Experimental investigation on the Electrohydrodynamic motion and Shape Deformation of a sedimenting Drop under Uniform Alternating Electric Field

Rajorshi Paul*, Guttapalli Naveen Kumar*, Shubhadeep Mandal*, N.K. Kishore†, SauravPramanik†, Suman Chakraborty*

*Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, Kharagpur-721302, West Bengal, India
†Department of Electrical Engineering, Indian Institute of Technology Kharagpur, Kharagpur-721302, West Bengal, India

***Abstract*—A leaky dielectric Newtonian drop suspended in another leaky dielectric Newtonian liquid medium deforms as it settles under the influence of a uniform alternating electric field. As a result of this deformation, the terminal velocity is affected. In this study we present a detailed experimental investigation of the effect of horizontally directed uniform alternating electric field on the settling velocity and deformation characteristics of silicone oil drop falling in castor oil medium. For the fluid pair used, the drop deforms to a prolate shape on application of electric field which retards the drop motion in the vertical direction. There is a marked decrease in drop velocity with increase in field strength of the alternating electric field.**

I. INTRODUCTION

Elecrohydrodynamics (EHD) is the study of motion of fluids subjected to electric fields. There are several potential applications of EHD ranging from different industrial processes to modern day microfluidic devices. These include the separation of emulsions of oils into the individual oils, transport of biological cells by enclosing them in droplets, enhanced heat and mass transfer due to mixing inside the drops and so on [1-4].

When a neutrally buoyant drop is subjected to an externally applied uniform electric field, the droplet deforms to ellipsoidal shape [5-17]. Allan and Mason experimentally observed that the droplet can deform to prolate (major axis of the ellipsoid is aligned in the direction of external electric field) or oblate (major axis of the ellipsoid is perpendicular to the direction of external electric field) shape in the presence of steady uniform electric field [20]. Taylor in his classical study proposed the *leaky dielectric model* and theoretically obtained that the prolate or oblate shape deformation is decided by the electrical conductivity, permittivity and viscosity of the droplet and suspending medium [17-19]. The leaky dielectric model assumes small but finite electrical conductivities for both the liquids. The non-zero conductivities of the fluid pair give rise to tangential electric stresses at the interface which drives fluid motion thereby generating hydrodynamic stresses. The resulting shape of the drop is established as a balance between the electric and the hydrodynamic stresses. Droplet dynamics in alternating electric field was first considered by Torza et al. [16]. They obtained that the deformation can be decomposed into a steady component and a time-dependent component which oscillates at a frequency twice that of the frequency of imposed electric field. This was experimentally verified later by Vizika et al. [15]. All of these studies investigate the effect of the electric field on neutrally buoyant droplets and the influence of gravity has not been accounted for.

Droplet having density different than the suspending medium moves vertically in the presence of gravity and the sedimentation/terminal velocity of the droplet is given by the Hadamard-Rybczynski solution [21]. In this case, the droplet shape has been found out to be spherical. Xu and Homsy experimentally investigated the settling velocity of a Newtonian droplet under the combined influence of steady electric field and gravity [22-23]. They have obtained that velocity of the droplet is significantly affected by the shape deformation and interfacial charge convection effects. In a very recent study, Bandopadhyay et al. studied the lateral migration of a sedimenting droplet in the combined presence of tilted electric field and gravity [24]. Till now, most of the study on droplet sedimentation in gravity has been focused on the dynamics of the droplets under the influence of steady electric fields. There have been studies on the deformation of droplets in alternating electric fields. However, the settling of droplets under the influence of alternating electric fields has not been studied in detail. In this paper we have presented an experimental study on the effect of alternating electric fields on the settling velocity of droplets.

II. EXPERIMENTAL SETUP

The experiments were conducted in a 14 cm X 14 cm X 20 cm Perspex cell fitted with two square brass electrodes 5 mm thick having dimensions 12 cm X 12 cm. The distance between the two electrodes was maintained constant at 12 cm. The edges of the brass electrodes were filed in order to remove any sharp edges. The surfaces of the electrodes were polished. All electrical connections were made using thick copper wires in order to avoid corona formation due to application of high voltage. Drops were injected using a 5 ml hypodermic syringe. To minimize the effect of the side wall, droplets are injected from the centre of the cross-section. The electric field is supplied through a High Voltage Testing transformer rated 60 KV. The frequency of oscillation of the electric field is kept at power frequency ~50 Hz constant throughout the experiments. An LED lamp placed behind the cell was used for illumination. The experiments were recorded using two different types of cameras. For observing the settling, a Nikon digital single lens reflex (DSLR) camera was used. For capturing the droplet deformation, a high speed camera capable of recording at 200 frames per second, integrated with a computer, was used. A schematic of the set-up is shown in Fig. 1.

