Electrohydrodynamic actuation of co-flowing liquids by means of microelectrode arrays

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Abstract. Electric fields induce forces at the interface between liquids with different electrical properties (conductivity and/or permittivity). We explore how to use these forces for manipulating two co-flowing streams of liquids in a microchannel. A microelectrode array is fabricated at the bottom of the channel and one of the two liquids is labelled with a fluorescent dye for observing the phenomenon. The diffuse interface between the two liquids is detected depending on the ac signal and conductivity (or permittivity) ratio between the liquids. Only a few volts are needed for observing the interface destabilization, in contrast with other electrode configurations where hundreds of volts are applied.

1. Introduction
The integration of microelectrode arrays in microchannels represent an opportunity for direct actuation either of the liquid or suspended particles [1]. Thus, electrohydrodynamics (EHD) in microsystems is of central interest in current microfluidics research and Lab-on-a-Chip technologies [2, 3].

Manipulation of two co-flowing fluids is a common operation in Lab-on-a-Chip devices. In this work, we present an experimental characterization of the actuation of coflowing fluids with different electrical properties (conductivity and/or permittivity) by an array of microelectrodes. Figure 1a) shows a sketch of the microelectrode array and the microchannels. Figure 1b) shows a picture of the actual device: platinum microelectrodes are fabricated on glass and a polymeric microfluidic channel (500 $\mu$m high and 100 $\mu$m wide) is built on it. Each liquid is inserted on one side and they flow together down the main channel, where the electrode array is placed. The microelectrode array consists of 100 parallel electrodes oblique to the channel. Electrodes are 10 $\mu$m wide separated by 10 $\mu$m gaps and they are energized with an ac signal of amplitude between 0-10 V and in the frequency range 1 kHz-1 MHz. Both fluids are driven by hydrostatic heads and the pressures are adjusted to have the same flow rate of both liquids prior to the application of the electric field. Working liquids are aqueous solutions where KCl is added to control the conductivity. In some experiments, ethanol with dissolved salts and water were used in order to have liquids with the same conductivity but different permittivity (for example: water with KCl as liquid 1; and ethanol with KCl as liquid 2). As demonstrated in [4], the boundary between the two liquids is deflected upon application of ac signals of only a few volts of amplitude. Figure 2 shows an example for two aqueous solutions. We use fluorescence microscopy and the liquid with higher conductivity is labelled with a fluorescent dye (fluorescein), while the less conducting liquid appears dark. When the voltage is on, the whole channel appears fluorescent,
indicating the presence of the more conducting liquid.

The electrical force in an incompressible fluid is given by \( f_E = \rho E - (1/2)|E|^2 \nabla \varepsilon \), where \( \rho \) is the free electrical charge density and \( \varepsilon \) the dielectric constant. The first term corresponds to the Coulomb force, while the second accounts for polarization forces. When we use water solutions, the polarization force vanishes since the permittivity is the same for both streams. However, as a consequence of the difference in conductivities, net free charge is induced at the interface between the two streams. It can be shown that an ac electric field of frequency \( \omega \) acting on a sharp interface between two media of equal permittivities and conductivities \( \sigma_1 \) and \( \sigma_2 \), respectively, induces a surface charge given by \( q_s = \varepsilon \left[ \left( \sigma_1 - \sigma_2 \right) / \left( \sigma_2 + i \omega \varepsilon \right) \right] E_1 \cdot n \) where \( E_1 \) is the electric field in medium 1 and \( n \) a vector normal to the interface. The charge, and therefore the electrical force, vanishes if the two liquids have the same conductivity and/or the applied frequency is high enough.

In the next section we present an experimental study of the interface deflection as a function of frequency, voltage amplitude and conductivity ratio between the two liquid streams. We also present results using ethanol and water as working liquids with the same conductivity but different permittivities. It demonstrates that the strength of polarization forces is also sufficient for producing an important deflection.

