

Electrohydrodynamic Flow around a Circular-Cylindrical Rod Submerged in a Dielectric Liquid

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비전도성 액체에서의 실린더 막대 주변에 생기는 전기동역학적 유체흐름

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Abstract

The induced-charge electroosmosis (ICEO) is a kind of electroosmotic flow which is generated by the electrical charge induced by an externally-applied electric field. That kind of electrokinetic phenomenon provides a non-mechanical technique to handle microscale flows and particles. In this work, we report that the ICEO-like flow is observed around two kinds of circular-cylindrical rod submerged in a dielectric liquid. The conductivity of the solution is varied by adding a surfactant. The flow field is visualized by the PIV method, and average flow speed shows a remarkable dependence on electrical input frequency. Interestingly, the characteristics of the flow are quite different from the conventional ICEO with respect to the flow direction and the locations of center of vortices.

1. Introduction

Recently, electrophoretic display (EPD) begins to draw much attention as a promising technology which can replace a conventional display as a flexible paper-like display.

It has been reported that colloidal particles migrate laterally like a Brownian motion beyond a certain voltage [1,2]. The instability limits the increase of driving voltage which is necessary to fasten the response time of the particles for a given input signal. Although this type of problem has been considered for a long time, a persuasive explanation has not been reported yet.

It has been reported that particles in aqueous electrolyte solutions tend to be clustered together or pushed aside when the particles are close to an electrode surface [3,4]. These phenomena have been interpreted in terms of hydrodynamic interaction resulting from

electroosmotic flow around each particle [5].

In the EPD, however, non-polar solvents are used as a medium. Therefore, there exist only too few ions in such a solution to expect the existence of such a strong electrokinetic flow. Interestingly, however, ions are generated in a dielectric liquid if we add a surfactant [6]. As a consequence, even if a non-ionic surfactant is added, the electrical conductivity increases with the concentration of the surfactant [7]. We assumed that these ions form an electrical double layer and then produce electroosmotic flow (EOF) which was supposed to cause the EPD instability. Recently, we truly observed the hydrodynamic flow around a small spherical particle placed on an electrode surface in a dielectric solution [8]. As far as we know, this sort of flow is reported by our group for the first time. We attempted to find out the cause of the flow by analyzing the flow field numerically within the frame work of the conventional induced-charge electroosmosis (ICEO) [9,10]. However, the result exhibited much different characteristics compared with the flow we observed in the dielectric solutions. This suggests that the flow in the dielectric solution has inherent peculiarities different from the conventional electrokinetic flow including the ICEO.

It was necessary to eliminate any cumbersome effects

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of electrode on the flow in order to figure out the cause of the flow more easily. Therefore we carried out experiments with a circular-cylindrical rod placed between the two electrodes. As the first step towards complete understanding of the origin of the flow, we investigated the effects of surfactant, the electrical property of the rod, and the frequency applied to the solution. In this paper, we report our preliminary results.

2. Experiment

Two parallel ITO-coated glasses are submerged in a dielectric liquid of dodecane(anhydrous 99%, SIGMA) as shown in Fig. 1. The gap distance between the two electrodes can be changed by a transverse. An electric signal generated by a function generator (33220A, Agilent) is amplified by using a voltage amplifier (Model 10/10B, TREK) by one thousand times. In order to visualize the flow field around the cylindrical rod, a laser sheet is generated by using a collimated line generator (Model c-10, Stockeryale Co.) and an Nd:Yag laser (GAM-200, Aixiz) which has the wavelength of 532 nm. As a seeding particle, fluorescent particles of 7 μm (Fluorescent polymer microspheres, Duke Scientific) are used. A CCD camera (INFINITY 2-2C, Lumenera) having a 1616 \times 1216 pixels array is used to obtain streamlines of the flow field and images for the PIV analysis. The amount of surfactant SPAN85 is fixed at 5wt%. The input frequency is varied from 0.01 mHz to 400 Hz. Two kinds of rod are used: one is the conducting rod of nickel and the other is the dielectric rod made of polymer (PEEK Tube, Chrome Tech). In order to obtain streamlines of the flow, the long time exposure technique is used. Images are recorded at 37 frames per second. The images are analyzed with a PIV analyzing software (MATPIV) to obtain the velocity field [11].

