Liquid bulk rotation induced by electric field at free surface

Tayebeh Saghaei, Ali-Reza Moradi, Reza Shirsavar, and Mehdi Habibi

Citation: Appl. Phys. Lett. **106**, 053506 (2015);
View online: https://doi.org/10.1063/1.4907254
View Table of Contents: http://aip.scitation.org/toc/apl/106/5
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS **106**, 053506 (2015)

Liquid bulk rotation induced by electric field at free surface

Tayebeh Saghaei,[1] Ali-Reza Moradi,[1,2,3,a)] Reza Shirsavar,[1] and Mehdi Habibi[4,5]
[1]*Department of Physics, University of Zanjan, P.O. Box 45195-313, Zanjan, Iran*
[2]*Optics Research Center, Institute for Advanced Studies in Basic Sciences, P.O. Box 45137-66731, Zanjan, Iran*
[3]*Department of Physics, Bilkent University, Cankaya, 06800 Ankara, Turkey*
[4]*Institute Of Physics, University of Amsterdam, Science Park 904, 1098XH, Amsterdam, The Netherlands*
[5]*Department of Physics, Institute for Advanced Studies in Basic Sciences, P.O. Box 45195-1159, Zanjan, Iran*

(Received 21 August 2014; accepted 21 January 2015; published online 4 February 2015)

In this paper, we induce rotation in a bulk of polar liquid with one free surface, by applying external crossed electric fields. We show that the induced rotation is due to the imposed stresses at the free surface of the liquid. A simple theoretical model was developed based on solving the Navier-Stokes equation that enables us to calculate the average induced stress in the liquid bulk, using experimental measurements of the angular velocity of the liquid. Our results indicate that the induced stresses and the angular velocities of the rotating liquid are independent from the electrical conductivity of the liquid. However, the induced stresses linearly depend on the external electric field and the applied electric voltage for passing the electric current through the bulk. Both experimental results and the theoretical model show that the angular velocity, linearly changes with depth. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4907254]

Hydrodynamics of fluids under an applied electric field has been studied widely.[1–5] With the extension of the concept of *Lab on a Chip*, in many studies, the electric field has been used to control the fluid flow on a small scale and has enabled scientists to design and fabricate micro-scale devices with integrated pumps, reagent dispensers, mixers, separators, and detection units to automatically return data or products.[1,6,7] Electric fields have also been studied to move or control charged or neutral particles immersed in a fluid.[1,8,9] Most of these studies are aimed at investigating biological systems such as controlling the fluid surrounding a single cell and drug delivery systems in the field of biotechnology.[10,11] Several techniques have been suggested for experiments on fluid movement. These techniques are based on the use of thermal gradients,[12,13] magnetic fields,[14,15] or electromechanical means such as piezoelectric actuators.[16] Many such experiments require fluid rotation[10,17,18] that itself requires mechanisms such as using AC and DC electric fields[19–21] or a magnetic field and a magnetic probe[17] to rotate a thin liquid film. A polar fluid, connected to a low DC voltage and high electric field, experiences a torque caused by the electric field maintenance of the equilibrium in polarization. Faetti *et al.*[22] and Morris *et al.*[23,24] have shown that passing an electric current through nematic and smectic freely suspended liquid crystal films produces vortices in the film. Amjadi *et al.* have shown that applying a uniform electric field to a water film (soap solution), which possesses a uniform electric current, produces a controllable rotating flow in the film.[19,20] The controllable rotation of a fluid film has also been reported for polar liquid films[19,20] and MBBA liquid crystal films.[21] In all of these cases, the rotation of a thin suspended film of fluid was studied. In this paper, we report a purely electrically driven rotation in bulk of a polar liquid such as water. Direction and velocity of the rotation are controllable by the electric field and the electric voltage for passing the electric current through bulk. We studied the changes in rotation characteristics under the effect of the depth of the bulk, strength of the applied electrical field, the geometry of the boundary conditions, and conductivity of the fluid.

