Mechanical behavior of micro-drops in EWOD systems: drop extraction, division, motion and constraining

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ABSTRACT

Digital microfluidics is now foreseen as a convenient way to perform many biological processes like DNA or protein manipulation and detection, and cell analysis. A promising method for droplet displacement is electro-wetting on dielectric (EWOD). It has been recently shown that many basic manipulations of drops can be achieved in such EWOD based microsystems.
In order to contribute to the developments of such microsystems, we have used a numerical approach based on surface energy minimization to better understand the physical phenomena and to improve the topological design of an EWOD microchip. We show that the problem is mostly topological and that the shape and arrangement of the electrodes is a predominant factor. We present here the computational approach and the consequences for the realization of an EWOD microsystem.

Keywords: electrowetting, EWOD, minimization theory, topology, surface tension.

INTRODUCTION

The technology of EWOD [1,2] is based on the observation that an electrical field modifies the contact angle of a conducting liquid with the solid substrat, according to the Lippmann-Young relation [3]

$$\cos\theta = \cos\theta_0 + \frac{1}{2}\frac{C}{\gamma_{LG}}V^2 \tag{1}$$

where θ, θ_0, C, γ_{LG} and V are respectively the actuated and not-actuated contact angles, the capacitance of the substrat, the surface tension between the liquid and the surrounding fluid (air or silicon oil) and the electric potential.

The present EWOD design is obtained by paving a substrat with electrodes recovered by a dielectric layer (SI_3N_4, 300 nm) and an hydrophobic layer (Teflon, 200 nm) as represented in figure 1.

It has been shown that many basic manipulations of drops can be achieved in such Microsystems [4]. However, some questions remain about the physical behavior of drops in EWOD systems, that hamper the optimal dimensioning of the micro-component. In this text, we investigate the conditions under which some key basic drop manipulations can be performed in EWOD Microsystems. These basic manipulations consist in (1) moving a drop from one electrode to the next one, (2) dividing a drop into two “daughter” drops, (3) extracting a drop from a reservoir, (4) moving drop from an open to a covered environment and back (this operation will be called here “drop constraining”).

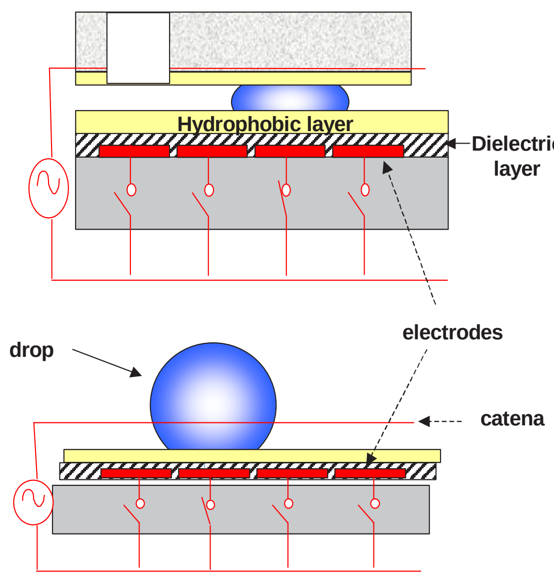

Fig. 1. Two types of EWOD design. Top: “covered” system, bottom “open” system.

The understanding of these processes conditions the optimal design of an EWOD Microsystem. Investigation of these basic manipulations has been performed by using a modeling approach combined with experimental verifications.

Modeling the precise dynamics of EWOD requires sophisticated numerical methods [5]. We follow here an original approach, based on the fact that the ratio between inertia and surface tension (Weber number for a drop)

$$We = \frac{\rho v^2 l}{\gamma_{LG}} \tag{2}$$

and the ratio between viscous forces and surface tension forces (Ohnesorge number)

$$On = \frac{\mu}{\sqrt{\rho\, l\, \gamma_{LG}}} \tag{3}$$

are very small in most cases. Thus a simplified quasi-steady state approach based on the topology of the electrodes is sufficient to predict some characteristic drop behavior (to the exception of liquid films) and to produce basic rules to dimension an EWOD microdevice. In this approach, we have used the Surface Evolver software [6] well adapted to topological problems.

