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Simulation of deformation and fragmentation of a falling drop under electric field

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ABSTRACT

Physical properties and especially the size of drops are important parameters in many industrial and medical applications. High voltage electric field is one of the effective means to control the final size of drops during the fabrication process which could greatly influence the final size of the product. Therefore a detailed study of electric field effect on a liquid drop is very important. In this work deformation and fragmentation of a falling droplet under gravity and electric force have been studied numerically. Electric force is used as an effective external controlling mechanism to influence the deformation of a drop. The three-dimensional deformation of a falling droplet is studied numerically using the open-source volume-of-fluid solver, Gerris. The numerical results are compared with previous analytical, experimental and numerical data and great agreements between the results are obtained. The results are presented for broad range of Bond numbers (*Bo*) from low Bond number (drop with small deformation) to large Bond number (drop breakup and fragmentation). The results revealed that the electric field can be used as a powerful controlling tool in delaying and expediting the falling drop breakup process. The results also showed that falling drop deforms severely by increasing *Bo* number which leads to the breakup and fragmentation compared to the cases of low *Bo* number in which the drop deforms mildly without breakup.

1. Introduction

In depth understanding of physics and dynamics of multiphase flow and in particular two-phase flow is very crucial due to its broad and practical applications in science and industry and also because of its complexity in scientific research with essential fundamental issues. These applications include atomization in aerospace industry for modeling the fuel injection in combustion chambers over the gas turbine, different types of combustion processes, drug delivery, engines with diesel fuels, ink-jet coating process, spray painting and drying, microfluidic applications, heat exchangers evaporation-based, desalination, emulsification, etc. Taylor [1] studied the shape and acceleration of a drop in a high speed air stream. Pilch and Erdman [2] studied the size of stable fragments for acceleration-induced breakup of a liquid drop using breakup time data and velocity history data. Hinze [3] studied the fundamentals of the hydrodynamic mechanism of splitting in dispersion processes in which he found out that the splitting of globules is an important phenomenon during the final stages of disintegration processes. Giffen E and Muraszew [4] studied the liquid fuel atomization and Faeth et al. [5] investigated the structure and breakup properties of sprays. Villermaux [6] thoroughly studied the atomization process and examined the drop, jets and liquid sheets fragmentations and bursting phenomena. And many other researchers that their main focus was on investigating drop deformation. Contrary to a lot of studies on drop deformation, very few studies have been done on a mechanism to control the drop behavior. One of these methods is applying an external force such as electric field. A drop suspended in a viscous liquid undergoes complicated behaviors such as abrupt transitions, breakup, deformation which depends on the magnitude of the electric field and also the properties of the fluids such as surface tension, electrical conductivity, viscosity, and permittivity. EHD field is used as an effective external controlling force to influence the drop's deformation in order to have a much better and more efficient distribution due to their importance in atomization, rain drop size distribution many other problems of industrial importance. Electrohydrodynamics (EHD) is a multidisciplinary subject that deals with the complicated interaction between fluid mechanics and electric fields in which the coupling between electrostatic and hydrodynamic forces is studied. Melcher [7] provided a thorough review of electrohydrodynamics. EHD can improve the control over spray mechanism to have a much better and finer atomization which is significantly important for the small compact combustion engines and therefore the fuel injection schemes can be developed economically at a much lower price. EHD increases the heat and mass transfer rates and is implemented in inkjet printing, and

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electrowetting which is a driving mechanism for a wide range of fluidic and electro-optic applications for modifying the surface tension of liquids on a solid surface. EHD efficiently improves the atomization of the hydrocarbon fuel which benefits a much wider range of engines and other types of non-combustion applications in pharmaceutical industry, such as pharmaceutical coating and micro/nano-thin-film deposition. Ryan et al. [8] studied that EHD atomization enhances the breakup of liquid fuel at lower pressures which produce high quality atomization in which there is no more fuel injection at high pressure required. Bio-fuels are one of the alternatives to the diesel with higher viscosity and water content that requires high pressures to atomize the fuel in the combustion chamber; because of that these types of fuels confined to larger and less efficient engines. EHD atomization is an applicable method for use in small combustion engines which reduces the high fuel injector pressures required by these engines to atomize the bio-oils fuels with high viscosity [9]. Another advantage of the enhancement of the fuel atomization is to more likely have a complete combustion during the burn cycle resulting in a better burning and less emission [10]. Moreover, the electric fields in the engine exhaust direct the burn residue such as soot, NOX to easily cleanable containers as the EHD atomization keep these residues charged [11]. Paknemat et al. [12] studied the effect of electric field on three different types of drop using a level set method. They conducted their numerical results for a different range of capillary number to observe different modes of breakup under the effect of DC electric field. Notz and Basaran [13] numerically investigated the effect of electric field on the formation and deformation of a perfectly conducting drop form a capillary. After validation of their results with the previous analytical and experimental works, they are studied the effect of an electric field with variable strength for the zero-flow rate case. They showed that for small values of change in the strength of the electric field the results of transient calculations are in a good agreement with the previous works. Jung et al. [14] numerically studied the deposition of droplets form a spray under the effect of an electric field. They used a three-dimensional Lagrangian model to study the application of electric fields on the characteristics of deposition pattern such as the spatial distribution and the average thickness distribution. The results of simulations showed that in general for the case with the electric field the deposition thickness in the intervening region of spray is less than the core region for all the control parameters such as moving speed of the nozzle. Van Poppel et al. [15] numerically studied the electrohydrodynamic (EHD) effect on a high Reynolds number multiphase regime of a liquid kerosene jet. They used a fully three-dimensional model to simulate the atomization process of a charged liquid jet and compared their results with the previous data. López-Herrera et al. [16] developed a conservative scheme for two-phase electrohydrodynamic (EHD) problems incorporating the Volume-of-Fluid (VOF) method. They implemented their scheme in a free and open-source software Gerris. They also compared the results obtained from the proposed scheme with the available analytical solution for droplet immersed in a conducting bath with showed an excellent agreement between the results. Baygents et al. [17] studied the motion of two leaky dielectric drops under the effect of a uniform electric field. They observed a significant deformation near drop contact because of the local enhancement of the electric field.

