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Original Research Paper

Breakup and deformation of a falling droplet under high voltage electric field

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ABSTRACT

In this paper the lattice Boltzmann method (LBM) is employed to simulate deformation and breakup of a falling drop under gravity and electric field. First the two-phase LBM is applied to verify the Laplace law for static drops. Then relaxation of a square droplet is conducted. Furthermore a comparison is made with Taylor theoretical results for different electrical capillary number, permittivity and conductivity ratio. It is seen that with permittivity ratio larger than conductivity, droplet takes an oblate and for lower ratio takes prolate shape. It is seen that for relatively low Eotvos number where the surface tension is a dominant factor and for high Ohnesorge number where the viscosity plays an important role shear breakup occurs. On the other hand it is also found that by increasing the Eotvos number and decreasing Ohnesorge number drop distorts more and back breakup happens in addition to shear breakup.

1. Introduction

The dispersion of one fluid into another immiscible liquid is an important process in a variety of industrial application. One of the most important examples is emulsification. Also regarding modifying the properties of the polymer, antistatic agents are added during mixing processes. Dispersion also enhances the mass transfer operations in liquid–liquid extraction. Traditionally the separation of water from oil in oil–water mixture produced from oil as the continuous phase with water dispersed as small droplets has attracted great attention in oil recovery technology [1,2]. Controlling the fusion of individual droplets in digital microfluidic applications were investigated recently [3]. Applications has been shown in some other aspects such as electrospraying [4], nucleate boiling [5]. Electroosmosis and electrothermal flows have been utilized as pumping mechanism to enhance mixing of different species at the microscale [6]. In (1962) the experiment conducted by Allan and Mason [7] showed that conducting droplet deforms into prolate spheroid compatible with the electrostatic theory. They have considered several fluid systems and found some perfect drops deformed to oblate spheroid (i.e., an ellipsoid with its major axis perpendicular to the direction of the electric field). In 1966, Taylor [8] pointed out considering drop as perfect conducting or dielectric fluid could not be proper in all situations. Taylor justified Allan and Mason results by solving electrohydrodynamic's equation in creeping flow regime. Torza et al. [9] revealed some discrepancies between theory and experiments. Feng and Scott [10] have shown that the leaky dielectric model is the correct model to predict the flow and deformation pattern when no net charge exists on the drop. The review article by Melcher and Taylor [11] present a summary of the governing electrohydrodynamics laws and their solution in the context of a planar interface separating two fluids and/or a suspended drop in quiescent and shear-driven creeping flows. Instability of a perfect dielectric or infinitely conducting drop in a perfect dielectric medium has been extensively studied by an analytical and numerical solution. Sherwood [12] simulated deformation up to break up of a drop for various range of permittivity and conductivity ratios using boundary integral method. Ha and Yang [13] considered experimentally the deformation and breakup of Newtonian and non-Newtonian conducting drops in surrounding fluid subjected to a uniform electric field. They examined three distinctive cases Newtonian-fluid pairs with different relative conductivities. The results on the Newtonian fluids demonstrated that when the conductivity of the drop is very large relative to that of the surrounding fluid, the deformation response of such highly conducting drops is described well by Electrohydrostatic theory. They also have shown that the highly conducting drop became stable in weak or moderate field strength when either the drop or the continuous phase was non-Newtonian. On the other hand, when both the phases were non-Newtonian, more complicated responses were observed depending on the ratio of zero-shear-rate viscosities. They also investigated of resistivity and viscosity ratios on the breakup modes and found that when at least one of the two contiguous phases possessed considerable non-Newtonian properties, tip streaming appeared. The literature on the stability and deformation of a drop due to exposition to an electric field is rich and the research is still ongoing [14–16].

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Nomenclature

h^{eq}	voltage equilibrium distribution function
h	voltage distribution function
U	electrical potential (V)
F_e	electrical body force (N/m^3)
E_0	external electric field (V/m)
q_v	charge density (C/m^3)
R_d	droplet radius (m)
$\mathrm{Ca_E}$	electrical capillary number
Eo	Eotvos number
R	conductivity ratio
S	permittivity ratio
P	pressure (N/m^2)
Greek symbols	
ε	permittivity (F/m)
γ	surface tension (N/m)
σ	conductivity (1/ohm m)
τ_h	relaxation time for potential
ε_0	permittivity of free space (F/m)
δ_x	lattice unit scale
δ_t	lattice time step
Subscript	
l	low
h	high
d	particle phase
m	medium (fluid) phase

Here, we make no attempt to address all the studies; rather we refer only to a few relevant ones. Taking LBM into account, He et al. [17] implemented the kinetic-based scheme and simulated 2D Rayleigh–Taylor instability. Their model tracks different phases and the interface between them using an index fluid with molecular interaction. The surface tension is implemented in the model using a term as a function of the gradient of the index fluid density. In this paper, we employ the leaky dielectric theory and LBM technique proposed by He. Junfeng et al. [18] presented a method to apply a multicomponent LBM to electrohydrodynamics studies. They appear to be the first who study electrohydrodynamic by LBM. Kupershtokh and Medvedev [19] considered electric charge transport via advection and conduction currents and also action of electric forces upon space charges in liquid. Their simulations showed the great potential for problems with free boundaries (system with vapor bubbles and multiple components with different electric properties). Weifeng et al. [20] by using permittivity-density relation investigated the behavior of freely-suspended liquid drops subjected to electrostatic fields. Medvedev [21] investigated pre-breakdown hydrodynamic flows and initial stages of the electric breakdown in dielectric liquids. He considered three models including, thermal, bubble and the combined model. Recently Lin et al. [22] presented a phase field model for studying two phase electrohydrodynamic flow generated by electric field.

