
Droplet-droplet approach over a liquid infused hydrophobic surface under electric field

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Abstract

Significant prospects for progress in a range of scientific and technological fields arise from the interaction of sessile droplets on hydrophobic surfaces under the action of electric fields. The ideal circumstances for two sessile droplets to approach one another are examined in this study. To achieve this, we created hydrophobic surfaces on an acrylic surface using spray paint and then evaluated dielectric liquid films on top of these substrates to regulate droplet behavior. We used rectangular copper electrodes on the side walls of the surfaces to apply electric fields between 28 and 500 kV/m. Our findings revealed three distinct phases of droplet interaction: initial movement within a defined electric field range, directed approach toward one another, and a dispersion phase leading to droplet fragmentation. Results varied significantly based on the type of dielectric film and the droplet ratios employed. In conclusion, this study advances our understanding of droplet interactions on hydrophobic surfaces, which leads the way for more refined applications in microfluidics and related technologies. The knowledge gained may have a significant impact on areas like chemical synthesis, biomedical device development, and digital microfluidics.

Keywords—Droplet-droplet approach, Micro-fluidics, coalescence, hydrophobic surface, electric field

I. INTRODUCTION

Droplet interaction with hydrophobic surfaces under the influence of direct current (DC) electric fields is an interesting area of research which expands through multiple scientific domains and with significant industrial applications. Understanding how droplets behave on hydrophobic surfaces is crucial for the development of novel technologies such as microfluidics, biomedical devices[1][2], anti-fouling systems, and efficient liquid transportation methods—[3][4]. The primary factor affecting these interactions is surface energy because it pushes droplets to avoid making as much contact with the surface as possible. Droplet behavior is necessary to be understood for its various applications[5] such as micro-fluidics[6], surface engineering, liquid transportation, biomedical devices, anti-fouling technologies, environmental monitoring, energy harvesting and storage, food and beverage industry, and agriculture. In micro-fluidics, droplet motion control is important in various devices, which are used in drug delivery, biochemical analysis and in medical diagnosis. These applications involve droplet manipulation techniques and electric field can make these techniques more efficient. These methods also require a high level of accuracy in determining variables such as droplet velocity and stability[6]. In surface engineering, with the understanding of droplet behavior, it leads to better development of hydrophobic coatings. These coatings are applied in many different industrial applications because they can minimize friction and remove fouling. Electric fields can also be used to control the behavior of these surfaces and to fine-tune their applicability and practical utility by actively controlling droplet position and dynamics. Bulk transport of small volume liquids is important in applications like ink-jet printing and lab-on-a-chip applications. It is possible to use electric fields for accurate positioning and transportation of droplets on the surfaces, which is a critical factor in applications where the handling of fluids is critical[7]. The ability to

control small amounts of liquids effectively is essential for developing new devices in the field of micro medical technology design. Applications such as drug delivery and microsurgery benefit from controlled droplet behavior, and these applications can be made more precise and effective with the use of electric fields[8]. This research is particularly useful to design self-cleaning surfaces and to improve the stability of materials applied in different contexts. In order to monitor pollutants or contaminants in water, one has to work with small portions of liquid samples. The use of electric fields to improve the sensitivity and accuracy of environmental monitoring devices is an important step forward that could help to detect dangerous compounds. Controlled programs of growth regulators, fertilizers, and pesticides are required for efficient agricultural practices. Electric field manipulation can be used to achieve efficient and targeted delivery, which increases the effectiveness of these applications.

The behavior of droplet interactions suspended in dielectric liquid or on hydrophobic surfaces in the presence of electric fields has been a topic of several ongoing studies[9]—[10][11]. There have been numerous studies of droplet interaction dynamics on hydrophobic surfaces, in the electric field context. For instance, Wang et al. —[10]examined how electric fields affect droplet motion and droplet coalescence on superhydrophobic surfaces and opened up the application in microfluidics. This work provided the underlying mechanisms but did not fully explore how various droplet size and surface characteristics complicate bioanalytical outcomes. And Kim et al. added to this field by studying the role of surface microstructure in droplet behavior in electric fields. In addition, the paper's emphasis was to underscore the impact surface topography can have on droplet dynamics, facilitating more efficient design of microfluidic devices. Nevertheless, most of these studies involve single variables and leave the joint effect of multiple variables that determine droplet dynamics dormant. Research by Lee et al.[12], also revealed that an electric field

could decrease biofouling on hydrophobic surfaces by altering droplet dynamics thus preserving surface integrity in marine environments. This study is valuable for their insights, but only covers this application of anti-fouling, not the broader implications of droplet control in other technologies. Zhang et al.[2] investigated energy harvesting by droplet manipulation and demonstrated a means to enhance the energy collection from moisture with electric fields. However, this research did not incorporate insight from other aspects of droplet dynamics to drive new environmental application avenues. Despite considerable progress in understanding droplet dynamics, there is an important need for comprehensive studies incorporating multiple variables affecting droplet behavior on hydrophobic surfaces in the presence of DC electric fields[13]. This study is novel, as it systematizes the exploration of how factors such as voltage, droplet size, and surface morphology interact to impact adhesion, a cellular interaction of immense importance. We address these interactions to gain insights that can yield better control and manipulation of droplets, necessary for optimally harnessing their use in microfluidics, biomedical devices and anti-fouling technologies.

