

A Liquid Film Motor

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It is well known that **electro-hydrodynamical effects** in freely suspended liquid films can flow the liquid. Here we report a purely electrically driven rotation in water and some other liquid suspended films with full control on the **velocity** and the **chirality** of the rotating vortices. The device, which is called “film motor”, consists of a quasi two-dimensional electrolysis cell in an external in-plane electric field, crossing the mean electrolysis current density. If either the external field or the electrolysis voltage **exceeds some threshold** (while the other one is not zero), the liquid film begins to rotate. The device works perfectly with **both DC and AC fields**.

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I. INTRODUCTION

In recent years, scientists have become interested in the physics of liquid films. Macroscopic thin films are important in physics, biophysics, and engineering. They can be composed not only of complex materials such as polymer solutions, but also of common liquids such as water or oil. When the films are subjected to the action of various chemical, thermal, structural or electrical factors, they display interesting dynamical phenomena such as wave propagation, wave steepening, and chaotic responses[1, 2]. Water films are more mysterious as the physics of the **hydrogen bonds** in the water film interface is not completely understood yet[3, 4]. Although, it is easy to produce pure water films, **dissolving surfactant molecules in water** makes the films more stable and thinner. Suspended liquid films as thin as hundreds of nanometers or less let us study physical phenomena in a **quasi-two-dimensional** media. For example, quasi-two-dimensional vortices in magnetically active films have been studied as a case of **2D turbulence** [5].

The effect of the electric field on the liquid films has been studied widely, both in **confined films between two transparent plates** [6, 7], and **freely non-confined suspended films** [8]. In the latter case the field can produce electrohydrodynamical (EHD) flow in the films. The two-dimensional EHD motion was observed in freely suspended films made of certain **thermotropic liquid crystal phases: nematic** [9, 10] and **smectic A** [11, 12]. By applying a sufficiently large electric field on thin film of nematic or smectic liquid crystals a pattern of **convective vortices** is observed. When the electric voltage is increased up to a threshold, some vortices are formed on the film. **The vortices rotate in two directions, and the velocity of the rotations depends on the magnitude of the electric voltage. The threshold voltage to enter to the vortex mode is proportional to both average film thickness and square root of electric conductivity of the film** [8]. **The presence of excess charges at the film surfaces** also plays a crucial role in formation of the vortex pattern.

The EHD motions also have been reported on the films of **aqueous solutions** [13]. **The driven motions is used in micro-fluidic systems to mix or phase separate liquids or particles in micro scale systems** [14].

Here, we introduce an EHD effect on freely suspended liquid films. The effect can produce purely electrically induced rotations on suspended films of **water and some other polar liquids**. We call the device “liquid film motor”, as **the direction and the speed of the rotation are controlled through the direction and strength of the applied electric fields**. The motor works perfectly just with pure water, but to **increase the film’s life-time**, we can dissolve some amount of **glycerin** and a little **detergent** in the water. In this way, we make more stable films with **micro- to nano-scale** thicknesses that rotate up to several minutes before they break.

II. THE EXPERIMENT

A. The set-up

The device consists of a 2D frame with two electrodes on the sides for electrolysis of water films. (Fig. 1). The frame is made of an ordinary blank printed circuit board with a rectangular hole at the center, and two copper strips on the sides of the rectangular hole as electrodes. Immersing the frame into a liquid and bringing it out simply makes a suspended liquid film on the frame. As water wets copper perfectly, connecting the electrodes to electrolysis voltage V_{el} causes average density of electric current \mathbf{J}_{el} in the liquid. The cell is located between two plates of a large capacitor. The capacitor produces an external electric field \mathbf{E}_{ext} in the plane of the film and almost perpendicular to the mean current density.

B. The rotation

If either the external field or the electrolysis voltage exceeds some thresholds (while the other one is not zero), the liquid film begins to rotate (Fig. 1). The direction and the speed of the rotation can be controlled through the direction and strength of the current and/or external electric field. The motor works perfectly with just pure water, but to increase the film's life-time, we can dissolve some amount of glycerin and a little detergent in the water. Depending on the aspect ratio of the film frame, the applied external electric field may produce several vortices with different radii (Fig. 1b and 1c), but all of the vortices rotate in the same direction. This shows that the vortices are not convective vortices. Increasing either V_{el} or E_{ext} increases the vortex rotation speed. To measure the rotation speed a digital video camera which takes 24 frames per second is employed. The color pattern of the film, because of white light interference on the film, can be followed on successive frames. In this way we are also able to find angular velocity profile of the film.

