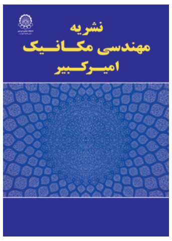

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Three Dimensional Numerical Simulation of a Drop and Drop-to-Wall Interaction under Uniform Electric Field

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ABSTRACT: The behavior of a drop and drop-to-wall interaction under a uniform electric field is studied by numerical simulations in three dimensions. The electric field is created by imposing an electric-potential difference. The Taylor Leaky Dielectric Model, is used to compute electric force. This force is added to Navier-Stokes equations as a body force. The drop can obtain an Oblate shape (deformation perpendicular to direction of electric field) or a Prolate shape (deformation in the direction of electric field) depending on the electric properties of drop and ambient fluid. It found that the deformation of the drop is in agreement with experimental results finding in literature. The interaction of the drop with the existing walls of the channel is investigated for both Oblate and Prolate drops. This is done at various capillary numbers. Attraction of both Oblate and Prolate drops to the wall, are the results. Increasing the electric capillary number reduces the time of attraction for both drops. For Oblate and Prolate drops with similar flows, higher electric capillary number causes distortion of drop surface near the wall. For another type of Prolate drops, increasing the electric capillary number eventuates to more distance between drop center and the wall.

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1- Introduction

Electro hydrodynamics as an interdisciplinary phenomenon has recently been investigated by several researchers. It deals with coupling of hydrodynamics and electrostatic and has numerous applications such as fuel atomization, design of microfluidic devices and separation of impurities. Generally, when a liquid drop is suspended in another immiscible fluid which is influenced by electric field, two different shapes and flow patterns may occur depending on the electric conductivity and permittivity ratio of the drop and the ambient fluids. Numerical simulation of drop deformation in electric field has been done by several researchers [1-3]. While this is a well-known problem, the effects of the wall on the drop behavior in electric field is not as complete as drop deformation. In other words, a comprehension work for this phenomenon does not exist. Fernandez et al. [4], used a 2D front-tracking method and reported attraction of oblate drops to the wall while their research was mainly about emulsion of oblate drops. Halim and Esmaeeli [5], reported the attraction of oblate and one type of prolate drops (their flow pattern are identical to oblate drops) to the wall and repulsion of another type of the prolate drops.

In this paper, general behavior of a single drop in uniform electric field is investigated in addition to drop-to-wall interaction. Also the effect of electric capillary number on interaction of drop-to-wall is studied.

2- Methodology

In this paper, a single drop is influenced by an external uniform electric field. The channel length and height are equal to eight times the drop radius. The electric field is applied by imposing an electric potential difference between the upper and lower walls of the channel. After finding the electric field and electric charge distribution, the electric forces are calculated through the following equation:

$$F_{El} = qE - \frac{1}{2}(E.E)\nabla\varepsilon + \nabla\left(\frac{1}{2}(E.E)\frac{\partial\varepsilon}{\partial\rho}\rho\right) \tag{1}$$

where, q is electric charge, E is electric field, ε is electric permittivity and ρ is density. If the electric conductivity and permittivity are constant in each fluid, this force acts only at the interface. The first term is due to presence of electric charge at the interface. The second term is the effects of polarization and the last term is due to variation in properties of each fluid. Because the properties of each fluid are constant, this term is neglected. Eventually, this force is added to Navier-stokes equations as a body force.

The numerical method is a modified version of front-tracking developed by Unverdi and Tryggvason [6]. The momentum equation is combined with the continuity equation which leads to a pressure equation that is solved by a multigrid method.

3- Results and Discussion

The electric forces can cause the drop to deform into both oblate (deformation perpendicular to electric field) and prolate (deformation in direction of electric field) shapes. Two different flow patterns are also induced inside and outside of the drop. There is a map of prediction for both deformation and induced flow types as depicted in Fig. 1 according to electric conductivity and permittivity ratios (σ_r and ε_r).

