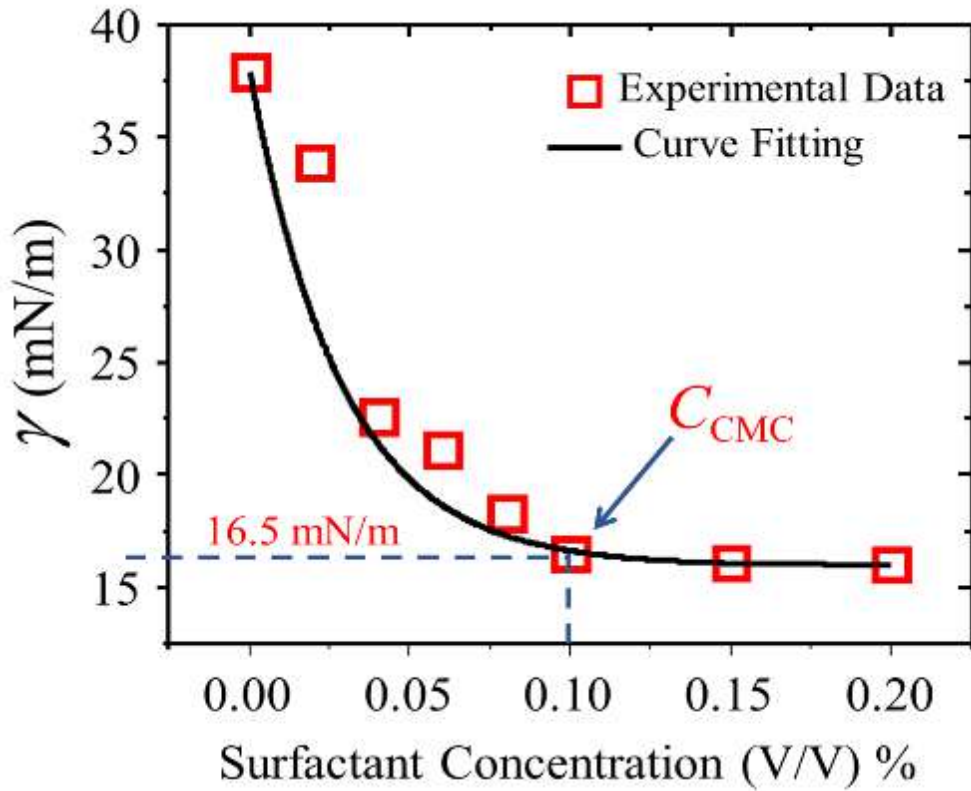
These practical applications demonstrate the wide-ranging impact of manipulating sessile droplets on hydrophobic surfaces using external electric fields spanning to fields such as healthcare, materials science, environmental engineering, and energy [2]. The ability to control droplet behavior opens up new possibilities for advanced technologies and innovative solutions in various industries.

Previous research conducted by Takeda et al. demonstrated that even small electric fields, both direct current (DC) and alternating current (AC), can effectively control water droplets on superhydrophobic surfaces [1], [2]. Additionally, Wei et al. developed a finite element modeling (FEM) simulation, elucidating that electrostatic forces generated by electrical fields drive the rolling behavior of water droplets [3], [4]. Jian Li, et.al. studied that the water droplet kept its spherical shape and stayed stationary on the super-hydrophobic coating surface at the initially low applied voltages because of the coating's low surface energy and micro-nano roughness. However, when the strength of the AC electric field grew, the water droplet became unstable and started to vibrate and somewhat distort. The periodic oscillation of the polarization charge within the water

droplet with the oscillating electric field may be responsible for this phenomenon [11]. M. Gunji and M. Washizu studied that the electrostatic force acting as the domain driving force plays a crucial role in the self-propelled motion of a water droplet on a super-hydrophobic surface in an oscillating electric field. This complex electrical and mechanical phenomenon involves electrostatics and hydrodynamics. The imbalance of the Maxwell stress causes the water droplet to accelerate once it starts travelling in a specific direction [12]. There have also been a few studies on the EHD of encapsulated droplets under an electric field [13], [14], [19]–[22]. Recently, Mandal et al. analytically studied the effects of surfactant molecules on the dynamics of a double droplet in the Stokes flow regime [15]. Various methods have been employed to manipulate and study the motion of sessile droplets on hydrophobic surfaces. These methods include capillary action, electrowetting on dielectric surfaces, electro coalescence using the level set method, external forces through electrodynamic effects, pressurized droplets in microfluidic devices, and airflow systems (Jet). Each method offers unique advantages and finds suitability for specific applications. This thesis focuses specifically on the motion of sessile droplets on hydrophobic surfaces using external direct current (DC) electric fields, with a particular emphasis on electrohydrodynamic forces.

The primary objective of this research is to identify the range of electric field strengths required to achieve precise control and linear motion of sessile droplets. To overcome surface resistance and facilitate droplet motion, different dielectric liquid films are infused over hydrophobic surface. By studying the contact angle, which is crucial in characterizing surface properties, the surfaces used in the experiments are confirmed to be hydrophobic. Sessile droplet comprising of water or surfactant solution of various concentrations are used to explore the dynamics. Here, we found different sessile droplet modes such as droplet elongation with no motion, elongated droplet

movement, droplet dispersion, and arrested elongation under different set of electrohydrodynamic and physical conditions. Moreover, this research aims to expand the understanding of manipulating sessile droplets on hydrophobic surfaces by investigating the role of external electric fields. By examining the effects of different parameters, such as electric field strength, droplet properties, and surface characteristics, a comprehensive understanding of the underlying mechanisms can be achieved.



**Figure 1.** Effect of surfactant concentration ( $C_s$ ) on interfacial tension of aqueous solution-silicone oil using asymptotic theory of Taylor [eqn. (1)].  $C_{CMC}$  is the critical micelle concentration and  $C^*(= C_s/C_{CMC})$  is the non-dimensional surfactant concentration.  $C^*$  equal to 0 corresponds to pure water without surfactant and  $C^*$  equal to 1 corresponds to critical micelle concentration.



