A Dynamic Electrowetting Simulation using the Level-Set Method

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Abstract: A simulation of electrowetting driven droplet dynamics is performed using the level-set two-phase flow application mode of COMSOL Multiphysics for a sessile droplet and for a droplet in a microchannel. For the sessile drop, the response of the drop to a step voltage is studied. For the droplet in a microchannel, the contact angle at one edge of the drop is varied in order to show droplet actuation.

Keywords: Level-Set Method, Electrowetting, Multiphase Flow, Contact Angle.

1. Introduction

Electrowetting is a surface wetting phenomenon resulting from the electrical control of the surface wetting properties on application of an electric potential. In recent years, the control of aqueous droplets on dielectrically insulated has become a hot topic. On the one hand, there are applications of electrowetting in electrical displays and liquid lenses [1-4] and on the other hand, it offers many exciting applications for microfluidic systems for lab-on-a-chip devices [5-8].

Lippmann first described how applying a voltage can change the contact angle [9]. In electrowetting on dielectric the variation of the contact angle θ on application of a voltage can be predicted by [10]:

$$\cos\theta(U) = \cos\theta(0) + \frac{\varepsilon_0 \varepsilon}{2d\gamma} U^2 \qquad (1)$$

where U is the potential drop across the dielectric layer, $\theta(0)$ is the contact angle of the liquid in absence of applied voltage, ε_0 is the permittivity of free space, ε is the dielectric constant of the insulating layer, d is the thickness of the insulating layer and γ is the liquid surface tension.

In this study, we present results made possible by the use of the two-phase flow module of COMSOL Multiphysics. This module deals with the movement of the interface between two immiscible phases within the framework of the Navier-Stokes equations by using the level-set method. The behaviour of the interface is governed by the surface tension of the two phases. Not only this, the wetting properties of the two fluids can be described by accounting for the contact angle.

2. Modelling

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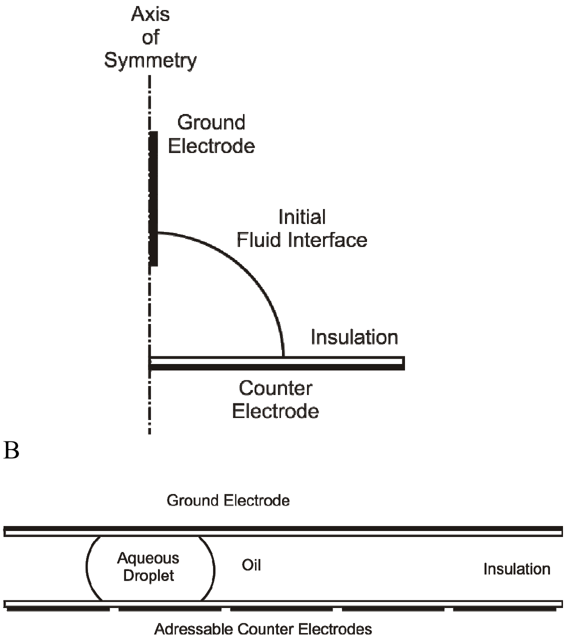

Figure 1. A schematic representation of the two geometries that were simulated, A: A sessile droplet B: A droplet sandwiched between two hydrophobic plates

We deal with the two geometries shown in Figure 1 – a sessile drop and a droplet in a microfluidic channel. In the case of the sessile drop, as shown in Figure 1A, the drop wets a planar surface and it can be modeled efficiently by making use of axial symmetry. In Figure 1B, the droplet in a microfluidic cell is an aqueous drop sandwiched between two plates and surrounded by oil. The top plate is a dielectrically-coated ground electrode and the bottom plate consists of dielectrically-coated addressable electrodes.