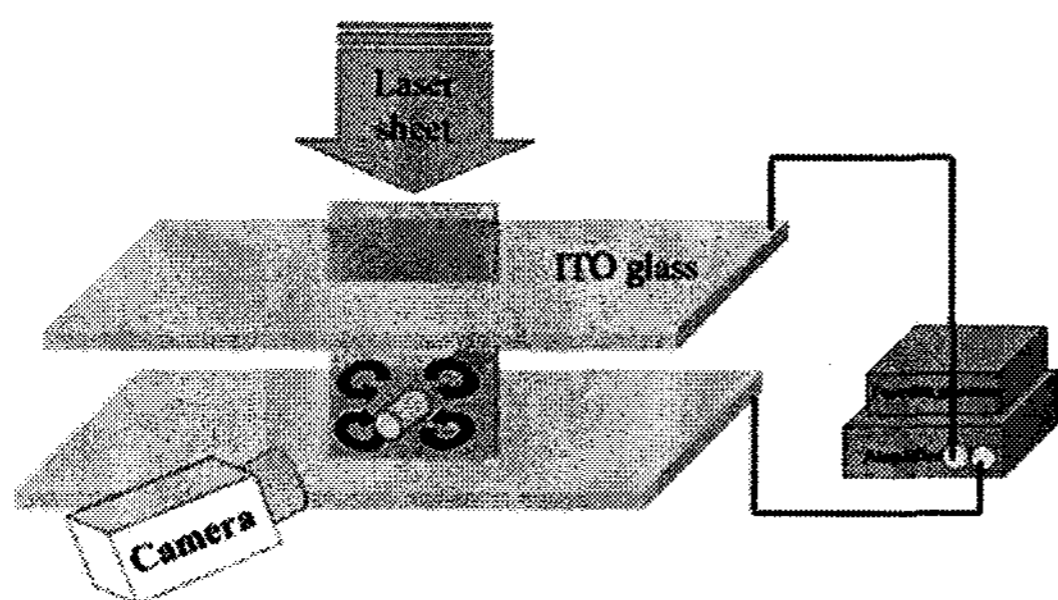


Fig. 1. Experimental setup

3. Results and Discussion

No flow is observed around a conducting cylinder in a pure dielectric liquid as shown in Fig. 2. However, when the surfactant SPAN85 is added, four regular vortices appeared around the conducting cylinder shown in Fig. 3. Figure 4 shows the PIV data corresponding to the case of Fig. 3. The flow pattern is found to be driven

from the 'equator' of the rod towards the 'poles' as shown in Fig. 4. Here, the equator corresponds to the right and left sides of the cylinder in photos, while the poles represent the lower and upper sides. Average flow speed is measured to be 1.3 mm/s in this case.

