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Oscillation, pseudo-rotation and coalescence of sessile droplets in a rotating electric field

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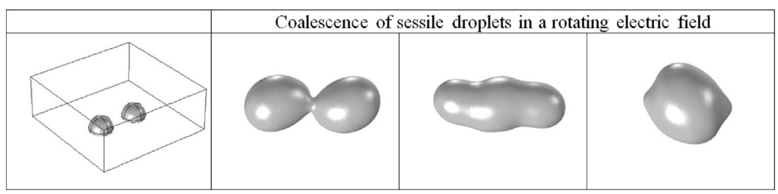
HIGHLIGHTS

- 3-D oscillations and coalescence of water droplets are studied.
- By increasing the contact angle, the resonant frequency is decreasing.
- A new design of an electrowetting mixer is presented.
- Two regimes were observed for droplet mixing.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper reports the 3-D oscillations and coalescence of water droplets deposited on a dielectric substrate under the effect of a rotating electric field, taking into account the effect of frequency of the applied AC voltage and the value of the contact angle. Motion of the fluid is governed by the Navier–Stokes equations, which are solved both inside and outside the droplet (ensuring the conservation of volume of the droplets).

The time variation of the shape of a perfectly conducting droplet placed between two orthogonal pairs of parallel electrodes with two-phase voltage excitation demonstrates that a water droplet vibrates strongly at certain frequencies. It was found that the resonance frequency and the magnitude of the deformation strongly depend on the surface properties.

This paper also presents a new design of an electrowetting mixer using the rotating electric field and offers a new method to effectively mix two droplets over a different range of AC frequencies. Two regimes were observed for droplet coalescence: (1) coalescence due to the high droplet deformation, (2) coalescence due to the interaction of electrically induced dipoles. Numerical simulations confirm that by increasing the electric capillary number, the first coalescence regime starts at lower frequencies.

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1. Introduction

Using an electric field as a tool to control the shape, the motion, and the generation of small droplets has recently received significant attention because of its lack of moving parts and low power consumption [1–4]. Electrowetting is one of the best methods to control the wetting behavior of liquid droplets on partially wetting surfaces by reducing the apparent contact angle of sessile droplets [5–7]. A water droplet located on a hydrophobic insulating surface deforms by the action of electric field and its motion depends on the material properties of the droplet and the surface. Under a DC electric field, a droplet elongates in the direction of the electric field and can form a water filament to bridge the electrodes [8].

Electrowetting using AC actuation voltages has also drawn attention [9–13]. The main advantage of using AC voltages over DC includes a decrease in the contact angle hysteresis. The shape of the water droplet varies with time under an AC electric field, depending on the frequency of the electric field. The interaction of droplets deposited on a surface of composite insulator and generation of conductive regions and filaments was studied experimentally in [14–16]. Krivda and Birtwhistle [17] showed that the natural vibrations of a water droplet result in a change of its shape during the AC cycle and so can effectively increase the risk of flashover by reducing the length of the insulation path. Oscillations of sessile

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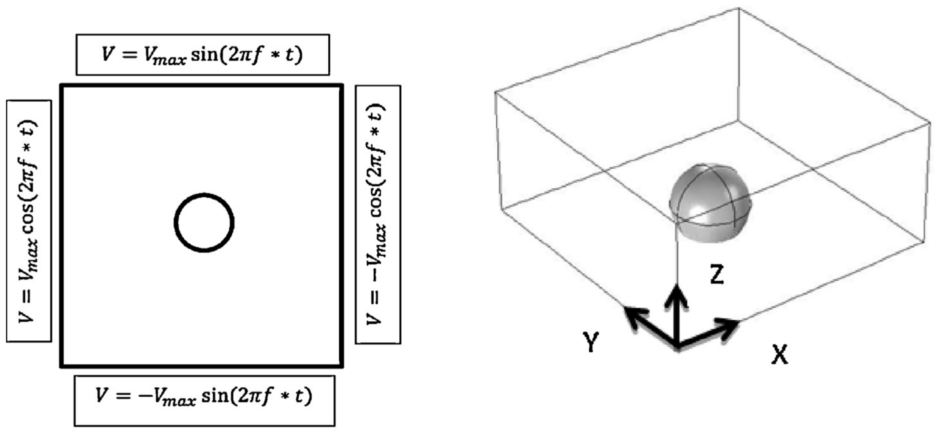

(a) (b)

Fig. 1. Model of a sessile droplet in a rotating field (a) top view, (b) 3-D model.