For the experiments, the pair castor oil (dispersing phase) and silicone oil (dispersed phase) have been used. Both the fluids are known to be Newtonian and incompressible in nature. The densities of the oils used are similar but the continuous medium (castor oil) is much more viscous compared to silicone oil (See Table 1). As a result, the drop settles slowly. The electrical conductivities of these oils are very small. Thus they act as good dielectric materials and can sustain very high electric fields.

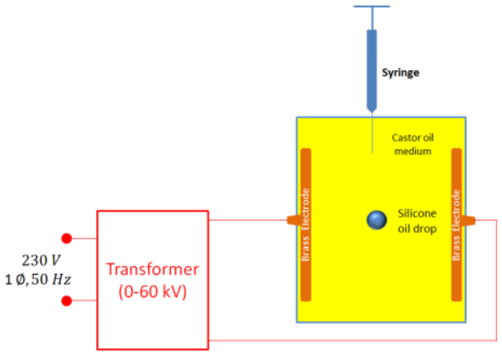

Fig. 1. Schematic of the experimental set-up

III. Experimental method

Three different sets of experiments were conducted. In the first set of experiments, the drop falls in absence of any electric field. In the second set of experiments, the settling velocity of the drop was observed with the help of a DSLR camera. The last set of experiments involves observing the drop deformation with the help of the high speed camera. Prior to starting the experiments, the camera is adjusted and focused for the best possible recording. The camera and the LED light source are positioned at the safe distance from the cell in order to avoid sparking from the connecting wires. This can damage the instruments. The drop is injected using a syringe from the center of cross-section of the cell. The volume of injected oil cannot be controlled in a syringe. The size of the injected drop was calculated from image processing later. After the drop falls through a certain height, the voltage is applied through the transformer. The cell is tall enough so that the drop attains a steady settling velocity before it reaches the bottom. The drop size was varied for each voltage value from ~1 mm diameter to ~4 mm diameter. The value of the voltage was increased in steps of 5 kV from 5 kV to 50 kV. As the density difference between the experimental fluids is very small, the duration of each experiment varies from ~2 minutes to ~10 minutes depending on the drop size. The experimental videos were processed using the Image Processing Toolbox in MATLAB. The results obtained from MATLAB were cross-checked by manual processing to ensure the accuracy of the processing.

IV. Results

A. Velocity of settling drop without any imposed electric field

Before investigating the pivotal effect of alternating electric field on the settling velocity of the droplet, we perform experiments on the settling velocity of the droplet in the absence of electric field. The terminal velocity of a settling drop is attained due to the balance between the drag force and the gravitational force on the drop. As the size of the drop increases, the weight of the drop increases more than the surface area dependent drop increases, the weight of the drop increases more than the surface area dependent drag force. Hence, the settling velocity of the drop increases with increase in drop diameter. The terminal velocity U_∞ for a drop settling in another immiscible fluid medium in absence of any other body force is given by the Hadamard-Rybczynski solution [21]:

$$U_\infty = \frac{2}{9}\left(\frac{\lambda+1}{\lambda+\frac{2}{3}}\right)\frac{R^2 g\rho(\kappa-1)}{\mu} \tag{1}$$

Here, λ and κ are the ratio of the viscosities and densities respectively of the drop to the dispersing medium, μ and ρ are the viscosity and density of the dispersing medium, R is the drop radius and g is the acceleration due to gravity. In this case, the drop shape is determined by the balance between the hydrodynamic stresses and the surface tension at the interface and the analytical solution shows that the drop is perfectly spherical.

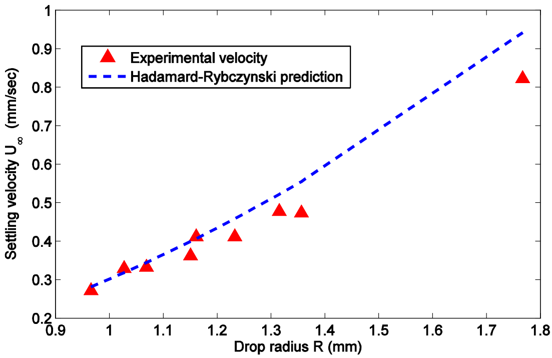

Fig. 2. Plot showing the variation of the settling velocity with drop radius for a drop falling under the influence of gravity alone. The experimental data (in red) has been compared to theoretical results (in blue)

In Fig. 2 the variation of the settling velocity with the drop radius is shown. The points plotted in red correspond to the experimentally obtained velocities and the dotted line represents the theoretically predicted values calculated from eqn. 1. A close match is obtained between the experimentally obtained values and those predicted by theory. The settling of drops under the influence of gravity is a well studied phenomenon. Hence the close agreement of experimental results with theory shows that the experimental procedure and the post-processing followed in this study is fairly accurate.