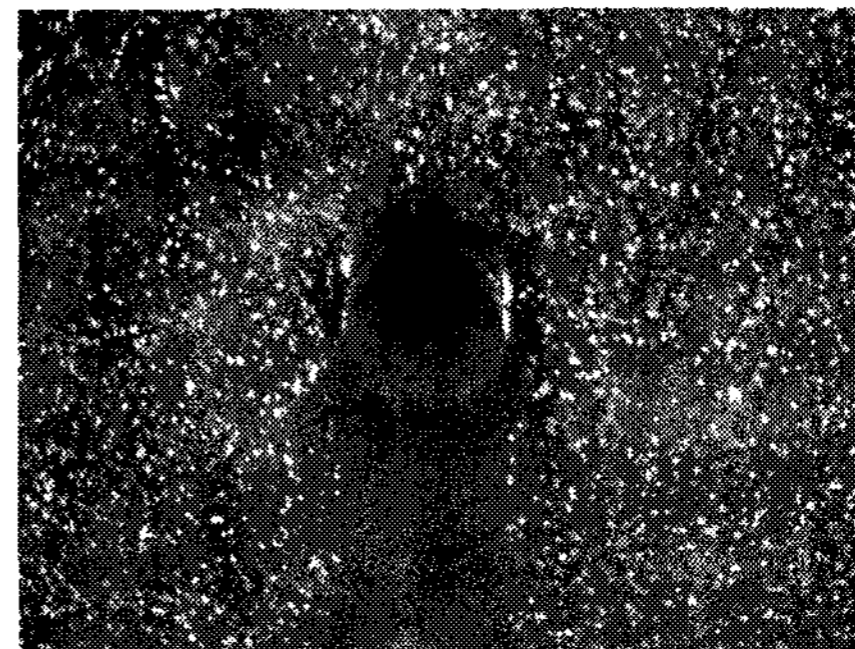


Fig. 2. Flow around a conducting cylinder with 1 mm diameter without surfactant in which $\Delta V = 4 \text{ kV}_{pp}$ and $f = 20 \text{ Hz}$

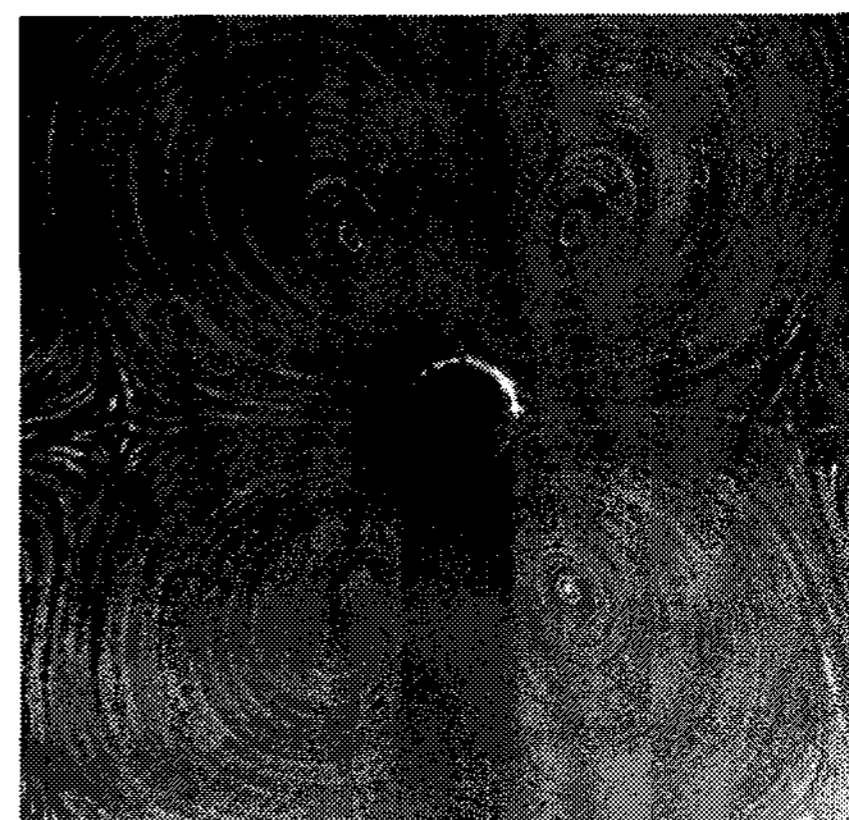


Fig. 3. Flow around a conducting cylinder with 500 μm diameter with surfactant in which $\Delta V = 4 \text{ kV}_{pp}$ and $f = 20 \text{ Hz}$