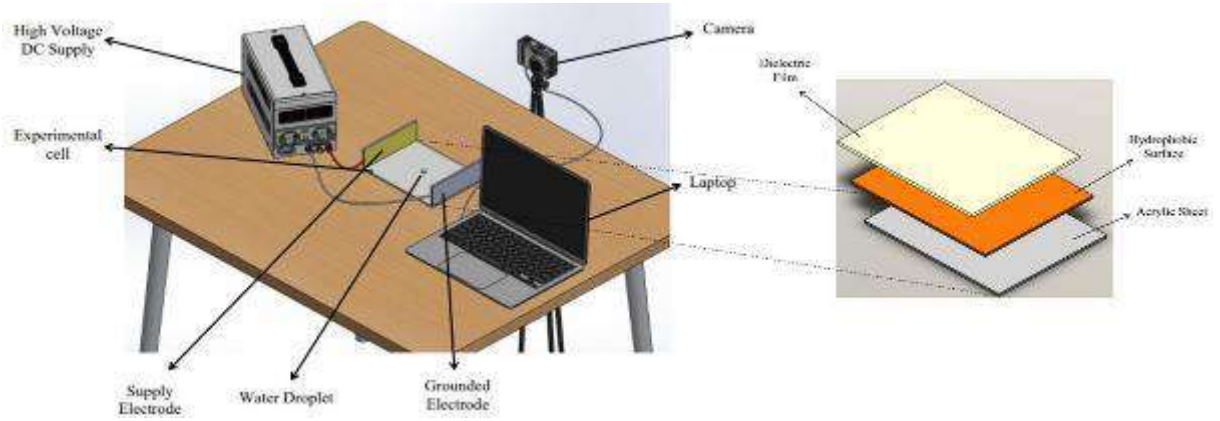
## Chapter No. 2

### Materials and Methods

#### 2.1 Experimental Cell

The experimental cell used to study the droplet behavior under electric field is as shown in **Figure 1**. The cell consists of acrylic base plate (3.5 x 2.5) cm with two side walls. Electrodes made from the copper tape are embedded at the two side walls of the acrylic experimental cell. Direct Current (DC) voltage supply (ELECTRONICS 2000, Pakistan) having range from (0-20) KV with a digital output display is connected to the supply and grounded electrodes. The accuracy of our DC supply was verified by performing experiments on suspended water droplet in silicone liquid chamber and comparing the deformation results against the Taylors Theory as shown in **Figure S1**. Acrylic base plate was first sprayed with hydrophobic material (Clear Lacquer Paint and Deodorant). Then, a thin film of dielectric liquid was formed over the coated surface. Three different liquids such as silicone oil (Homayoun chemicals, Lahore), sunflower oil (SUFI, Pakistan), and canola oil (SUFI, Pakistan) were used to form the dielectric film layer over the hydrophobic coated acrylic base plate, one used at a time for each experiment. The properties of the liquid oils and water are shown in **Table 1**. The water or surfactant laden droplet of known volume (4.2 micro-liter) was dispensed over the dielectric infused hydrophobic surface using micro-pipette (0.1-10 micro-liter). For each experiment after the droplet dispensation over the surface, the droplet dynamics were recorded using camera (NIKKON) along with macro lens (APEXEL) having 60 pixels per seconds with proper stand for stable visualization. The videos were recorded and post-processed for data acquisition using an

open-source software IMAGEJ. Contact angle measuring apparatus with Micro lens (DMWIFI) was used to measure the contact angle of sessile droplet with the dielectric infused hydrophobic surfaces. The corresponding results are presented in **Table 2**. In order to observe the behavior of surfactant laden sessile droplet, different aqueous solutions of surfactant (Ethoxylated Cocoamidopropyl Betaine, Pakistan) having different concentrations in volume-by-volume percentage (V/V) % were formed.



**Figure 2.** Experimental setup for observing the sessile droplet dynamics under direct current (DC) electric field. Inset shows different layers that constitute the hydrophobic substrate.

**Table 1.** Properties of Oils and water

Liquid Type	Density ( $\text{kg/m}^3$ )	Viscosity (Pa.s)	Dielectric constant	Electrical Conductivity (S/m)	Water-Oil Interfacial Tension (mN/m)
Silicone oil	971	0.022	3.2	$8.7 \times 10^{-13}$	$37.5 \pm 1$
Sunflower oil	918.8	0.033	2.8	$4 \times 10^{-10}$ [16]	$27.49 \pm 0.33$

Canola oil	915	0.044	1.8	$15 \times 10^{-9}$ [17]	$11.7 \pm 0.1$
Water	1000	0.001	80.3	$5.5 \times 10^{-6}$	NA

## 2.2 Interfacial Tension Measurement

Interfacial tension measurement is a technique used to quantify the force or energy required to deform or separate two immiscible phases at their interface. In the case of a sessile droplet, it refers to the measurement of the interfacial tension between the droplet and the surrounding medium.

When a liquid droplet rests on a solid surface, it assumes a characteristic shape known as a sessile droplet. The interfacial tension between the droplet and the solid, as well as the interfacial tension between the droplet and the surrounding gas or liquid medium, play a crucial role in determining the droplet's shape and stability.

These interfacial tension measurements provide valuable information about the physicochemical properties of the droplet and its interaction with the surrounding medium. For sessile droplets, interfacial tension influences parameters such as contact angle, spreading behavior, and evaporation rate. Understanding these dynamics is important in various fields such as surface science, material characterization, and industrial processes, including coatings, adhesives, and microfluidics.

To calculate the interfacial tension between the oil and the aqueous phase (O/W), we used Taylor's linear asymptotic theory [18] for small droplet deformation ( $D$ ):

$$\gamma = \frac{9}{16D(R+1)^2} \varepsilon E_0^2 r \varphi, \quad (1)$$

where:

$$\varphi = \left\{ R^2 + 1 - 2S + \frac{3}{5} (R - S) \left( \frac{2+3r}{1+r} \right) \right\}.$$

Interfacial tension can be accurately and conveniently measured using above equation [23], [24]. The conventional techniques such as the Pendant drop and Wilhelmy plate method are inaccurate owing to the high viscosity of the outside liquid. We measured the oil–water interfacial tension using **eqn. (1)** at different surfactant concentrations (Ethoxylated Cocoamidopropyl Betaine) at least four times each, and the results are plotted in **Figure. 2.**

$$C^* = C_s / C_{CMC}, \quad (2)$$

where  $C^*$  is the non-dimensional surfactant concentration,  $C_s$  is the surfactant concentration, and  $C_{CMC}$  is the critical micelle concentration.  $C_{CMC}$  is that concentration of surfactant after which the surface tension doesn't change. In our case it was  $\sim 0.1$  V/V%. Therefore,  $C^*=0$  corresponds to pure water case and  $C^*=1$  corresponds to critical micelle concentration.

