QUASI-STATIC BUBBLE FORMATION FROM SUBMERGED NEEDLE UNDER NON-UNIFORM ELECTRIC FIELD

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Summary We study here the process of bubble formation on a needle tip submerged in a dielectric fluid in the presence of electric field using a coupled level-set and volume-of-fluid (CLSVOF) algorithm. The effect of electric field strength and needle length on the bubble shape and volume at detachment is studied. Our numerical simulations show that for longer needles and higher electric field strengths smaller bubbles are generated at the needle tip.

INTRODUCTION

In various industrial and medical applications, such as bubble column reactors, froth flotation processes in metallurgy and blood oxygenators, smaller bubbles are desired to increase the rate of heat and mass transport at the bubble interface. The size of the bubbles forming at an orifice can be reduced by applying an external field, for example, ultrasonic waves, cross flow and electric field. The effect of electric field on the bubble formation process from a submerged orifice was studied by Cho et al.[1] by incorporating the electric field stresses in the normal stress balance equation at the bubble interface. They showed that the strength of the applied uniform electric field has little influence on the bubble volume. Gerlach [2], using a coupled level-set and volume-of-fluid (CLSVOF) algorithm [3], showed that although bubbles forming at an orifice are elongated, the volume of the detached bubbles is independent of the applied electric field. However, a decrease in the volume of the detached bubble was predicted in the presence of a non-uniform electric field[2, 4].
In the present study, we perform numerical simulations of the bubble formation process at a needle tip using a CLSVOF algorithm. We show that the needle length has an influence on the volume of the detached bubbles with smaller bubbles generated for longer needles. Also, we show that even a small electric field strength reduces the volume of bubbles substantially. However, reducing the length of the needle emerging from the electrode to zero leads to a uniform electric field and the volume of the bubble is then independent of the applied electric field strength.

Formulation

Figure 1 shows the geometry of the needle (of inner radius R) through which gas is injected. Bubble formation and detachment from the needle is simulated using an axisymmetric CLSVOF algorithm [3]. Outflow and slip boundary conditions are applied at the top boundary and side walls, respectively. No-slip condition is applied at the bottom boundary. A uniform e-field is applied at the top boundary and the bottom surface is assumed to be at zero potential. The fluids are assumed to be homogeneous and incompressible ($\nabla \cdot \mathbf{v} = 0$) and the governing equations of motion of the fluids are the Navier-Stokes equations,

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \nabla \cdot \left[\mu \left(\nabla \mathbf{v} + \nabla \mathbf{v}^T \right) \right] + \rho \mathbf{g} + \mathbf{f}_v^\gamma + \mathbf{f}_v^E \tag{1}$$

where ρ is the fluid density, $\mathbf{v}$ is the velocity, p is the pressure, μ is viscosity and $\mathbf{g}$ is the gravitational field. In the CLSVOF algorithm, the normal and tangential stress balance are imposed implicitly by introducing the surface forces, namely, surface tension and electric field, as volumetric forces, $\mathbf{f}_v^\gamma$ and $\mathbf{f}_v^E$, respectively. Surface tension force is given by $\mathbf{f}_v^\gamma = \gamma \kappa \mathbf{n} \delta_s$ where γ is surface tension coefficient, κ is interface curvature, and δ_s is the smoothed (over 3 grid cells in our simulations) surface Dirac delta function [3]. The injected and the ambient fluids are both considered to be perfectly dielectric and in the absence of any time varying electric field ($\nabla \times \mathbf{E} = 0 \Rightarrow \mathbf{E} = -\nabla \psi$), the governing equation for electric field is given by,

$$\nabla \cdot (\epsilon \epsilon_0 \mathbf{E}) = \nabla \cdot (-\epsilon \epsilon_0 \nabla \psi) = 0, \tag{2}$$

where ψ is the electric potential and ϵ is the relative permittivity of the fluid. In the absence of any free charge, no tangential electric field forces act on the interface and therefore no electrophoretic effects are expected in our simulations. The electric body force is given by,

$$\mathbf{f}_v^{E,d} = \frac{\epsilon_0}{2} \left(\frac{(\mathbf{D} \cdot \mathbf{n})^2}{{\epsilon_0}^2} \nabla \left(\frac{1}{\epsilon} \right) - (\mathbf{E} \cdot \mathbf{t})^2 \nabla \epsilon \right) \tag{3}$$

where $\mathbf{n}$ is the unit normal vector and $\mathbf{t}$ is the tangent vector at the interface. The details of the implementation of the CLSVOF algorithm are given in Tomar et al.[3]. The various non-dimensional numbers of interest here are the Bond number, $Bo = (\rho_l - \rho_g) * |\mathbf{g}| * R^2/\gamma$, Weber number, $We = \rho_l U^2 R/\gamma$, Capillary number, $Ca = \mu_l U/\gamma$ and the electric Bond number, $Bo_E = \epsilon_l \epsilon_0 E_\infty^2 R/\gamma$. Here, ρ_l and ρ_g are the densities of the ambient liquid and the injected gas, respectively. The electric permittivities of the liquid and the gas are denoted by ϵ_l and ϵ_g, respectively.