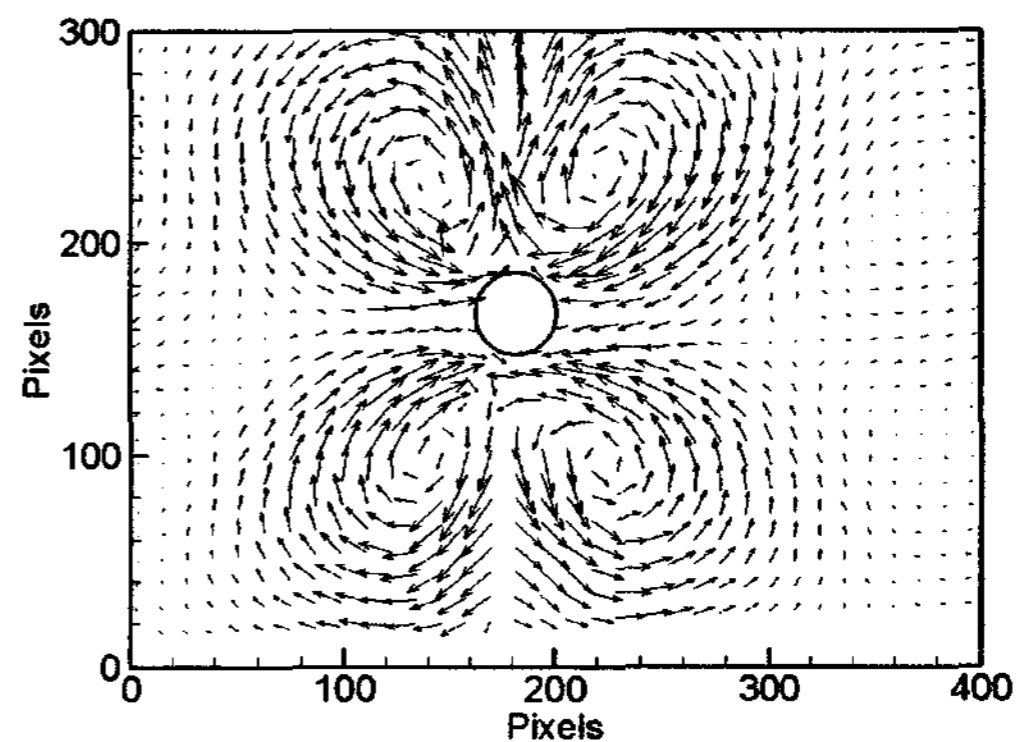


Fig. 4. PIV data for the case of Fig. 3. (One pixel corresponds to 14 μm)

At first, we regarded the flow as one of the conventional ICEO. To check if it is true, we numerically analyzed the flow field within the framework of the conventional ICEO. Figure 5 shows the numerical results for the electric field (left) and the flow field (right). However, the numerical result represents that directions and positions of the vortices are not consistent with our experimental result. Most of all, the direction of the flow is totally reversed. In addition, the centers of the vortices are located a little far away from the cylinder compared with the experimental results. This means that our experimental result cannot be explained by the conventional ICEO and requires other theories.

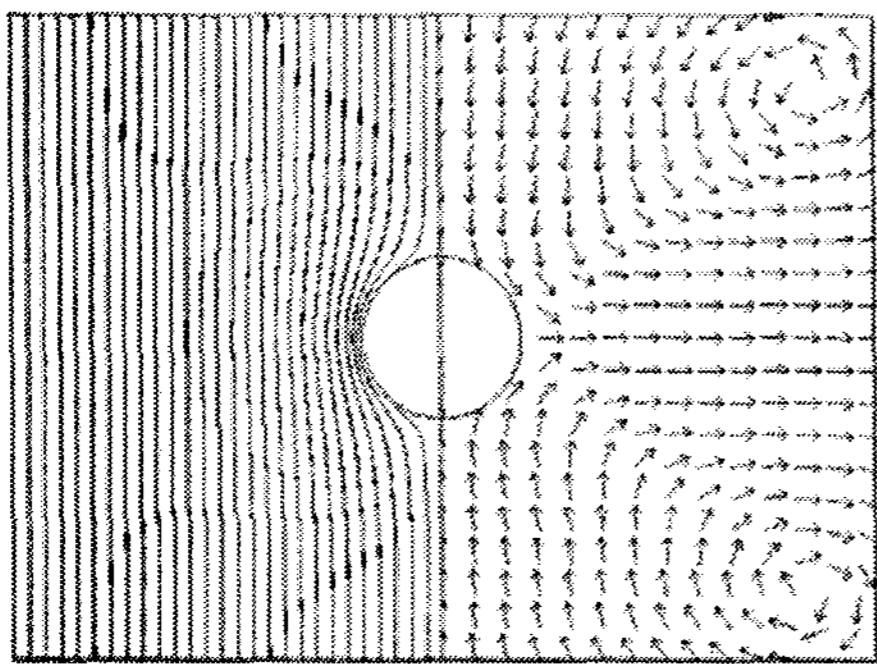


Fig. 5. Simulation of the conventional ICEO with conducting cylinder using COMSOL Multiphysics.