**Table 2.** Contact angle of water under different laminations

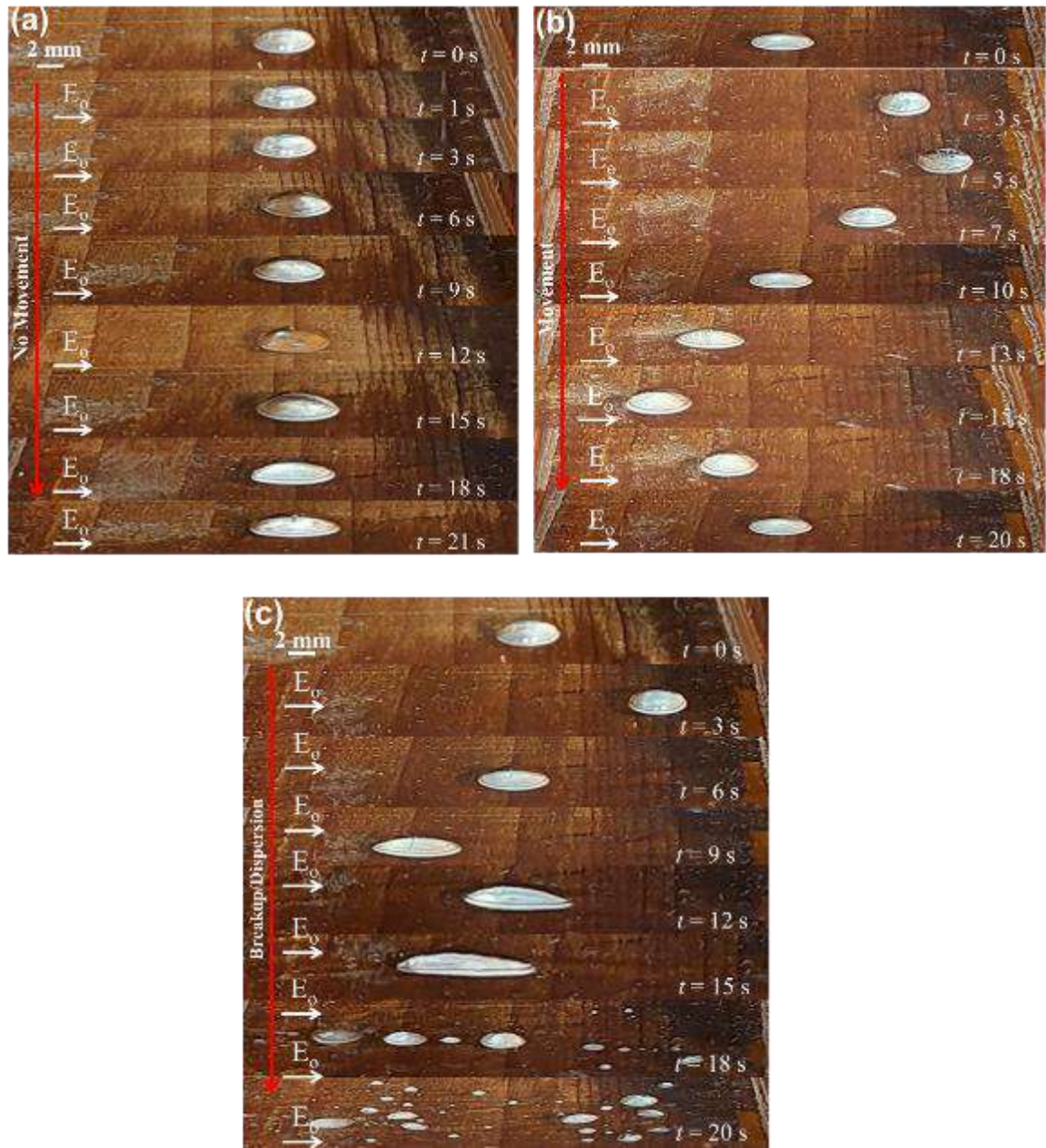
<b>Lamination</b>	<b>Contact Angle (Degrees)</b>
Silicone Oil	124
Sunflower Oil	110
Canola Oil	105

## Chapter No. 03

### Results and Discussions

The objective of our research is to determine the optimal range of conditions for elongating sessile droplets without inducing motion, ensuring uniform motion, and getting dispersion on a hydrophobic surface under the influence of an external electric field. The droplets used in experiments had a volume of 4.2 micro liters. In this investigation, we explored the dynamics of sessile droplets on hydrophobic surfaces while subjecting them to the influence of an external DC electric field. The experimental results obtained are presented and analyzed in this section, accompanied by a theoretical framework that aims to provide a comprehensive understanding of the observed phenomena.

