AC ELECTRO-Osmotic MICROMIXER USING A FACE-TO-FACE, ASYMMETRIC PAIR OF PLANAR ELECTRODES

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ABSTRACT
This paper reports the mixing performance of an AC electroosmotic micromixer based on the three-dimensional extensional flow generated by a face-to-face, asymmetric pair of planar electrodes. This work represents the first successful use of such an asymmetric electrode pair in an AC electroosmotic micromixer. Due to the highly 3-dimensional flow pattern generated by the face-to-face electrode pair, the mixing enhancement factor (\(\frac{\text{mixing time by diffusion}}{\text{mixing time by the micromixer}}\)) of the reported micromixer is 10 times larger than those using co-planar electrode pairs, and the mixing performance is uniform across the entire height of the fluid cavity.

KEYWORDS: AC electroosmotic flow, Micromixer, Asymmetric electrodes, Mixing

INTRODUCTION
It is well known that the fluid flow in a microchannel is usually laminar and the fluid mixing is mainly achieved by molecular diffusion. Use of the AC electroosmotic (AC-EO) micromixer is one attractive way to effectively enhance the fluid mixing in microchannels. AC-EO micromixers can function under low applied voltages, while maintaining AC electric field frequencies much higher than the inverse faradic time constant to significantly reduce bubble formation [1]. Other advantages of AC-EO micromixers include the easy control of the position and direction of microvortices by the use of different electrode layouts, and the easy control of the mixing capability by applying different voltages and frequencies.

In the past, most of AC-EO micromixers used co-planar, asymmetric pairs of planar electrodes [2-5]. When co-planar, asymmetric pairs of planar electrodes are used, the flow induced by the Coulomb force generated in the electric double layer has the largest velocity just above the surface of the electrode and the flow velocity reduces drastically as the distance from the electrode surface increases. As a result of this reduction in the flow velocity, the mixing capability of the micromixer is reduced significantly with the increased distance from the electrode surface.

In this paper we report the mixing performance of an AC-EO micromixer based on the 3-D extensional flow generated by a face-to-face, asymmetric pair of planar electrodes. Due to the highly 3-dimensional flow pattern generated by the face-to-face electrode pair, the mixing enhancement factor of the reported micromixer is one order larger than those using co-planar electrode pairs [4, 5], and the mixing performance is uniform across the entire height of the fluid cavity. In addition, the electrodes of the reported micromixer are coated with dielectric and anti-fouling layers to prevent electrolysis at high voltages and non-specific adhesion problems in biological applications.

EXPERIMENTAL
Figure 1(a) shows the schematic diagram of the AC-EO micromixer using a face-to-face, asymmetric pair of planar electrodes. The height of the fluid cavity is 128 \(\mu\)m. The large top electrode is rectangular, with a dimension of 3 \(\times\) 6 cm\(^2\). The bottom electrode is much smaller, as shown in Fig. 1(b), and has a rectangular shape (500 \(\times\) 700 \(\mu\)m\(^2\)) with two protrusions. The fabrication process of the micromixer is the same as that described in Ref. [6]. During flow visualization experiments, the flow fields at different distances from the bottom plate are observed with an inverted fluorescent microscope (IX71, Olympus, Inc.) and a digital imaging camera system (i-SPEED, Olympus, Inc.). The solution used in the flow visualization experiments is de-ionized water containing 1-\(\mu\)m fluorescent particles (3.6×10\(^{10}\) particles/ml) and has an electrical conductivity of 5×10\(^{-4}\) S/m (at 22 °C). To investigate the mixing performance of the AC-EO micromixer, conventional dilution experiments with fluorescent dye solution are carried out in this work. DI water is mixed with a fluorescent dye (2.65 M Acid Yellow 73, SIGMA, USA). The fluorescence images at different distances from the bottom plate are recorded with the above mentioned inverted fluorescence microscope and CCD camera to determine the mixing index and mixing time (defined below).

To quantitatively characterize the mixing efficiency of the AC-EO micromixer, the mixing index, defined as one minus the relative standard deviation (standard deviation \(\sigma\) divided by the mean \(I_{ave}\)) of fluorescence intensity of the pixel over the internetered area [7], is measured in this work.

\[ \text{Mixing index (\%)} = \left(1 - \frac{\sigma}{I_{ave}}\right) \times 100\% \]
The mixing index of the initial (not mixed) or fully mixed state is represented as 0 or 100%, respectively. The mixing time used in this study is defined as the time needed to reach a mixing index of 90%.