B. Settling velocity under uniform horizontally directed alternating electric field

As the silicone oil drop settles in the immiscible castor oil medium, the velocity of the drop increases to a steady value when the net force on the drop becomes zero due to balance between the hydrodynamic drag and the gravitational force. In presence of an electric field, the settling velocity becomes a function of both the drop size and the strength of the electric field for fixed electrohydrodynamic properties. As the drop size increases, the settling velocity increases as explained in section A.

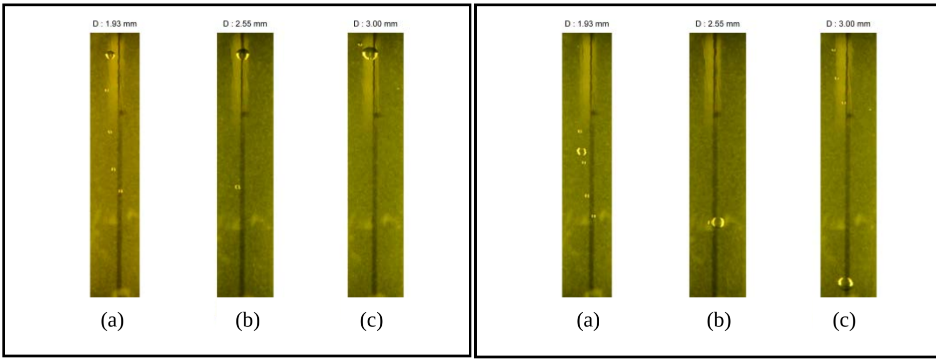

Fig. 3.Variation of settling velocity with drop speed. The image on the left shows the position of three drops of different sizes at t=0. The image on the right shows the positions of the same drops at t=68 sec. The applied electric field is 3.33 kV/cm.

Fig. 3 demonstrates the effect of drop diameter on the settling velocity of the drop in presence of a horizontally directed uniform alternating electric field. Three drops of different sizes subjected to the same electric field (3.33 kV/cm) are settling in the castor oil medium separately. At t = 0, the drops are at the same location, but at t = 68 sec, the drop having the maximum diameter falls through the largest distance.

In fig. 4 the droplet velocity variation with drop diameter for three different values of electric field strength is shown. For a fixed value of drop diameter, fig. 4 depicts that the settling velocity of the droplet decreases with increase in the field strength. Two governing factors which affect the drop settling velocity in electric field are interfacial charge convection and shape deformation. But Xu has previously shown that the effect of charge convection at the droplet interface is less important in alternating electric field due to the fact that there is no steady component of surface charge [23]. So, in the present situation the shape deformation effect will be the deciding factor. We observe prolate deformation of the silicone oil drop in castor oil medium. This prolate shape leads to increase in cross-sectional area of the drop in the direction of settling which further increases the hydrodynamic drag. This increase in hydrodynamic drag force on the droplet finally reduces the droplet velocity for higher field strength.

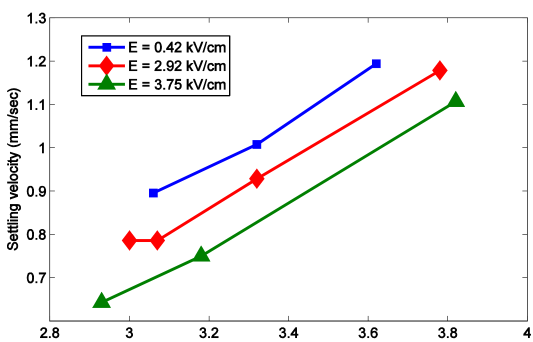

Fig. 4. Variation of drop settling velocity with drop diameter for different electric fields

C. *Deformation of a settling drop under uniform horizontally directed alternating electric field*

When a silicone drop is injected into the castor oil medium using a syringe, the drop falls under the effect of gravity. As the electric field is switched on, the drop deforms which in turn affects the settling velocity of the drop. The deformation of the drop has been observed to be dependent on the size of the injected drop and also on the strength of the electric field. The deformation of the drop is expressed in terms of the deformation ratio D given by:

$$D = \frac{a-b}{a+b} \tag{2}$$

Here, a is the length of the drop axis parallel to the direction of the electric field and b is the length of the axis perpendicular to it as shown in Fig. 5.