In this work we investigate droplet interactions with hydrophobic surfaces under the effects of a DC electric field. In our research we study controlling variables like voltage, droplet size, and surface morphology to understand the fundamental mechanisms governing droplet behavior within the complex interfacial system. We present extensive experimental observations to provide valuable knowledge for such manipulation of liquid droplets on hydrophobic surfaces[11][14]. Moreover, as droplet dynamics is enhanced by this research, it also provides a basis for future innovations in many scientific and industrial disciplines. The results will unlock new possibilities for electric field manipulation in a broad range of

TABLE I Properties of oils and water

Liquid Type	Density (kg/m ³)	Viscosity (Pa.s)	Dielectric constant	Electrical Conductivity (S/m)	Interfacial Tension (mN/m)
Sunflower oil	918.8	0.033	3.1	6.9×10^{-10} [15]	27.49 ± 0.33
Canola oil	915	0.044	3.0	18×10^{-8} [16]	11.7 ± 0.1
Water	1000	0.001	80.3	5.5×10^{-6}	NA

applications to make further progress toward advancing the state of the art in droplet-based technologies.

II. MATERIALS AND METHODS

In this work, we aimed to study droplet behavior under an electric field using a specialized experimental cell. The experimental setup used to study the droplet behavior under electric field is as shown in Fig. 1. One of the cell walls was constructed from a rectangular acrylic base plate, 3.65 cm by 5 cm, that was supported by 2 side walls. We buried copper tape electrodes within these walls, which we used to impose the electric fields required for our experiments. A DC voltage supply adjustable from 0 to 20 kV was mounted to the cell and its status read was displayed digitally. In order to manipulate the droplet on the surface, we coated the acrylic surface to be hydrophobic; using a combination of clear lacquer paint and deodorant, which greatly increased the surface tendency to repel water.

We formed a thin dielectric liquid film over the hydrophobic surface to create a consistent experimental environment. For this purpose, we employed two types of dielectric liquids: sunflower oil (SUFI, Pakistan) and canola oil (SUFI, Pakistan). The properties of the liquid oils and water are shown in Table I. Appropriate choices for these liquids were such that they offered varied dielectric properties, which, in turn, greatly influence droplet dynamics when exposed to an

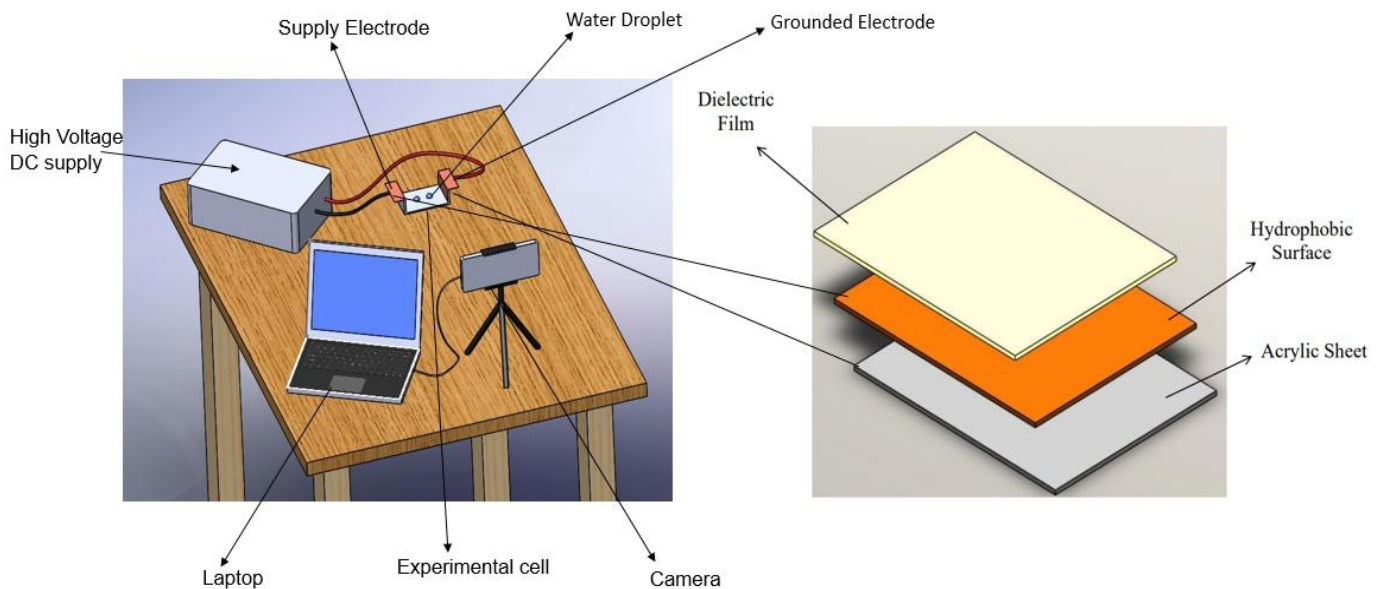


Fig. 1. Experimental setup for observing the Droplet-droplet approach over dielectric infused hydrophobic surface under DC electric field. Inset shows different layers that constitute the hydrophobic substrate.

