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Electro-hydrodynamic behavior and interface instability of double emulsion droplets under high electric field

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ABSTRACT

Dynamics of multiphase flow under high voltage has attracted extensive research interests due to its wide industrial applications. In this paper, numerical solution of electro-hydrodynamic behavior and interface instability of double emulsion droplet is presented. Level set method and leaky dielectric model coupled with Navier-Stokes equation are used to solve the electro-hydrodynamic problem. The method is validated against the theoretical analysis and the simulation results of the other researchers. Double emulsion droplet with inner droplet (core) and outer droplet (shell) phases immersed in continuous phase is subjected to high electric field. Shell/continuous and core/shell interfaces of the droplet undergo prolate-oblate or oblate-prolate deformation depending on the extent of the penetration of electric potential and sense of charge distribution at the interfaces. The deformation of the shell deviates from theory at larger volume fraction of core for oblate-prolate case whereas it follows theory for prolate-oblate case. The interfaces showing oblate-prolate deformation split at the poles whereas, for prolate-oblate, they split away along the equator. The re-union of the interfaces under high electric field results with production of daughter droplet at the core. The large decrease in critical electric field for oblate-prolate case shows their less interface stability at larger volume fraction of core. When the core is eccentric, the electric field drives it towards the shell center or to the shell/continuous interface depending on electrical parameters. The study is beneficial in understanding the electro-hydrodynamic behavior of emulsion droplets and efficient design of related industrial processes.

1. Introduction

The existence of stable water-oil (w/o) or oil-water-oil (o/w/o) emulsions in conventional and un-conventional crude oils is the matter of great concern in oil refining and processing. There are different conventional methods available for oil dehydration based on centrifugation, gravitational and buoyance forces and chemical treatment [1,2]. Due to various disadvantages associated with the conventional methods of dehydration, electrostatic technique for phase separation has emerged as the cleanest and most effective method [3]. Multi-phase emulsions with single droplet inside the outer droplet are known as double emulsions [4]. The interface stability and electro-hydrodynamics of single droplet is well studied by various authors using different methods [5–21]. However, the electro-hydrodynamics of double droplet under high electric field has not yet been fully explored. Our main concern in this study is the dynamic behavior of such emulsion droplets under high electric field.

Taylor [17] presented a theory on electro-hydrodynamics based on the assumptions that droplet is neutrally buoyant in an immiscible liquid under a quasi-static electric field with no charge convection. He found that even a small conductivity of the medium fluid would allow some charge to reach and accumulate at the interface. Such fluids are named as leaky dielectric fluids and the theory is known as leaky dielectric model [15]. Torza et al. conducted a series of experiments and showed that the predictions from Taylor's theory are in good agreement with the experimental results for small deformations [19]. However, for large deformations, simulations and numerical modelling give more accurate predictions than theory [10–12,18]. The breakup of the droplets subjected to electric and magnetic fields was studied by Sherwood [16] using boundary integral method. Baygents et al. [7] using boundary integral method investigated the interacting motion of two droplets under uniform electric filed. They found that

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under leaky dielectric model, two droplets can have attractive or repulsive forces between them depending on their electrical properties. Using leaky dielectric model, Hua et al. [10] studied the deformation of axisymmetric droplet under steady electric field by changing the electrical parameters using front tracking finite element method. The results obtained were in agreement with the Taylor's theory at small deformations but deviated at large deformations. Lin et al. [12] using phase field method simulated the deformation of single droplet and observed the coalescing behavior of two droplets under uniform electric field. They also investigated the effects of surface tension and viscosity on the deformation and electro-hydrodynamic coalescence and showed that very low surface tension can cause a droplet breakup to small droplets after coalescence. Volume of fluid (VOF) method was adopted by Tomar and his colleague [18] to simulate the deformation of the droplet and observed the coalescence behavior of two droplets under uniform electric field and the results were validated against Taylor's theory. Lin [11] using level set method simulated the deformation of single droplet modelled as leaky and perfect dielectric. Atten et al. [6] investigated the coalescence of water droplets in insulating fluid. They derived the expressions for coalescence rate and reported that the shear plays an important role in bringing the droplets in contact. Ghazian et al. [9] investigated the head on collision of charged droplets with air as medium fluid using level set method. They found that the amount of charge on the droplets plays an important role in the formation of satellite droplets. Recently, Mhatre et al. [13] have discussed the electro-coalescence of two droplets immersed in oil.