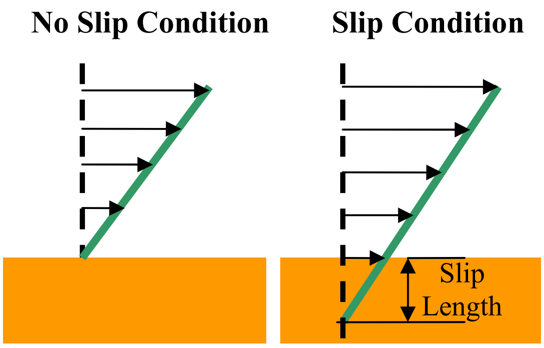

Figure 2. Comparison of the no-slip boundary condition and the slip boundary condition.

In this way, the electric field simulation can take the movement of the interface inherent in two-phase flow into account.

In both cases, a section of the geometry is modeled by two-phase laminar flow. In this section of the geometry, we solve for the volume fraction, ϕ, of one of the media using the level-set method. The volume fraction of the other medium is by definition: $1 - \phi$. In addition we perform a DC Conductive Media electric current simulation for the sessile drop, this allows the electrical stimulus to be directly coupled to the hydrodynamic response. In this way, a truly electrohydrodynamic simulation can be performed. In exactly the same way that density, ρ, and viscosity, μ, are related to ϕ in the region of the two-phase flow;

$$\rho = \rho_{oil} + \left(\rho_{water} - \rho_{oil}\right)\phi$$
$$\mu = \mu_{oil} + \left(\mu_{water} - \mu_{oil}\right)\phi \qquad (2)$$

we can use the volume fraction to define, for example, the conductivity, σ, or permittivity, ε, of the media;

$$\sigma = \sigma_{oil} + \left(\sigma_{water} - \sigma_{oil}\right)\phi$$
$$\varepsilon = \varepsilon_{oil} + \left(\varepsilon_{water} - \varepsilon_{oil}\right)\phi \qquad (3)$$

In the implementation of multiphase flow in COMSOL Multiphysics, the boundary condition at a wetted wall requires the user to define a slip length β, that is, the distance behind the surface at which the fluid velocity can be extrapolated to zero. This is described by a frictional force, $\mathbf{F}_{fr}$:

$$\mathbf{F}_{fr} = -\left(\eta/\beta\right)\mathbf{u} \qquad (4)$$

where η is the viscosity and $\mathbf{u}$ is the fluid velocity. It is advised that the slip length takes a value equal to the mesh size. The usual boundary condition, the no-slip boundary condition, requires that the fluid has a zero-valued tangential velocity at the surface. In most basic fluid mechanics textbooks, it is stated that there is no slip at the boundary between an elastic solid and a viscous liquid [11]. In recent years, nevertheless, there have been many experimental reports of slip at solid boundaries [12-14]. In addition, slip is necessary for the translation of the contact line of a droplet on a solid surface, both experimentally and for modeling movement [15]. In particular, when simulating the movement of a droplet on a surface, the use of the no-slip condition leads to a singularity at the contact line [16].

For both models, the multiphase flow must be initialized so that the simulation starts from a stable initial position. For the case of the sessile drop, a circular arc was drawn, so that one quadrant of a circle represents the droplet. By making use of axial symmetry this spares much computational power. The droplet is initialized so that the initial contact angle of the droplet is 120°. For the droplet positioned between two electrodes, the droplet was initialized so that the contact angle of all surfaces with which it wets is 120°.

For the sessile droplet, the contact angle was evaluated using equation 1. The potential drop across the insulation, U, was calculated by means of the electric field simulation and this was used to set the contact angle for the hydrodynamic part of the model. In this way, the electric field simulation was coupled to the fluid dynamic simulation so that a true simulation of electrowetting was performed. We also repeated the same procedure for the drop sandwiched between two plates, and although the simulation was running successfully, we were forced to eliminate the electric field simulation in order to compute the solution in a reasonable amount of time. In this case, we imposed a contact angle change as the wetting condition above the actuated electrodes.