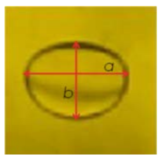

Fig. 5. Drop deformation is quantified in terms of the deformation ratio which depends on the lengths of the polar and equatorial axes of the drop.

The analytical solution derived by Torza et al. shows that the drop shape oscillates at a frequency twice that of the imposed electric field [16]. This has been validated by experiments. Torza et al. predicted that the deformation of the drop is a superposition of a steady component and a time varying component. In our experiments, the DSLR camera has been set to record at 50 frames per second. As the frequency of the applied electric field is 50 Hz, the camera captures a particular point in the cycle. Hence the deformation recorded by the DSLR camera remains constant. As the frequency of the electric field is high, the oscillatory part of the deformation is very small compared to the steady component [16]. Hence, for all practical purposes, we have treated the deformation observed from the DSLR camera as the steady component of the deformation.

As the electric field strength is increased the drop deformation increases. Fig. 6 shows the variation of the drop deformation with the electric field strength. Here the drop sizes are similar.

(a) (b) (c)

Fig. 6. Drop shape observed by increasing the electric field from 0 to 4.17 kV/cm (peak value). The drop diameter is similar in all the three cases.

For neutrally buoyant drops under the influence of alternating electric fields, it has been shown that the steady part of the deformation D_S varies linearly with ${E_0}^2R$ where R is the radius of the undeformed drop, as [16]:

$$D_S = \frac{9\epsilon}{16\gamma}\Phi\,({E_0}^2R) \quad (3)$$

Here, E_0 is the peak electric field, ϵ is the permittivity of the dispersing medium, γ is the surface tension and Φ is a function of the ratios of conductivity, permittivity and viscosity. Our study reveals a similar trend for the steady state deformation and the factor ${E_0}^2R$ as shown in Fig. 7.

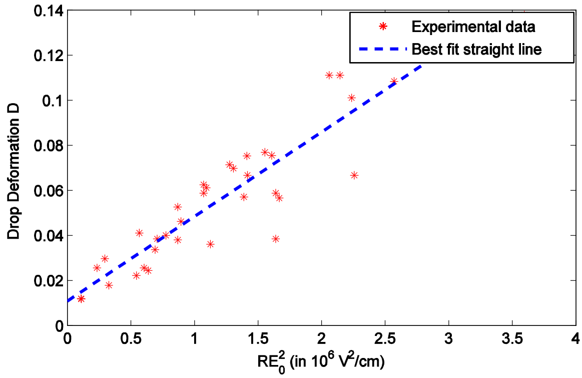

Fig. 7. Plot showing variation of drop deformation with ${E_0}^2R$

However, a very important thing to note from the images presented in figure 6(b-c) that there is an asymmetry in the droplet shape with respect to a horizontal plane. This asymmetry in droplet shape is more for higher field strength as observed in figure 6(c). Similar asymmetry in droplet shape is also reported by Xu and Homsy for settling of droplet in steady electric field which is the coupled effect of gravity and electric field [22].

TABLE 1: PROPERTIES OF EXPERIMENTAL FLUIDS

Experimental fluids	Castor oil	Silicone oil
Density (kg/m³)	958	1023
Viscosity (Pa s)	0.693	0.0232
Electrical conductivity (S/m)	2.78×10^{-10}	9.26×10^{-11}
Dielectric constant	7.70	3.88

V. CONCLUSION

Electrohydrodynamic motion and shape deformation of a sedimenting viscous drop in the presence of externally applied alternating electric field are investigated experimentally. Here we study the nonlinear coupling of gravity (acting vertically) and alternating electric field (acting perpendicular to the gravity) on the motion and deformation characteristics of a non-neutrally buoyant droplet. Towards elucidating the effects of shape deformation and interfacial charge dynamics on the droplet motion, we perform controlled experiments using silicone oil droplets suspended in castor oil medium. We study the droplet motion for different strength of applied electric field but with fixed frequency of 50 Hz. Present study shows that the horizontally applied electric filed retards the drop motion in the vertical direction by deforming the drop in prolate shape. There is a significant decrease in drop velocity with increase in strength of applied electric filed. Though the drop deforms to a prolate shape, there is a noticeable asymmetry in the deformed shape. These studies on the motion of drops under the combined influence of gravity and electric fields would help in designing more efficient strategies for the separation of oils.

VI. ACKNOWLEDGEMENTS

We are grateful to Dr. Rochish M. Thaokar and Dr. Manu Vashishtha at the Chemical Engineering department in the Indian Institute of Technology Bombay for helping us carry out conductivity and permittivity measurements using a broadband Dielectric Spectrometer. We would also like to thank the technical staff at the Electrical and Mechanical Engineering departments in the Indian Institute of Technology Kharagpur for assisting us while conducting the experiments.

