A rotating fluid bulk characterization

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Based on the use of an external intense electrical field we rotate a bulk fluid and investigate the effects of bulk depth, fluid concentration, boundary conditions, and fluid conductivity on the angular and linear velocity of the rotating bulk. A polar fluid in crossed electric fields, connected to a low dc voltage within an intense electric field, experiences a torque of rotation caused by the electric field maintenance of polarization equilibrium. The angular and linear velocities are extracted from post processing of recorded image sequences. Our experimental results show an increase in the rotating rates by increasing the fluid depth, and conductivity has not an effective change on the velocity. However, the boundary conditions may change the rotating rate, or avoiding the rotation even in an intense electric field. Experimental results are in a good agreement with the theoretical model based on inserting an external force along the rotation direction in Navier-Stockes equation.

PACS numbers:

Introduction Movement control and manipulation of small volumes of fluids have been of high interests being subject of many researches in recent years [1,2]. These researches are mostly aimed to investigate the biological systems such as single cell surrounding fluid control and drug delivery systems in the field of biotechnology [3,4]. Moreover, applications from microfluidic machine use to material pumps have been utilized fluid movement mechanisms [5]. Fluid movement has been used to pump fluids either as a mechanism of propulsion for the micromachines or to move materials across the surface of an analytical probe [6]. Several methods to achieve microscopic pumps based on the use of thermal gradients [7], magnetic fields [8], or electromechanical means such as piezoelectric actuators [9] have been utilized. To perform many of these tasks means are required to rotate fluids. In predated studies mechanisms such as using AC and DC electric fields to rotate a thin film [10 shirsavar], or magnetic field and a magnetic probe to rotate a fluid containing bacteria [11 anderson] have been used. In [12] couple of electric fields have been applied various materials including liquid crystals to achieve stable rotation motors. Theoretical investigations on the origins of such mechanisms have been also presented [13,14]. However, rotation of a bulk fluid using electric fields has not yet reported. The capability of a bulk rotation may be a crucial task for many studies including biological studies in which the organelles need to be contained in volumes of their normal buffer. In this Rapid Communication, for the first time to the best of our knowledge, we report a purely electrically driven rotation in a bulk of polar liquid such as water. We studied the rotation characteristic under the influence of depth change of the bulk, applied cross electrical fields' strength, surface boundary conditions, and conductivity of the bulk under study.

Experiments Figure 1 shows the experimental setup. The setup is based on an inverted home-made microscope. The sample on the microscope stage is illuminated by the light from illumination source, and is imaged onto the detection device (DCC1545M, Thorlabs, 8 bit dynamic range, and 5.2 m pixel pitch) by an objective lens (4x, Olympus). A small volume (0.34 cm^3) of distilled water including suspended tracers was used as a polar sample. We used silica microspheres (50 μm) as tracers for the detection procedure. The particles are suspended in various depths of fluid enabling measurement of rotating velocity in different depths. The device

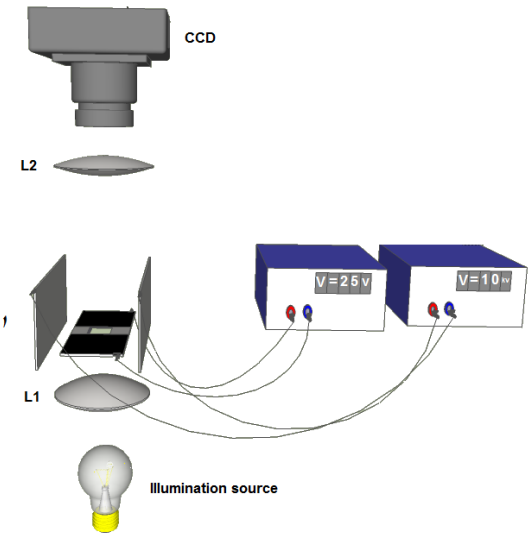

FIG. 1: The experimental setup scheme.