In this figure, there is a solid line (with discrimination function of $\Phi_{2d}=\sigma_r^2+\sigma_r+1-3\varepsilon_r=0$) that determines the drop

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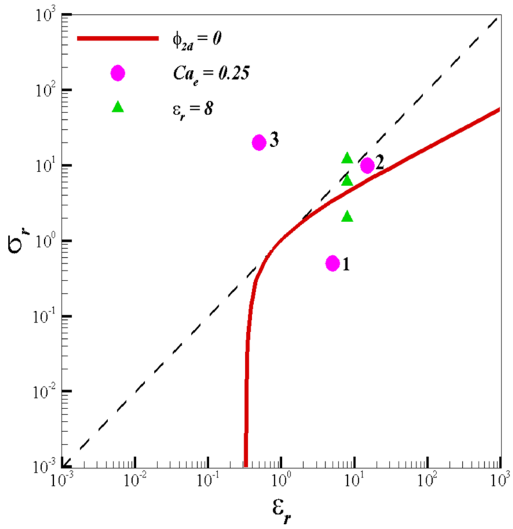

Fig. 1. Map of prediction for both deformation and induced flow types inside and outside of the drop

deformation. For drops with $\Phi_{2d}<0$ an oblate shape is obtained and for $\Phi_{2d}>0$ a prolate shape will happen. The dashed line determines the induced flow patterns. Below this line ($\sigma_r<\varepsilon_r$) the direction of flow is from the poles to equator and above that ($\sigma_r>\varepsilon_r$) the direction of flow is from equator to the poles. Triangle symbols are used to simulate the drop-to-wall interaction and the points 1, 2 and 3 are the cases that are used for description of the drop behavior.

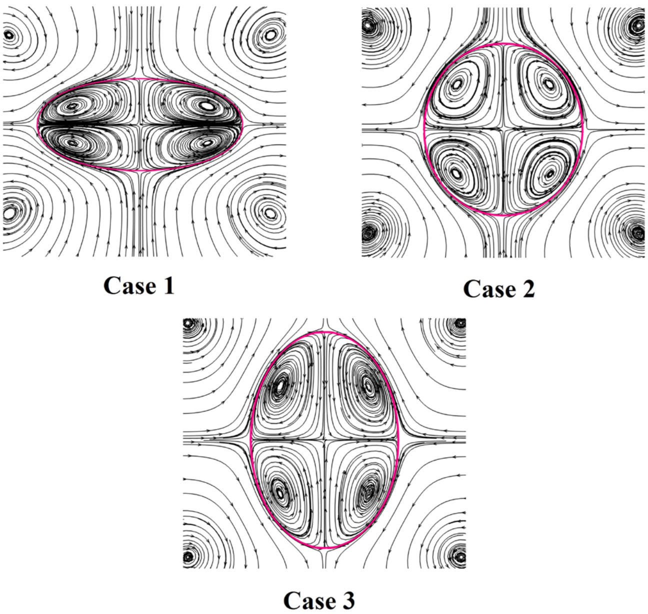

Fig. 2. Deformation type and induced flow patterns inside and outside of the drops for cases 1, 2 and 3 in Figure 1

For point 1, $\Phi_{2d}<0$, the drop takes an oblate shape and for points 2 and 3, $\Phi_{2d}>0$, they obtain a prolate shape. Also for points 1 and 2, $\sigma_r<\varepsilon_r$, the direction of flow is from the poles to equator and for point 3, $\sigma_r>\varepsilon_r$, the direction of flow is from equator to the poles. Fig. 2 represents the flow patterns and drop deformation for these points.

The drop-to-wall interaction is studied next. Initial position of the drop is determined by definition of dimensionless distance as $h=d_w/a$. In this equation d_w is initial separation distance from the wall and a is drop radius. For triangle symbols in Fig. 1 from bottom to top, σ_r=2, 6 and 12 respectively and ε_r=8 for all of them. All three cases are released at h=2. Oblate drop and one type of prolate drop (σ_r=2 and 6) move towards the wall but another prolate drop is not influenced by the wall. For h=1.667 this drop will also move towards the wall. Fig. 3 shows the final state of the drops settling on the wall together with steady state streamlines.

