한국가시화정보학회지, 제8권, 제4호, (2010) 13~18
<일반논문> (투고일: 2010.09.27/수정일: 2010.10.19/심사완료일: 2010.10.27)
DOI : 10.5407/JKSV.2010.8.4.013

마이크로 채널 내 유도-전하 전기삼투에 의한 혼합

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Mixing in a Microchannel by using Induced-charge Electro-osmosis

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Abstract. This paper presents an experimental study on the performance of a micro-mixer using AC electro-osmotic flow. The microchannel is made of PDMS for the side and top walls and glass patterned with ITO for the bottom wall. We first investigated the effect of the applied potential as well as the frequency on the slip velocity. We have found that the slip velocity is roughly proportional to the applied voltage in line with the Helmholtz-Smoluchowski equation and there is an optimum frequency at which the slip velocity becomes maximized. To find the optimum parameters for mixing device we tested our device for various design parameters. It turned out that the best mixing effect is obtained approximately when the electrode angle is 30°, electrode width 200 μm, and the frequency of power supply 700 Hz.

Key Words: AC Electro-osmosis flow(교류전기삼투 유동), Flow visualization(유동가시화), Mixing index(혼합지수), Optimum design(최적설계)

1. Introduction

Lab-on-chips receive increasing attention in view of their possibility of practical applications in broad areas such as biology and chemistry. Lab-on-chips are composed of micro-size mechanical and electrical systems which enable pumping, mixing, separation, sequencing, reaction and even cell growth. Characterized by very low Reynolds numbers, the system encounters difficulty in mixing of fluids. In order to enhance mixing, various ideas have been proposed in the literature. Cha et al.(1), e.g., proposed a three-dimensional micro-mixer combing the focusing and split and recombination functions called the ‘chessboard’ mixer. Suh et al.(2) presented a new design channel composed of a series of cross baffles within a channel. Le et al.(3) performed numerical simulation of mixing caused by the motion of magnetic beads subjected to a time-varying magnetic field.

Recently greater attention has been paid in controlling the fluid flow in microfluidic devices by use of electro-kinetic forces, e.g. transportation of fluid and/or mixing of reagents. When a charged microchannel surface is brought into contact with an electrolyte solution, an electric double layer (EDL) is formed in the vicinity of the channel surface. Most of the surfaces are charged negatively when they are in contact with aqueous solution and collect more cations than anions within the EDL. The term ‘zeta potential’ corresponds to the potential drop across the EDL caused by the accumulation of charge there. Applying an external DC electric field in the tangential direction then drives the cations towards the cathode, and these cations drag the surrounding liquid in the same direction through the viscous action. This is the theory behind the DC electro-osmotic flows(4-6). Generally DC electro-osmotic pumps do not use electrodes. The Helmholtz-Smoluchowski formula predicts that the

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magnitude of the slip velocity of the electro-osmotic flows is proportional to the zeta potential and the external electric field.

AC electro-osmotic flow, on the other hand, uses a different principle. Consider a pair of coplanar electrodes, which are attached to a bottom surface with a small gap between them (typically 20 μm) immersed in an electrolyte solution. When an AC voltage with suitable frequency is applied, a non-equilibrium accumulation of ions around the electrodes takes place. During the first half period of the AC cycle, one of the electrodes is charged negatively and the other positively. Accumulation of counter ions takes place on each electrode. During later half period the reverse process occurs. This produces a non-zero electric field outside the EDL together with a certain finite amount of the zeta potential and external electric filed change signs simultaneously so that the flow direction is unchanged.

DC forces are generally useful for pumping liquid inside a long microchannel having certain amount of surface charge. But AC forcing presents extra advantages in locally controlling the fluid flow and is more useful for fluid mixing. In the present study we conduct experiments to study the performance of a micro mixer with inclined electrodes at the bottom of the microchannel using AC.

2. Experimental methods

2.1 Mixing device

Figure 1 shows the schematic of the mixing device employed in this study. The width and depth of the microchannel are 200 μm and 100 μm, respectively. The bottom surface of the channel is bonded to an ITO glass by plasma treatment. The ITO glass comprises a plurality of ITO electrodes having constant width and a certain pattern is formed on the transparent glass substrate. The electrode pattern is inclined to the lengthwise direction of the microchannel at a predetermined angle. The gap between electrodes is 20 μm. AC power is supplied to the electrodes as shown in Fig. 1 (b). To find the optimum parameters of the device for the best mixing performance, we conducted parametric study by changing the following parameters; electrode pattern (angle of inclination), electrode width, AC power supply (voltage and frequency).

