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Spreading and retraction control of charged dielectric droplets

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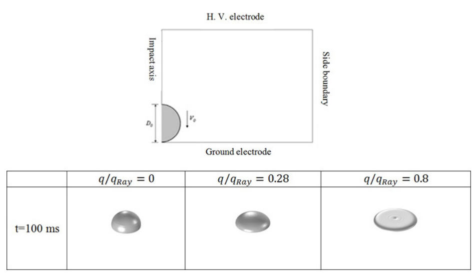
HIGHLIGHTS

- Spreading and impact of a dielectric droplet are investigated.
- The effects of electric field strength and surface charge are taken into account.
- The results are reported for contact angles from 40° to 150°.
- Droplet maximum spreading diameter increases with surface charge density.
- The maximum wetting diameter can be conserved by increasing the surface charge.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, the dynamics of spreading and impact of a dielectric droplet onto a dry conductive substrate in the presence of an external vertical electric field are investigated numerically. The effects of electric field strength, surface charge, droplet properties, and surface wettability are taken into account. Studies were made for droplet charge of 0.05, 0.1, 0.2, and 0.3 nC, corresponding to drop charge of 15–80% of the conducting drop Rayleigh Limit. The results are reported for contact angles from 40° to 150°. In the first part, the spreading of a charged dielectric droplet placed on a ground electrode is simulated. It was found that the droplet maximum spreading diameter and the rate of spreading increase with increasing the surface charge density. In the second part, the suppression of the droplet receding phase, after it has been impacted onto a surface, is investigated using a vertical field parallel to the impact axis. Our results show that the maximum wetting diameter can be conserved by increasing the surface charge. It was also observed that increasing the droplet charge beyond some threshold level not only prevents the droplet from receding, but also may increase the final wetting diameter. This mechanism of retraction control differs from those described in literature. The numerical simulations are shown to reproduce experimentally observed droplet behavior quantitatively, in both the spreading and receding phases.

1. Introduction

The impacting and spreading of liquid drops on solid surfaces are the important processes in many applications, such as spray coating, delivery of agricultural chemicals, ink jet printing, and rapid spray cooling of heated targets [1–3]. The impact of liquid droplets on solid surfaces can be categorized into spreading, recoil, rebound, and splashing. At some time after the impact, the drop spreading diameter reaches a maximum and then recedes depending on the wettability of the surface. Droplet retraction starts right after the spreading phase. A recent overview of droplet impact can be found in [4–6].

In most of the existing models, the impact is controlled by contact angle θ, impact Reynolds number $Re = (\rho D_0 U_0/\mu)$ and Weber

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number $We = (\rho D_0 U_0^2/\mu)$, where D_0 and U_0 are the initial drop diameter and impact velocity, and ρ, μ, and σ are the liquid density, viscosity, and surface tension, respectively. One of the most important parameters relevant to the applications mentioned earlier is the maximum spreading diameter D_{max}, which is often normalized to the original diameter of the droplet prior to impact. The non-dimensional maximum spreading diameter can be defined as follows:

$$\beta_{max} = \frac{D_{max}}{D_0}$$

Numerical simulations of droplet impact onto dry surfaces have been conducted by many researchers [7–15]. The numerical methods used in previous work can be categorized into two groups. One is based on fixed grids such as a Cartesian grid. The other uses a finite element method (FEM) with moving grid [11,13]. The volume of fluid method and the level set method can easily handle large deformation including topology change in the liquid interface when a fixed grid is used. Most of the existing correlations for the maximum spreading diameter have been considered in the available range of the impact parameters ($10 < Re < 40{,}000$ and $2 < We < 8000$) [6]. It has been shown that if the impact Reynolds and Weber numbers are high, the value of the maximum spreading diameter is only slightly dependent on the wettability of the substrate: the change in β_{max} is less than 5% [16].