for the fluid container consists of a 3D frame with two

graphite electrodes on the sides for electrolysis of water. The frame consists of a cylindrical hole in the center with 6 mm radius and 3 mm depth. The electrodes were connected to electrolysis voltage V_{el} causing a uniform density of electric current $\mathbf{J}_{el}$ in the water. The frame is located between two conducting plates of a large capacitor driven by a high voltage supplier to produce an external electric field $\mathbf{E}_{ex}$. As illustrated in Fig. 1 this external electric field is perpendicular to the current density direction performing a crossed electric fields arrangement capable for fluid rotation. The image sequences were acquired at the frame rate of 25 fps. We examined both AC and DC electrical fields to observe the phenomenon. However, the use of AC fields requires a fast image acquisition at least of the order of the AC frequency. Instead, DC fields may cause a more steady fluid rotation at a constant rotation rate for an adequate time, and a simple analysis. Hence, in all of our measurements we have used DC electric fields.

Theory Reynolds' number of a small volume of a liquid like water is bigger than one requiring nonlinear terms of the Navier- Stokes' equation. Assuming a steady movement of fluid, time-dependence of the equation can be neglected. According to the experimental observations a constant force along the rotation axis can be inserted in the equation as an external force for a steady rotation:

$$\rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \eta \nabla^2 \mathbf{v} + \mathbf{F}_{ex}, \qquad (1)$$

where, η and rho are the fluid's viscosity and density, respectively. Considering a cylindrical coordinate (ρ, ϕ, z), since radial and height components of the velocity are zero, and according to the symmetry in azimuth direction the derivative of velocity in the azimuth direction vanishes, and the equation is reduced to:

$$\frac{\partial^2 v_\phi}{\partial \rho^2} + \frac{\partial^2 v_\phi}{\partial z^2} + \frac{1}{\rho}\frac{\partial v_\phi}{\partial \rho} - \frac{v_\phi}{\rho^2} + \frac{A}{\eta} = 0. \qquad (2)$$

In this equation the external force originated from the crossed electric fields is considered as $F_{ex} = A\hat{\phi}$, where A is a constant and the force is along the rotation axis. Boundary conditions for the present experimental configuration include a zero rotation velocity at the bottom of bulk container and a maximum velocity at the free surface on top of the frame. Moreover, to remove the wall proximity effects we assume that the depth of the bulk is much smaller than the radial size (approximately 1:10). The sample container was designed and fabricated with the same depth to radius ratio to match with the theoretical model. Within these approximations the following expression for the velocity dependence to the bulk depth can be achieved:

$$v_\phi = \frac{A}{2v} z^2 + (-\frac{Ah}{v})z, \qquad (3)$$

where h is the thickness of the bulk, and z is measured from the bottom of bulk container. The above equation is used for fitting the linear velocity data measured from the image sequences processing. The goodness of curve fitting may result in validating the presented theoretical background for a rotating bulk.

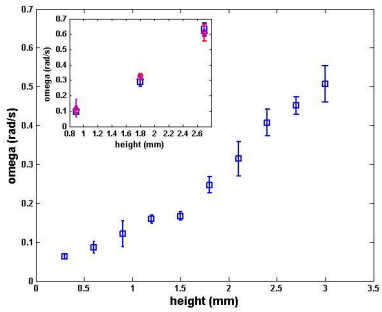

FIG. 2: Fig2 snaps

Experiment results Figure 2 shows four snaps of a rotating bulk at times $t_1 = 0$, $t_2 = 1$ s, $t_3 = 2$ s, $t_4 = 3$ s, when the particles in depth of 1.2 mm were in focus of imaging system. The bulk fluid is distilled water including silica microspheres of 100 μm size. Finding the rotation center, tracing a distinguished particle, and knowing the time intervals between data acquisition, the rotational velocity can be measured. These tasks were performed for every image sequences (which were obtained from converting acquired movies into images) for various experimental conditions, and rotating parameters of the samples were determined. Figure 3 shows the angular velocity of a rotating bulk fluid in different layers of the bulk. The focused images of various layers were acquired in every 0.3 mm from 0.3 mm to 3 mm. Figure 4 shows the calculated linear velocity of the same sample, in which a second degree polynomial $v = az^2 + bz + c$ is fitted according to the theoretical prediction. However, to ensure that the experiment conditions are within the theoretical model, we kept and depicted only the data for layers of $h/r < 1$. The fitting parameters are $a =$, $b =$, and $c =$, which are quite close to the theoretical prediction. However, . (what is A?). In the inset of Fig. 4, the results of the same procedure to find the $v - h$ relation are shown for three NaCl solved in water solution of different concentrations $c =$, , and . These experiments may state that the angular velocity of a polar bulk in a crossed electric field arrangement is independent from the conductivity of the fluid bulk. This is in agreement with the theoretical presented model, in which the only possibility to be affected by the change in conductivity is the applied voltage to flow appreciable electrical current in the fluid to rotate it.