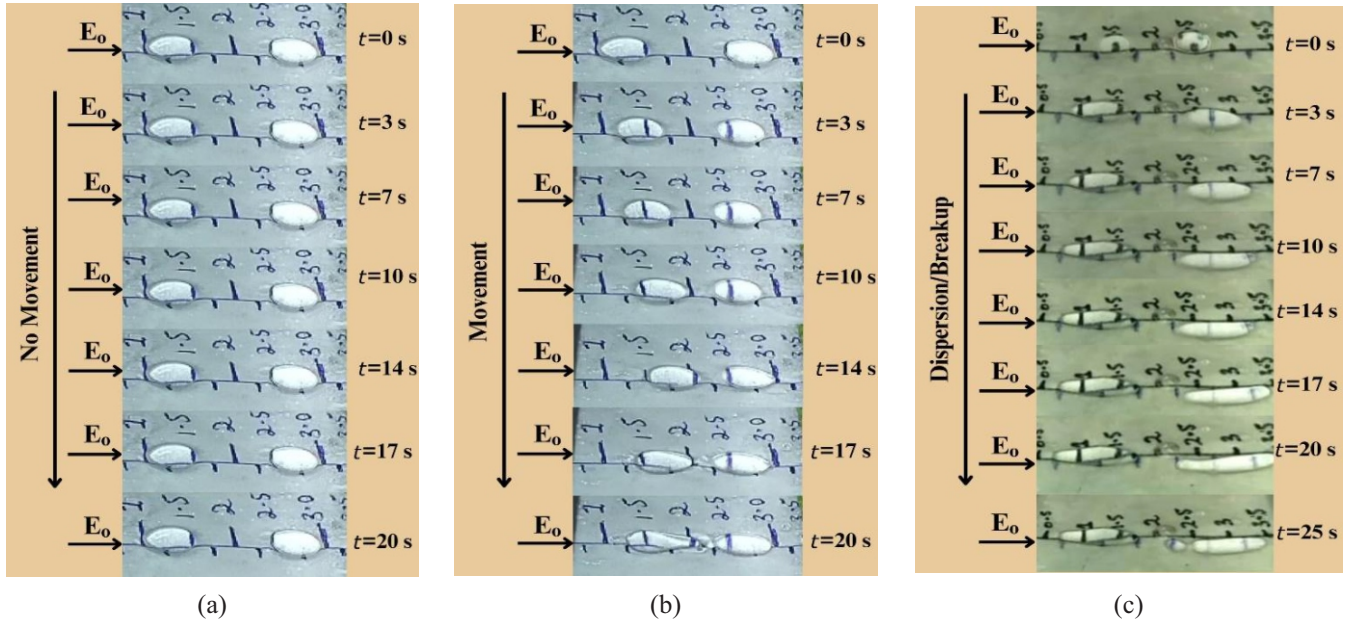


Fig. 2. (a) Droplet behavior under low electric fields (0-250 kV/m). No observable movement was detected. (b) Droplet behavior under moderate electric fields (250-385 kV/m). Droplets exhibited initial movement and coalescence. (c) Droplet behavior under high electric fields (above 385 kV/m). Droplets underwent fragmentation and dispersion.

electric field. We then dispensed droplets of deionized water, each of a given volume of 10 microliters, onto the prepared surface with an adjustable micropipette that was designed to deliver volumes ranging from 0.1 to 10 microliters. It had to be this precise so that every experiment would be uniform.

When the droplets were placed on the surface, we connected the copper tape electrodes to the DC voltage supply using one electrode to the DC voltage supply and grounding the other. Effects of the voltage on droplet behavior were observed for voltage from 0 to 20 KV. High speed video was recorded using a camera (NIKON) capable of acquiring 60 frames per second, which was used to examine the dynamics of the droplets under the influence of the electric field. The camera was securely mounted on a stable stand to guarantee minimal vibration affecting the observations.

We then did post processing of our recorded videos after the

experiments with ImageJ, which is open-source software for image analysis. By leveraging this software, we were able to dissect the droplet dynamics and measure movement, deformation and other important behaviors, in response to the applied electric field. Using this comprehensive method, we were able to fully capture these droplets' intricate behavior with regard to the dielectric properties of the liquids being used. The fundamental interactions of electric fields with liquid droplets are this study's contribution to two technological areas: microfluidics and materials science.

III. RESULTS AND DISCUSSIONS

In this study, we attempted to observe the behavior of droplets under electric fields particularly, to find a range within which 10 microliter droplets move and approach each other. For sessile droplet placed on the hydrophobic surfaces, the dynamics were studied under different

