Induced soap-film flow by non-uniform alternating electric field

R. Shirsavar
Department of Physics, University of Zanjan, P O Box 45195-313, Zanjan , Iran

A. Ramos
Departamento Electrónica y Electromagnetismo, Facultad de Física, Universidad de Sevilla, Sevilla, Spain

A. Amjadi, J. Taherinia, and M. Mashhadi
Department of Physics, Sharif University of Technology, P.O. Box 11155-9161, Tehran, Iran

A. Nejati
Physikalisches Institut and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany

PACS numbers:

I. INTRODUCTION

AC Electrokinetics and Electrohydrodynamics refer to the manipulation of particles and fluids by using alternating electric fields. Today, it is a vibrant interdisciplinary field of study with promising applications in microelectromechanical industry, chemical analysis, and biotechnology, the ultimate goal being the development of 'lap-on-chip' or 'factory-on-chip' devices with integrated pumps, reagent dispensers, mixers, separators and detection units that would automatically return data or products [1, 2].

Ramos et al. [3, 4] investigated the electrolyte flow generated by microelectrodes energized by ac voltages. This fluid flow is originated by electrical forces in the double layer between the electrode and the electrolyte and was called ac electroosmosis. Later, Ajdari [5] predicted that the same mechanism produces pumping on an asymmetric electrode array, a fact which was promptly demonstrated experimentally by designing an AC micropump by Brown et al. [6]. AC electrokinetics has been further utilized for trapping micro-particles [7, 8] and mixing of fluids in micro scale [9]. The state of the art in this field is provided in a review by Squires et al. [10]. Most recently, Kim et al. [11] have developed a method of pumping dielectric (or non-polar) liquids using AC/DC non-uniform electric fields which produces a fast and regular flow around electrodes.

Another relevant vein of research is the Electrohydrodynamics of films made of complex structured fluids. Faetti et al. [12, 13] and Morris et al. [14, 15] have shown that passing an electric current through nematic and smectic freely-suspended liquid crystal films produces vortices on the film. Amjadi et al. [16] have shown that applying a uniform electric field on a water film (soap solution) which passes a uniform electric current, produces a controllable rotating flow on the film. The controllable rotation of fluid film have been also reported for polar liquid films [17] and MBBA liquid crystal films [18].

Soap films as two-dimensional complex fluids have been studied by Gharib et al. [19], Chomaz et al. [20] and Rutgers et al. [21]. In these studies, the dominant forces are the gravitational force and the surface–air interaction, and the flow of the soap film is not controllable. In the present work, we have induced a controllable flow in soap films via non-uniform alternating electric fields at sufficiently high frequencies, and demonstrated that changing the configuration of electrodes alters the flow of the soap film in a controllable manner. We have investigated the dependency of the flow pattern and velocity on the electric field configuration.

II. EXPERIMENT

A. Experimental setups

1. *Thin soap films*

To produce the soap films, we dissolve 1 gr of sodium dodecyl benzene sulfonate in 100 ml of distilled water. To increase the stability of the film, we add 10 ml of glycerin to the solution. By drawing a rod wetted with the solution over an electrically-insulating aperture, a suspended soap film is obtained. The dimension of the aperture is ~ 4 cm^2. Such films have a relatively long lifetime ($\sim$ min) compared to other pure liquid films (with lifetimes of ~ 10 sec) [17]. Moreover, we can produce such soap films with dimensions $\sim 10 \times 10$ cm^2, while other pure liquid films can have only

dimensions $\sim 0.5 \times 0.5$ cm^2. Generally, the films can be as thin as 10 μm $-$ 10 nm, while *e.g.*, producing water films of thickness less than 1 μm is quite difficult. Other surfactants (domestic detergents) also showed the same behavior.

2. Particle image velocimetry

After producing a soap film, we wait until a colorful pattern could be observed on the film (due to the interference of incident white light in soap films). Interference color patterns of white light can be used for detecting the soap film flow. For a more accurate detection of the flow velocity, tracer particles such as gold or aluminium flakes smaller than 50 mm, were added to the film and its flow were recorded by a high speed camera (Casio EX-F1) at the rate of 300 frames per second. For each measurement, we have taken 50 consecutive images with a time separation of 3.3 ms. These images can be used for obtaining the PIV pattern by using a VPIV code [17, 18].

3. Setup with non-uniform alternating electric field

To produce a controllable non-uniform alternating electric field, we use an AC power supply which is connected to two parallel rod-like electrodes. The frequency and voltage of the power supply is adjustable. In addition, we can change the non-uniform pattern of the field by changing the configuration of the electrodes. For simplicity, we use two rod-like electrodes which are installed parallel to each other and connected to an AC power supply. The cross-section radius R of rod-like electrodes is 0.5 ± 0.01 mm. The distance d between the electrodes is fixed at 1 ± 0.1 cm. We use a voltage with a sinusoidal shape and an amplitude V_0 in the range $0 - 3$ kV with a frequency range of $0 - 80$ kHz. The distance between electrode tips (d), and between electrode tips and the soap film h is also adjustable.

Here we consider three cases: (1) The "disconnected" setup, in which both electrode tips are perpendicular to the horizontally extended soap film and at a distance $h = 0.5 \pm 0.1$ mm from the film surface (Fig. 1); (2) the "singly-connected" setup, in which both electrode tips are perpendicular to the horizontally extended soap film and one of the electrode tips is connected to the film while the other remains disconnected (Fig. 2); and (3) the "connected" setup in which both electrode tips are perpendicular to the horizontally extended soap film and both of the them are connected to the film. However, in this case, the applied electric voltage passes an electric current through the film which in turn, causes a time-dependent pattern and an unstable flow. Another problem with this case is that bubble formation, chemical reactions and electrolysis also occur in the film in contrast to the previous two cases. Thus, we will focus mainly on the first two setups.

B. Results and Discussion

1. Disconnected setup

In the disconnected setup (no connection between electrodes and the film), there appears two jet flows on the film from the midpoint between electrode positions towards the electrodes. These two jet flows produce four vortices: two rotating clockwise and two counterclockwise (Fig. 3a). Fig. 3b shows the pattern of flow velocity for a typical soap film.

2. Singly-connected setup

In the singly-connected setup (only one electrode connected to the film), there appears a jet flow from the connected electrode to disconnected one. This jet flow produces two vortices rotating in opposite sense (Fig. 4a). Fig. 4b shows the pattern of flow velocity for a typical soap film.

3. Vortices on the soap film

The applied alternating voltage produces time-independent vortices on the film in the disconnected and singly-connected setups (Fig. 3a and Fig. 4a). The non-uniform alternating electric field produces a jet flow on the film, and the frame boundaries limit the spatial extension of the flows. The reflection of the jet flows from the stiff boundary walls results in the observed vortices on the film.

In both disconnected and singly-connected setups, varying R, h, d, the shape of the electrodes, or the frequency or voltage of the power supply changes the velocity of jet flow but does not change its direction.

4. Frequency- and voltage-dependence of the flow

In the connected setup (both electrodes connected to the film), DC or low-frequency electric fields produce a *time-dependent* flow on the soap film, which is not of our interest in this article. For the disconnected or the singly-connected setup, under ac electric fields with frequencies lower than 1 kHz, observing flow on the soap film is not easy while above 10 kHz, the flow can be easily observed. In those experiments, we increased the frequency up to 80 kHz. This increase changes the average flow velocity on the soap film, but does not change the jet flow direction. The measured values for the flow velocity versus frequency in the singly-connected setup are shown in Fig. 5. A quadratic polynomial fit is in excellent agreement with the experimental data, i.e. the average velocity of jet flow $\overline{v}_{jet}$ and the frequency of the applied voltage ω is $\overline{v}_{jet} \propto \omega^2$ in this limited range of frequencies. The observations imply that, at a constant applied voltage, increasing the frequency will rapidly increase the velocity of the jet flow. The average jet flow velocity versus the amplitude of the applied electric voltage is also shown in Fig. 8 which indicates an increase in average jet flow velocity upon increasing the applied voltage. The same behavior was confirmed for the disconnected setup.

5. Thickness of the film

Another effective parameter is the film thickness. This thickness can be measured by interferometry or estimated from the interference colors observed on the film. The thickness of the soap film is usually not constant; it depends on the position and decreases with time.

The films thickness can range from $\sim \mathcal{O}(10)$ μm to $\mathcal{O}(10)$ nm. The film thinning is spontaneous due to evaporation or draining, and hence, cannot be controlled.

However, films (before their rupture) usually approach a minimum thickness of $\sim \mathcal{O}(10)$ nm and hence, are composed of a few layers of soap molecules. At this point, they look black ("black films") [**?**]. Our observations show that thick films ($\sim \mathcal{O}(10)$ μm) do not flow easily under non-uniform AC electric fields; the flow velocity increases with decreasing thickness, although the flow pattern is independent of thickness. In order to have an almost constant thickness in the experiments, we first let the films reach their minimum thickness ("black film") before starting the measurements. The flow patterns of the black films are the same as those for the thicker films (for example, see Fig. 7a). The thickness-dependence of fluid flow velocity implies that the observed phenomena are surface effects and predicts that such fluid flows would not occur in bulk fluid. Therefore, the results can be relevant for the generation of fluid flows in thin suspended films.

III. EXPLANATION OF THE MECHANISM

Fig. 3 and Fig. 4show maximum flow velocity near the disconnected electrode and that near the connected electrode the velocity is small. This latter observation conforms to the non slip condition for a liquid in contact with a solid wall. Since maximum flow is near the disconnected electrode, we think that the mechanism for soap film flow in the configurations of Fig. 1 (two electrodes are disconnected) and Fig. 2 (one electrode is connected) is that of Electrohydrodynamic induction [22]. In effect, the electrode close to the soap film induces charges of opposite sign on the film, which has some electrical conductivity. Upon this charge the electric field tangential to the soap film actuates. The maximum velocity is observed near the disconnected electrode and the flow direction is towards the electrode. We employ the leaky dielectric model in the analysis, i.e. we consider the soap film to be characterized by an electrical conductivity and a dielectric permittivity. For very low frequency of the applied voltage, the soap film behaves as a conductor and because there is a gap between the disconnected electrode and the soap film, there is no current. Therefore, there is no tangential electric field and no tangential force. As the frequency increases, displacement current starts to flow in the gap between the electrode and the soap film and, therefore, there is electrical current along the soap film as well as there is a tangential electric field. We can see it in terms of an RC circuit. The disconnected electrode in front of the soap film behaves as a capacitor and the soap film as a resistor. At very low frequency the impedance of the capacitor is very high and the voltage is dropped mainly in the capacitor, so that the soap film is an equipotential. In this situation, there is surface charge on the soap film but there is no tangential electric field, and no force. As the frequency increases, there is more and more current in the circuit: the displacement current in the capacitor is equal to the ohmic current in the soap film. In this situation, there are both surface charge on the

soap film and tangential electric film, so there is force. At higher frequency, the capacitive impedance is much smaller than the film resistance and all the voltage is dropped in the resistance. In this situation there should be a plateau of the force as a function of frequency. At very high frequency, the dielectric limit is reached in the soap film: the displacement current in the soap film exceeds the ohmic current. In the dielectric limit, there is no free surface charge and, therefore, no force. If we analyze Fig. 5, we can see that the flow increases with frequency. The high frequencies required to observe the dielectric limit has not been reached ($\omega \gg \sigma/(2\pi\varepsilon)$ with σ and ε the electrical conductivity and dielectric permittivity, respectively, of the soap film). This is why it is not observed a maximum of fluid velocity in figure 5.

The capacitance between the electrode and the soap film is of the order of $C = (\varepsilon_0 \pi r^2)/h$, with electrode radius $r = 0.5$mm, gap $h = 0.5\,$mm, which leads to $C \sim 1.4 \times 10^{-14}\,$F. The resistance of the soap film should be of the order of $R = d/(\sigma w t)$, where σ is the electrical conductivity of the film, t is the thickness of the film, d the distance between electrodes and w is the width of the resistor (which should be between $2r$ and d). Using $t \sim 1\,\mu$m, $d = 10\,$mm, $w \sim 5\,$mm, and an electrical conductivity of $\sigma \sim 0.05\,$S/m, the resistance of the soap film is of the order of $R \sim 40\,$MΩ The characteristic frequency of this RC circuit is of the order of $\omega = 1/(2\pi RC) \sim 300\,$kHz. The electrical conductivity is estimated from the concentration of NaDS in water: 1 gr of NaDS per 100 ml of distilled water is around 0.035 mol/l (1 mol NaDS equals to 288 gr). According to reference [23] the electrical conductivity is then around 0.1 S/m. We estimate a smaller value of 0.05 due to the increase of viscosity because of the 10% added glycerin. We expect to see a plateau for velocity against frequency around 300 kHz and a decrease of velocity at frequencies of 10 MHz. The fact that flow velocity is small for thick soap films can be explained using this mechanism. The thicker the film is, the lower the film resistance is. For a given frequency, the voltage dropped in the soap film decreases if the resistance decreases, as well as the tangential electric field and force. Looking at figure 5, if we reduce the soap film resistance the graph should move to the right (the characteristic frequency increases). Therefore, as the thickness of the film increases, and for the frequencies of the experiment, we should observe a decrement in flow velocity associated to a decrement in tangential electric field. Using NaDS in water, this EHD induction flow can be observed because we are using a soap film. A liquid pool of NaDS in water would have much smaller resistance and the EHD induction flow would require very high frequencies to be observed. In other words, the soap film in front of an electrode is a special system for generating flow.

IV. CONCLUSIONS

We have reported the observation that applying non-uniform alternating electric fields by two rod-like electrodes can produce jet flows on thin soap films. The direction of such flows depends only on the configuration of electrodes. For the configurations depicted in Figures 1 and 2, we ascribe the generation of fluid flow to an EHD induction mechanism. The fluid flow is generated close to the disconnected electrode. This implies that by applying alternating electric fields to thin soap films one can produce fairly-controllable and robust jet flows. Using Sodium dodecyl sulfate in water, the effect is only observed for very thin films (thickness $\sim \mathcal{O}(1)\ \mu\text{m} - \mathcal{O}(10)$ nm). Therefore, the results would be relevant for the generation of fluid flows on thin suspended films by the action of ac electric fields.

V. FIGURES

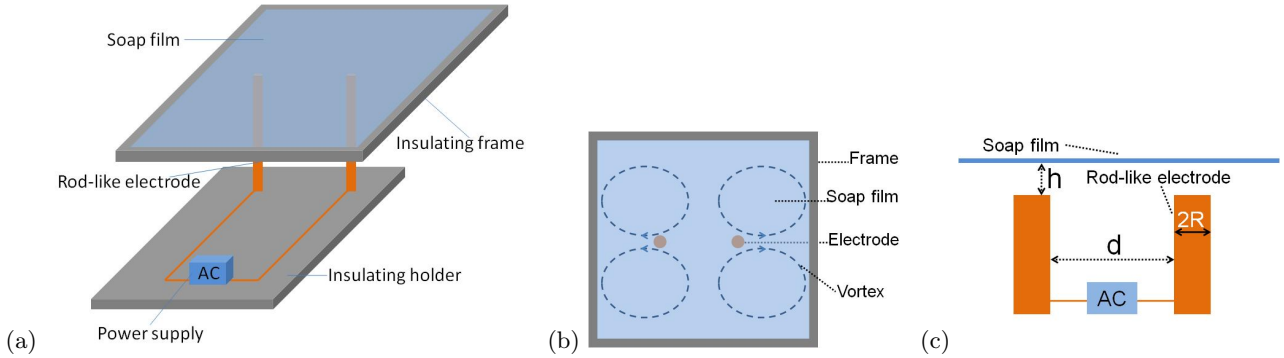


FIG. 1: The disconnected case. (a) Setup for the experiment; (b) top view; (c) side view.

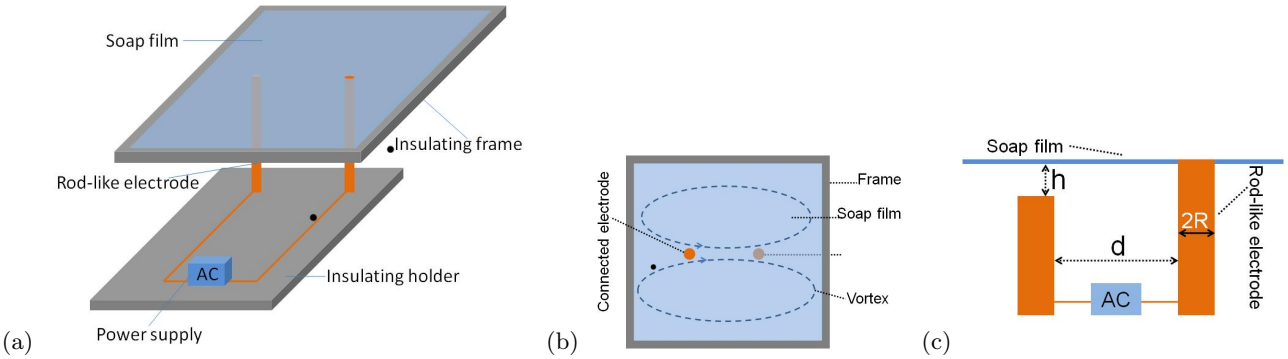


FIG. 2: The singly-connected case. (a) Setup for the experiment; (b) top view; (c) side view.

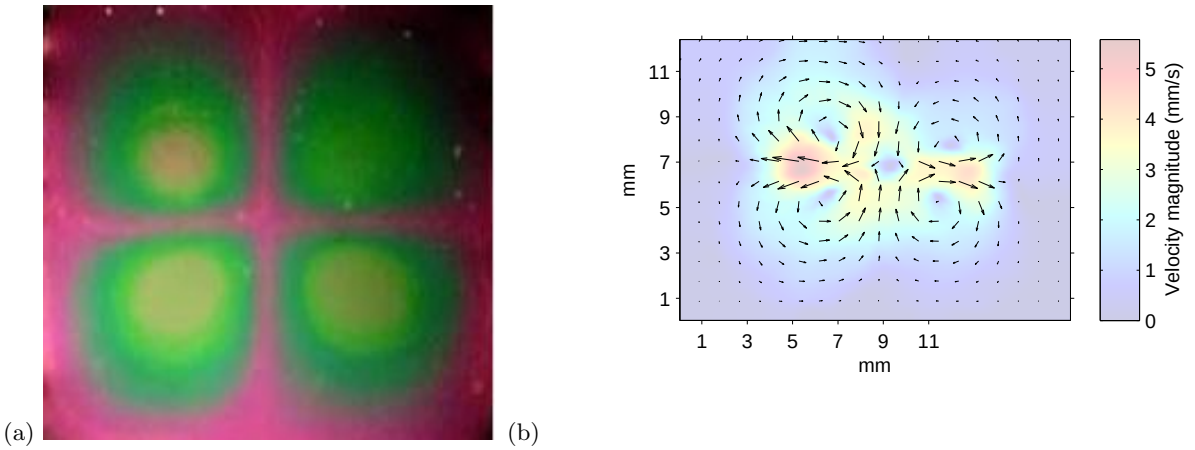


FIG. 3: (a) Four vortices on the soap film in the disconnected setup. The shape of the applied voltage is sinusoidal with amplitude 3 kV and frequency 20 kHz. (b) PIV pattern: two clockwise and two counterclockwise vortices

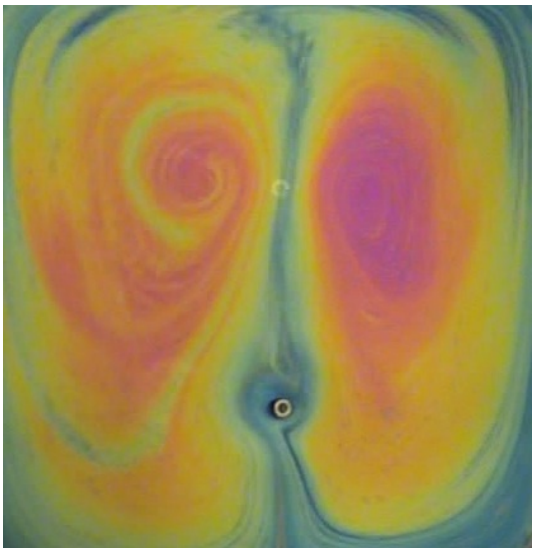
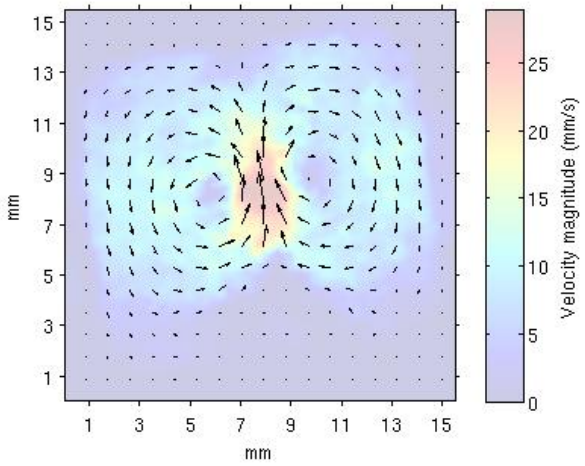
(a)  (b) 

FIG. 4: (a) Two vortices on the soap film in the singly-connected setup. The shape of the applied voltage is sinusoidal with amplitude 3 kV and frequency 40 kHz. (b) PIV pattern showing the jet flow along with the clockwise and counterclockwise vortices

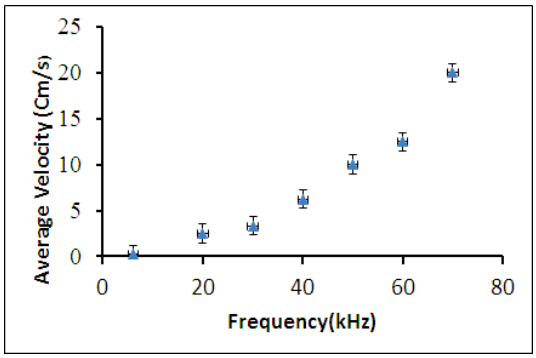
(a) 

FIG. 5: Average jet flow velocity versus the frequency of the applied electric voltage for the singly-connected setup. The applied voltage is 3 kV. The soap film surface is $\sim 4\ cm^2$ and $d = 1\ cm$, $h = 1\ mm$ and $R = 0.5\ mm$

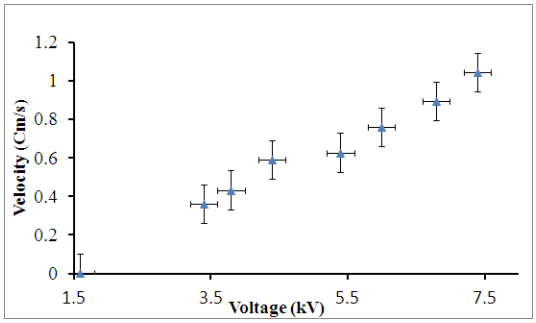
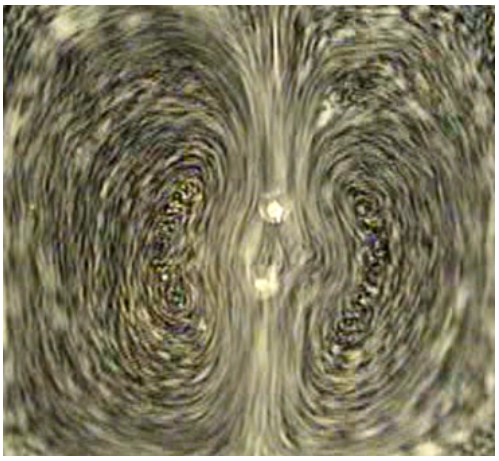


FIG. 6: Average jet flow velocity versus the applied electric voltage for the singly-connected setup. The frequency of applied voltage is 40 kHz. The soap film surface is $\sim 4\ cm^2$ and $d = 1\ cm$, $h = 1\ mm$ and $R = 0.5\ mm$

[1] A. Manz, N. Graber, and H. Widmer, Sensors and actuators B: Chemical **1**, 244 (1990).
[2] M. P. Hughes, Nanotechnology **11**, 124 (2000).

(a) 

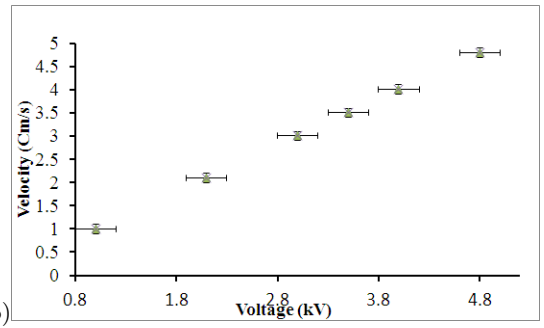
(b) 

FIG. 7: (a) Vortices on a black film for the singly-connected setup. (b) Average jet flow velocity versus applied electric voltage in a black soap film for the singly-connected setup. The black film surface is $\sim 1\ cm^2$ and the frequency of the applied electric field is 10 kHz and $d = 0.5\ cm$, $h = 1\ mm$ and $R = 0.5\ mm$

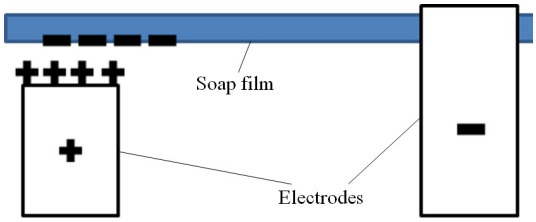


FIG. 8: **Please complete the caption and refer it in the text**

[3] A. Ramos, H. Morgan, N. Green, and A. Castellanos, Journal of Physics D: Applied Physics **31**, 2338 (1998).
[4] N. G. Green, A. Ramos, A. Gonzalez, H. Morgan, and A. Castellanos, Physical review E **66**, 026305 (2002).
[5] A. Ajdari, Physical Review E **61**, R45 (2000).
[6] A. Brown, C. Smith, and A. Rennie, Physical review E **63**, 016305 (2000).
[7] T. Müller, A. Gerardino, T. Schnelle, S. G. Shirley, F. Bordoni, G. De Gasperis, R. Leoni, and G. Fuhr, Journal of Physics D: applied physics **29**, 340 (1996).
[8] L. Y. Yeo, D. Hou, S. Maheshswari, and H.-C. Chang, Applied physics letters **88**, 233512 (2006).
[9] S. Shin, I. Kang, and Y. Cho, Journal of Micromechanics and Microengineering **15**, 455 (2005).
[10] T. M. Squires and S. R. Quake, Reviews of Modern Physics **77**, 977 (2005).
[11] W. Kim, J. Chun Ryu, Y. Kweon Suh, and K. Hyoung Kang, Applied Physics Letters **99**, 224102 (2011).
[12] S. Faetti, L. Fronzoni, and P. A. Rolla, J. Chem. Phys **79**, 5054 (1983).
[13] S. Faetti, L. Fronzoni, and P. A. Rolla, J. Chem. Phys **79**, 1427 (1983).
[14] S. W. Morris, J. R. Debbuyn, and A. D. May, Phys. Rev. Lett **65**, 2378 (1990).
[15] Z. A. Daya, S. W. Morris, and J. R. deBruyn, Phys. Rev. E **55**, 2682 (1997).
[16] A. Amjadi, R. Shirsavar, N. H. Radja, and M. R. Ejtehadi, Microfluidics and Nanofluidics pp. 1–5 (2008).
[17] R. Shirsavar, A. Amjadi, A. Tonddast-Navaei, and M. R. Ejtehadi, Expeiments in Fluids **50 (2)**, 419 (2011).
[18] R. Shirsavar, A. Amjadi, M. R. Ejtehadi, M. R. Mozaffari, and M. S. Feiz, Microfluidics and Nanofluidics (2012).
[19] M. Gharib and P. Derango, Physica D: Nonlinear Phenomena **37**, 406 (1989).
[20] J. Chomaz and B. Cathalau, Physical Review A **41**, 2243 (1990).
[21] M. Rutgers, R. Bhagavatula, A. Petersen, W. Goldburg, et al., Physics of Fluids **8**, 2847 (1996).
[22] J. Seyed-Yagoobi, Journal of Electrostatics **63**, 861 (2005).
[23] M. Abe and K. Ogino, Journal of Colloid and Interface Science **80**, 58 (1981).