Different correlations for the time evolution of the spread diameter ($\beta = D/D_0$) have also been proposed in literature [17–20]. The most recent and probably the most refined model of such type predicts the dimensionless maximum spreading diameter D_{max} of a drop impacted onto a dry substrate as a root of the dimensionless cubic equation [21]:

$$(We + 12)D_{max} = 8 + D_{max}^3[3(1 - \cos\theta) + 4We Re^{-0.5}] \quad (1)$$

This model predicts very well the value of the maximum spreading diameter for a wide range of impact parameters. The models of Scheller and Bousfield [22]

$$\beta_{max} = 0.16(Re^2 Oh)^{0.166} \quad (2)$$

where $Oh = \mu/\sqrt{\rho D_0 \sigma}$ is the Ohnesorge number and Roisman [23]

$$\beta_{max} = 0.87Re^{1/5} - 0.4Re^{2/5}We^{-1/2} \quad (3)$$

showed good predictive capability for the Newtonian drops [24]. However, the effect of wettability, defined by the contact angle θ, has been neglected in these models.

According to German and Bertola [5], maximum spreading diameter can also be found as the real root of the following cubic equation:

$$\left[\frac{1}{4}(1 - \cos\ \theta) + \psi\frac{We^{0.83}}{Re^{\kappa}}\right](\beta_{max})^3 - \left(\frac{We}{12} + 1\right)(\beta_{max}) + \frac{2}{3} = 0$$
$$\psi = 0.07\ We^{0.2}, \quad \kappa = 0.45\,Oh^{0.05} \quad (4)$$

These models [5,21,23] are all based on the energy balance approach: the initial droplet kinetic energy and surface energy prior to an impact is compared with the final surface energy (when the droplet reaches its maximum diameter and is stationary) plus the energy dissipated in overcoming liquid viscosity that resists spreading. The rate of energy loss from viscous dissipation is considered the most difficult quantity to estimate accurately because flow velocity profiles and the degree of flow recirculation can only be approximated [5]. To predict the maximum spreading of the drops, the correlation of German and Bertola [5] will be used in this article (Section 2).

Several experimental and theoretical studies can be found in literature on passive retraction control of aqueous droplets on hydrophobic surfaces [25–28]. In this work, a new method is proposed and it is relies on application of electrostatic forces, which affect the fluid dynamics of impacting dielectric droplets especially for controlling the receding phase. Recently, perpendicular corona discharge was applied to a liquid–vapour interface to investigate a new type of interfacial electrohydrodynamic instability, which is the so-called rose-window instability [29,30].

The effect of the electric charge on the spreading of conducting droplets impacting on dielectric substrates has been investigated by Ryu and Lee [31]. It was found that the diameter of the electrically charged droplet at the maximum spread turned out to be larger compared to that of neutral droplet and the difference becomes larger with increased electric charge.

The effect of corona discharge on the spreading and retraction control of dielectric drops has also been experimentally investigated by Mahmoudi et al. [32,33]. It was shown that the interaction of the surface charge density and intense electric field generates an electrical pressure and leads to a uniform axisymmetric spreading of the droplet in the radial direction. A new active method based on the same concept was proposed [33] to control the deposition of an impacted dielectric droplet. It was demonstrated that the electrical pressure effectively suppresses the droplet retraction at voltages above the corona discharge threshold.

2. Problem formulation

To the best of the author's knowledge, the use of a vertical electric field to control the spreading and recoiling phases of dielectric liquid droplet has not been numerically investigated. The present work focuses on the prediction of the maximum spreading diameter of a drop impacting normally on flat, dry solid surfaces with different wettability in the presence of the external electric field and/or surface charge. The results have been compared with the available experimental data.

In the first part of the article, the effect of the vertical electric field on the forced spreading dynamics of the millimetric-sized charged drop placed gently on solid surfaces will be investigated.

Subsequently, the impact of the charged droplets on solid surfaces in the wide range of Reynolds and Weber numbers will be discussed.

The formulation of the problem and description of the initial conditions have already been described elsewhere [34,35]. 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 ($\mathbf{F}_{st}$) and electric stress ($\mathbf{F}_{es}$).

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = \nabla\cdot[-P\boldsymbol{I} + \mu(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^{T})] + \rho\boldsymbol{g} + \boldsymbol{F}st + \boldsymbol{F}es \quad (5)$$
$$\nabla\cdot\boldsymbol{u} = 0$$

where $\mathbf{u}$ denotes fluid velocity, ρ is the fluid density, $\boldsymbol{g}$ is the gravitational acceleration, μ is the dynamic viscosity, $\boldsymbol{I}$ 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. In this method, instead of zero thickness the interface is considered to have a finite thickness of the same order as the mesh size. The physical properties of both media change smoothly from the value on one side of the interface to the value on the other side in the interfacial transitional zone.