Fig. 1 shows the experimental setup. This setup is based on an upright home-made microscope. The sample is illuminated from below and is imaged onto a camera (DCC1545M, Thorlabs, 8 bit dynamic range, and 5.2 μm pixel pitch) by an objective lens (4×, Olympus). The image sequences are acquired at the frame rate of 25 fps. Distilled water, water with different concentrations of NaCl, silicone oil with different viscosities, and glycerol (80%) are used as working

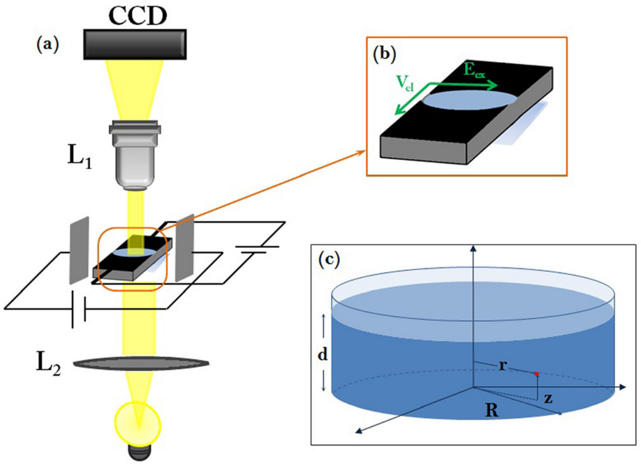

FIG. 1. (a) Schematic diagram of the experimental setup; L_1: focusing lens, L_2: collecting lens. (b) External electric field ($\mathbf{E}_{ex}$) and current vectors (V_{el}) directions. (c) Three-dimensional schematic diagram of the bulk of the fluid container; r: tracer distance from the center, z: depth of the bulk fluid, R: radius of the container, d: depth of the container.

---

[a] Author to whom correspondence should be addressed. Electronic mail: moradika@znu.ac.ir

0003-6951/2015/106(5)/053506/4/$30.00

fluid. Silica micro-spheres (50 μm diameter) are used as tracers to determine the velocity field of the fluid at different depths. The velocity field can be determined by taking a movie of a tracer at a certain depth. The concentration of the tracers is about 16×10^{-2} particles/mm^3 and the effect of the tracer on the velocity field can be ignored. The fluid container consists of a circular cylinder with radius $R = 8$ mm and depth $d = 3$ mm covered by a glass cover slip at the bottom (Fig. 1(b)). The container is an insulating frame with two graphite strips on two opposite sides of it acting as electrodes to supply an electric current. These electrodes are connected to a DC voltage (V_{el}), in the range 20–45 V, generating a uniform density of electric current in the fluid. The container is located between two conducting parallel plates of a capacitor, which was driven by a high DC voltage power supply (1.2–3.03 kV/cm) to produce an external electric field $\mathbf{E}_{ex}$, perpendicular to the direction of the electric current.

In order to check the effect of the polarity of the molecules on the rotation of the fluid, several series of experiments were performed with polar and non-polar fluids. Distilled water and glycerol (80% with a viscosity of about 55 cSt) were used as polar fluids, and rotation was observed for both samples. The angular velocity of the fluid for glycerol was much smaller than that of the water due to the high viscosity of glycerol compared to water. When the same experiment was conducted for silicone oil with three different viscosities (10, 20, and 100 cSt) and hexane (0.45 cSt) as non-polar fluids, the rotation was not observed in the whole range of the experimental parameters. In another series of experiments, the free surface (upper surface) of the distilled water in the container was covered by a glass cover slip or a thin layer of non-polar liquid (hexane) to check whether the rotation was imposed on the free surface or in the bulk. In both experiments, rotation was not observed, which provides strong evidence that rotation is imposed on the free surface of the polar liquid. In the second case, some chaotic movements were observed due to the electric current on the surface at high electric fields, but bulk rotation was not detected. In the second configuration, adding a small amount of surfactant removed the non-polar layer and lead to the onset of rotation. Fig. 2 shows electrically induced rotation in a bulk of water, in which the imaging plane is changed during the experiment to demonstrate rotation in various depths in the bulk. Fig. 3 shows the angular velocity of the fluid at a radius of $r = 2$ mm from the center at different bulk depths (z) for distilled water. The inset of Fig. 3 is velocity vs. depth on a logarithmic scale and the slope of the fitted line is equal to 1.1 ± 0.1. The deviation from the linear behavior for some of data might be resulted from the electrolyze effect which causes irregularities in the fluid rotation due to inducing translational movements. In Fig. 4, the angular velocity of fluid vs. depth for three different concentrations of NaCl in water is shown. The angular velocity of the fluid at a fixed depth is almost the same for different concentrations of salt in the range of the error bars. Fig. 5 illustrates the change in the angular velocity of distilled water with respect to the change in external electric field. These results show that the angular velocity increases with respect to the electric field but the rate of increase depends on the depth. Fig. 6 shows the angular velocity vs. V_{el} at a radius of $r = 2$ mm and an external electric field of $E_{ex} = 3.03$ kV/cm for three different depths. The results show the same behavior in Fig. 5.