It may be noted that the ratio between gravitational forces and surface tension forces (Bond number)

$$Bo = \frac{\rho\ g\, R^2}{\gamma} \tag{4}$$

is also small, but because the gravitational forces derive from a potential they may be taken into account by the Evolver approach, so that larger drops may be included in the modeling.

NUMERICAL APPROACH

In our numerical approach, the electrical tension V does not appear explicitly. The reasoning is based on the actuated and non-actuated contact angles and the corresponding values of V are deduced from the Lippmann equation (1).The principle is to minimize the free energy E of the system given by [7]

$$E = \gamma_{LG}\ S_{LG} - \gamma_{LG} \iint_{S_{SL}} \cos\theta\ dA \tag{5}$$

where the index L denotes the liquid, G the surrounding gas (or fluid), S the solid surface and S_{LG} and S_{SL} the contact areas. θ is the contact angle defined by Young's equation

$$\cos\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}} \tag{6}$$

It can be shown that the minimization approach is equivalent to solving the Laplace equation for the pressure drop at each point of the liquid-gas interface

$$\Delta P = \gamma_{LG}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{7}$$

along with Young's equation (6). R_1 and R_2 are the two curvature radius, ΔP the pressure difference between the two sides of the drop interface.
In the Evolver approach, only the surface of the drops is meshed and the nodes are iteratively moved until the minimum energy position is found (fig 2).

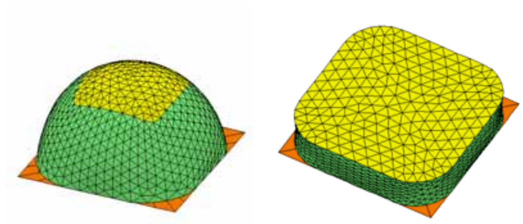

Fig.2. Left: droplet on a square electrode in an open EWOD configuration; right: same droplet in an covered EWOD configuration (top plate has been dematerialised for better representation).

DROP MOTION

Drop motion due to a difference - or a gradient - of wettability is well known [8,9]. This behavior is confirmed by the results of the Surface Evolver numerical program: the figure 3 shows that a water droplet initially placed at the transition between a hydrophilic and hydrophobic surface, moves towards the hydrophilic surface. It is assumed that the surfaces are supposed ideally smooth. The equilibrium position is when the droplet is spherical and tangent to the transition line.

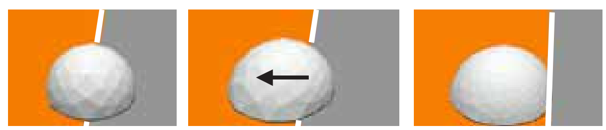

Fig. 3. Motion of a water droplet towards the hydrophilic surface (Evolver)

With a similar reasoning, it is shown numerically how micro-dents between the electrodes facilitate drop motion between two electrodes (figure 4) when the drop is too small to overlap the next electrode

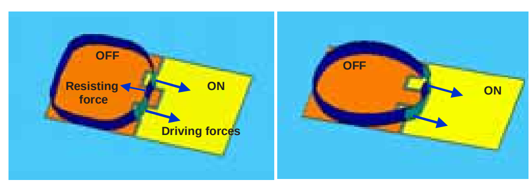

Fig. 4. Deformation of the drop due to micro-dents on the edges of the electrodes (Evolver)

This has led to the design of crenelated electrodes as shown in the figure 5.

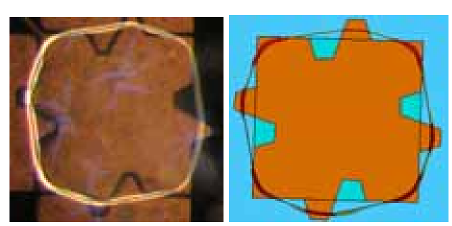

Fig. 5. Droplet on crenelated electrode. Left: experimental image; right: Evolver calculation.