Figure 5 illustrates the change of angular velocity with respect to the applied high voltage change. The results were obtained for three different depths of the bulk. Our results show that in small ranges of depths the angular velocity doesn't vary appreciably with the changes

of the applied voltage. However, in higher depths it increases dramatically through a linear relation. The other parameter that may affect the angular velocity for rotating bulk of polar fluids is the low voltage between the two electrodes of them during the experiments. Figure 6 shows the result of varying that voltage and the resulting changes in the angular velocity. These results show the dramatic changes in the angular velocity in higher depths when increasing the electrodes voltage. We examined the possibility of rotation of a bulk for various fluids. most of the above results are for Newtonian fuids having a low viscosity. The experiments were conducted for two $non_Newtonian fluids(y)$ and three silikon oils NaCl solutions with different viscosities.

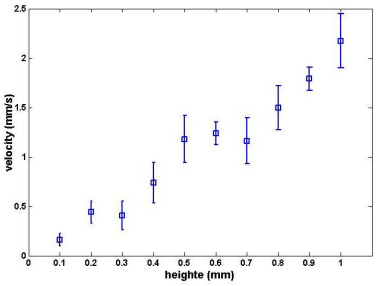

FIG. 3: Fig4 v-z

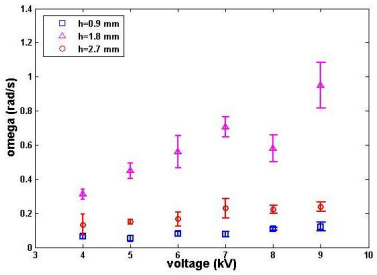

FIG. 4: Fig4

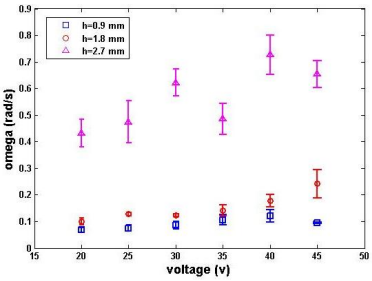

FIG. 5: Fig5

We showed experimentally that a system of two droplets of different sizes at the ends of a microchannel can behave in three different ways. Considering the different possibilities we developed a numerical scheme needed for dealing with the system of two finite connected droplets. The importance of different phases for observing a flow from the larger droplet to the smaller one was shown.

By changing the properties of the surface underneath each droplet we can generate situations in which the phase of the process is determined through out the whole process (FIG **??**), and therefore we can manage to get the back flow by choosing the appropriate initial conditions. This provide a different possible interpretation of the experiments by Berthier, Beebe and Ju et al. [11, 12], who observed backflow in situations similar to the ones described here. They argue that inertia, originating from a rotating flow in the bigger droplet, is responsible for the backward flow. However, the Reynolds number in their experiment being $Re \simeq 2\times10^{-2}$ casts some doubt on this interpretation of their experiments (The Capillary number in their experiments was $Ca \sim 10^{-5} - 10^{-6}$). In our experiments, we changed the wetting properties, but it should also be possible to create a backflow by controlling the surface roughnesses on either side of the channel.

In addition, we have shown by taking advantage of dynamic manipulation of the effective surface properties by electro-wetting, that a bidirectional microchannel can be made. The possibility of changing the flow direction back and forth by simply turning the voltage off and on, can make the capillary pumping method a much more powerful tool in microfluidic technologies.

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