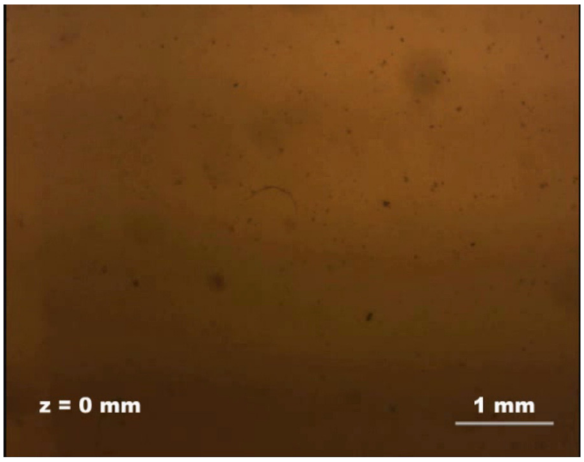

FIG. 2. Electrically induced rotation in a fluid bulk with one free surface. The imaging plane is changed during the experiment to demonstrate the rotation of the tracers in various depths. (Multimedia view) [URL: http://dx.doi.org/10.1063/1.4907254.1]

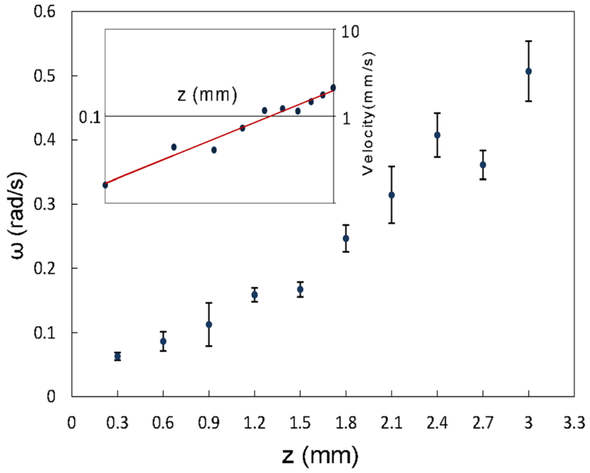

FIG. 3. Angular velocity vs. depth of the bulk of fluid. $V_{el} = 50$ V, $E_{ex} = 3.03$ kV/cm, and $r = 2$ mm. Inset: velocity vs. depth in logarithmic scale. Slope of the fitted line is 1.1 ± 0.1.

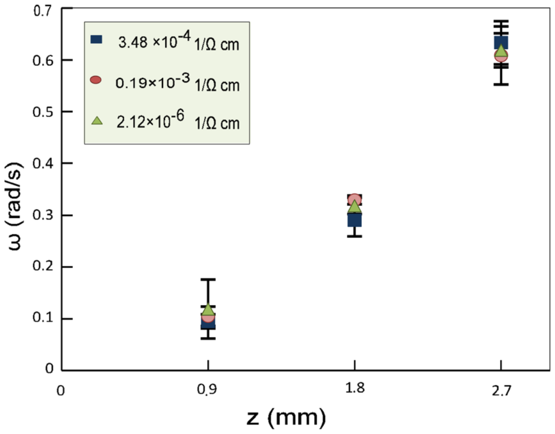

FIG. 4. Angular velocity vs. depth for three different concentrations of NaCl, $c = 1.5 \times 10^{-1}$ mol/l (■), $c = 2.5 \times 10^{-3}$ mol/l (●), and $c = 1.2 \times 10^{-3}$ mol/l (▲). $V_{el} = 50$ V, $E_{ex} = 3.03$ kV/cm, and $r = 2$ mm.