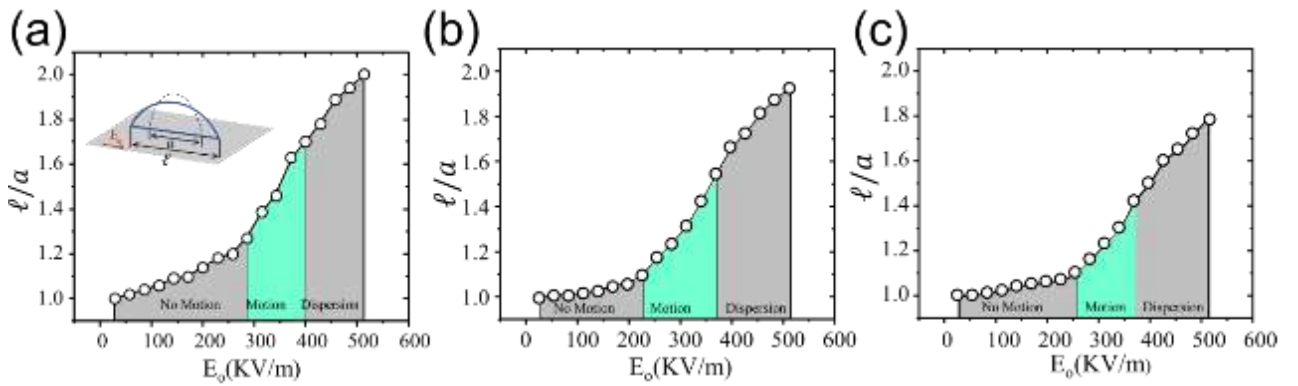
The investigation focused on examining the shape transformation of droplets when subjected to an electric field. **Figure 3 (a)** illustrates the sessile droplet shape evolution on a hydrophobic surface with a silicone oil lamination at various time intervals under weak electric field strengths ( $E_o = 285.7$  kV/m). The experimental findings indicate that the droplet exhibited elongation without motion and adopted a flatter shape. On the other hand, **Figure 3 (b)** shows that the droplet slightly elongated and moved over the surface when moderate electric field strength ( $E_o = 400$  kV/m) was applied. It traveled over the entire length of the hydrophobic surface along the direction of the electric field and maintained a stable shape. Finally, as the electric field exceeded a certain threshold, that surpassed the surface tension of the droplet, lead to its dispersion. This is shown in **Figure 3 (c)** where the dispersion of droplets on a hydrophobic surface occurred after some time when  $E_o = 485.7$  kV/m was applied.



**Figure 3.** Dynamics of sessile droplet over dielectric liquid infused hydrophobic surface under a DC electric field. **(a)** Elongation of sessile aqueous droplet with no movement over silicone oil infused hydrophobic surface under applied electric field strength ( $E_0$ ) equal to 285.7 kV/m. **(b)** Motion of elongated sessile aqueous droplet over silicone oil infused hydrophobic surface under applied electric field strength ( $E_0$ ) equal to 400 kV/m. **(c)** Dispersion of elongated sessile aqueous droplet over silicone oil infused hydrophobic

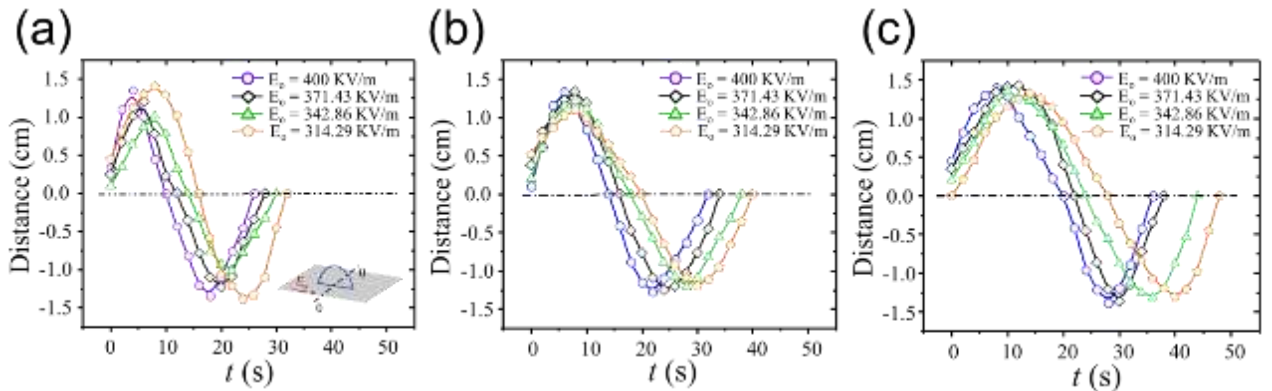
surface under applied electric field strength ( $E_0$ ) equal to 485.7 kV/m. In all the dynamic regimes, the volume of the droplet is kept same equal to 4.2  $\mu\text{L}$  and  $C^*$  is kept fixed at 0.

**Figure 4** showcases the correlation between electric field strength and droplet elongation for different oil laminations. The graph illustrates that initially, the elongation of the droplet increases gradually. However, beyond a certain threshold value of electric field strength, the elongation experiences a rapid increase leading to the dispersion of the droplet on the hydrophobic surface. The elongation ( $\ell/a$ ) scales as  $\sim E^2$ . Greater the strength of the electric field, larger will be the electrical Maxwell stresses acting at the droplet interface and more will be the elongation. As the electrical stresses dominate the capillary stresses, the droplet disperses. As the viscosity of the lamination increased, the droplet experienced more resistance to elongate and consequently  $\ell/a$  decreased [See. **Figure 4 (a), (b), and (c)**].



**Figure 4.** Experimental results representing the elongation ( $\ell/a$ ) of the aqueous sessile droplet under a DC electric field.  $C^*$  is fixed at 0. **(a)** With silicone oil infused hydrophobic surface, **(b)** With sunflower oil infused hydrophobic surface, **(c)** With canola oil infused hydrophobic surface. Shaded region depicts three different dynamic regimes.

In **Figure 5**, we illustrate the motion of droplets on a hydrophobic surface within the droplet movement zone for different oil laminations. The graph showcases the relationship between the distance covered by the droplets and the elapsed time. The observed motion can be attributed to the electrophoretic effects exerted on the slightly charged droplet. As this force overcomes the pinning forces caused by surface defects or roughness, it enabled the droplet to move along the hydrophobic surface. The droplet follows to and fro motion between the electrodes. As the viscosity of the dielectric liquid layer was increased the velocity of the motion decreased and it took more time to complete one cycle of linear motion. An increase in the electric field strength resulted in the droplets covering the distance faster. This indicates that the motion of the droplets becomes more pronounced and extensive as the applied electric field becomes stronger. This is because the electrophoretic effects scales with applied electric field and droplet can easily overcome the pinning forces. On the other hand, the resistive pinning forces increase with the viscosity of the dielectric layer and hence the motion is diminished with an increase in the time required to travel the distance as shown in **Figure 5 (a), (b) and (c)**.