Experiments are carried out for different frequencies of 10 mHz, 20 Hz, 100 Hz, and 200 Hz for the conducting cylinder. Among them, the case of $f = 10$ mHz is considered to investigate the characteristics of DC electric field. As shown in Fig. 6, the average flow speed decreases monotonically with increasing frequency. No flow is observed if the input frequency is greater than 400 Hz. We also performed experiment for the dielectric cylinder. The centers of vortices are closer to the rod (Figs. 7(a) and (b)) for the conducting cylinder. The flow pattern is driven from the 'equator' of the cylinder towards the 'poles' for both kinds of cylinders as shown in Figs. 8(a) and (b). Average flow speed is 2.0 mm/s of the conducting rod which is slightly faster than 1.6 mm/s of the dielectric rod.

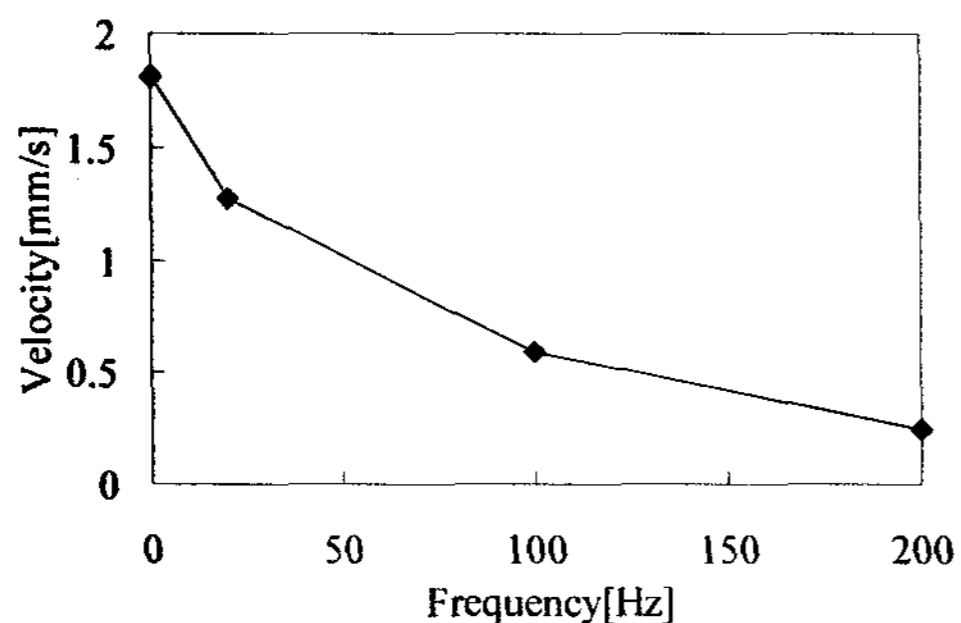
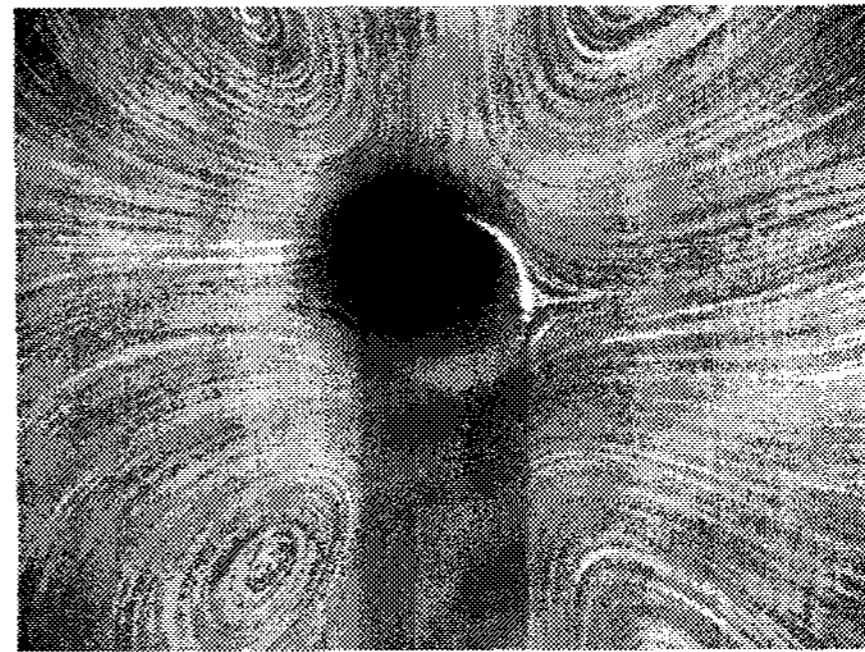
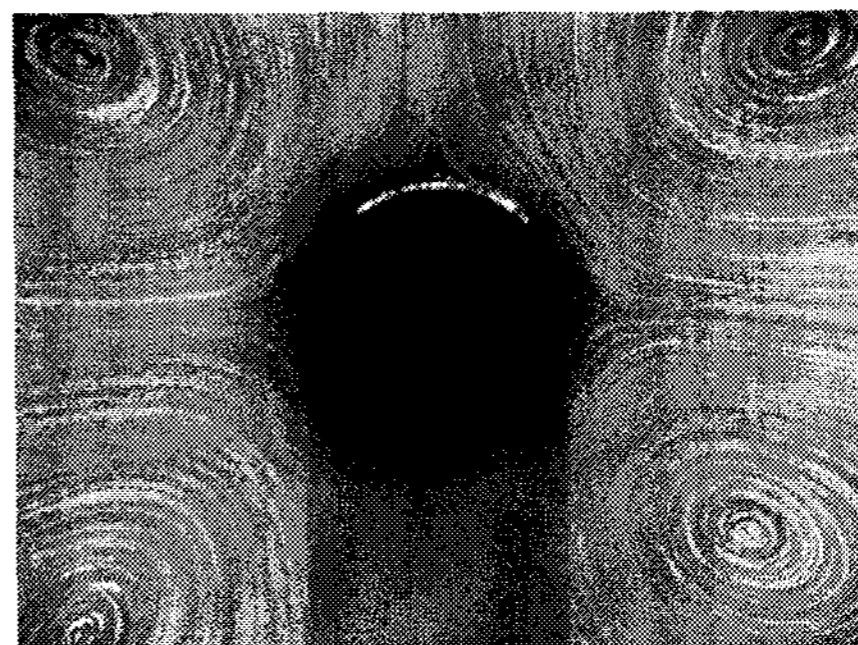