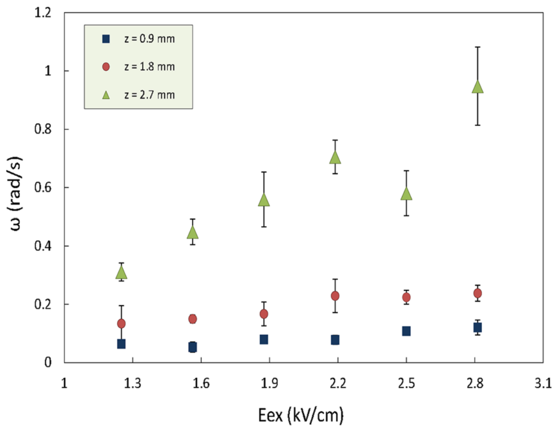

FIG. 5. Angular velocity vs. the electric field applied to the rotating bulk for three different depths ($V_{el} = 50$ V and $r = 2$ mm).

Reynolds number of the studied system for water as the working liquid is about 1, which means we need to consider the inertial term in the Navier-Stokes (NS) equation for steady rotation

$$\rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \eta \nabla^2 \mathbf{v}, \tag{1}$$

with the boundary conditions

$$\begin{cases} z = 0, & v_\phi = 0 \\ z = h, & \tau_{\phi z} = \sigma, \end{cases}$$

where η, ρ, and $\tau_{\phi z}$ are the viscosity and density of the fluid, and the shear stress on the liquid free surface due to the cross electric field, respectively. No external pressure is applied; therefore, the first term at the right side of Eq. (1) equals zero. Considering Fig. 1(c), we can write the NS equation in the cylindrical coordinates (r, ϕ, z). According to our experimental results and considering the symmetry of the system, we know that the only velocity component is in the ϕ direction and the other components are zero. The derivative of the velocity in the azimuthal direction vanishes because of symmetry, and the equation is reduced to

$$\frac{\partial^2 v_\phi}{\partial r^2} + \frac{\partial^2 v_\phi}{\partial z^2} + \frac{1}{r}\frac{\partial v_\phi}{\partial r} - \frac{v_\phi}{r^2} = 0. \tag{2}$$

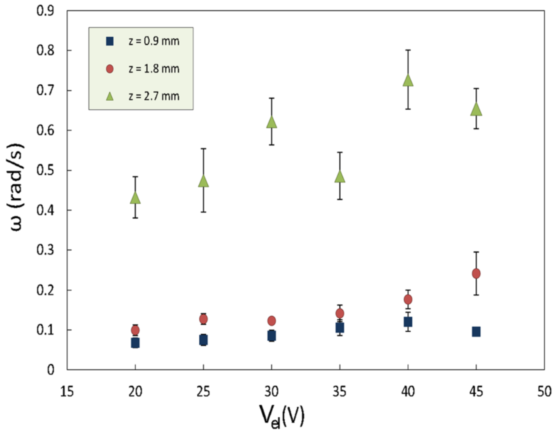

FIG. 6. Angular velocity vs. the electric voltage between the two electrodes (V_{el}) for three different depths at a fixed external field, $E_{ex} = 3.03$ kV/cm, and radius $r = 2$ mm.

By assuming that the radial length scale is much larger than the height of the film, the boundary condition at the perimeter could be ignored and the final equation is simplified as

$$\frac{\partial^2 v_\phi}{\partial z^2} = 0. \tag{3}$$

By considering no slip condition at the bottom and constant shear stress (σ) induced by the crossed electric fields at the free surface on the top of the liquid, a linear velocity profile in the z direction is obtained

$$v_\phi = \frac{\sigma}{\eta} z. \tag{4}$$

The shear stress, σ, depends on the electric field, the applied electric voltage for passing the electric current through bulk, and liquid properties. Using the above equation, σ can be calculated for a specific velocity profile.