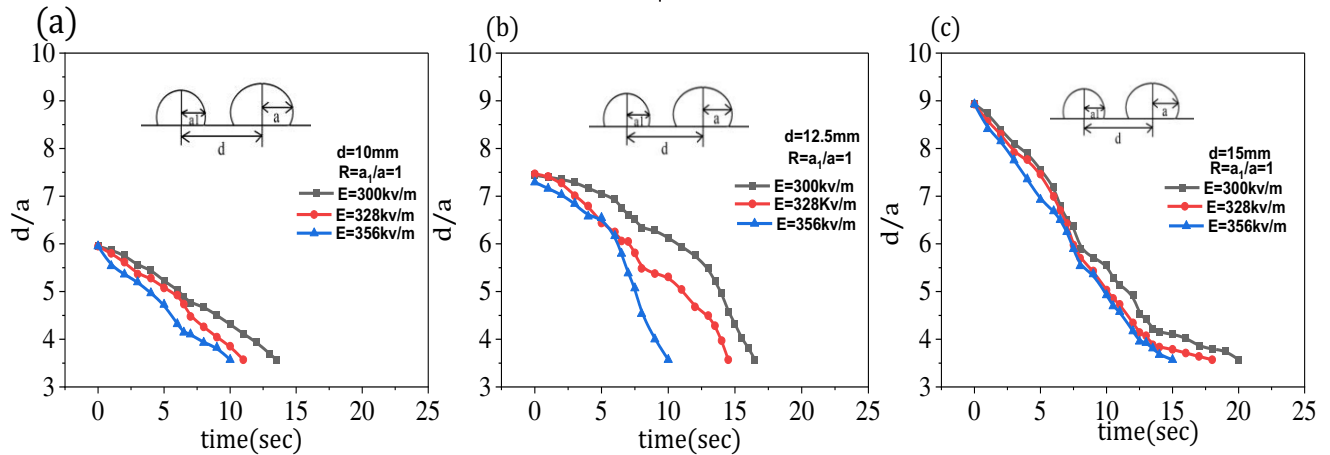


Fig. 3. Droplet-droplet approach at different separation over dielectric infused surface under electric field. (a) at a separation of 10 mm. (b) at a separation of 12.5 mm. (c) at a separation distance of 15 mm.

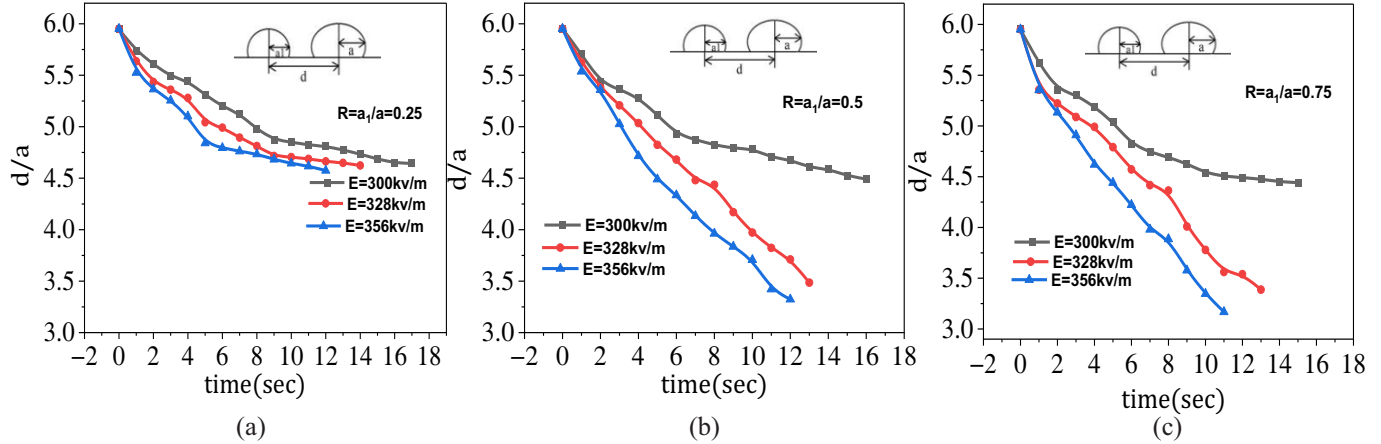


Fig. 4. Time for droplet-droplet approach for different droplet ratios over dielectric infused surface under electric field. (a) For a droplet ratio of 0.2, (b) for a droplet ratio of 0.5 and (c) for a droplet ratio of 0.75. Separation distance is kept same, and canola oil is used as a dielectric layer.

DC electric fields.

We first studied the effect of electric field strength on droplet motion. Fig. 2 shows droplets movement across varying electric fields. We found no significant movement of the droplets when the electric field was maintained between 0 and 250 kV/m. The lack of motion can be attributed to raising the minimum electric field strength beyond the combined effect of inertia and surface tensions which intrinsically resist droplet motion[17]. But when we started to apply the electric field to a range between 275 kV/m to 385 kV/m, the droplets started to contact each other. According to electrophoresis principles, droplets, usually charged slightly, react to the force generated by the electric field. Similarly, we demonstrate the relationship between the force (F), charge (Q), and electric field strength (E) $F = QE$. This shows how small charges on the droplets can produce noticeable movement in these strong fields[18].

We observed an interesting phenomenon where, at electric field strength greater than 400. kV/m the droplets initially acquire an elongated shape. The action of the electric field distorting the equilibrium shape of the droplets, to minimize their surface energy, explains this elongation[19]. This elongation says that the electric field is strong enough to affect the droplet's surface tension dynamics. Nevertheless, this state was transient, and we subsequently noticed that the droplets started to spread out into smaller droplets. We find that the observed fragmentation at this stage can be attributed to the

destabilizing aspects of the electric field and increased droplet forces[20]. Fragmentation was furthered by forces that could exceed the cohesive forces within the droplet when the electric field becomes more intense.

