Modeling microdrop motion between covered and open regions of EWOD microsystems

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ABSTRACT

EWOD Microsystems are now widely used in digital microfluidics. Two different types of EWOD Microsystems are developped: open systems - in which a sessile drop is sitting freely on a horizontal substrate - and covered systems - where the droplet is confined between two horizontal plates. In order to combine the advantages of the two systems, a dual open/covered system has been developed. The concept relies on the fact that motion between a covered and open region – and back - is possible under electrowetting actuation. In this work, the mechanism of such a motion is analyzed by using a numerical model based on energy minimization, and a domain of possible droplet motion is defined by an analytical model based on a simplification of the numerical model. The validity of the models is checked against experimental results.

Keywords: electrowetting, electrocapillary force, Laplace law, energy minimization, Evolver.

1 INTRODUCTION

Digital microfluidics is a promising way to manipulate biological targets like DNA, proteins or cells in very small liquid volumes. The advantages of such devices are the use of lesser quantities of costly reagents, better biochemical reaction efficiency and shorter operating times. Digital microfluidics based on ElectroWetting On Dielectric (EWOD) is a fast developing technology [1,2]. It has been shown that basic manipulations of drops can be achieved in such Microsystems [3].

Two different types of EWOD Microsystems have been developed: covered systems where the droplets are confined between two plates and open systems where the sessile droplet is sitting freely on a horizontal solid substrate (fig 1 and 2). Each one of these systems has his own advantages. Drop dispense, motion and splitting are easier in covered EWOD systems whereas mixing and evaporation (for species concentration) are preferably performed in the open configuration [4]. Thus, the concept of a dual open/covered EWOD microsystem has been developed. This concept relies on the fact that motion between a covered and open region is possible under electrowetting actuation. In this work, we analyze the possibilities of such a motion. The approach is performed in three steps. First, we use the Surface Evolver software [5] to model the displacement of the droplet from one region to the other. This simplified model assumes that the capillary forces - including the electrical forces - are dominant over inertial and viscous forces (i.e. the Weber number and the Ohnesorge numbers are small). Second, from the Evolver results, and using the Laplace law, we deduce a very simple condition for the possibility of droplet motion. Finally experimental results are compared with the results of the modeling steps.

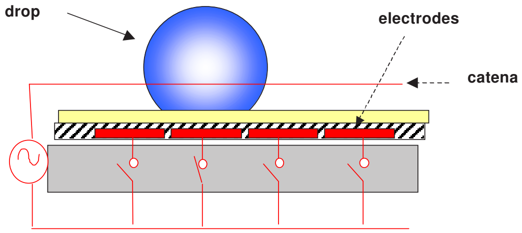

Fig.1. Principle of open EWOD Microsystem [6]

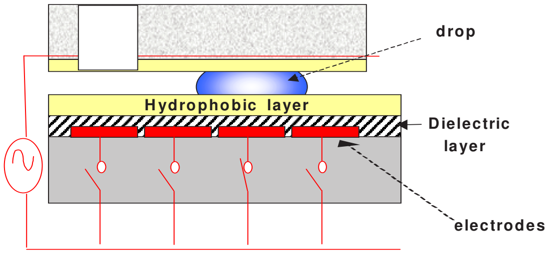

Fig.2. Principle of covered EWOD Microsystem

2 SURFACE EVOLVER MODEL

In this approach, the electrowetting effect is considered equivalent to an electro-capillary effect according to the Lippmann-Young law [7]

$$\cos\theta - \cos\theta_0 = \frac{C}{2\gamma_{LG}} V^2 \qquad (1)$$

where C is the capacitance (per unit area) of the dielectric layers, V the electric potential, θ and θ_0 the actuated and non-actuated contact angles.

It has been shown that the minimization theory correctly predicts microdrop behavior under electrowetting conditions [8]. The Surface Evolver numerical program has been used to perform the minimization of the droplet surface energy under the Lippmann-Young conditions [9]

$$E = \gamma_{LG} S_{LG} - \gamma_{LG} \iint_{S_{SL}} \cos\theta \, dA \qquad (2)$$

Typical features of droplet motion calculated by the minimization approach are shown in figure 3.b and compared to experimental results (fig. 3.a). A close-up view of the crossing of the covered/open boundary is shown in figure 4.

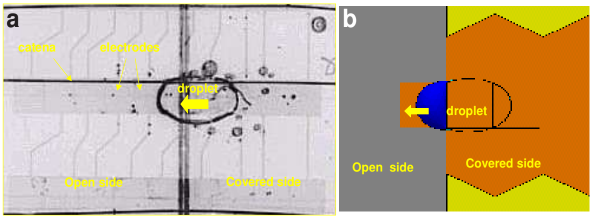

Fig.3. Left: experimental view of a droplet crossing the frontier between the covered region and the open region. The drop moves from right to left. Right: same motion predicted by a quasi-static approach using Surface Evolver software.