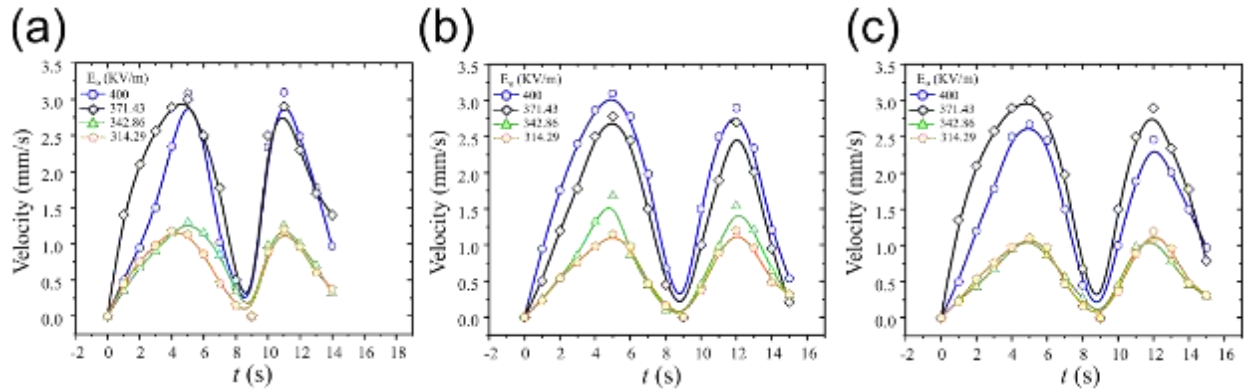


**Figure 5.** Experimental results representing the distance travelled by aqueous sessile droplet at different time intervals over the dielectric liquid infused hydrophobic surface



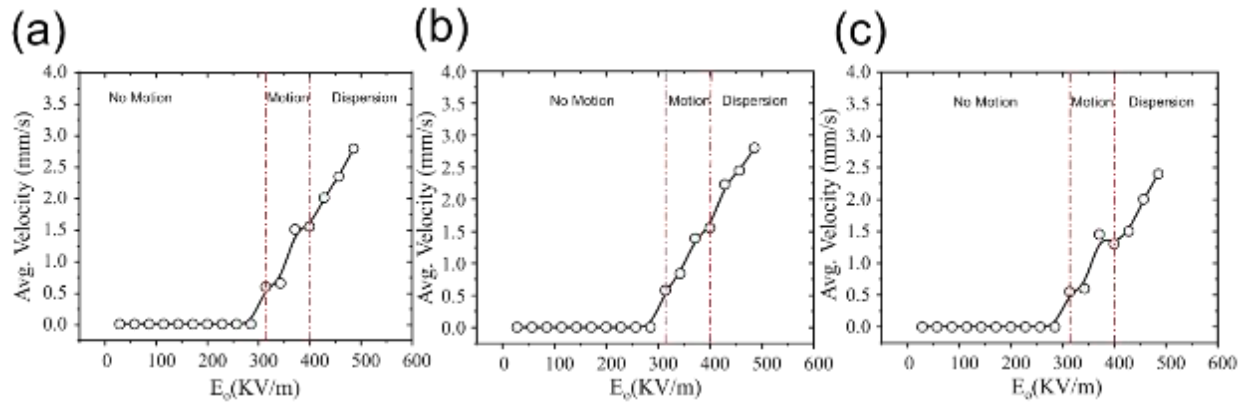
under a DC electric field.  $C^*$  is fixed at 0. The droplet volume is kept constant as  $4.2 \mu\text{L}$  and electric field strength ( $E_0$ ) is varied. **(a)** With silicone oil layer, **(b)** With sunflower oil layer, **(c)** With canola oil layer.

The droplet velocity accelerated to a maximum before de-acceleration to zero near the electrodes [See. **Figure 6 (a), (b), and (c)**].



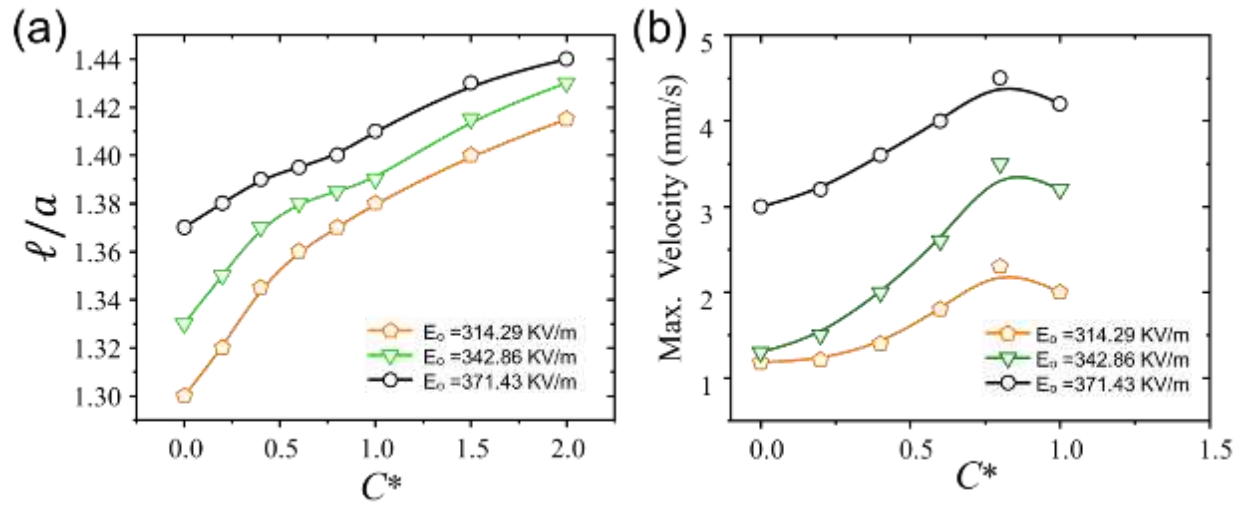
**Figure 6.** Experimental results representing the velocity of aqueous sessile droplet at different time intervals over the dielectric liquid infused hydrophobic surface under a DC electric field.  $C^*$  is fixed at 0. The droplet volume is kept constant as  $4.2 \mu\text{L}$  and electric field strength ( $E_0$ ) is varied. **(a)** With silicone oil layer, **(b)** With sunflower oil layer, **(c)** With canola oil layer.