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RESULTS AND DISCUSSIONS

We perform here simulations of bubble injection through a needle for different values of Bo_E and needle length. The bubble is assumed to be pinned at the nozzle tip. The liquid to gas density ratio is $\rho_l/\rho_g = 100$ and the permittivity ratio is $\epsilon_l/\epsilon_g = 2$. The values of other non-dimensional numbers are $Bo = 0.1$, $Ca = 0.01$ and $We = 0.01$. The ratio of the viscosities of the ambient liquid and the injected gas is $\mu_l/\mu_g = 10$. The inner radius of the nozzle is $1mm$ (see Figure1). Figure 1 shows the liquid-gas interface at time $t = 0.145s$ for different values of electric Bond number and for a flow-rate $Q = 3.14 \times 10^{-8} m^3/s$. Electric field lines are shown in the left half of the figure for $Bo_E = 4.5$ and needle length of $2mm$. Velocity vectors are shown in the right half of the figure. The volume of the bubbles at this instance is the same for different Bo_E, as the influx at the needle inlet is maintained to be constant. The electric field elongates the bubble in the vertical direction leading to the formation of thinner and longer bubbles at higher values of Bo_E. In comparison to the bubble formation in the absence of electric field ($Bo_E = 0$), bubble necking starts even for moderate values of Bo_E which indicates that the frequency of bubble injection is higher in the presence of electric field. Figure 1 also shows that, at higher Bo_E, the bubble base is pushed inwards into the needle. We expect that if the strictly pinned condition imposed in our simulations is relaxed, the contact line would move on the inner surface of the needle.

Figure 2 shows the variation in the volume of the detached bubbles with Bo_E and for different needle lengths. Here V denotes the volume of bubbles and V_0 is the bubble volume for $Bo_E = 0$. At higher Bo_E, V/V_0 decreases asymptotically to a constant value which is a function of the needle length. For a longer needle, the electric field around the needle tip is more non-uniform leading to higher electric stresses at the bubble base. These stresses lead to an early detachment of bubbles resulting in smaller bubbles ejected at a higher frequency. This is in stark contrast to the bubble formation from a submerged orifice (zero needle length) where the volume of the detached bubble is independent of the applied electric field [2]. However, our simulations without the electric field show that the needle length has negligible effect on the bubble volume. Also, the extent of the non-uniformity induced in the electric field due to the needle would become independent of the needle length beyond a certain length.

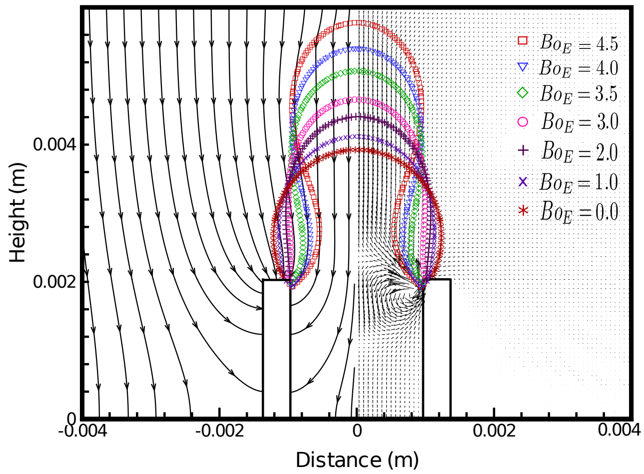

Figure 1. Bubble profiles at $t = 0.145s$ for various electric Bond numbers, Bo_E, orifice radius = 1mm, $\epsilon_l/\epsilon_g = 2.0$, $\rho_l/\rho_g = 100.0$ and $\mu_l/\mu_g = 10.0$.

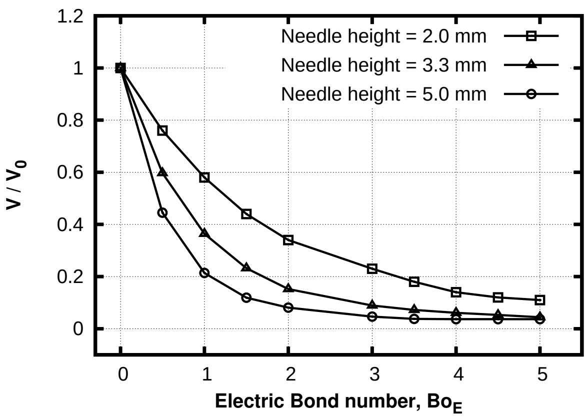

Figure 2. Variation in the volume of the detached bubble (normalized by the volume for $Bo_E = 0$) with electric Bond number, Bo_E and for different needle lengths.

CONCLUSIONS

The process of bubble formation from a needle in the presence of electric field was studied using a CLSVOF algorithm [3]. An externally applied electric field reduces the size of the bubbles formed during gas injection through the needle. Also, the length of the needle has an effect on the volume of detached bubbles and bubbles with smaller volumes are formed for longer needles. The reduction in the bubble volume is due to high electric stresses at the interface near the needle tip which cause an early detachment of bubbles. A non-uniform electric field is an effective way of producing smaller sized bubbles, which is often the requirement in many industrial equipments.

References

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