![Figure 1. a) Sketch of the microfluidic device showing the inlets for the two fluids and the outlet. An array of interdigitated microelectrode is placed in the middle of the main channel. b) Photograph of the device. Microelectrodes are 10 \( \mu m \) wide and the channel is 500 \( \mu m \) wide and 100 \( \mu m \) high. The pads are for electrical connections.](image)

2. Experimental Results

The experimental procedure relies on quantitative measurements of the fluorescence intensity in a given position of the channel. Grayscale images of two co-flowing streams are captured to a PC and, from these images, we extract the intensity profiles along a straight line transverse to the channel (see yellow lines in figure 2). This intensity results from the light coming from all fluorescent molecules within the depth of the channel. In other words, we do not just collect the light coming from the focal plane (as in confocal microscopy) but integrate the light over the thickness of the fluid layer. We checked this by taking images while focusing at different planes and we obtained the same intensity profiles. Note that, with this measurement, we obtain how much of the fluorescent liquid moved to the region of lower conductivity and vice versa but we do not obtain a full 3D picture of the phenomenon. Therefore, we have also used fluorescent beads suspended in the more conducting liquid. Focusing the beads allows us to distinguish the region occupied by each liquid (these beads diffuse slowly for the typical time of the experiment). We have checked that, after application of the electric field, the more conducting liquid occupies the region near the electrode array, i.e. the region where the electric field is more intense. Because
of incompressibility, the upper part is occupied by the less conducting liquid.

For analyzing the effect of frequency, voltage and conductivity ratio, we fix our attention on a given point in the channel. We chose a position on the right half of figure 2, that is, a region occupied by the less conducting liquid in the absence of applied field. Therefore, the fluorescence is zero when no voltage is applied and relative changes in the fluorescence intensity indicate the presence of the more conducting liquid. Figure 3 shows the fluorescence intensity as a function of the signal amplitude for two different conductivity combinations. Figure 4 shows the fluorescence intensity as a function of frequency. The results are normalized so 0 corresponds to no fluorescence at all and 1 to maximum intensity (that is, fluorescence intensity given by the channel filled with the more conducting liquid). As expected, the phenomenon disappears for frequencies higher than the reciprocal of the charge relaxation time and, interestingly, it also vanishes for low frequencies. Figure 5 shows the impedance of the complete array with the liquids of conductivity $0.75 \text{ mS} / \text{m}$ and $1.5 \text{ mS} / \text{m}$ on it. The impedance of the system increases for frequencies below tens of Hertz. This is due to polarization of the electrodes, i.e. counterions accumulate at the electrode-electrolyte interface and screen the electric field. This is the reason that the phenomenon also disappears at low frequencies.

Finally, figure 6 shows results for water and ethanol with the same conductivity. Dielectric forces are also capable of producing an important interface deflection. In this case, the phenomenon is almost independent of frequency.

3. Conclusions

Using fluorescent dyes is a practical way of characterizing the behaviour of the two coflowing liquids under ac fields. We found that ac signals of a few volts are enough to produce the deflection of the diffuse interface between two water streams with different conductivities over a wide frequency range. The more conducting liquid occupies the region near the electrodes, where the electric field is higher. At low frequencies the phenomenon disappears because of the electrode polarization (the electric field in the bulk vanishes) in accordance with impedance measurements. Experiments with water and ethanol show also that dielectric forces are capable of producing a considerable interface deflection, the liquid with higher permittivity occupies the
Figure 3. Fluorescence intensity vs voltage at a position in the channel where, with no applied field, there would only be non-fluorescing liquid.

Figure 4. Fluorescence intensity vs frequency, the phenomenon disappears at both high and low frequencies.

Figure 5. Impedance measurements of the system vs frequency. The increase of the impedance at low frequencies is due to electrode polarization.

Figure 6. Fluorescence intensity vs frequency for water and ethanol with the same conductivities. Intensity 1 corresponds to the channel filled with water.

region of more intense electric field.

Acknowledgments
Authors are thankful to Dr. N.G. Green and Prof. H. Morgan from Southampton University for providing the microelectrode arrays. Financial support from the Spanish Government Ministry MEC and Regional Government Junta de Andalucía under Contracts FIS2006-03645 and P09-FQM-4584, respectively, are acknowledged. M.F. acknowledges financial support from the Rhône-Alpes region (France).

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