Both the droplet velocity and elongation increased with an increase in electric field strength. In the droplet movement zone with stability that onset at  $E_0 \sim 300 \text{ kV/m}$ , we got an average maximum velocity of  $\sim 1.5 \text{ mm/s}$  at  $E_0 \sim 400 \text{ kV/m}$  after which the droplet lost its stability and dispersed as shown in **Figure 7 (a), (b), and (c)**.



**Figure 7.** Experimental results pertaining to the average velocity of the aqueous sessile droplet over the dielectric liquid infused hydrophobic surface at different electric field strengths ( $E_0$ ).  $C^*$  is fixed at 0. The droplet volume is kept constant as 4.2  $\mu\text{L}$ . **(a)** With silicone oil layer, **(b)** With sunflower oil layer, **(c)** With canola oil layer. The dashed lines delineate the three dynamic regimes.

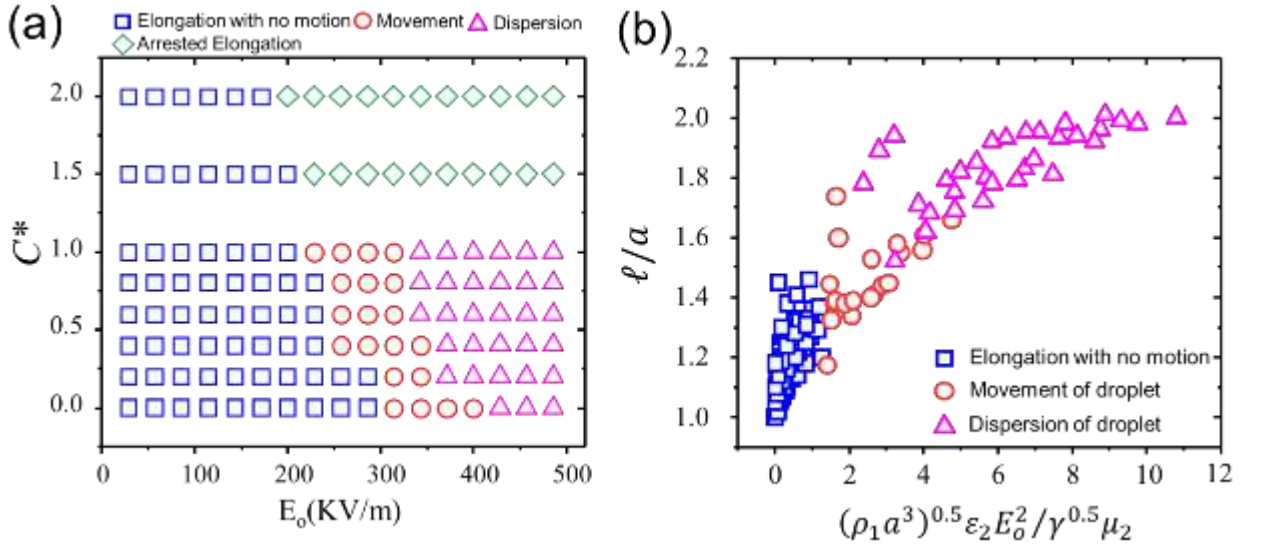
We next explored the effects of surfactant on the droplet dynamics. **Figure 8 (a)** illustrates that the elongation of the droplets at  $E_0$  increased with an increase in surfactant concentrations. This was expected as the surfactant decreases the interfacial tension and thus electric stresses dominate. The increase in elongation  $\ell/a$  nearly scaled as  $\sim C^{*1/2}$  at lower electric fields and became nearly linear at higher electric field strengths. An increase in maximum velocity was also observed with a use of surfactant as in **Figure 8 (b)**. However, the velocity dipped near the critical micelle concentration ( $C^* \approx 1$ ). Moreover, no droplet motion was observed as  $C^*$  becomes greater than 1. This indicates that the surfactant concentration plays a crucial role in determining the droplet's maximum velocity, emphasizing the importance of critical micelle concentration as a key parameter in droplet dynamics.



**Figure 8.** (a) Effect of surfactant concentration ( $C_s$ ) on the elongation ( $l/a$ ) of the aqueous sessile droplet under a DC electric field. (b) Effect of surfactant concentration ( $C_s$ ) on peak velocity of droplet during its translation over hydrophobic surface. Here, the electric field strength ( $E_o$ ) is varied, and the silicone oil is used as a dielectric layer over the hydrophobic surface.  $C^*(= C_s/C_{CMC})$  is the non-dimensional surfactant concentration.

Finally, the comprehensive experimental results are presented in **Figure 9 (a)** wherein transition between different modes is mapped in the  $E_o$  vs. non-dimensional surfactant concentration ( $C^* = C_s/C_{CMC}$ ) parametric space. where  $C_s$  is the surfactant concentration. At lower electric field strengths and non-dimensional surfactant concentrations sessile droplet only elongates and exhibits no motion. However, as the electric fields become stronger, droplet begin to move. Very strong electric fields make the droplets disperse with the ejection of daughter droplets. It can be seen that the surfactant laden droplets show same modes as that for pure droplet up to critical micelle concentrations. However, as  $C^* > 1$ , interesting dynamics are observed wherein the droplet elongates without motion or dispersion. This new mode was the arrested elongation of the droplet where the abundant