REFERENCES

[1] D. Di Carlo et al., "Continuous interfacial focusing, ordering and separation of particles in Microchannels", *Proc. Natl. Acad. Sci. USA*, 104 (48), pp. 18892-18897, 2007.

[2] A. Bhagat et al., "Microfluidics for cell separation", *Med. Biol. Engng. Comput*., 48 (10), pp. 999-1014, 2010.

[3] T. Geislinger and T. Franke, "Sorting of circulating tumor cells (MV3-melanoma) and red blood cells using non-inertial lift", *Biomicrofluidics*, 7 (4), 044120, 2013.

[4] Y. Chen, "Inertia and deformation driven migration of a soft particle in confined shear and Poiseuille flow", *RSC Adv.*, 4 (34), pp. 17908-17916, 2014.

[5] T. Ward and G. Homsy, "Electrohydrodynamically driven chaotic mixing in a translating drop", *Phys. Fluids*, 13 (12), pp. 3521-3525, 2001.

[6] T. Ward and G. Homsy, "Electrohydrodynamically driven chaotic mixing in a translating drop II. Experiments", *Phys. Fluids*, 15 (10), pp. 2987-2994, 2003.

[7] T. Ward and G. Homsy, "Chaotic streamlines in a translating drop with a uniform electric field", *J. Fluid Mech.*, 547, pp. 215-230, 2006.

[8] J. Feng and T. Scott, "A computational analysis of electrohydrodynamics of a leaky dielectric drop in an electric field", *J. Fluid Mech.*, 311, pp. 289-326, 2006.

[9] E. Lac and G. Homsy, "Axisymmetric deformation and stability of a viscous drop in a steady electric field", *J. Fluid Mech.*, 590, pp. 239-264, 2007.

[10] G. Supeene, C. Koch, S. Bhattacharjee, "Defrmation of a droplet in an electric field: nonlinear transient response in perfect and dielectric media", *J. Colloid Interface Sci.*, 318 (2), pp. 463-476, 2008.

[11] R. Thaokar, "Dielectrophoresis and deformation of a liquid drop in a non-uniform axisymmetric AC electric field", *Eur. Phys. J.*, E 35 (8), pp. 1-15, 2012.

[12] J. Lanauze, L. Walker, A. Khair, "The influence of inertia and charge relaxation on electrohydrodynamic drop deformation", *Phys. Fluids*, 25 (11), 112101, 2015.
[13] J. Zhang, J. Zahn, H. Lin, "Transient solution for droplet deformation under electric fields", *Phys. Rev.* E 87 (4), 043008, 2013.
[14] S. Deshmukh and R. Thaokar, "Deformation and breakup of a leaky dielectric drop in a quadrupole electric field", *J. Fluid Mech.*, 731, pp. 713-733, 2013.
[15] O. Vizika and D. Saville, "The electrohydrodyamic deformation of drops suspended in liquids in steady and oscillatory electric fields", *J. Fluid Mech.*,239, pp. 1-21, 1992.
[16] S. Toza, R. Cox and S. Mason, "Electrohydrodynamic deformation and burst of liquid drops", *Phil. Trans. R. Soc.*, A 269, pp. 295-319, 1971.
[17] J. Melcher and G. Taylor, "Electrohydrodynamics: a review of the role of interfacial shear stresses", *Annu. Rev. Fluid Mech.*, 1, pp. 111-146, 1969.
[18] D. Saville, "Electrohydrodynamics: The Taylor-Melcher leaky dielectric model", *Annu. Rev. Fluid Mech.*, 29, pp. 27-64, 1997.
[19] O. Ajayi, "A note on Taylor's electrohydrodynamic theory", *Proc. R. Soc.*, A 364, pp. 499-507, 1978.
[20] R. Allan and S. Mason, "Particle behaviour in shear and electric fields. I. Deformation and burst of fluid drops", in *Proc. R. Soc.*, A 267, pp. 45-61, 1962.
[21] L. G. Leal, *Advanced Transport Phenomena*, Cambridge University Press, 2007.
[22] X. Xu and G. Homsy, "The settling velocity and shape distortion of drops in a uniform electric field", *J. Fluid Mech.*, 564, pp. 395-414, 2006.
[23] X. Xu, *Electrohydrodynamic flow and chaotic mixing inside drops*, PhD thesis, UCSB, 2007.
[24] A. Bandopadhyay et al., "Uniform electric-field-induced lateral migration of a sedimenting drop", *J. Fluid Mech.*, 792, pp. 553-589, 2016.