DROP DIVISION

Division of a drop in two "daughter" drops is a necessary operation for bio-analysis. The principle of drop division is to exert an elongation force on two sides of the drop and a pinching force in the middle of the drop (fig. 6).

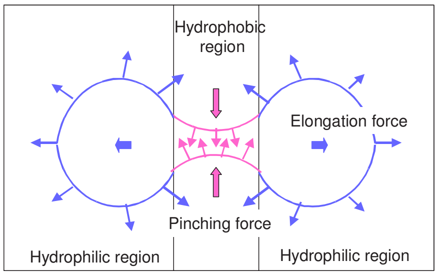

Fig. 6. Principle of drop division

a-open system. Evolver results show that it is not possible to split a spherical drop (open system) because the energy level of the splitting is too high for EWOD actuation (fig. 7).

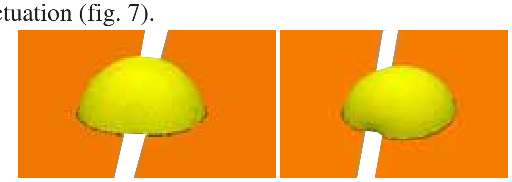

Fig. 7. A spherical drop cannot be split ; it just escapes to any one of the two hydrophilic regions.

Furthermore, numerical simulations show that, in an open EWOD configuration, a drop may be split if it has been previously elongated (fig. 8,9).

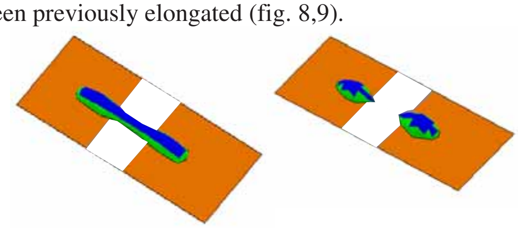

Fig. 8. Splitting of an elongated drop

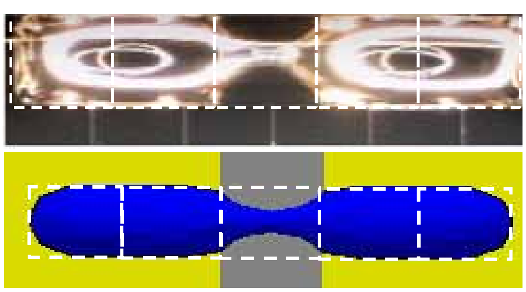

Fig. 9. Splitting of an elongated drop of ionic liquid. Top: experimental view; bottom: numerical results.

It may be shown that the initial elongation ratio between drop length and drop width, and the "cutting" ratio between pinching length and total drop length are key factors for drop division.

b-covered system. It can be shown analytically that a covered system requires less energy to split a drop because the increase in free surface is less important than for an open system. The numerical result of figure 10 is to be compared to that of figure 7.

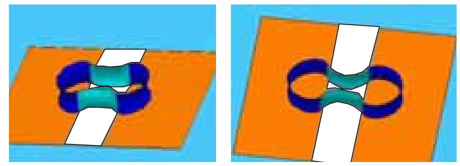

Fig. 10. Splitting of a confined drop (the upper plate has been dematerialized for visualization). The hydrophobic contact angle is 110°, the hydrophilic contact angle is 80°, the liquid/gas surface tension is 70mN/m.

The validity of the calculation has been checked by comparison with the experiment (fig. 11).

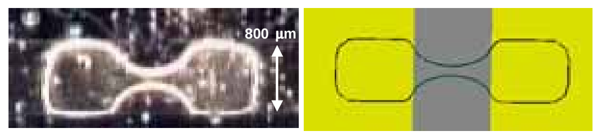

Fig. 11. Division of drop in a covered system. Top: experimental view, bottom, numerical results

DROP EXTRACTION

At the beginning of the process, micro-drops are extracted from a reservoir. To be effective, extraction is constituted by three steps: (1) liquid extrusion from a reservoir onto the electrode row, (2) followed by a pinching effect on the "cutting" electrode and (3) completed by back pumping into the reservoir (figure 12). Conditions for satisfactory extraction are derived and it is shown that, without some back pumping, extraction is not possible. The model shows also how the size of the "cutting" electrode closely controls the size of the final extracted drop (figure 13).