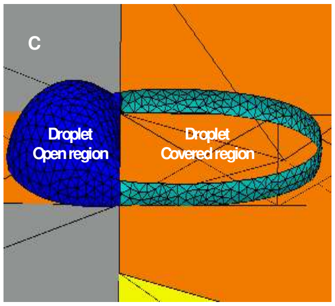

Fig.4. Close up view of the droplet crossing the covered/open boundary (the upper plate of the covered region has been dematerialized for clarity).

Figure 5 shows the general pressure evolution in the droplet during a cycle. A cycle is defined by motion from the open region (noted 3D/open) to the covered region (noted 2D/covered) and back. Suppose the droplet starts from the 3D/open region (top left, figure 5). Electrodes in the 3D/open region are not actuated whereas the electrodes in the 2D/covered region are actuated. The droplet then moves towards the covered region. When it has crossed the boundary, and is located in the 2D/covered region (bottom right), the actuation is switched off and the droplet internal pressure suddenly increases (top right). The actuation in the 3D/open region is then switched on and the droplet moves back to this latter region. When the droplet is entirely located in the 3D/open region (bottom right) the actuation is switched off and the droplet recovers its initial conditions.

This analysis leads to the conclusion that a motion from one region to the other is accompanied by a monotonous decrease in pressure. And the condition for the motion from open to covered region is

$$P_{open,not-actuated} > P_{covered,actuated} \qquad (3)$$

and inversely, for the motion from covered to open region

$$P_{covered,not-actuated} > P_{open,actuated} \qquad (4)$$

Note that if the covered region has electrodes embedded in its top and bottom plates, i.e. actuation can be switched on on both plate, the crossing towards the covered region is facilitated (dashed line in figure 5).

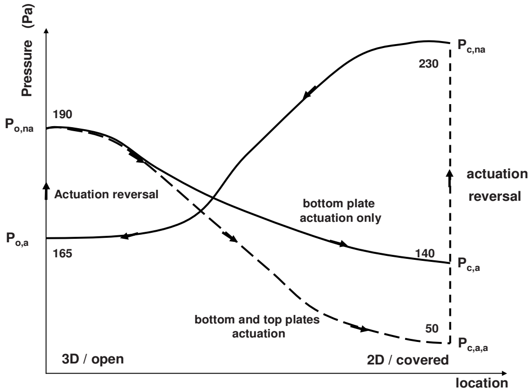

Fig.5. Droplet internal pressure during a cycle: the motion of the droplet corresponds to a decrease in pressure. Increase in pressure is obtained by suppressing the electric actuation when the droplet is on either side of the device.

However, there exists an exception to the rule stated by inequalities (3) and (4). If the drop volume is too large compared to the electrode size, i.e. the droplet overfills the corresponding electrode volume, blockage of the drop due to a pinching effect may occur during the motion from covered to open configuration (figures 6 and 7). This case corresponds to a non monotonous pressure curve. This drawback can easily be avoided by increasing the width of the electrodes at the transition region.

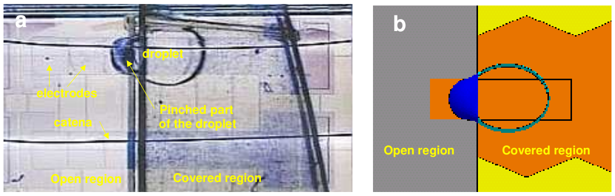

Fig.6. Left: experimental view of a droplet blocked on the covered/open boundary by pinching effect at the open region electrode. Right: same situation predicted by Surface Evolver calculation.

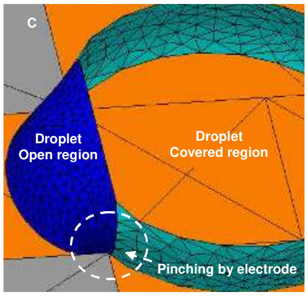

Fig.7. Close up view of the droplet blocked the covered/open boundary due to a pinching effect provoked by a narrow electrode (the upper plate of the covered region has been dematerialized for clarity).

3 ANALYTICAL MODEL

Droplet pressure in each region can be calculated by using Laplace law. First, for a drop of volume V, confined between two horizontal plates separated by a distance δ, internal pressure is given by

$$P_C = \gamma_c\left(\frac{-\cos\theta_t - \cos\theta_b}{\delta} + \sqrt{\frac{\pi\delta}{V}}\right) \qquad (5)$$

where θ_t and θ_b are the contact angles with the top and bottom plates and γ_c the surface tension in the covered region - which can be different from that of the open region γ_o depending on the surrounding fluid (oil or air). In (5) the first term of the right hand side corresponds to the vertical curvature, and the second term to the horizontal curvature.