The experiment shows that the threshold values of the fields to start rotation in the film are highly related to each other. To see this we fix the value of one of the fields and increase the other until the film start rotation. The measured external-field thresholds for starting the rotations at different electrolysis voltages, are shown in Fig. 2. The log-log plot of the electric field versus electrolysis voltage indicates a slope of -1.00 ± 0.02 for solutions with different glycerin concentration, C . Thus the experiments propose that the threshold fields obey simple scaling relation of $V_{\text{el}}E_{\text{ext}} = \text{Const.}$ The constant value depends on the average and the profile of the film thickness. To fix this parameters we tilt the water film plane by $\theta = 5^\circ$ from the horizon. In this way the thickness profile changes

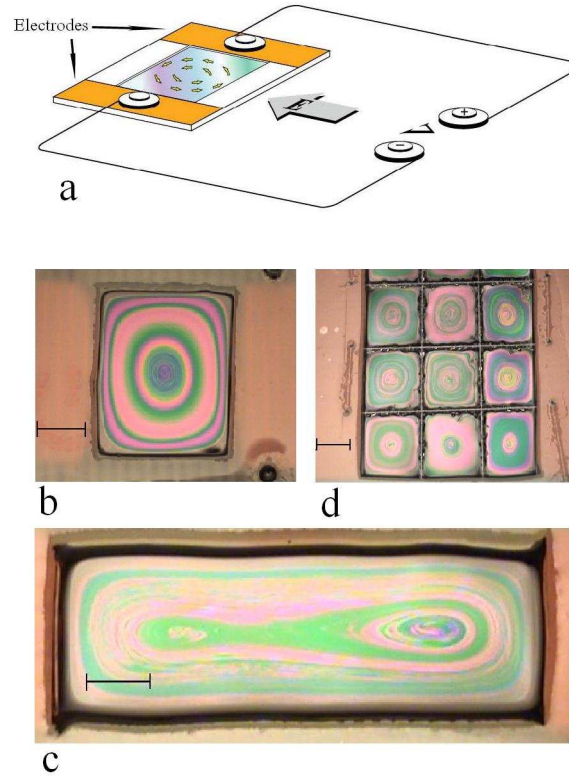


FIG. 1: (a) The set-up of the experiment. (b) A rotating soap film. Different colors on the film are the effect of local thicknesses. (c) Because of the effect of boundary condition, the pattern of rotation may be affected by the shape of the frame. A rectangular cell produces two vortices with the same direction of rotations. (d) The film is meshed by cotton strings. The direction of the rotations in all compartments are the same. Bars on the figures indicate scales of one centimeter. (Movies are available on <http://softmatter.cscm.ir/FilmMotor>)

continuously with time and let us to manage the experiment when it reaches to the similar patterns of interference.

C. The direction of the rotation

The direction of the rotation of the film is on the direction of $\mathbf{E}_{\text{ext}} \times \mathbf{J}_{\text{el}}$. If \mathbf{E}_{ext} is perpendicular to \mathbf{J}_{el} , we have the maximum rotation speed. While by decreasing the angle between \mathbf{E}_{ext} and \mathbf{J}_{el} from 90° to 0° , the rotation velocity monotonically drops down to zero.

Depends on the shape of the cell it is possible that one observes more than one vortex on the film. For example, in the case of the rectangular frames with large enough aspect ratio of the sides two vortices with the same direction of rotation are observed. Also if we divide the cell to smaller compartments using cotton strings there are individual

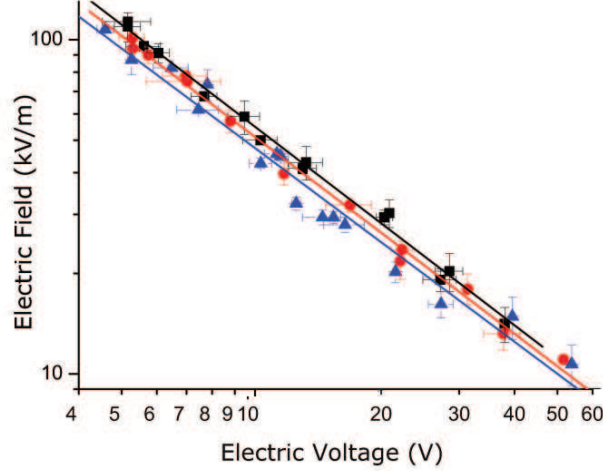


FIG. 2: The electric field versus the electric voltage at the rotating threshold for the solutions with different volume fractions of glycerin (c). $c = 0.1$ (Square). $c = 0.3$ (Circle). $c = 0.5$ (Triangle).

vortices in separate compartments all of rotating in the same direction obeying the above mentioned rule.

