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Numerical simulations of bubble formation from a submerged orifice and a needle: The effects of an alternating electric field

Shyam Sunder, Gaurav Tomar *

Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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ABSTRACT

In many applications, such as bubble column reactors, electric field is employed to provide a greater control on the sizes of bubbles forming at orifices and needles. In this study, we investigate the effects of an alternating electric field on the bubble dynamics. We perform numerical simulations of an alternating electric field coupled with two-phase flow using a Coupled Level-Set and Volume-of-Fluid method. We show that bubbles forming at orifices and needles decrease in size (up to 30%) only for a range of applied frequency and for other frequencies, the size of bubbles can be much bigger compared to the bubbles forming in the corresponding DC electric field case. The oscillating electric forces excite capillary waves on the bubble interface resulting in applied frequency dependent bubble oscillations. The numerically observed resonance for the needle case corresponds to $2\omega\tau_c = 0.75$, where 2ω is the frequency of the oscillation of the electric field force at the interface and τ_c is the capillary time scale, indicating that the resonance behavior is indeed governed by the interactions between the capillary and electric field force. A decomposition of bubble profile shapes into Legendre modes shows that for orifice as well as the needle case, second mode is most dominant followed by the fourth mode.

1. Introduction

In various bubble injection systems, such as those employed in aerators and bubble column reactors, it is desired to reduce the size of the detached bubbles for more efficient heat and mass transfer. In ink-jet printers, it is desired to control the size of the droplets from the nozzle for high-quality printing. Electric field has been successfully used to reduce the bubble and droplet sizes in bubble and drop injection systems, see for example, [1–5]. Electric forces have also been shown to imitate gravitational forces and cause bubble and droplet detachments from nozzles in microgravity conditions (see [6–9]). Use of alternating electric fields further enhances the electrohydrodynamic effects resulting in decreased bubble and drop sizes.

Alternating electric field leads to interfacial oscillations in bubbles and drops. Sato [10,11] performed experiments to study the effects of an alternating electric field on bubble and droplet formation from needles. During the formation of distilled water (weakly conducting) droplets in air as well as in kerosene oil, a 'synchronous region' was observed where the number of droplets produced was proportional to the oscillation frequency of the externally applied electric field. Using half order Bessel and Hankel functions, Yang and Carleson [12] investigated oscillations of a conducting drop inside a dielectric fluid in the presence of an alternating electric field. They concluded that the resonant frequency for forced oscillation is equal to the natural frequency for inviscid drops and the viscous effects decrease the resonance frequency. Trinh et al. [13,14] investigated the oscillation dynamics of acoustically levitated droplets and bubbles driven by either a modulated ultrasonic field or a time varying electric field. Common conclusions from the above two studies were that the degeneracy between axisymmetric and non-axisymmetric modes is removed and due to viscous damping the resonant frequency is detuned for larger amplitudes. They observed that even numbered modes couple only weakly with the odd modes whereas the odd modes excite even modes strongly. In both the studies it was shown that the higher modes sub-harmonically excite lower modes and very less driving energy was transferred to higher order modes at their respective resonant frequencies because of high viscous damping. Kweon et al. [5] observed that an alternating electric field leads to bubble interface oscillations causing an early breakup and a substantial decrease in bubble size is observed at a certain critical applied voltage for a given frequency. Bellini et al. [15,16] observed that a uniform electric field excites only the second Legendre shape

* Corresponding author. Tel.: +91 80 2293 3062; fax: +91 80 2360 0648.
E-mail address: gtom@mecheng.iisc.ernet.in (G. Tomar).

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mode while a quadrupolar electric field excites the second as well as the fourth mode for the case of an isolated spherical bubble.

Lee et al. [17] experimented with dripping pendant drops of water and DNA solution under an alternating electric field between electrodes separated by a short distance. They observed a two-stage drop formation process. During the first stage, the drop oscillated and elongated forming a liquid bridge which eventually generated a drop on the lower electrode upon breakup during the second stage. Tran et al. [18] studied the axisymmetric and non-axisymmetric oscillations and jetting of liquid meniscus on a nozzle tip under ac, ac superimposed on dc, and pulsed dc voltages. They observed that the ac waveform led to jet formation at higher voltages while the meniscus oscillated axisymmetrically at lower voltages. The ac waveform along with a mean dc component generated a normal jet or a Taylor cone jet depending on the ratio of the two voltages. Tran et al. [19] performed semi-analytical and experimental studies on AC electric field driven oscillations of sessile droplet on conducting, hydrophobic and hydrophilic surfaces. They investigated the effects of liquid physical properties and the contact radius on droplet oscillations. Sommers and Foster [20] studied the effects of an electric field on the shape and volume modes of oscillating bubbles. Their experimental procedure, similar to Trinh et al. [13], consisted of trapping bubbles at the node of a standing acoustic wave and then induce oscillations using AC electric field. It was observed that the non-uniform electric field excited the first three even Legendre shape modes. They further numerically calculated the electric field inside experimentally captured bubble profiles and found increased strength of electric field inside the bubbles. Corti et al. [21] used the amplitude of the quadrupolar bubble oscillation mode to calculate the net surface charge on an oscillating bubble. By performing numerical simulations of the complete bubble formation cycle, Sunder and Tomar [22] investigated the phenomenon of bubble volume reduction under non-uniform electric field caused by a needle. They showed that non-uniform electric stresses push the bubble interface into the needle leading to a premature neck formation and bubble detachment thus resulting in smaller bubbles. Recently, Sharma et al. [23,24] studied the effects of a constant and an alternating electric field on the formation of oil droplets inside water at the exit of a 'T' shaped microchannel. They observed that a plug flow of the oil phase can be transformed into a flow with smaller oil droplets by the application of a constant electric field. For an alternating electric field, they observed that weakly conducting fluids are more responsive to a change in the AC frequency compared to the purely dielectric fluids and smaller droplets are formed at lower AC frequencies.