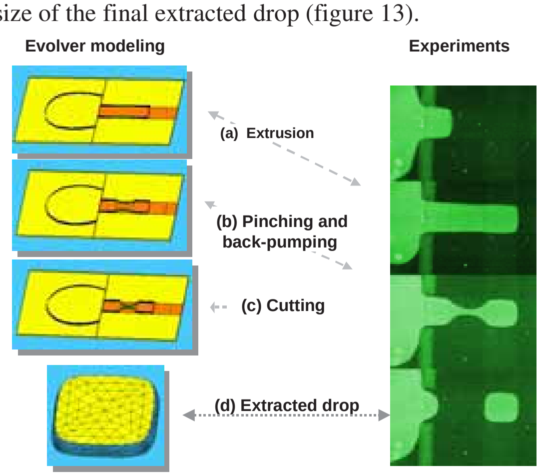

Fig. 12. Comparison between the model and the experimental results for drop extraction.

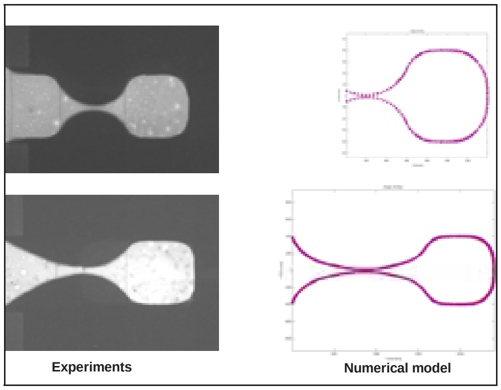

Fig.13. Enlarged view of the drop at the very moment of the splitting. Left: experimental results; right: numerical results. Top: one "cutting" electrode; bottom, two "cutting" electrodes.

It appears that the size of the cutting electrode is determinant for the reproducibility of the extracted drop volume.

DROP CONSTRAINING

It can be convenient – when performing amplification of DNA strands for example– to switch from a 2D constrained drop to a 3D spherical drop and to be able to reverse this operation. The figure 14 shows how a spherical drop at the limit of a covered region can be moved inside the covered region by adequate actuation of the electrodes.

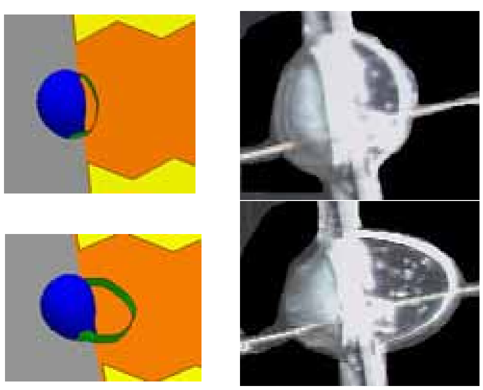

Fig. 14. Transfer of a droplet from an open environment to a closed environment. Left: basic mechanism from simulation; right, comparison with experiments

CONCLUSION

The principles of Electro-Wetting On Dielectric (EWOD) are now well established. However, the design of an efficient microchip based on these principles requires precise knowledge of the different operations that take place on the electrodes.

Based on a dimensional analysis that shows that inertia and viscosity effects can be neglected in front of capillary forces, we have treated the problem as being quasi steady state and dominated by topology. On the computational point of view, the problem has been reduced to an energy minimization problem. We have shown that this approximation, even if it does not take into account some dynamical effects like liquid films, is in good agreement with the experimental results. It has the advantage of being a very efficient help to the dimensioning of the different parts that constitutes the EWOD device.

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