In addition, we investigated how far two droplets were in relation to the strength of the electric field. Fig. 3 shows the relation between droplets interaction when they were placed at different distances between them using canola oil as a dielectric layer. We found that droplets placed 10 mm apart approached each other more quickly than those separated by greater distances. This observation highlights the fundamental principle of electrostatic interactions, where the electric force between charged bodies is inversely proportional to the square of the distance separating them. As the distance increases, the electrostatic attraction diminishes, resulting in slower approach rates[21]. In our experiments we observed that the times for droplets to meet were shortest at 10 mm and longer at 12.5 mm and 15 mm, consistent with this principle.

Their motion under varying droplet ratios was also studied. Fig. 4 shows droplet-droplet approach time for different droplet ratios using canola oil as a dielectric layer. When we held the distance constant and adjusted the ratios, droplets at a ratio of 0.25 showed minimal movement. Taken together with previous findings of slower movement with small droplets, these results suggest that reduced electrostatic interaction promotes this slower movement[22]. Despite

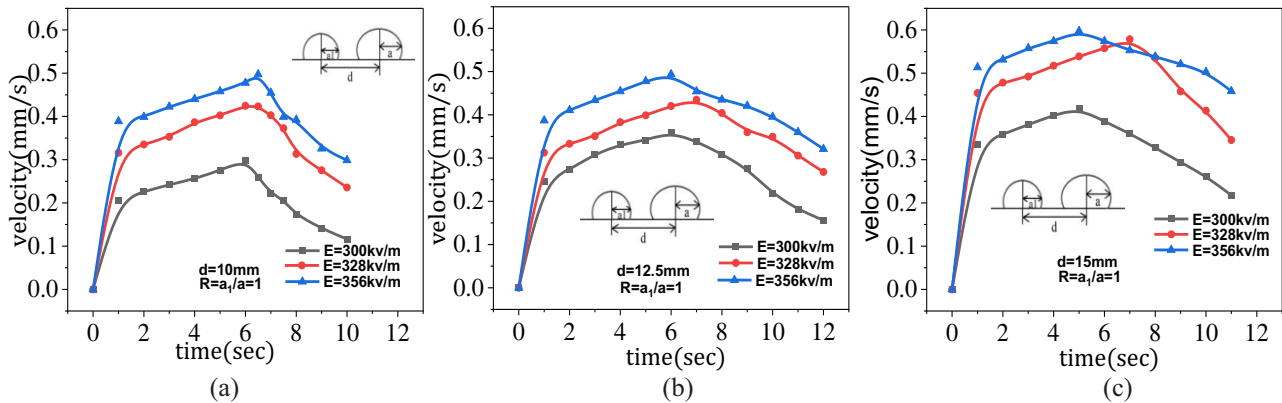


Fig. 5. Velocity of droplet-droplet approaches over dielectric infused surface for different droplet ratios under electric field. (a) For a droplet separation distance of 10 mm. (b) For a droplet separation distance of 12.5 mm. (c) For a droplet separation distance of 15 mm. Droplet size ratio is kept constant and canola oil is used as a dielectric layer.

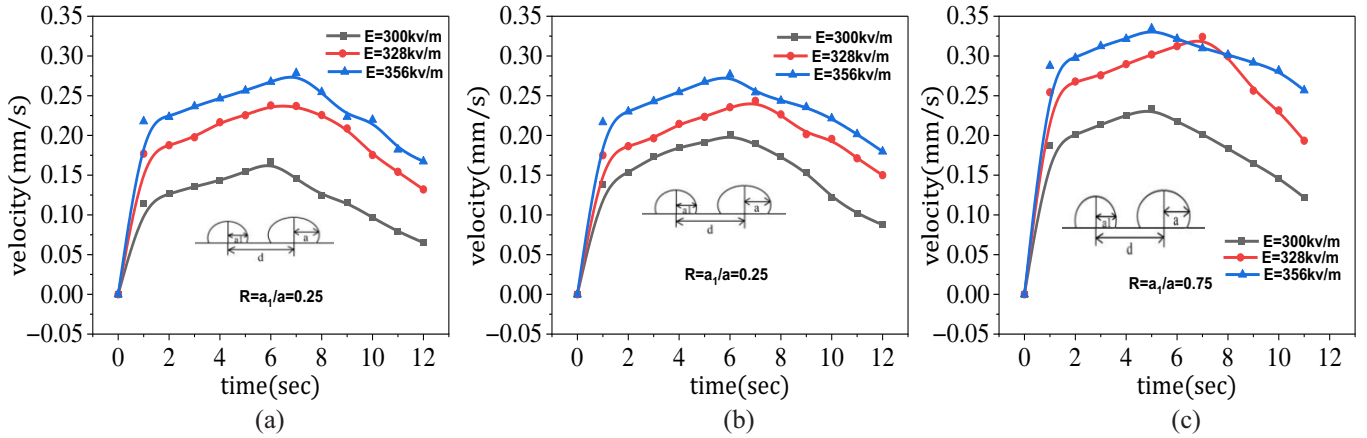


Fig. 6. Velocity of droplet-droplet approaches over dielectric infused surface for different droplet ratios under electric field. (a) For a droplet ratio of 0.25. (b) for a droplet ratio of 0.5. (c) for a droplet ratio of 0.75. Separation distance is kept same, and canola oil is used as a dielectric layer.

a lower ratio, increasing the voltage increased droplets' movement, suggesting although the droplet ratio determines overall motion, the strength of the electric field is critical for facilitating movement—[23]. As the droplet ratio rose to 0.5, we observed that good tracking distance, and approach speed were attributable to high charge density. The more the droplet size, the larger the overall charge thus stronger the electrostatic forces, the more the droplet motion. The highest velocities were recorded at a droplet ratio of 0.75, reinforcing the correlation between charge accumulation and droplet movement.