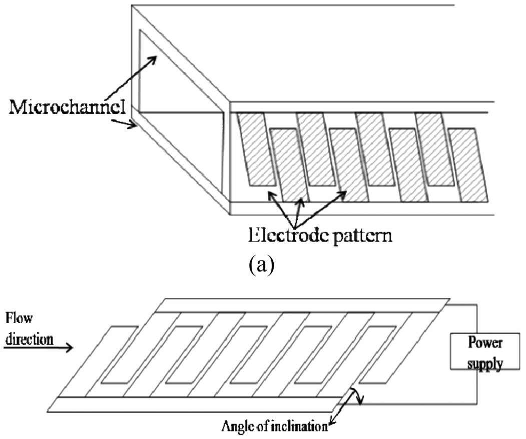
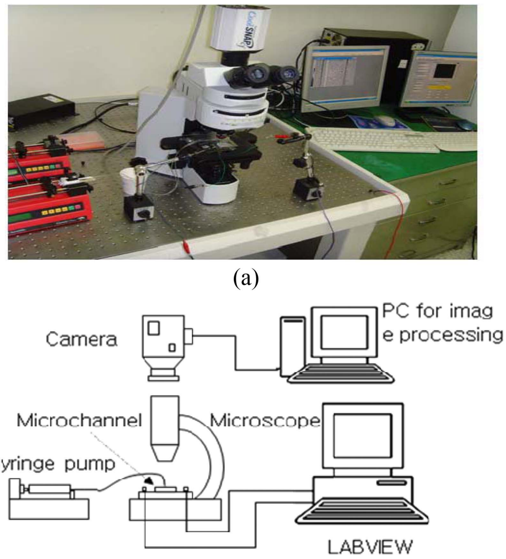


Fig. 1. Schematic representation of the mixing device. (a) microchannel and ITO electrodes patterned on the bottom wall; (b) AC power supply to the electrodes.

2.2 Experimental set-up

In our experiment LABVIEW is used to control the AC power supply and a CCD camera of 1360×1024 pixels and a microscope (BX51: Olympus) are used for observation of particle motion and data-recording. The main channel is made up of PDMS elastomer. The standard fabrication is used for the channel construction. Two access holes are punched at the end of the channel using a 2-mm circular punching device, and they are connected to the syringe pump to create pressure driven flow. Next, the fabricated PDMS microchannel and the glass substrate with ITO electrode pattern are bonded together by using a high frequency plasma generator, BD-10A. After the plasma-generator treatment, -CH3 on the PDMS surface is replaced with H_2O and CO_2. As a result, Si-O-Si covalent bonding occurs between the glass substrate and PDMS(7). We used the sodium chloride solution (NaCl) with concentration of 0.1 mM as the



(a)

(b)

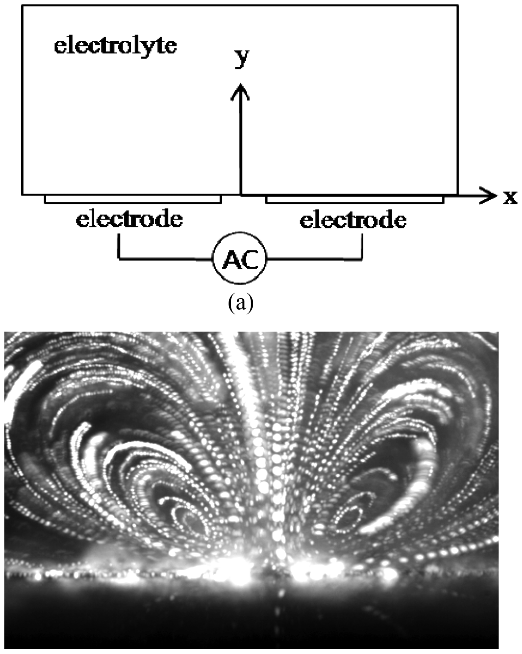
Fig. 2. Experimental set-up: (a) photo of the overall set-up; (b) schematic diagram of the set-up.

electrolyte to analyze the mixing performance of the channel. The flow through the microchannel is observed by seeding micro particles from one end of syringe pump. We selected the particles of sufficiently large size (around 1 μm) as they should efficiently scatter light.

3. Experiment results

3.1 Principle of mixing

Figure 3(a) shows a schematic illustrating the experimental set-up for understanding the principle of AC-electro-osmotic flow(8, 9) generated by a pair of co-planar electrodes by a small gap, 20 μm. Figure 3(b) shows the flow visualization inside the microchannel. We can see that the applied AC potential generates a pair of vortices of opposite circulation near the edges of the electrodes. These vortices resultantly play significant role in the enhancement of mixing in devices. We use this principle in the present study. To quantify the fluid flow we calculated the slip velocity near the electrode surfaces by using the PIV technique.