Dynamics of dielectric double droplet were studied experimentally by Tsukada et al. [22] under steady electric field. They used silicon oil and vegetable-mixture oil for the analysis with core and ambient phases consisting of same material. Ha and Yang [23] studied the dynamics of double droplet analytically using domain perturbation procedure. Behjatian and Esmaeeli [24] analytically explored the electro-hydrodynamics of double emulsion droplet using domain perturbation method and plotted the circulation maps for different configurations. Soni et al. [25] investigated the dynamics of double emulsion droplet under uniform electric field using phase field method. The inner droplet and medium fluid were assumed to have same properties. In all these studies [22–25], authors mainly discussed how the presence of inner droplet affects the sense of deformation and fluid circulations around the interfaces. However, they did not discuss the breakup phenomenon and interface instability of double emulsion droplet under high electric field. Moreover, the behavior of eccentric configuration under steady electric field has not yet been fully explored to the best of our knowledge.

Dynamic interface models are generally categorized as implicit or explicit types [26]. Level set method is implicit dynamic interface method where the interface is defined as a contour of a level set function, which is solved in fixed mesh domain with other variables. This function is smooth across the interface and easily predict the interface advection as well as can calculate the curvature with high order of accuracy [11,27]. Volume of fluid and level set methods can also simulate the coalescence and droplet break-up phenomenon without any further treatments as required by front tracking method [10] and boundary element methods [16]. However, volume of fluid (VOF) method requires reconstruction of the interface for every time step that is not needed for level set methods. Phase field method which is based on Cahn-Hilliard equation is also an implicit method of tracking interface but requires very high resolution due to the presence of fourth order spatial derivative [12].

In the present study, we are using conservative level set method as suggested by Olsson et al. [27]. This method overcomes the drawback of mass loss that occurred in conventional level set method. The properties across the interface are smoothly transformed by the level set function. To the best of our knowledge, this method has not yet been used to study the dynamics of double droplet under high electric field. The present work consists of four aspects. Firstly, the numerical model is benchmarked with theoretical analysis and results from other researchers. Secondly, the effect of electric potential, charge density, fluid flow and volume fraction of core on interface deformation of leaky dielectric double droplet is studied. Thirdly, the mechanism of double droplet breakup and the interface instability over a wide range of electrical parameters, incorporating the effect of volume fraction of core, is explored. Lastly, the behavior of eccentric droplet subjected to electric field is presented. The model presented here will serve as a tool to understand and predict the dynamics and interface stability of double emulsion droplets that will be helpful in designing more efficient related industrial processes.

2. Theory

2.1. Multi-phase fluid flow under electric field

It is assumed that the flow is incompressible, laminar and is modelled as axi-symmetric. The free boundaries of the droplet are defined using the conservative level set method. The dynamics of double emulsion droplet in two phase fluid system is investigated by defining the density ρ, and viscosity μ, as a function of level set variable ϕ expressed across shell/continuous interface “23” as

$$\rho = \phi(\rho_2 - \rho_3) + \rho_3 \tag{1}$$

$$\mu = \phi(\mu_2 - \mu_3) + \mu_3 \tag{2}$$

Here the subscript “2” and “3” are used to denote the shell and continuous phase, respectively. The properties across the core/shell interface “12” are defined as

$$\rho = \phi(\rho_2 - \rho_1) + \rho_1 \tag{3}$$

$$\mu = \phi(\mu_2 - \mu_1) + \mu_1 \tag{4}$$

The value of level set variable ϕ is “1” for shell phase and changes to “0” for core and continuous phase. The interface between the two fluids is evolved by a fixed contour of a level set function $\phi = 0.5$ in the level set equation given as

$$\frac{\partial\phi}{\partial t} + \nabla\cdot(\overrightarrow{v}\phi) = \alpha\nabla\cdot\left(\psi\nabla\phi - \phi\ \ (1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{5}$$

Here $\overrightarrow{v}$ is the velocity field inside the domain and ψ is the parameter that controls the thickness of the interface, α is the stability parameter known as re-initialization parameter and $\left[\phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right]$ is known as artificial flux. The term in the Laplacian in equation (5) can be thought of as a kind of diffusion term which is trying to enlarge with the interface width. This is countered by the divergence of flux. The thickness of the interface ψ is kept constant by the equilibrium of these two terms [28]. The velocity of the fluid $\overrightarrow{v}$ for an incompressible flow is calculated using the Navier-Stokes equation given as

$$\rho\left(\frac{\partial\overrightarrow{v}}{\partial t} + (\overrightarrow{v}\cdot\nabla)\overrightarrow{v}\right) = -\nabla p + \mu\nabla^2\overrightarrow{v} + \overrightarrow{f}_{st} + \overrightarrow{f}_{e} \tag{6}$$