For a sessile drop of same volume (3D/open configuration), we obtain, again using Laplace law

$$P_O = 2\,\gamma_o\left(\frac{3V}{\pi\left(2-3\cos\theta+\cos^3\theta\right)}\right)^{-\frac{1}{3}} \qquad (6)$$

where θ is the contact angle with the substrate. We are then left with two conditions derived from (3) and (4); the first one for the motion from the open to covered region

$$P_O(\theta=\theta_0) - P_C(\theta_b=\theta_a) \geq 0$$

So that

$$2\,\gamma_o\left(\frac{3V}{\pi\left(2-3\cos\theta_0+\cos^3\theta_0\right)}\right)^{-\frac{1}{3}} - \gamma_c\left(\frac{-\cos\theta_a - \cos\theta_t}{\delta} + \sqrt{\frac{\pi\delta}{V}}\right) \geq 0 \qquad (7)$$

And, the second one for the opposite motion

$$P_C(\theta_b=\theta_0) - P_O(\theta=\theta_a) \geq 0$$

So that

$$2\,\gamma_o\left(\frac{3V}{\pi\left(2-3\cos\theta_a+\cos^3\theta_a\right)}\right)^{-\frac{1}{3}} - \gamma_c\left(\frac{-\cos\theta_0 - \cos\theta_t}{\delta} + \sqrt{\frac{\pi\delta}{V}}\right) \leq 0 \qquad (8)$$

where θ_0 is the non-actuated contact angle with the solid substrate and θ_α the actuated contact angle.

4 EXPERIMENTAL RESULTS

Experiments have been performed on the EWOD chip shown in the figure 3 and 6. The electrodes are 800x800 µm. Different conditions have been tested: the water droplet can be surrounded by air (γ=72mN/m) or by silicon oil (γ=33mN/m), and the height of the vertical gap in the covered region can take the values 110, 200, 360 or 450 µm. The zero potential electrode is a provided by a catena that runs all along the electrode row, just below the level of the upper plate.

The non-actuated contact angle is close to 113°, and electric potential was chosen so that the actuated contact angle is 80° (potential value close to 60 V). The contact angle on the upper plate of the covered region (with no underlying electrodes) is a very important parameter of the problem, as is shown in figure 8.

Figure 8 (left) shows that the motion from open to covered region is not possible if the vertical gap is too small: the counter-pressure in the covered region is then too large and equation (7) is not satisfied. Motion in the opposite direction is not possible if the gap is too large, i.e. equation (8) is not satisfied because the driving pressure in the covered region is too small. There is a domain where both motions are always possible. This domain is shown in figure 9. It appears immediately that this domain is sufficiently large to leave room to build a component where forth and back motions are possible.

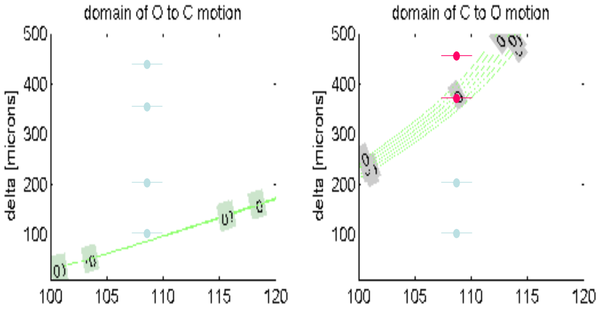

Fig.8. Left: conditions for water droplet motion (in air) from open to covered EWOD configuration. Right: conditions for droplet motion from covered to open EWOD configuration. Vertical scale "Delta" is the vertical gap in the covered region and the horizontal scale is the contact angle θ_t on the upper plate in the covered region. Continuous lines correspond to the analytical model and separate the domain where motion is possible from the domain where motion is impossible. Dots are the experimental results. Blue dots correspond to observed drop motion from one configuration to the other, while red dots signify that the motion was not obtained. The different continuous lines correspond to different non-actuated contact angle values θ_0 (bottom plate).

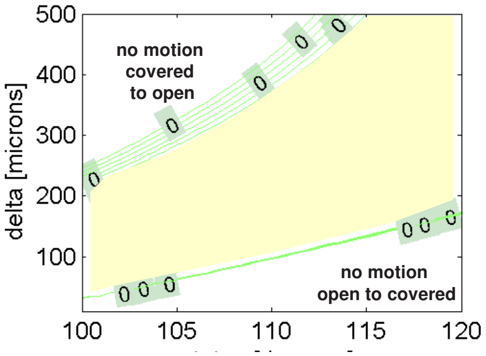

Fig.9. Superposition of the two previous figures. The domain for which the motion is possible both ways is the yellow region comprised between the green lines.

5 CONCLUSION

From this analysis, it has been shown that the motion from an open to a covered region of an EWOD microdevice - and reciprocally - is closely related to the difference of drop internal pressure between the departing and arriving regions.

Electrodes at the covered/open region boundaries must be adequately designed in function of the liquid droplet volume, they should not be too narrow in order to avoid a pinching effect resulting in a stopping of the motion.

For a droplet of water in air, motion from open to covered region is possible provided that the vertical gap in the covered region is not too small, and motion from covered to open region is possible if the vertical gap is not too large.

Contact angle with the upper plate θ_t is an important parameter of the motion; below 90° the droplet will have difficulties to exit the covered region towards the open region due to hydrophilic grip on the upper plate; above 120°, the motion towards the covered region will be increasingly difficult due to hydrophobic repulsion on the upper plate

There is an important leeway to dimension a component where both motions are easily possible. A vertical distance of about 200 microns seems to work well for buffer liquid drops of 0.5 to 1 µl on Teflon ® substrate and electrodes of 800x800 µm.

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