In order to model the flow of the fluid in two dimensions, we constructed a loop geometry whereby there is a fluid connection between each end of the microchannel.

3. Results

3.1 Electrowetting Response of Sessile Drop

Figure 3 shows the first and last position of a sessile droplet from the simulation of the electrowetting-driven change of contact angle of a sessile drop. The drop starts from an initial position with a contact angle of 120°. When a potential of 80 V is applied to the plane electrode beneath the droplet, there is a voltage drop across the insulating layer. This voltage drop is equivalent to stored energy and this in turn leads to a change of contact angle. The contact angle reduces within some milliseconds and oscillates around a final position, which is shown in the frame at 20 ms.

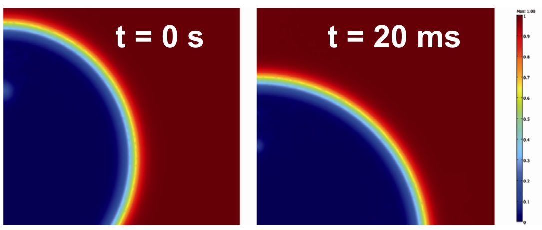

Figure 3. The screen shot on the left shows the initial fluid interface with 120° contact angle with no applied potential at t = 0 s. The screen shot on the right shows the electrowetting-driven change in contact angle on applying 80 V at t = 20 ms. The color bar shows the volume fraction.

Figure 4 shows the contact angle dynamics, the contact angle changes immediately to an almost constant level. In contrast, the contact radius oscillates before it reaches a constant value. It must be noted that the dependence of the contact angle dynamics on fluid velocity has been ignored in this simulation [17].

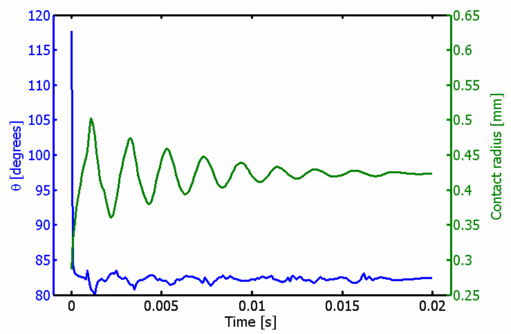

Figure 4. Time dependence of the contact angle and contact radius of the sessile drop.

3.2 Surface-Wetting Driven Actuation of a Drop in a Microchannel

The actuation of a droplet by means of contact angle change above an electrode is shown in Figure 3. The droplet starts at a position whereby all contact angles are 120°. When the contact angle above the electrode is changed to 70°, the contact angle at the contact point above the electrode begins to change and once it has changed the droplet moves rapidly across the electrode until it reaches the edge.

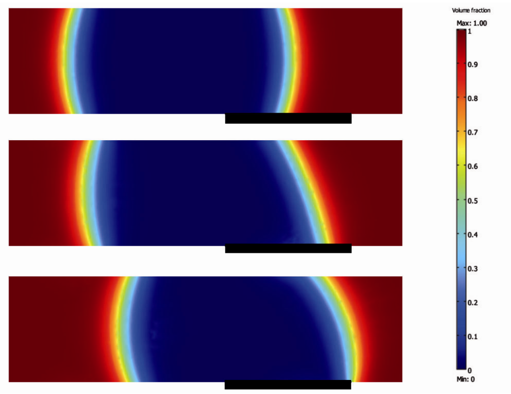

Figure 5. The movement of a droplet in a microchannel due to the application of a contact angle of 70° above the actuated electrode. The color bar shows the volume fraction. The extent of the activated electrode is indicated by the black bar.

4. Conclusions

An electrowetting simulation was performed by making use of the multiphase laminar flow application mode of COMSOL Multiphysics. Droplet movement was dynamically simulated for two geometries; a sessile droplet and a droplet in a microchannel. The hydrodynamic modeling was coupled with electric field simulation for the sessile drop, so that a true electrowetting simulation could be performed.

5. References

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