droplets in electrowetting on a dielectric with a coplanar-electrode configuration were studied experimentally under the actuation of AC voltage with different frequencies by Hong et al. [18]. It was found that the experimental resonance frequencies and the number of lobes at different resonance modes agree reasonably well with the previous linear analysis. The transient response of a millimeter-sized sessile droplet to an electrical actuation was experimentally investigated by Dash et al. [19]. Systematic experiments were conducted over a frequency range of 5–200 Hz and actuation voltages of 40–80 V_{rms} to determine the dependence of droplet oscillation on these parameters. The dependence of the contact angle and contact radius on the applied frequency and voltage of a periodic sinusoidal signal was revealed. The experimentally determined resonance frequencies were shown to be well estimated by Lamb's expression [20] for the natural frequency of a droplet. Amplitude and phase spectra and the beat phenomenon of water droplet oscillation driven by AC electrowetting have been studied using a frequency scanning method by Lai et al. [21]. It was found that at resonant frequencies of water droplets phase differences between the driving voltage and the droplet motion are $\pm 90^\circ$.

When a liquid droplet is slowly placed on a solid, flat substrate, it spreads to its equilibrium configuration with the contact angle specified by Young's equation:

$$\cos\theta_Y = \frac{\sigma_{SV} - \sigma_{SL}}{\sigma_{LV}} \quad (1)$$

The surface energy (tension) between the various phases indicated by subscripts (S – solid, V – vapour, L – liquid) is denoted by σ. Thus, according to Young's equation, the contact angle θ is a material parameter dependent only on the involved surface energies.

Electrowetting is well understood as long as the applied voltage is low. Sufficiently far away from the contact line, the voltage dependence of the contact angle is given by the Lippmann equation [5],

$$\cos\theta_L = \cos\theta_Y + \eta \quad (2)$$

where θ_L is the Lippmann contact angle, θ_Y is Young's contact angle, $\eta = \varepsilon_0\varepsilon_r V^2/2\sigma_{LV}d$ is a dimensionless number representing the ratio of electrostatic and capillary forces, V is the applied electric potential, ε_r and d are the dielectric constant and the thickness of the insulating layer, respectively, ε_0 is the dielectric permittivity of vacuum. It was found that the contact angle approaches Young's angle in the vicinity of the substrate, when the Lippmann angle is small [22,23].

The rotation of particles in an electric field has also been considered in the literature to investigate the rotation of living cells and human peripheral blood lymphocytes [24,25]. The rotation and stability of a weakly conducting droplet around its axis of symmetry under the action of the external electric field was investigated by Dolinsky and Elperin [26,27]. It was shown that depending upon the ratios of the particle electric conductivity and permittivity to the corresponding parameters of the host medium the direction of rotation of the particle can be in the same or opposite to the direction of rotation of the external electric field.

The flow field generated during droplet oscillation at low AC frequencies can be used to enhance the mixing in a droplet [28,29]. Mugele et al. [30] studied the frequency dependence of the internal flow field on a droplet using tracer particle tracking. Paik et al. [31] studied the mixing caused by droplet motion between parallel plates. The effect of shape oscillation on the internal mixing pattern of a droplet has been studied by Miraghaie et al. [32].

The first part of this paper is devoted to the numerical study of droplet oscillation placed on different hydrophobic surfaces under the effect of applied rotating AC electric field including the effect of the ambient gas. The first set of simulations investigated the effect of the rotating AC frequency and identified the resonant frequency. Subsequently, different hydrophobic surfaces were considered.

In the second part of this study, the coalescence and merging of two droplets are reported. This is the first time that the electro-coalescence of droplets placed on a hydrophobic surface has been numerically investigated considering the effect of the frequency of the applied AC field.

2. Problem statement

Fig. 1 illustrates the top view and the 3-D model of the configuration considered in our study for a droplet behavior in the rotating electric field. A small liquid droplet is deposited on a solid surface, surrounded by another immiscible fluid and exposed to a rotating AC electric field, which is parallel to the solid surface. This field is generated by applying a sinusoidal electric potential difference to the orthogonal electrodes having 90° phase shift relative to each other.

The center of the droplet is placed in the middle of the square. The interface separating the two fluids is assumed to have a constant interfacial tension coefficient. The electrodes distance is 10 times the droplet radius and the size of the computational domain in the vertical direction is 5 times the droplet radius. At the initial stage, the shape of the droplet is assumed to be a spherical cap and both fluids are motionless. In order to check the effect of domain size on the numerical results, three different distances between

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