III. THE ROTATION MECHANISM

There are several charge based mechanisms which can be responsible as the source of the rotations. For example non-uniform ion distribution, caused by the external electric field (the electrophoresis effect), can break the symmetry under translation of the frictional forces acting on the liquid molecules. An other mechanism has been suggested by Chiragwandi *et al.* to explain observed micro-scale vortices in water based transistors [15]. Their mechanism is based on ionization of the water molecules in the electrolysis double layers close to the electrodes.

By applying the boundary condition on the electric field components excess charges on the liquid-air interface exist. To explain the electrically induced convective vortices, which has been observed experimentally in suspended films of liquid crystals by Morris and his coworkers for smectic A [11, 12], and by Faetti *et al.* for Nematic [9, 10] this surface charges are employed.

However all above mentioned charge based mechanisms could be relevant to the rotation and at least they predict the direction of rotation as observed, we have enough reasons to show non of them is dominant mechanism. In all of them the source of rotation is sitting on the borders of the cell. But investigating angular velocity of vortex shows it rotates faster in the center (fig 3). Also changing the conductivity of the water by adding salt to it do not change speed of rotation significantly while it can increase the conductivity by orders of magnitude. There are also other

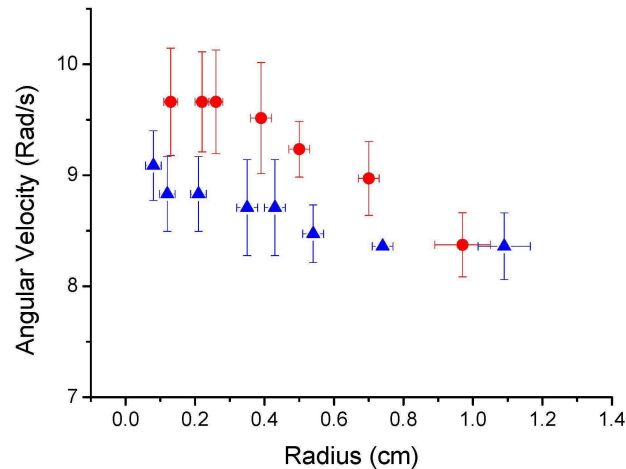


FIG. 3: The film's angular velocity decreases monotonically with the radial distance from the vortex center. We have waited for 45 seconds (circles) and 7 minutes (triangles) after the rotation has started.

observations which can not be explained by these suggested mechanism. When we divide the electrolysis cell to a number of separate compartments using non-conducting cotton strings (Fig 1d), it is interesting that we observe similar rotations in different compartments. looking at the compartment in the middle, surely it has different charge distribution both in volume and surface and there is no ionization chemical reaction on its boundaries, but it rotates as fast as the outer compartments.

On the other hand we have observed that in addition to water films, the film motor operate with some other polar liquids, e.g. Aniline, Anisole, Chlorobenzene and Diethyleoxalate. The characteristics of the rotation for these liquids are similar to each other, then the mechanism of the rotation could be the same for all of them. For example, the direction of the rotation of all liquids that rotate, obeys the same previously mentioned simple rule. Also the threshold values of the fields are in the same order of magnitudes for all the liquids with different electrical conductivity, viscosity and/or density.

We do not observe a clear rotation in the film of non-polar liquids. In particular for 1-Dodecene which is a non-polar liquid with stable films, we do not see any induced rotation. This suggests that the intrinsic polarity of the liquid molecules should involve in the mechanism of the rotation. According to these experiments any long lasting film of liquids with polar molecules rotate well, even if they have a very small conductivity and/or do not contain hydrogen bonds.