Throughout our experiments, we maintained a uniform electric field, which allowed us to consider dielectrophoretic effects as negligible[24]. Thus, the motion we observed can primarily be attributed to electrophoretic forces acting on the droplets. The size of the droplets is crucial; larger droplets tend to accumulate more charge, resulting in stronger forces that propel them forward[25]. This behavior underscores the interplay between droplet size, charge accumulation, and resultant motion, suggesting that manipulating these parameters could lead to improved control over droplet dynamics.

To further understand the dynamics at play, we conducted a comparative analysis of droplet velocities at different distances and different droplet ratios. **Fig. 5** shows droplet velocity as a function of applied voltage for different droplet separation distance using canola oil as a dielectric layer. **Fig. 6** shows droplet velocity as a function of

applied voltage for different droplet ratios using canola oil as a dielectric layer. Our results demonstrated that droplets positioned closer together experienced stronger electrostatic forces, leading to higher velocities[26]. Specifically, droplets at 10 mm apart recorded the highest velocities due to the strong electrostatic attraction, as the electric field's intensity is inversely proportional to the square of the distance[27]. This relationship is fundamental in electrostatics and was clearly illustrated in our findings.

In addition to exploring the effects of electric fields and droplet ratios, we examined the impact of fluid viscosity on droplet behavior. **Fig. 7** shows comparison of droplet displacement over time for different oils under varying electric fields. **Fig. 8** shows a comparison of droplet velocity over time for different oils under varying electric fields. (a) for sunflower oil. (b) for canola oil.

We performed experiments using sunflower oil and canola oil, which differ significantly in viscosity. The internal friction associated with viscosity acts as a resistive force against droplet motion. As droplets move under the influence of an electric field, the viscosity of the surrounding medium opposes this movement. Our observations indicated that droplets in sunflower oil exhibited higher velocities compared to those in canola oil, attributed to sunflower oil's lower viscosity. The greater internal resistance encountered in canola oil

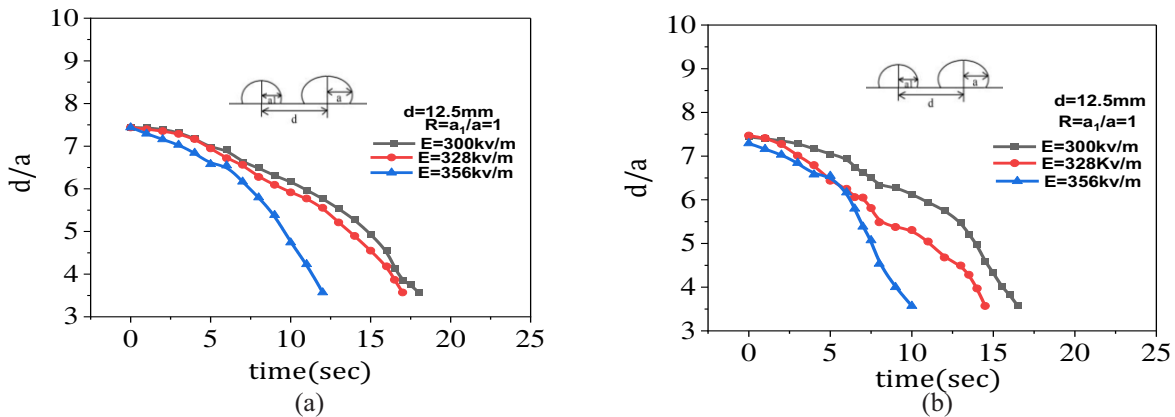


Fig. 7. Comparison of droplet displacement over time for different oils under varying electric fields. (a) for canola oil. (b) for sunflower oil.

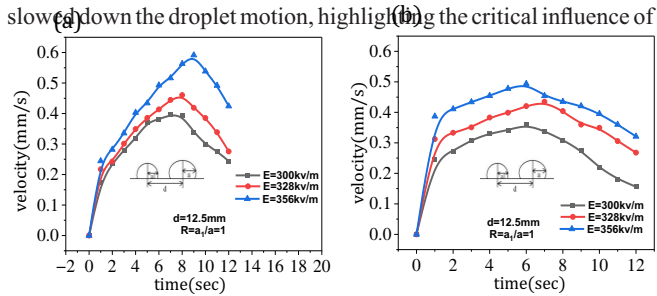


Fig. 8. Comparison of droplet velocity over time for different oils under varying electric fields. (a) for sunflower oil. (b) for canola oil.

fluid properties on droplet dynamics[28]. The conditions under which uniform droplet motion takes place under electric fields are fully revealed by our research. Finally, the electric field strength and droplet ratios were shown to have significant effects on droplet behavior as shown in Fig. 9. At lower electric field strengths and lower droplet ratios, the droplets do not move. The electrophoretic forces are not strong enough to overcome the resistive viscous forces imparted by the dielectric liquid layer. At moderate electric field strengths and moderate droplet ratios, the droplet approaches each other and coalesce. This is because the electrophoretic forces overcome the viscous forces of the dielectric layer, and the droplet moves. At strong electric field strengths and larger droplet ratios, dispersion of the droplets is observed to be dominant. This is due to strong electric forces overcoming the interfacial capillary forces. The droplet fails to retain its instant configuration and collapses. The mapping provides a guideline for effective control and manipulation of the droplet-droplet approach over a hydrophobic surface under electric field. This not only helps us understand the droplet dynamics but also provides us with ideas of how to use these factors in the future to develop their practical uses.

