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Head-on collision of electrically charged droplets

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ABSTRACT

Interaction between two identical charged droplets is investigated numerically. In the first part, the mechanism of Coulomb attraction between two conducting droplets is investigated. Numerical simulation shows that two conducting droplets carrying charges of the same polarity under some conditions may be electrically attracted.

The second part of the study concerns the collision dynamics of two identical dielectric charged droplets. At low Weber numbers, two droplets carrying charges of the same polarity can repel each other. As Weber number increases, the drop collision leads to their coalescence. With Weber number further increased, satellite droplets are formed.

Introduction

Charged droplets play a significant role in a wide range of applications, such as electrospray atomization [1–4], fuel injection and formation of clouds [5,6].

The electric force can also be used to enhance the separation and coalescence of small droplets. The interaction between electric field and single charged droplets has already been extensively studied [7–10], but droplet collision is still not well understood. Park [11] produced collisions between streams of water droplets traveling in still air and showed pictorially that near head-on collision between pairs of equally sized droplets resulted in stable coalescence. Ashgriz and Poo [12] developed models for predicting the boundary between the coalescence and separation regimes. In general, the outcome of the drop collision can be categorized into four different types: bouncing, coalescence, separation, and shattering collisions. At higher Weber number for head-on or near head-on cases, reflexive separation may happen resulting in formation of satellites. “Shattering” occurs at extremely high Weber numbers, which is beyond the scope of the conventional application.

As reported by Qian and Law [13], for head-on collisions of water droplets at atmospheric pressure bouncing is not observed; for the same conditions however, the collision between hydrocarbon droplets may result in bouncing. The collision behavior of fuel droplets was found to vary significantly from those of water droplets. The most noticeable difference is the bouncing phenomena. Estrade et al. [14] published information about the number of satellite droplets, their sizes and velocities produced by bouncing collisions. Brenn et al. [15] produced a nomogram for the various collision regimes and for the number of satellite droplets formed during droplet collision depending on the Weber number and impact parameter, which agreed quite well with the experimental results of Ashgriz and Poo [12].

There are a few studies on the numerical simulation of the droplet collision. Nobari et al. [16] used the front tracking method in axi-symmetric formulation for the central collision; the method was able to capture the features of bouncing, coalescence and reflexive separation with up to one satellite droplet formed. Mashayek et al. [17] studied the coalescence collision of two droplets in axi-symmetric geometry, using a Galerkin Finite Element Method. Recently, Pan and Suga [18] using the implicit continuous-fluid Eulerian method coupled with the level set methodology for a single phase in a fixed uniform mesh system, simulated the three major regimes of binary collision (bouncing, coalescence and separation), both for water and hydrocarbon droplets. Their numerical results suggest that the mechanism of bouncing collision is governed by the macroscopic dynamics, while the mechanism of coalescence is related to the microscopic dynamics. Tanguy and Berlemont [19] performed simulation using a Level-Set Method. Results of coalescence, reflexive separation and stretching separation were found in good agreement with experiments. Nikolopoulos et al. [20,21] conducted numerical investigation of both head-on and off-center droplet collision based on the volume of fluid (VOF) method. Their results provided a detailed

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Nomenclature

d_0	initial distance of droplets
D_0	initial droplet diameter
$\boldsymbol{E}$	electric field
$\boldsymbol{F}_{es}$	electric force
$\boldsymbol{F}_{st}$	surface tension force
$\boldsymbol{I}$	identity matrix
$\boldsymbol{n}$	interface normal
P	pressure
q	droplet charge
q_{Ray}	Rayleigh limit
r	droplet radius
Re	Reynolds number
$\boldsymbol{T}$	capillary pressure tensor
$\boldsymbol{T}_{\boldsymbol{M}}$	Maxwell stress tensor
$\boldsymbol{t}$	nondimensional time
t_0	time scale
u	velocity
U_0	impact velocity
We	Weber number

Greek symbols

α	reinitialization parameter
ε_r	relative permittivity
ε_{ls}	parameter controlling the interface thickness
ε_0	permittivity of vacuum
ϕ	level-set function
ρ_{air}	air density
ρ_{drop}	droplet density
μ_{air}	air dynamic viscosity
μ_{drop}	droplet viscosity
σ	surface tension

picture of the collision process, the ligament formation and dimensions, the pinch-off mechanism, as well as the creation of the satellite droplet. They further investigated the effect of gas, liquid properties and droplet size ratio on the central collision between two unequal-size droplets in the reflexive regime [22], results of which show that the droplet size ratio, rather than the Reynolds number based on the gas properties, is an important parameter affecting the collision outcome. Chen et al. [23] analyzed energy and mass transfer during binary droplet collision based on the VOF simulation. The mass transfer process was studied in detail, whereas the energy transfer process was only investigated with the overall energy balance. Estrade et al. [14] for the first time included information about the number of the satellite droplets in separation collisions.