IV. THE ROTATION WITH AC ELECTRIC FIELDS

A. The rotation without electro-chemical reactions

To eliminate any electro-chemical reactions near two electrodes that are connected to a liquid film, we have used electrodes covered with insulating paint. Passing the electric current through the liquid film in this case is possible by applying an alternating voltage. With this technique, the electric current passes without any chemical reactions near the electrodes.

If we repeat the experiment with alternating electric voltage and current (in phase with same frequency), the film will rotate. Our experiments on water films have been done with frequencies up to 40 kHz, and the characteristics of the rotation remain the same as in DC case. Thus, the mechanism for the rotation is independent of the electro-chemical reactions.

B. The phase and frequency effect on the rotation

Applying the external and internal fields on a liquid film, with different frequencies, does not produce rotating vortices, but it causes vibrational movements. If the applied alternating fields have exactly the same frequencies, the liquid film rotates. In this case, the threshold and the velocity of the rotation, depend on the phase difference between the fields, ϕ as well as the magnitude of the fields.

For investigation of the effect of phase difference on the threshold, we have applied alternating electric field and voltage,

$$E(t) = E_0 \sin(2\pi ft) \quad (1)$$

and

$$V(t) = V_0 \sin(2\pi ft + \phi), \quad (2)$$

with $f = 50$ Hz. By changing the magnitude of the phase difference, the voltage threshold changes while the magnitude of external electric field is kept constant. For two different given E_0 , the values of V_0 in terms of $\cos \phi$ is shown at threshold points (Fig. 4). To justify these experimental data, we suppose that at threshold points, the time average of EV , \overline{EV} , should be constant. Having

$$\overline{EV} = E_{\text{rms}} V_{\text{rms}} \cos(\phi), \quad (3)$$

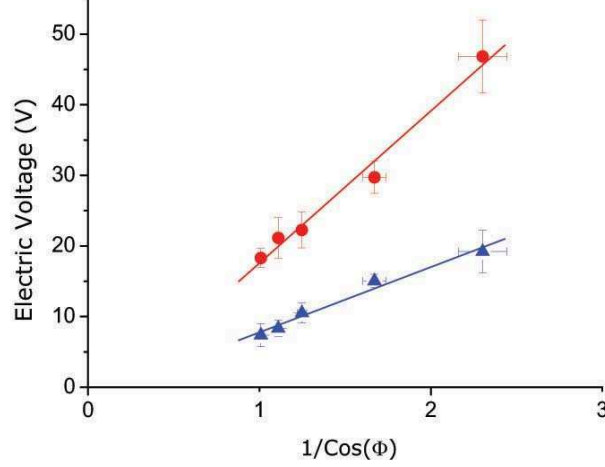


FIG. 4: Threshold voltage, V_0 , versus $1/\cos(\phi)$ for two different values of E_0 . $E_0 = 50$ kV/m (circle) and $E_0 = 100$ kV/m (triangle). In both experiments, the fields frequency are 50 Hz.

thus,

$$E_{\text{rms}} V_{\text{rms}} \propto \cos(\phi)^{-1}. \quad (4)$$

This argument is well consistent with experimental data (Fig. 4). If the frequencies of the fields are not the same the time average in large intervals is zero and the film only vibrates. The vibration frequency is the beating frequency.

V. CONCLUSIONS

Our experimental observations have shown that the suspended films of some liquids can rotate by applying pure electric fields. In contrast with the convective vortices in suspended films, speed and direction of the rotation in the case of our film motor is fully under control by the mean values of the crossed electric fields. In our experiments the films with length scales from tenth of millimeter up to several centimeters have been examined, and there is no reason that it does not work in smaller length scales. This phenomenon may have wide industrial application, e.g. in liquid based centrifuge or liquid mixing devices.

Liquid films rotate without any electro-chemical reactions near the electrodes. Dissolving some amount of a salt in a pure liquid, although increases the electrical conductivity by a few orders of magnitude, but has not a notable effect on the rotation velocity and threshold. Therefore, the ion movement has not significant effect in the rotation, in contrast to the role of the intrinsic dipole moment of a liquid molecule which is deeply vital. Examining different

liquids shows that polar liquids rotate well.

Any efforts to rotate a bulk of liquid was defeated. The fact that only thin liquid films rotate notably and that rotation can not be observed in relatively thick films even at high fields, implies that this phenomenon is a surface effect.

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