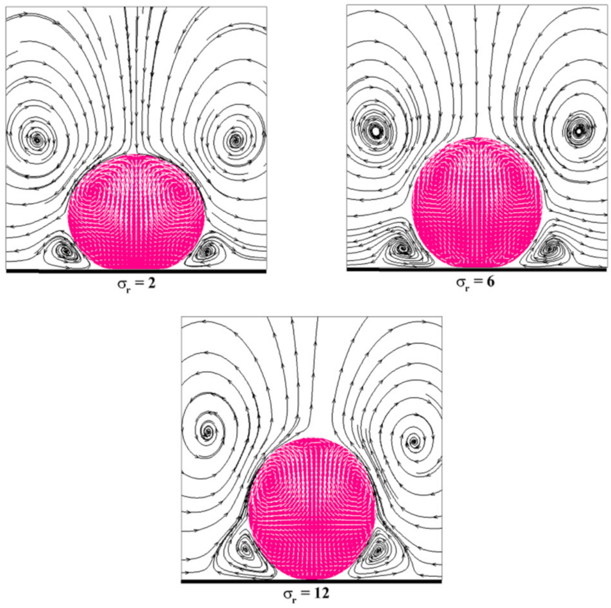

Fig. 3. Final state of drops settling on the wall with steady state streamlines

The effect of electric capillary number on drop-to-wall interaction is also studied at four electric capillary numbers. Fig. 4 illustrates the trend of h versus time for migration of

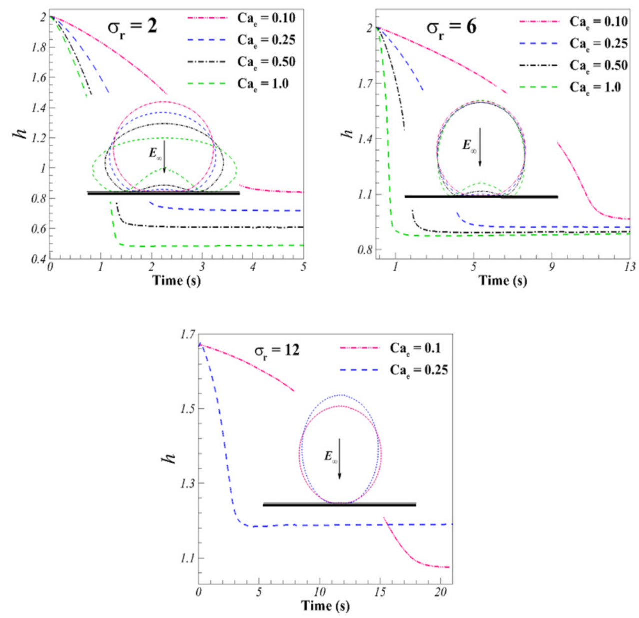

Fig. 4. Trend of *h* versus time for migration of oblate and two prolate drops towards the wall with the final state of drops on the wall

these drops towards the wall in addition to final states of the drops on the wall. Increasing electric capillary number will reduce the time of drop migration towards the wall. Also increasing electric capillary number will cause distortion of the drop surface for both oblate and one type of prolate drop with flow pattern similar to oblate drop. But the surface drop for another type of prolate drop (σ_r=12), does not change significantly.

4- Conclusions

In this paper, general behavior of a drop suspended in another immiscible fluid under influence of uniform electric field is investigated. Two types of deformation and induced flow patterns were also studied. Drop-to-wall interaction for three types of drops were simulated. All of them attracted towards the wall. Increasing electric capillary number will reduce the time of drop migration towards the wall and also cause distortion of drop surface for oblate and prolate drops where the direction of the flow pattern is from the poles to equator.

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