2. Multiphase LBM

The Boltzmann equation for non-ideal fluids may be written as:

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \xi \cdot \nabla f = -\frac{f - f^{eq}}{\lambda} + \frac{(\xi - \mathbf{u}) \cdot (\mathbf{F} + \mathbf{G})}{\rho RT} f^{eq} \tag{1}$$

where f is the single particle distribution function, ξ and $\mathbf{u}$ are the microscopic and the macroscopic velocities, respectively, f^{eq} is the equilibrium distribution function, λ is the relaxation time, $\mathbf{G}$ is the gravitational force, R is the gas constant, ρ is the fluid density, T is the temperature, and F is the effective interaction force which can be written as

$$\mathbf{F} = -\nabla\psi + \mathbf{F}_s \tag{2}$$

where

$$\mathbf{F}_s = k\rho\nabla\nabla^2\rho \tag{3}$$

In the above relation $\mathbf{F}_s$ is the surface tension force and the parameter k determines the magnitude of the surface tension. The function ψ is related to pressure by

$$\psi(\rho) = p - \rho RT \tag{4}$$

In order to solve Eq. (1) without instability, the following transformation is used:

$$g = fRT + \psi(\rho)\Gamma(0) \tag{5}$$

where g is the pressure distribution function and Γ relates to the equilibrium distribution function by

$$\Gamma = \frac{f^{eq}}{\rho} \tag{6}$$

By substituting Eq. (5) into Eq. (1) we get to the following equations:

$$\begin{cases} \frac{Df}{Dt} = -\frac{f - f^{eq}}{\lambda} + \frac{(\xi - \mathbf{u}) \cdot \nabla\psi(\phi)}{RT}\Gamma(\mathbf{u}) \\ \frac{Dg}{Dt} = -\frac{g - g^{eq}}{\lambda} + (\xi - \mathbf{u}) \cdot [\Gamma(\mathbf{u}) \cdot (\mathbf{F}_s + \mathbf{G}) - (\Gamma(\mathbf{u}) - \Gamma(0))\nabla\psi(\rho)] \end{cases} \tag{7}$$

where ϕ is the index function and its role is to track the interface between different phases. Using the Carnahan–Starling equation of state, $\psi(\phi)$ can be expressed as

$$\psi(\phi) = \phi^2 RT \frac{4 - 2\phi}{(1 - \phi)^3} - \alpha\phi^2 \tag{8}$$

where the parameter α, which is set to 12RT in the current work, determines the strength of the molecular interaction. Discretization of Eq. (7) is done in a D2Q9 lattice structure with the microscopic velocities defined as

$$\mathbf{e}_\alpha = \begin{cases} (0,0) & \text{for } \alpha = 0 \\ c(\cos[(\alpha - 1)\pi/4],\ \sin[(\alpha - 1)\pi/4]) & \text{for } \alpha = 1,2,3,4 \\ \sqrt{2}c(\cos[(\alpha - 1)\pi/4],\ \sin[(\alpha - 1)\pi/4]) & \text{for } \alpha = 5,6,7,8 \end{cases} \tag{9}$$

along with the following weight coefficients:

$$\omega_\alpha = \begin{cases} 4/9\ \alpha = 0 \\ 1/9\ \alpha = 1,3,5,7 \\ 1/36\ \alpha = 2,4,6,8 \end{cases} \tag{10}$$

We consider $\delta_x = \delta_t = 1$, hence $c_s^2 = RT = \frac{1}{3}$, where c_s is the lattice speed of sound. To have an explicit method, the following transformation variables are used

$$\begin{aligned} \bar{f}_\alpha &= f_\alpha + \frac{(\mathbf{e}_\alpha - \mathbf{u}) \cdot \nabla\psi(\phi)}{2RT}\Gamma_\alpha\delta_t \\ \bar{g}_\alpha &= \bar{g}_\alpha - \tfrac{1}{2}(\mathbf{e}_\alpha - \mathbf{u}) \cdot [\Gamma_\alpha \cdot (\mathbf{F}_s + \mathbf{G}) - (\Gamma_\alpha - \omega_\alpha)\nabla\psi(\rho)]\delta_t \end{aligned} \tag{11}$$

by substitution of Eq. (11) into Eq. (7), we obtain the following equations: