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

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Fluid flows generated on soap films by non-uniform alternating electric fields are studied. Two parallel metal rods subjected to an AC voltage are placed perpendicular to the soap film, which is anchored in a dielectric frame. The fluid flow is generated by electrohydrodynamic induction. At very low signal frequencies there is induced surface charge, but there is no tangential electric field at the surface, so there is no force and no flow. Fluid flow is observed increasing the frequency, when there are both surface charge and tangential electric field. The flow velocity increases with decreasing thickness of the soap film.

Introduction

AC-electrokinetics and -electrohydrodynamics refer to the manipulation of particles and fluids by using alternating electric fields. Today, the electrical manipulation at the micrometer scale is a vibrant interdisciplinary field of study with promising applications in micro-electromechanical industry, chemical analysis, and biotechnology, the ultimate goal being the development of 'lab-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] have investigated the electrolyte flow generated by nonuniform ac electric fields generated by microelectrodes, where the fluid flow was originated by electrical forces on the induced charge in the double layer between the electrode and the electrolyte, and was called 'AC electro-osmosis'. 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 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 were the gravitational force and the surface–air interaction. 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.

Experiments

Experimental setups

Thin soap films

To produce the soap films, we dissolve 1 g 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-

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insulating aperture, a suspended soap film is obtained. The dimension of the aperture is ~4 cm^2. Such films have a relatively long lifetime (~1 min) compared to other pure liquid films (with lifetimes of ~10 s) [17]. Moreover, we can produce such soap films with dimensions ~10 × 10 cm^2, while other pure liquid films can have only dimensions ~0.5 × 0.5 cm^2. Generally, such 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 show the same behavior.

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 aluminum flakes smaller than 50 μm, are added to the film and its flow is recorded by a high speed camera (Casio EX-F1) at the rate of 300 frames per second. For each measurement, we take 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].

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 ± 0.1 cm. The applied ac voltage has an amplitude V_0 in the range 0–3 kV and a frequency in the 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 and unstable flow pattern. In addition, 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.

Results and discussion

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.

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.

Vortices on the soap film

The applied alternating voltage produces time-independent vortices on the film in the disconnected and singly-connected setups (Figs. 3a and 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.

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 $\bar{v}_{jet}$ and the frequency of the applied voltage ω is $\bar{v}_{jet} \propto \omega^2$ in this limited range of frequencies. The observations imply

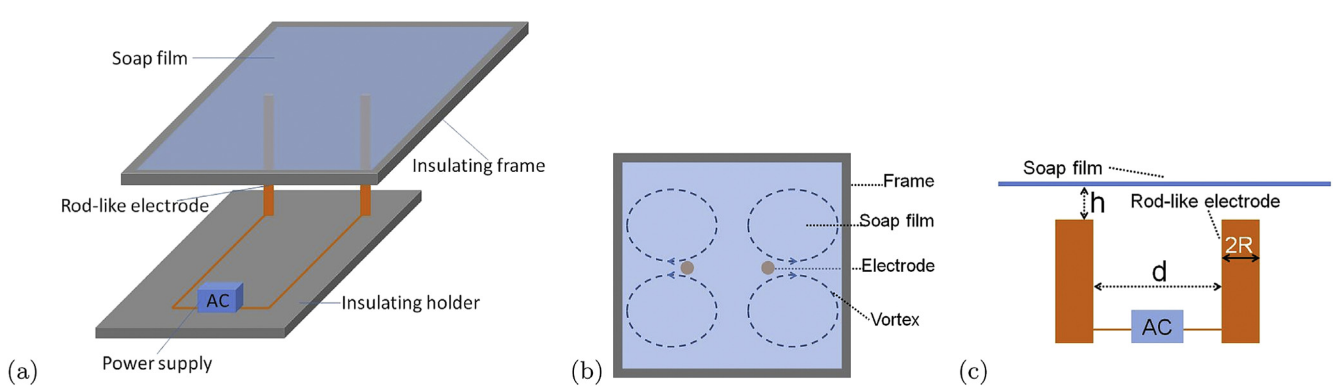

Fig. 1. The disconnected case. (a) Setup for the experiment; (b) top view; (c) side view.