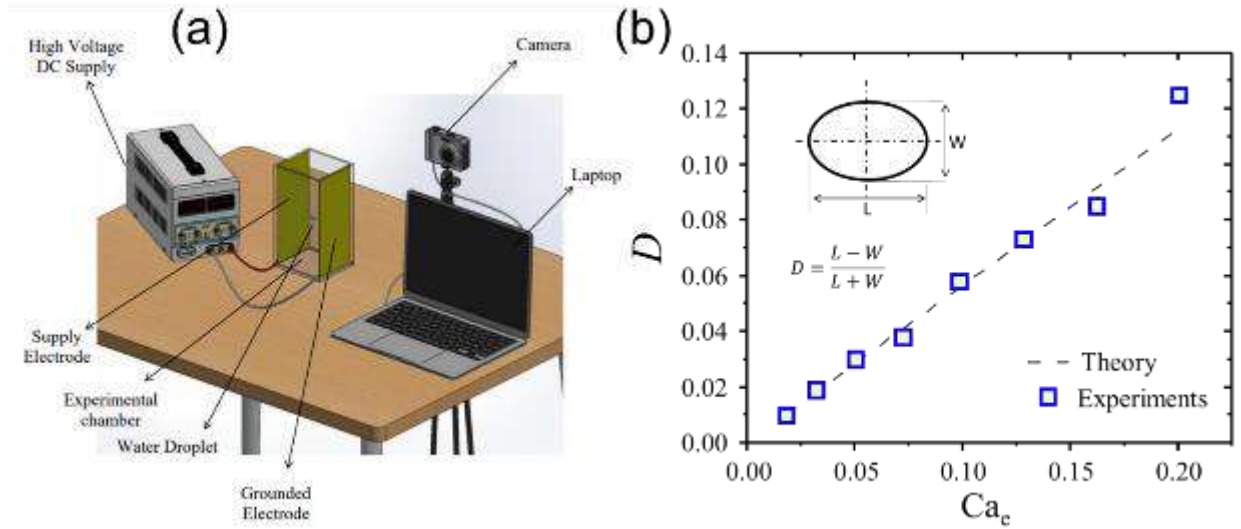
availability of surfactant molecules makes the interface saturated. These molecules hold the interface despite the strong electric stresses and help the droplet to retain its shape without dispersion. If the elongation of the sessile droplet is represented by the elongation time scales as  $t_{\text{elongation}} \sim (\rho_d r_d^3)^{0.5} / \gamma^{0.5}$  and the drainage of the dielectric liquid film infused over the hydrophobic scales as  $t_{\text{drainage}} \sim \mu_f / \epsilon_f E_o^2$ , then the relative importance of these two timescales is represented as  $\tau \sim (\rho_d r_d^3)^{0.5} \epsilon_f E_o^2 / \mu_f \gamma^{0.5}$ . It is more likely that the droplets will elongate only without dispersion if  $t_{\text{drainage}}$  dominates  $t_{\text{elongation}}$ , whereas droplet likely to disperse if  $t_{\text{elongation}}$  dominates  $t_{\text{drainage}}$ . A value of  $\tau \approx 3$  provides a critical condition delineating the two scenarios as shown in **Figure 9 (b)**. It should be noted that  $\ell/a \geq 1.5$  for the dispersion to take place.



**Figure 9.** (a) Mapping diagram delineating different regimes of the dynamics of aqueous sessile droplet over a dielectric liquid infused hydrophobic surface under a DC plotted in the electric field strength ( $E_o$ ) vs. dimensionless surfactant concentration ( $C^*$ ) parametric

space. The open symbols represent different dynamic regimes of the droplet as labeled in the figure. **(b)** Stable and unstable (dispersion) regime of the droplet. Nondimensional timescale ( $\tau$ ) delineating the sessile droplet dynamic regimes according to the relative importance of the elongating timescale [ $t_{elongation} \sim (\rho_d r_d^3)^{0.5} / \gamma^{0.5}$ ] and the dielectric film-drainage timescale ( $t_{drainage} \sim \mu_f / \epsilon_f E_0^2$ ) over the hydrophobic surface.  $\rho_d$  represents the density of the sessile droplet,  $\mu_d$  represents the viscosity of the dielectric liquid film over the surface, and  $\gamma$  represents the interfacial tension between the sessile droplet and the dielectric layer infused over the hydrophobic surface. Here, we changed the electric-field strength, and interfacial tension.

We believe that this study provides important physical understanding regarding the electric-field-stimulated dynamics of sessile droplets on dielectric liquid infused hydrophobic surfaces and is useful for their application in various areas, including Lab on a chip, bioengineering and chemical sciences.



**Figure S1. (a)** Experimental setup to find surface tension of different concentration v/v % of surfactant solutions. **(b)** Benchmarking of High Voltage DC supply by comparing the deformation results obtained for water droplet suspended in silicone oil as ambient liquid

with Taylors Theory [18].  $Ca_e = \epsilon\epsilon_0 r E_0^2 / \gamma$ , where  $r$  is the radius of the droplet,  $E_0$  is the strength of the electric field,  $\epsilon$  is the permittivity of free space,  $\epsilon_0$  is the dielectric constant of ambient liquid and  $\gamma$  is the interfacial tension. Here,  $r = 1$  mm.

## Chapter No. 4

### Conclusion

In conclusion, this thesis investigates the manipulation of sessile droplets on hydrophobic surfaces using external electric fields. The research contributes to the fundamental understanding of droplet dynamics, surface interactions, and the underlying physical mechanisms. The findings have broad implications in fields such as microfluidics, surface tension measurement, chemical reactions, medicine, and biomedical engineering. By accurately controlling droplet behavior, advancements in various applications can be achieved, leading to improved technologies, processes, and devices.

The findings have wide-ranging implications across various fields, providing valuable insights into the underlying physical mechanisms governing droplet motion. Furthermore, this research expands the understanding of manipulating sessile droplets on hydrophobic surfaces through the investigation of external electric fields and the examination of different parameters.

The experimental findings indicate that the droplet exhibited slightly elongated and also moved over the surface and maintained its stable shape between electric field strength range of 400 to 485.714 kV/m. After that it led to dispersion. Our experimentation also concluded that the surfactant droplets show same modes as that for pure droplet up to critical micelle concentrations ( $C_{CMC}$ ) which in our case is 0.1% with surface tension of 16.5 mN/m. However, as  $C^* > 1$ , arrested elongation was observed wherein the droplet elongates without motion or dispersion. Arrested elongation of the droplet occurs when the abundant availability of surfactant molecules makes the interface saturated.