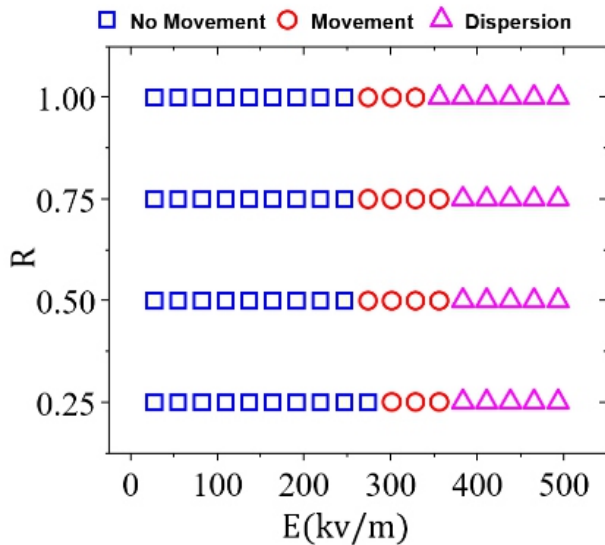


Fig. 9. Droplet behavior at varying droplet size ratios and electric field. The figure highlights distinct thresholds where droplets transition from no movement to movement and ultimately dispersion, providing valuable insights into the system's behavior under varying conditions.

The implications of this work include a great number of fields in which it might be possible to design and use new technologies for manipulation of fluids if droplet motion can be controlled with extreme precision, for instance targeting delivery systems, microfluidic devices, or even new forms of cooling. Continuing work, allowing variation in the fluid composition, the droplet size, and the environmental conditions, will provide additional knowledge and expand the uses of the electric field driven droplet manipulation.

IV. CONCLUSION

In conclusion, this paper investigates the droplet-droplet approach over hydrophobic surface using electric field. We found three different modes wherein the sessile droplets composed of water show no motion, elongate with motion and approach one another, or disperse into tiny daughter droplets before approaching one another under different range of electro-physical conditions. We also found that the changing of ratio between the droplets affects the velocity as well as the distance covered by the droplets along with the time taken by them. The higher the ratio is used, the higher the velocity and the less the time taken by the droplets to cover the distance. The experiments performed at various distances showed us that the closer the droplets are, the higher the velocity with which they have to move towards each other and vice versa. The experiments with different oils' layers showed that the higher viscosity oil results in droplets taking more time to approach each other and hence lower velocities. The study provides a valuable insight into the role of competing forces such as electrophoretic and viscous in droplet manipulation. Moreover, the importance of magnitude and dominance of interfacial capillary stresses over interfacial electric stresses is very important in retaining the droplets shape and stability.

ACKNOWLEDGMENT

This work was supported by the National Research Program for Universities, Higher Education Commission, Islamabad, Pakistan (HEC-NRPU-14816).

REFERENCES

- [1] W. Xu et al., "A droplet-based electricity generator with high instantaneous power density," *Nature*, vol. 578, no. 7795, pp. 392396, Feb. 2020, doi: 10.1038/s41586-020-1985-6.
- [2] X. Wang, Z. Zhuang, X. Li, and X. Yao, "Droplet Manipulation on Bioinspired Slippery Surfaces: From Design Principle to Biomedical Applications," *Small Methods*, vol. 8, no. 4, Apr. 2024, doi: 10.1002/smt.202300253.
- [3] X. Liang, V. Kumar, F. Ahmadi, and Y. Zhu, "Manipulation of droplets and bubbles for thermal applications," *Droplet*, vol. 1, no. 2, pp. 8091, Oct. 2022, doi: 10.1002/dro.2.21.
- [4] K.-C. Park et al., "Condensation on slippery asymmetric bumps," *Nature*, vol. 531, no. 7592, pp. 7882, Mar. 2016, doi: 10.1038/nature16956.
- [5] L. Chen and E. Bonaccorso, "Effects of surface wettability and liquid viscosity on the dynamic wetting of individual drops," *Phys. Rev. E*, vol. 90, no. 2, p. 022401, Aug. 2014, doi: 10.1103/PhysRevE.90.022401.
- [6] G. M. Whitesides and A. D. Stroock, "Flexible Methods for Microfluidics," *Phys. Today*, vol. 54, no. 6, pp. 4248, Jun. 2001, doi: 10.1063/1.1387591.