In the present study, we investigate the role of alternating electric field on the bubble formation process from submerged orifices and needles. We perform numerical simulations using the Coupled Level-set and Volume-of-fluid (CLSVOF) algorithm along with an electrohydrodynamic formulation to study the effects of an alternating electric field on bubble dynamics. We consider both the gas and the liquid as perfect dielectric materials and the electrode configuration is chosen so as to obtain a non-uniform electric field (see [22]). We analyze the reduction in bubble volume in comparison to a DC electric field. We observe that for a critical frequency the volume of the detached bubbles is observed to be minimum, whereas at other frequencies an increase in the detached bubble sizes is observed. For the bubble oscillation modes, we show that the second Legendre shape mode is the most dominant oscillation mode followed by a decreasing contribution from the higher order even modes. Although the Legendre modes vary with time, the amplitude of second mode always remains positive while that of the fourth mode is always negative implying that the bubbles oscillate around an elongated, ellipsoidal mean shape. The paper is organized as follows. In Section 2, we formulate the problem and present the equations governing the fluid flow and electrohydrodynamics. Section 2.4 presents the details of the numerical algorithm. Results and important conclusions are discussed in Sections 3 and 4, respectively.

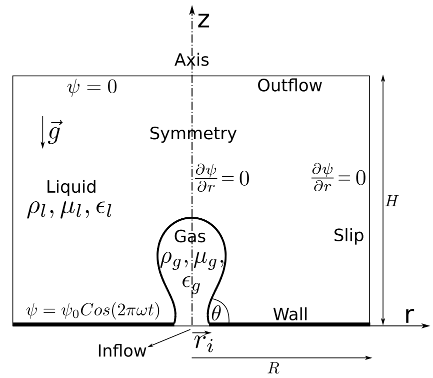

Fig. 1. Computational domain for the case of bubble formation from an orifice, R = domain radius, H = domain height, r_i = orifice radius, ρ = density, μ = viscosity, ϵ = relative permittivity, ψ = electric potential, ω = angular frequency of electric field oscillation, θ = contact angle with respect to bottom plate, $\vec{g}$ is the gravity vector, subscripts l and g denote respectively the liquid and gas phases.

2. Problem formulation

2.1. Computational domain

We model bubble formation at orifices and needles using an axisymmetric formulation. Figs. 1 and 2 show the computational domain for the bubble formation from a submerged orifice and a needle, respectively. In both figures, R and H denote respectively the radius and height of an axisymmetric computational domain. For all the simulations presented in this study, we use $R = 10$ mm and $H = 20$ mm. A dielectric gas is injected through an orifice/needle, of radius $r_i = 1$ mm and placed at the bottom, as shown in Figs. 1 and 2. In the case of gas injection through an orifice, the bottom conducting plate is given a sinusoidally varying electric potential while a zero potential is given to the top boundary. This generates an alternating but spatially uniform electric field inside the domain. In the case of bubble formation at a needle, we consider a conducting needle of internal radius $r_i = 1$ mm, outer radius $r_o = 1.5$ mm and height $h = 6$ mm with the center line of the needle coinciding with the axis of symmetry in the computational domain. A sinusoidally varying electric potential is applied to the needle and a zero potential is applied at the outer side boundary ($r = R$). This generates a spatially non-uniform alternating electric field. The above configurations can be realized in experiments by using a conducting wire-mesh frame which can be easily earthed or put at some reference potential. The position of the wire-frame, if it is put at a constant electric potential, would dictate the strength of the electric field in the domain. Therefore, one would have to accordingly choose the vertical location. Similarly, in the needle case, the needle is employed as an electrode with a sinusoidally varying potential and the side walls are imposed with a zero potential (see Fig. 2).

In addition to the difference in the flow behavior around the growing bubble, the two configurations (Figs. 1 and 2) show different contact line dynamics. During the bubble growth at needles and orifices the contact line is expected to be pinned at the tip of the inner surface of the needle and orifice edge, respectively. Contact angle, θ, in the case of orifice is measured from the horizontal surface. Whereas, in the case of needles the contact angle should be measured from the horizontal surface or vertical inner surface depending upon the tendency of the motion