The current work studies the effect of the electric field on deformation and fragmentation of the falling drop under gravitational force. The electric field is used as an external force for controlling the drop deformation. Direct numerical simulation by Gerris has been used for 3-D molding of the deformation and breakup process of the drop.

2. Problem definition and geometry

Fig. 1. shows the computational domain used in the current work along with the boundary conditions. The dimensions of the domain and drop are shown in the figure. The width of the computational domain is 40R with the height of 160R. A spherical droplet with density and viscosity of ρ_d, μ_d and radius R falls under the action of gravity g. The drop falls at the height of 15R from the bottom of the domain with zero initial velocity. The surrounding medium has a viscosity of μ_m and density of ρ_m.The initial location of the drop and also the size of the computational domain are considered such that the boundaries have negligible effect on the falling droplet beak-up process. Symmetry boundary conditions are applied on the boundaries and the drop falling down under effects of external EHD force which has been applied on the side boundaries.

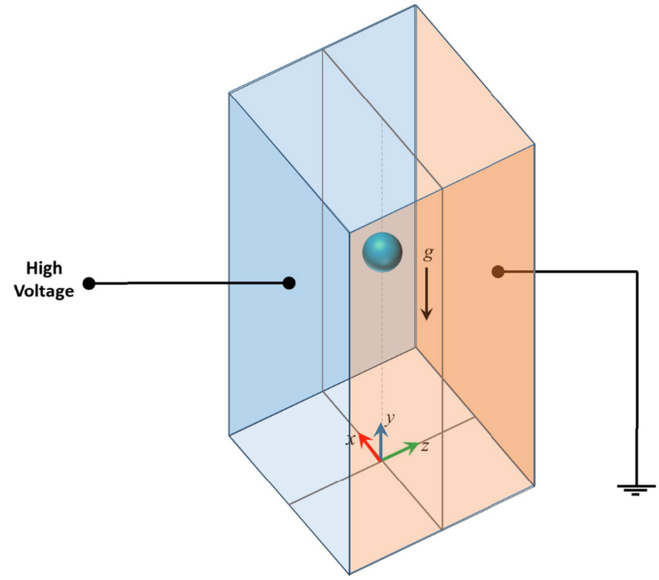

Fig. 1. Schematic of the problem and the boundary conditions.

The governing equations are:

$$\nabla \cdot \vec{u} = 0, \tag{1}$$

$$\rho\left(\partial_t \vec{u} + \vec{u}.\nabla\vec{u}\right) = \nabla p + \nabla.\left(2\mu \vec{D}\right) + \sigma\kappa\delta_s \vec{n} + \rho g + \vec{F}_e \tag{2}$$

$$\partial_t c + \nabla.\left(c\,\vec{u}\right) = 0, \tag{3}$$

$$\rho(c) = c\rho_d + (1-c)\rho_m \tag{4}$$

$$\mu(c) = c\mu_d + (1-c)\mu_m \tag{5}$$

where $\vec{u} = (u, v, w)$ is the velocity vector, and $\rho = \rho(\vec{x}, t)$ and $\mu = \mu(\vec{x}, t)$ are the local fluid density and dynamic viscosity, respectively. $D = D_{ij} = (\partial_i u_j + \partial_j u_i)/2$ is the deformation tensor. The Dirac delta δ_s states the fact that the surface tension term is concentrated on the interface. In Eq. (2), σ is the surface tension coefficient, κ and $\vec{n}$ are the curvature and normal vector with respect to the interface, respectively and c is the volume fraction, $c(\vec{x}, t)$. The density and viscosity are calculated based on the volume fraction of the first fluid, $c(\vec{x}, t)$.

Electrical phenomena are stated by:

$$\rho_e = \nabla.\left(\varepsilon\,\vec{E}\right) \tag{6}$$

and the electric field $\vec{E}$ is assumed to be irrotational $\nabla \times \vec{E} = 0$, where ρ_e is the volumetric charge density. In terms of the electric potential, φ, the electrostatic limit follows the Poisson equation,

$$\nabla.(\varepsilon\nabla\varphi) = -\rho_e \tag{7}$$