Our experiment with polar and non-polar liquids shows that for non-polar liquids no rotation is induced, while for polar liquids even for higher viscosity the rotation can be observed. For a suspended film of liquid, which was called a liquid film motor,[19,20] the same results were reported. When the free surface of the polar liquid is covered with a non-polar thin film, the rotation dies. These results indicate that the rotation in bulk of fluid is due to stresses which are induced by crossed electric fields on the polar molecules at the free surface of the liquid. This observation is in agreement with the previous experimental and theoretical studies on the rotation of a suspended film of liquid.[19,20,25,26] From Fig. 4, one can conclude that the angular velocity is independent of the concentration of NaCl. In other words, applied stress on the free surface is independent of the conductivity of the fluid. These results are in agreement with the theoretical model for the rotation of a suspended liquid film.[25–27] In Refs. 20 and 19, the linear behavior of the angular velocity of the rotating liquid film with respect to the change of the applied electric voltage and external electric field is reported. Furthermore, the theoretical investigations of Liu *et al.*[25] and Shiryaeva *et al.*[26] have predicted a similar linear behavior of the active torque driving the rotation of the liquid film motor to the applied electric voltage and external electric field. The theoretical model includes considering the liquid film as a Bingham plastic fluid with equivalent electric dipole moment and explains most of the observed experimental phenomena. According to Fig. 3, the velocity profile of the fluid is linear with depth and is in agreement with the theoretical prediction of Eq. (4). As shown in Fig. 5, the angular velocity increases with the increase in the external electric field. The other parameter that may affect the angular velocity is the applied electric voltage for passing the electric current through bulk (V_{el}). Fig. 6 shows that the angular velocity increases with increasing V_{el}. The rate of increase depends on the depth, similar to what we observed for the external electric field.

Using Eq. (4), the shear stress σ can be calculated from the experimental data of the angular velocity. Fig. 7 shows σ vs. external the electric field (◆) and V_{el} (●), respectively, on a logarithmic scale. Angular velocities are obtained for an

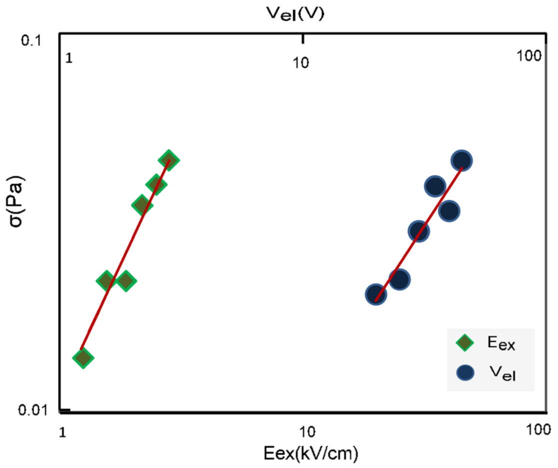

FIG. 7. Shear stress on the free surface σ vs. external field (◆) and electric potential difference (●) on a logarithmic scale. Slopes of the fitted lines are 1.3±0.2 (◆) and 1.0±0.2 (●).

experimental case where the ratio of the radius to the height is about 8 and the approximation in Eq. (3) is valid. Power-law fits to the data in Fig. 7 give exponents of 1.3 ± 0.2 (◆) and 1.0 ± 0.2 (●), respectively, for external field and the applied electric voltage for passing the electric current through bulk, which means that the shear stress approximately shows linear dependence on the external electric field and the applied voltage.

A crossed electric field configuration was used for the rotation of a bulk of fluid confined in a container with one free surface. The presented mechanism can induce effective rotation in a bulk of smaller scale down to micrometer and make a platform for microfluidics application. Our results have revealed that the rotation in the bulk of a fluid in a crossed electric fields is due to the stresses induced at the free surface and is a surface phenomenon. The method was applied for various types of liquids including polar and non-polar liquids with different viscosity and conductivities. A simple theoretical model is developed based on solving the Navier-Stokes equation. The prediction of this model for the velocity profile with respect to the depth is linear and in agreement with the experimental results. In addition, the induced stresses at the free surface are independent of the conductivity of liquid, but follow approximately linear relations with the external electric field and the applied electric voltage.

The authors believe these results are much of interest in the field of biology, where, controllable flow is important and in the field of micro-fluidics for micro-rheology or designing micro-mixers and micro-pumps.

The authors would like to thank Dr. Bahman Farnudi for editing the paper from the English language point of view. A. R. Moradi acknowledges the support of Abdus Salam ICTP (International Center for Theoretical Physics), Italy – the Junior Associateship Program.

[1] T. M. Squires and S. R. Quake, Rev. Mod. Phys. **77**, 977 (2005).
[2] P. Atten, IEEE Trans. Dielectr. Electr. Insul. **3**, 1 (1996).
[3] D. A. Saville, Ann. Rev. Fluid Mech. **29**, 27 (1997).
[4] S. M. Lee and I. S. Kang, J. Fluid Mech. **384**, 59 (1999).
[5] S. M. Lee, D. J. Im, and I. S. Kang, Phys. Fluids **12**, 1899 (2000).
[6] A. Manz, N. Graber, and H. Widmer, Sens. Actuators B **1**, 244 (1990).
[7] M. P. Hughes, Nanotechnology **11**, 124 (2000).
[8] R. B. Schoch, J. Han, and P. Renaud, Rev. Mod. Phys. **80**, 839 (2008).
[9] H. Wen and Sh. Ding, Nonlinear Anal. **12**, 1510 (2011).
[10] A. Terray, J. Oakey, and D. W. M. Marr, Science **296**, 1841 (2002).
[11] T. Bourouina, A. Bosseb, and J. P. Grandchamp, Micromech. Microeng. **7**, 186 (1997).
[12] G. Fuhr, T. Schnelle, and B. Wagner, Micromech. Microeng. **4**, 217 (1994).
[13] M. Felten, P. Geggier, M. Jager, and C. Duschl, Phys. Fluids **18**, 051707 (2006).
[14] A. V. Lemoff and A. P. Lee, Sens. Actuators B **63**, 178 (2000).
[15] A. Homsy, S. Koster, J. C. T. Eijkel, A. Van den Berg, F. Lucklum, E. Verpoorte, and N. F. de Rooij, Lab Chip **5**, 466 (2005).
[16] S. Shoji and M. Esashi, Micromech. Microeng. **4**, 157 (1994).
[17] A. Sokolov and I. S. Aranson, Phys. Rev. Lett. **103**, 148101 (2009).
[18] M. S. Yoon, B. J. Kim, and H. J. Sung, Heat Fluid Flow **29**, 269 (2008).
[19] A. Amjadi, R. Shirsavar, N. H. Radja, and M. R. Ejtehadi, Microfluid. Nanofluid. **6**, 711 (2009).
[20] R. Shirsavar, A. Amjadi, A. Tonddast-Navaei, and M. R. Ejtehadi, Exp. Fluids **50**, 419 (2011).
[21] R. Shirsavar, A. Amjadi, M. R. Ejtehadi, M. R. Mozaffari, and M. S. Feiz, Microfluid. Nanofluid. **13**, 83 (2012).
[22] S. Faetti, L. Fronzoni, and P. A. Rolla, J. Chem. Phys. **79**, 1427 (1983).
[23] S. W. Morris, J. R. de Bruyn, and A. D. May, Phys. Rev. Lett. **65**, 2378 (1990).
[24] Z. A. Daya, S. W. Morris, and J. R. de Bruyn, Phys. Rev. E **55**, 2682 (1997).
[25] Z. Q. Liu, Y. J. Li, G. C. Zhang, and S. R. Jiang, Phys. Rev. E **83**, 026303 (2011).
[26] E. V. Shiryaeva, V. A. Vladimirov, and M. Y. Zhukov, Phys. Rev. E **80**, 041603 (2009).
[27] Z. Q. Liu, Y. J. Li, G. C. Zhang, and S. R. Jiang, Phys. Rev. E **85**, 036314 (2012).