Fig. 6. Frequency dependence of the average flow speed when $\Delta V = 4 \text{ kV}_{pp}$

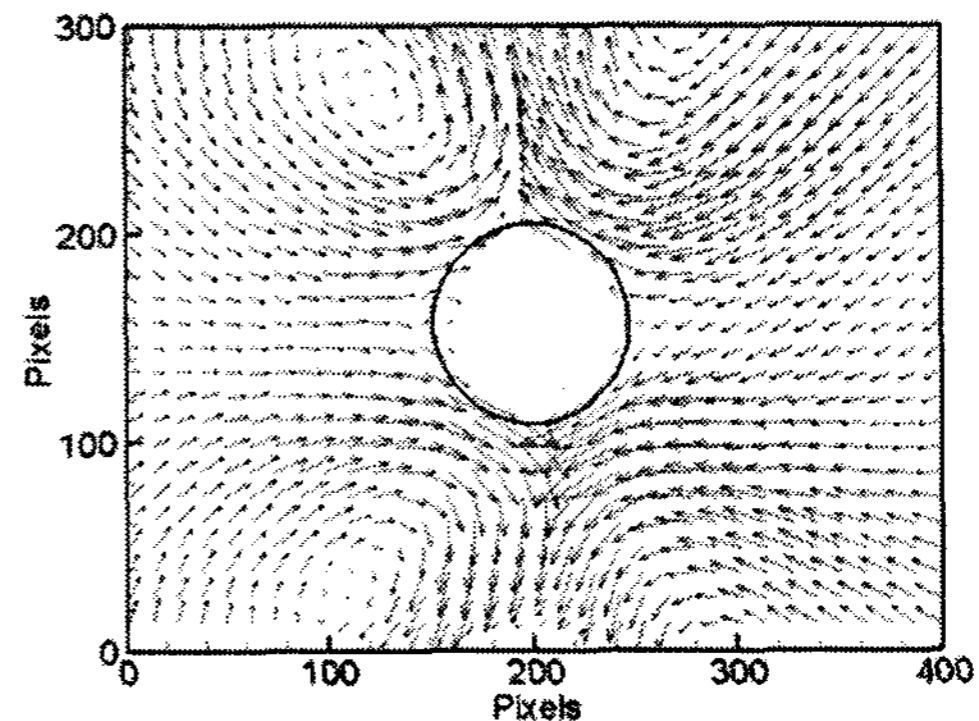


(a)