- [7] M. Medina-Sánchez, S. Miserere, and A. Merkoçi, "Nanomaterials and lab-on-a-chip technologies," *Lab Chip*, vol. 12, no. 11, p. 1932, 2012, doi: 10.1039/c2lc40063d.
- [8] N. M. R. de Oliveira, "Biomedical Devices Engineered Based on the Control of the Surface Wettability," 2017.
- [9] 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. 89058911, 2019, doi: 10.1039/C9SM01623F.
- [10] K. Wang, Q. Liang, R. Jiang, Y. Zheng, Z. Lan, and X. Ma, "Morphology evolution and dynamics of droplet coalescence on superhydrophobic surfaces," *AIChE J.*, vol. 64, no. 7, pp. 29132921, Jul. 2018, doi: 10.1002/aic.16169.
- [11] M. S. Abbasi, R. Song, S.-M. Kim, H. Kim, and J. Lee, "Mono-emulsion droplet stretching under direct current electric field," *Soft Matter*, vol. 15, no. 11, pp. 23282335, 2019, doi: 10.1039/C8SM01750F.
- [12] J. B. Lee and S. H. Lee, "Dynamic Wetting and Spreading Characteristics of a Liquid Droplet Impinging on Hydrophobic Textured Surfaces," *Langmuir*, vol. 27, no. 11, pp. 65656573, Jun. 2011, doi: 10.1021/la104829x.
- [13] A. M. Qamar, M. S. Abbasi, A. T. Jafry, M. Arslan, and M. Usama, "Behavior of a sessile droplet over dielectric infused hydrophobic surface under direct current electric field," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 683, p. 133050, Feb. 2024, doi: 10.1016/j.colsurfa.2023.133050.
- [14] 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. 22922300, 2019, doi: 10.1039/C8SM02230E.
- [15] M. Spohner, "DIELECTRIC PROPERTIES OF NATURAL OILS FROM DIFFERENT OILSEEDS," 2017.
- [16] J. Soucek, J. Hornak, M. Svoboda, M. Gutten, and T. Koltunowicz, "Comparison of the electrical properties of canola oil with commercially available mineral oil," in 2015 16th International Scientific Conference on Electric Power Engineering (EPE), IEEE, May 2015, pp. 634637. doi: 10.1109/EPE.2015.7161087.
- [17] C. Yang, Q. Zeng, J. Huang, and Z. Guo, "Droplet manipulation on superhydrophobic surfaces based on external stimulation: A review," *Adv. Colloid Interface Sci.*, vol. 306, p. 102724, Aug. 2022, doi: 10.1016/j.cis.2022.102724.
- [18] W. D. Ristenpart, J. C. Bird, A. Belmonte, F. Dollar, and H. A. Stone, "Non-coalescence of oppositely charged drops," *Nature*, vol. 461, no. 7262, pp. 377380, Sep. 2009, doi: 10.1038/nature08294.
- [19] C. T. OKonski and H. C. Thacher, "The Distortion of Aerosol Droplets by an Electric Field," *J. Phys. Chem.*, vol. 57, no. 9, pp. 955958, Sep. 1953, doi: 10.1021/j150510a024.
- [20] Y. Sun et al., "Experimental study on the falling and coalescence characteristics of droplets under alternating electric fields," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 603, p. 125136, Oct. 2020, doi: 10.1016/j.colsurfa.2020.125136.
- [21] S. Mhatre et al., "Electrostatic phase separation: A review," *Chem. Eng. Res. Des.*, vol. 96, pp. 177195, Apr. 2015, doi: 10.1016/j.cherd.2015.02.012.
- [22] X. Yan et al., "Droplet Jumping: Effects of Droplet Size, Surface Structure, Pinning, and Liquid Properties," *ACS Nano*, p. acsnano.8b06677, Jan. 2019, doi: 10.1021/acsnano.8b06677.
- [23] R. Pethig, "Review Article Dielectrophoresis: Status of the theory, technology, and applications," *Biomicrofluidics*, vol. 4, no. 2, Jun. 2010, doi: 10.1063/1.3456626.
- [24] R. Pethig, "Dielectrophoresis: Using Inhomogeneous AC Electrical Fields to Separate and Manipulate Cells," *Crit. Rev. Biotechnol.*, vol. 16, no. 4, pp. 331348, Jan. 1996, doi: 10.3109/07388559609147425.
- [25] J. Eow, "Electrostatic enhancement of coalescence of water droplets in oil: a review of the technology," *Chem. Eng. J.*, vol. 85, no. 23, pp. 357368, Jan. 2002, doi: 10.1016/S1385-8947(01)00250-9.
- [26] J. S. Eow, M. Ghadiri, A. O. Sharif, and T. J. Williams, "Electrostatic enhancement of coalescence of water droplets in oil: a review of the current understanding," *Chem. Eng. J.*, vol. 84, no. 3, pp. 173192, Dec. 2001, doi: 10.1016/S1385-8947(00)00386-7.
- [27] 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*, vol. 35, no. 11, pp. 39373948, Mar. 2019, doi: 10.1021/acs.langmuir.8b04254.
- [28] M. Chiesa, S. Ingebrigtsen, J. A. Melheim, P. V. Hemmingsen, E. B. Hansen, and Ø. Hestad, "Investigation of the role of viscosity on electrocoalescence of water droplets in oil," *Sep. Purif. Technol.*, vol. 50, no. 2, pp. 267277, Jun. 2006, doi: 10.1016/j.seppur.2005.12.003.