## References

- [1] L. Chen *et al.*, “Superhydrophobic micro-nano structures on silicone rubber by nanosecond laser processing,” *J Phys D Appl Phys*, vol. 51, no. 44, p. 445301, Nov. 2018, doi: 10.1088/1361-6463/aae13d.
- [2] M. Abdelgawad and A. R. Wheeler, “The Digital Revolution: A New Paradigm for Microfluidics,” *Advanced Materials*, vol. 21, no. 8, pp. 920–925, Feb. 2009, doi: 10.1002/adma.200802244.
- [3] I. Egry, H. Giffard, and S. Schneider, “The oscillating drop technique revisited,” *Meas Sci Technol*, vol. 16, no. 2, pp. 426–431, Feb. 2005, doi: 10.1088/0957-0233/16/2/013.
- [4] S. Y. Shigeyuki Yamakita, Y. M. Yoshikazu Matsui, and S. S. Showko Shiokawa, “New Method for Measurement of Contact Angle (Droplet Free Vibration Frequency Method),” *Jpn J Appl Phys*, vol. 38, no. 5S, p. 3127, May 1999, doi: 10.1143/JJAP.38.3127.
- [5] F. Mugele, J.-C. Baret, and D. Steinhauser, “Microfluidic mixing through electrowetting-induced droplet oscillations,” *Appl Phys Lett*, vol. 88, no. 20, May 2006, doi: 10.1063/1.2204831.
- [6] S. H. Ko, H. Lee, and K. H. Kang, “Hydrodynamic Flows in Electrowetting,” *Langmuir*, vol. 24, no. 3, pp. 1094–1101, Feb. 2008, doi: 10.1021/la702455t.
- [7] J. Barman, W. Shao, B. Tang, D. Yuan, J. Groenewold, and G. Zhou, “Wettability Manipulation by Interface-Localized Liquid Dielectrophoresis: Fundamentals and Applications,” *Micromachines (Basel)*, vol. 10, no. 5, p. 329, May 2019, doi: 10.3390/mi10050329.
- [8] S. Chakraborty, I.-C. Liao, A. Adler, and K. W. Leong, “Electrohydrodynamics: A facile technique to fabricate drug delivery systems,” *Adv Drug Deliv Rev*, vol. 61, no. 12, pp. 1043–1054, Oct. 2009, doi: 10.1016/j.addr.2009.07.013.
- [9] X. Bian, H. Huang, and L. Chen, “Motion of droplets into hydrophobic parallel plates,” *RSC Adv*, vol. 9, no. 55, pp. 32278–32287, 2019, doi: 10.1039/c9ra05135j.



- [10] W.-P. He, L. Wang, Y.-D. Jiang, and S.-Q. Wan, “An improved method for nonlinear parameter estimation: a case study of the Rössler model,” *Theor Appl Climatol*, vol. 125, no. 3–4, pp. 521–528, Aug. 2016, doi: 10.1007/s00704-015-1528-5.
- [11] J. Li, Y. Wei, Z. Huang, F. Wang, and X. Yan, “Investigation of the Electric Field Driven Self-propelled Motion of Water Droplets on a Super-hydrophobic Surface”, doi: 10.1109/TDEI.2016.005923.
- [12] M. Gunji and M. Washizu, “Self-propulsion of a water droplet in an electric field,” *J Phys D Appl Phys*, vol. 38, no. 14, pp. 2417–2423, Jul. 2005, doi: 10.1088/0022-3727/38/14/018.
- [13] M. S. Abbasi, R. Song, H. Kim, and J. Lee, “Multimodal breakup of a double emulsion droplet under an electric field,” *Soft Matter*, vol. 15, no. 10, pp. 2292–2300, 2019, doi: 10.1039/c8sm02230e.
- [14] P. Soni, D. Dixit, and V. A. Juvekar, “Effect of conducting core on the dynamics of a compound drop in an AC electric field,” *Physics of Fluids*, vol. 29, no. 11, Nov. 2017, doi: 10.1063/1.4999986.
- [15] S. Mandal, U. Ghosh, and S. Chakraborty, “Effect of surfactant on motion and deformation of compound droplets in arbitrary unbounded Stokes flows,” *J Fluid Mech*, vol. 803, pp. 200–249, Sep. 2016, doi: 10.1017/jfm.2016.497.
- [16] P. L. T, R. A. J, T. D. B, and S. R. M, “Electric Properties of Sunflower Oil under Pressure,” *International Journal of Scientific Engineering and Applied Science (IJSEAS)*, no. 8, 2022, [Online]. Available: [www.ijseas.com](http://www.ijseas.com)
- [17] M. Spohner, “A Study of the Properties of Electrical Insulation Oils and of the Components of Natural Oils,” *Acta Polytechnica*, vol. 52, no. 5, Jan. 2012, doi: 10.14311/1652.
- [18] M. S. Abbasi, R. Song, and J. Lee, “Breakups of an encapsulated surfactant-laden aqueous droplet under a DC electric field,” *Soft Matter*, vol. 15, no. 43, pp. 8905–8911, 2019, doi: 10.1039/c9sm01623f.
- [19] A. Behjatian and A. Esmaeeli, “Electrohydrodynamics of a compound drop,” *Phys Rev E*, vol. 88, no. 3, p. 033012, Sep. 2013, doi: 10.1103/PhysRevE.88.033012.

- [20] P. Soni, R. M. Thaokar, and V. A. Juvekar, “Electrohydrodynamics of a concentric compound drop in an AC electric field,” *Physics of Fluids*, vol. 30, no. 3, Mar. 2018, doi: 10.1063/1.5009645.
- [21] T. Tsukada, J. Mayama, M. Sato, and M. Hozawa, “Theoretical and experimental studies on the behavior of a compound drop under a uniform DC electric field.,” *JOURNAL OF CHEMICAL ENGINEERING OF JAPAN*, vol. 30, no. 2, pp. 215–222, 1997, doi: 10.1252/jcej.30.215.
- [22] M. S. Abbasi, R. Song, H. Kim, and J. Lee, “Electronic Supplementary Information [ESI] Multimodal breakup of double emulsion droplet under electric field Electronic Supplementary Material (ESI) for,” 2019.
- [23] R. B. Karyappa, S. D. Deshmukh, and R. M. Thaokar, “Breakup of a conducting drop in a uniform electric field,” *J Fluid Mech*, vol. 754, pp. 550–589, Sep. 2014, doi: 10.1017/jfm.2014.402.
- [24] A. Varshney, S. Ghosh, S. Bhattacharya, and A. Yethiraj, “Self organization of exotic oil-in-oil phases driven by tunable electrohydrodynamics,” *Sci Rep*, vol. 2, 2012, doi: 10.1038/srep00738.