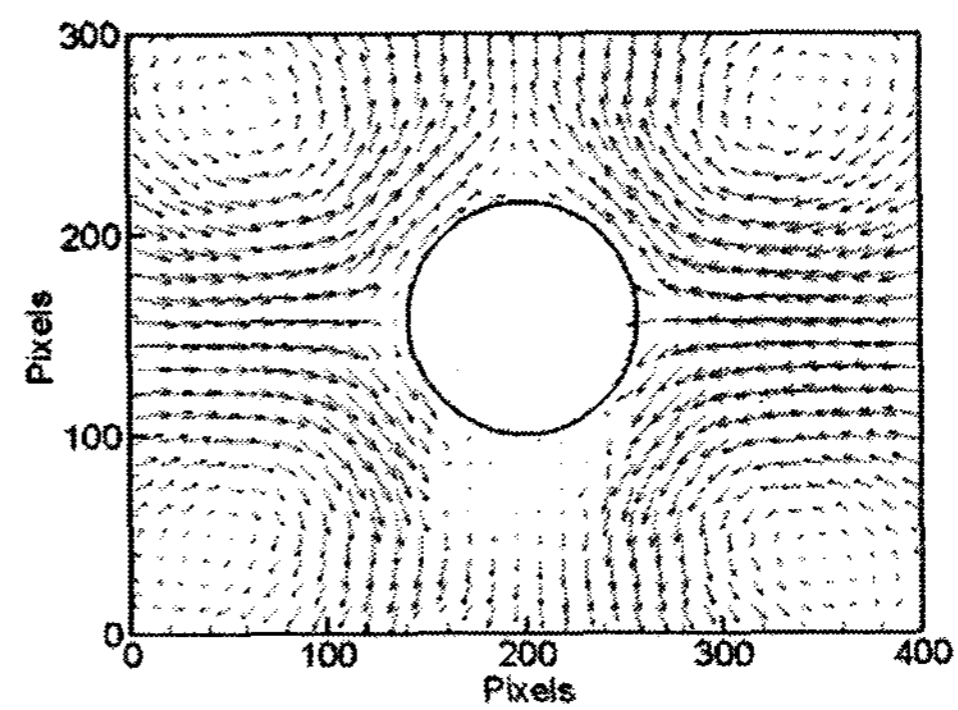


(b)

Fig. 7. Streamlines for the conducting cylinder of 1 mm diameter (a) and dielectric cylinder of 1.58 mm diameter (b), when $\Delta V = 4 \text{ kV}_{pp}$ and $f = 20 \text{ Hz}$



(a)



(b)

Fig. 8. PIV data for the conducting cylinder of 1 mm diameter (a) and dielectric cylinder of 1.58 mm diameter (b), when $\Delta V = 4 \text{ kV}_{pp}$ and $f = 20 \text{ Hz}$

4. Conclusion

From the foregoing investigations, we obtained the following conclusions

- 1) We observed a novel electrokinetic flow in the dielectric liquid, which is distinct from the ICEO.
- 2) There is no regular flow field without adding a surfactant. When we add a surfactant, a regular flow field is generated in the frequency range of 0.01 mHz to 400 Hz for the conducting cylinder.
- 3) Average flow speed is decreased monotonically with increasing the input frequency. It may be concerned with the relaxation process in forming an electrical double layer around the cylinder.
- 4) There is some difference in flow pattern between those of conducting and dielectric cylinders. In order to find out the cause of such difference, it is required to carry out experiment with other cylinder of different permittivities.
- 5) The flow observed in the present experiment can be applied to a micro-pump for non-polar liquids by arranging electrodes in an appropriate way in a microchannel.

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