(a)

(b)

Fig. 3. AC Electro-osmotic flow generated by a pair of co-planar electrodes. (a) Schematic diagram of the set-up; (b) typical flow pattern near the electrodes.

Figure 4 shows the variation of maximum flow velocity with the frequency for different values of applied voltages. Here the maximum velocity is

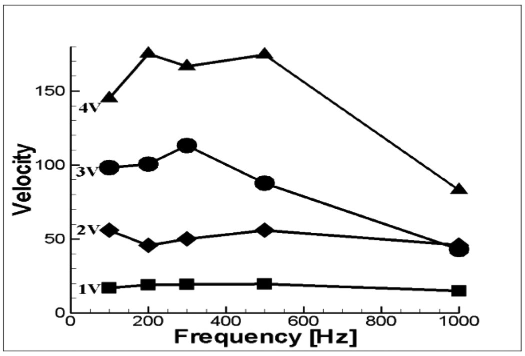
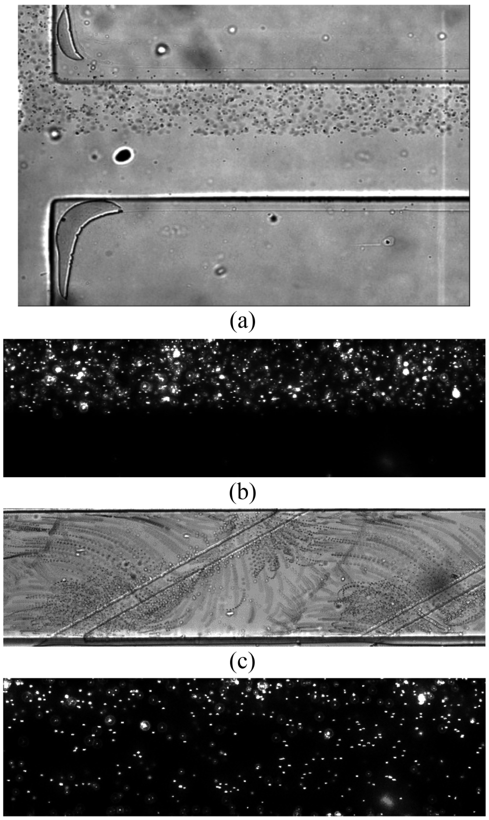


Fig. 4. Effect of the frequency on the maximum fluid velocity obtained at various applied voltages.

measured on the line x=0. The effect of frequency is negligible at low potentials but significant at high potentials. Increase of the applied voltage increases the fluid velocity. But the burning of electrode is taking place if we increase the voltage value beyond 4 V. So, in this work all experiments are conducted by fixing the applied voltage at 4 V.

3.2 Parametric study

We conducted a parametric study to find the best mixing effect of our micro-mixer; we considered a T-shaped channel with two inlets and one outlet. Flow is driven by syringe pumps, which are attached to the two inlets. The seeding particles are injected from one of the inlet. Figure 5 (a) and (b) show the instantaneous state of the flow, when the external potential is not applied, visualized by different kinds of light.


(a)

(b)

(c)

(d)

Fig. 5. (a)Initial state of flow without external potential, (b)Visualization of Fluorescent particles with laser, (c) In electrodes image when AC power is activated, (d) In Back flow image after all particles pass the electrodes.

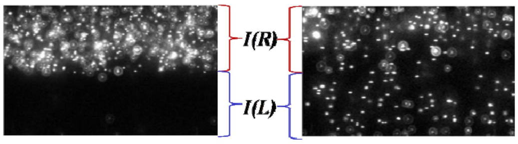


Fig. 6. Typical images of particle scattering without (left) and with (right) the external potential, and corresponding regions where two magnitudes, $I(R)$ and $I(L)$, are obtained.

Figures 5 (c) and (d) show the streak lines and instantaneous particle scattering, respectively, when AC power supply is activated. Application of the external potential indeed perturbs the fluid flow in the channel due to the electro-osmotic effect and thus mixing of two streams takes place.