Literature on the investigation of interactions between two charged droplets is extremely scarce [24]. The feasibility of coalescence of two perfectly conducting, electrically charged droplets was studied from a thermodynamic point of view by Gallil et al. [25]. A suitable expression was developed for the electrical energy of the two droplets which make the initial contact. It was proven by Lekner [26] that two charged conducting spheres will almost always attract each other at a close distance. Surprisingly, this is true even when they have like charges. The one exception is when the two spheres have a charge ratio which would result from droplets making mechanical contact. Phase Doppler anemometry measurements and flow visualizations were used to measure the structures of electrostatically atomized hydrocarbon fuel sprays by Shrimpton and Yule [27].

The purpose of the present study is to investigate the electrostatic interaction of charged droplets considering different physical parameters and impact velocities with the aim of providing broader and more in depth insight into the collision of charged droplets and different outcome regimes. The Navier–Stokes equations with the volumetric forces due to surface tension and electric charges are solved numerically by the finite element methodology.

There are three aspects of the present investigation. First, in order to validate the model the numerical results are compared in detail with the images of the simulated liquid droplet collision obtained by Pan and Suga [18]. Secondly, the mechanism of Coulomb attraction between two like charged conducting droplets is investigated. The third aspect of the study concerns the collision dynamics of two charged droplets and satellite droplet formation.

The mathematical model

The flow is considered as axi-symmetric, incompressible and laminar. The main parameters affecting the process are grouped in two dimensionless numbers: Reynolds $Re = \rho_{drop} D_0 (2U_0)/\mu_{drop}$ and Weber $We = \rho_{drop} D_0 (2U_0)^2/\sigma$, where D_0 is the initial drop diameter, U_0 is the impact velocity, and ρ_{drop}, μ_{drop} and σ are the liquid density, viscosity and surface tension, respectively.

In order to investigate the dynamics of droplet deformation in an electric field it is necessary to solve the Navier–Stokes equations governing the fluid motion, as well as track the interface between both fluids. The laminar two-phase flow studied here is coupled with the applied electric field and electric charges on the interface. Additional body forces are added to the Navier–Stokes equations for considering the surface tension ($\boldsymbol{F}_{st}$) and electric stress ($\boldsymbol{F}_{es}$).

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = \nabla\cdot\left[-P\boldsymbol{I} + \mu\left(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T\right)\right] + \boldsymbol{F}_{st} + \boldsymbol{F}_{es}$$
$$\nabla\cdot\boldsymbol{u} = 0 \tag{1}$$

where $\boldsymbol{u}$ denotes fluid velocity, $\boldsymbol{I}$ is the 3×3 identity matrix and p is the pressure.

To represent the free boundaries of the droplet, the Level-Set Method has been incorporated into the simulations. The method describes the evolution of the interface between the two fluids tracing an iso-potential curve of the level set function (ϕ). In general, inside the droplet ϕ equals to one ($\phi = 1$) and in ambient fluid ϕ equals to zero ($\phi = 0$). The interface is represented by the 0.5 contour of the level set function ($\phi = 0.5$). The function ϕ is governed by

$$\frac{\partial \phi}{\partial t} + \nabla\cdot(\phi\boldsymbol{u}) = \alpha\nabla\cdot\left(\varepsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{2}$$

where ε_{ls} is the parameter controlling the interface thickness and α is the reinitialization parameter. For identifying each phase separately a volume fraction is introduced. The values of density ρ and viscosity μ are calculated using linear interpolation between the values of the two phases.

It is assumed that there is no space charge in the fluids except the surface charge on the interface. Assuming that the fluids are incompressible, the electric stress can be calculated by taking the divergence of the Maxwell stress tensor, which couples