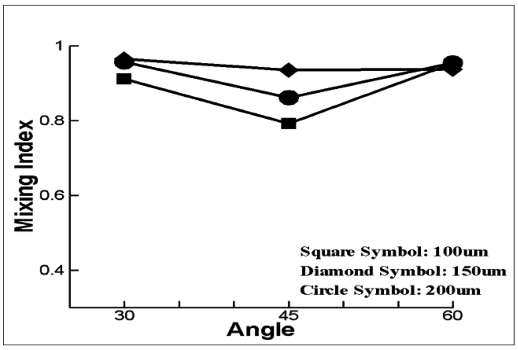
To assess the performance of the micro mixer, a mixing index is quantified by the following formula:

$$MI = \frac{|I(R) - I(L)|}{I(R) + I(L)} \qquad (1)$$

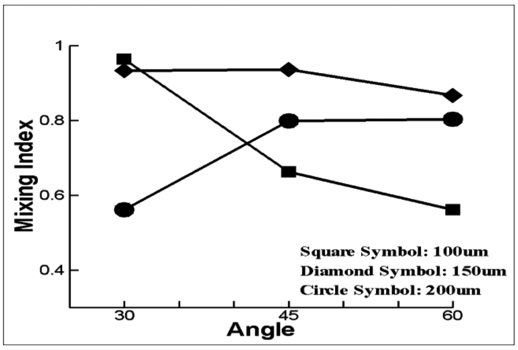
Here $I(R)$ and $I(L)$ denote the number of particles in the top-half and bottom-half areas, respectively, as shown in Fig. 6. Therefore, a lower value of MI implies a better mixing effect, and vice versa.

Figure 7 shows the variation of mixing index with the electrode angle and the electrode width at different cross sections of the microchannel. In all the cases, the voltage and frequency of the power supply is fixed at 4 V and 700 Hz respectively. From Fig. 5(a) we can infer that at the bottom of the microchannel the mixing efficiency is poor as the mixing index is higher than 0.8. The reason is that accumulation of particles takes place at the bottom of the microchannel due to the unknown surface effect on the electrode. From Fig. 5(b) we notice that the mixing efficiency at the top of the microchannel is higher than that at the bottom. The mixing index is as low as 0.3 at the middle of the microchannel when the electrode width is at 200 μm and the angle of inclination of electrode is at 30^o to the flow direction indicating that good mixing is established there.

Figure 8 shows the variation of the mixing index with the frequency of power supply at different cross sections of the microchannel. The electrode pattern and width are fixed at 30^o and 200 μm respectively. From this we can deduce that mixing efficiency is high because the mixing index is as low as 0.3 at the centre of the microchannel and the optimum frequency is found to be 700 Hz for the best mixing performance.



(a)



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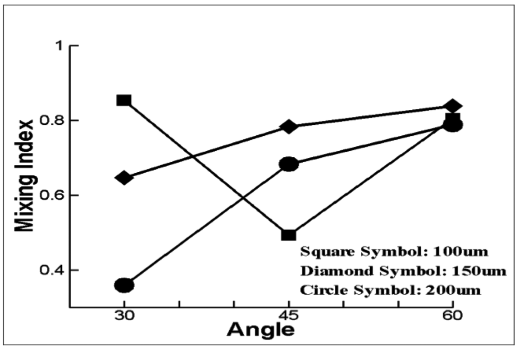

(c)

Fig. 7. Variation of the mixing index with the inclination angle of electrodes for various electrode widths (a) at the bottom, (b) at the top, and (c) at the center of the channel.

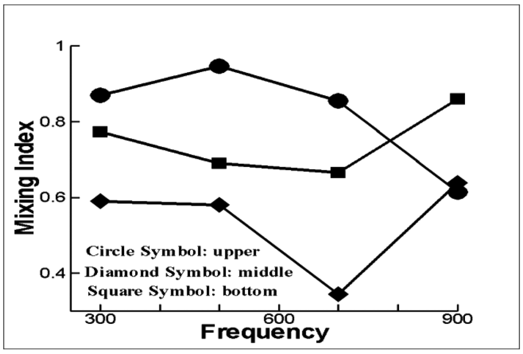

Fig. 8. Variation of the mixing index with the frequency at different cross sections of the microchannel.

4. Conclusions

In this study, we have performed an experiment with a micro mixer, which uses AC electro-osmotic effect for fluid mixing. Initially we performed experiments on simple coplanar electrodes and found that the fluid velocity is proportional to the applied voltage which is in line with the Helmholtz-Smoluchowski theory. To check the performance of a micro mixer contrived in this paper we conducted parametric study by changing the electrode pattern, electrode width, and the frequency. We calculated the mixing index in each case. The mixing efficiency is highest at the middle of the microchannel in all the cases. We found that the optimum parameters for the best mixing are: inclination angle of the electrode at 30^o, electrode width at 200 μm, and the frequency of power supply at 700 Hz.

Acknowledgment

This work was supported by NRF grant No. 2009-0083510 through Multi-phenomena CFD Engineering Research Center. This work was also supported by grant No. F0004021-2009-32 from the Information Display R&D Center, one of the Knowledge Economy Frontier R&D Programs funded by the Ministry of Knowledge Economy of Korean Government.

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