RESULTS AND DISCUSSION

Figure 2 shows the observed flow patterns at three different heights of the fluid cavity. The observed flow pattern shows a stagnation-point flow in the center region caused by the impinging of the vertical upward and downward flows on each other, driven respectively by the bottom and top electrodes. This stagnation-point flow is further modified by the vortices at the four corners of the bottom electrode to generate the 3-dimensional extensional flow at the center region. At the region near the bottom electrode, as shown in Fig. 2(a), the upward flow of fluid functioned to draw the surrounding fluid into the center region of the bottom electrode. Figure 2(b) clearly shows the four microvortices located at the four corners of the electrode. Figure 2(c) shows that the fluid flows upward into the center region of the bottom electrode and then left toward the east and west sides, forming an extensional flow field.

Figure 2: Flow patterns at (a) \( z = 0 \mu \text{m} \), (b) \( z = 64 \mu \text{m} \), and (c) \( z = 128 \mu \text{m} \). The flow is observed with an inverted fluorescence microscope and a digital imaging camera system. The fluid used in this figure contains \( 1 \mu \text{m} \) fluorescent particles \( \left( \text{3.6} \times 10^{10} \text{ particles/ml} \right) \) in de-ionized water. Arrows represent major directions of flow.

The highly 3-dimentional flow pattern causes extremely efficient mixing of stationary fluids in the entire fluid cavity as shown in the recorded fluorescence images given in Fig. 3. From the recorded fluorescence images, the mixing index is found to increase with time, as shown in Fig. 4. From Fig. 4, the mixing times (time needed to reach 90% mixing index) are determined to be 0.86, 0.53, and 0.99 sec at \( z = 0, 64, 128 \mu \text{m} \), respectively. This indicates that the reported micromixer can provide a very uniform mixing performance over the entire height of the fluid cavity, when compared with micromixers using co-planar electrodes [4, 5]. Figure 4 also shows that the mixing time by diffusive mixing is 270 sec at \( z = 64 \mu \text{m} \). This gives a mixing enhancement factor of 342, and suggests that the mixing time for the reported micromixer is 342-fold faster than diffusive mixing. Table 1 shows that the mixing enhancement factor of the reported micromixer is 10 times higher than those using co-planar electrode pairs discussed in Refs. [4] and [5]. The reported micromixer provides a significant mixing enhancement and can be applied to various microfluidic systems.

CONCLUSION

The reported micromixer has the following three characteristics. (1) Due to the 3-D nature of the flow pattern generated by the face-to-face electrode pair, the mixing capability is uniform over entire height of the fluid cavity. For the AC-EO micromixers based on co-planar electrode pairs, the flow velocity and mixing capability usually reduces with the increase in the distance from the surface where the electrodes are located. (2) The mixing is highly efficient. The mixing time of the reported micromixer for stationary fluids is 342-fold faster than that of mixing by diffusion. In the existing literature the reported ratios are 15-to 30-fold faster for mixing stationary or continuous fluids using AC-EO micromixers. (3) The electrodes are coated with dielectric and anti-fouling layers of Teflon-AF and Parylene C to prevent electrolysis and non-specific adhesion problems, when used in biological applications. The reported micromixer provides a significant mixing enhancement and can be easily integrate into various microfluidic systems.
Figure 3: Fluorescence images showing the mixing of two stationary fluids (2.65 M Acid Yellow 73 solution and de-ionized water). The images are taken at (a) \(z = 0\) \(\mu\)m, (b) \(z = 64\) \(\mu\)m and (c) \(z = 128\) \(\mu\)m. The applied voltage and frequency are 340 Vrms and 140 KHz, respectively.

Figure 4: Time-variation of mixing index for the reported micromixer at the heights of 0, 64, and 128 \(\mu\)m and for diffusive mixing at the height of 64 \(\mu\)m.

Table 1. Comparison of mixing enhancement factor* of the present work with those reported in open literature.

<table>
<thead>
<tr>
<th>Refs.</th>
<th>Type of electrodes</th>
<th>Mixing enhancement factor</th>
<th>Flow condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Work</td>
<td>Face-to-face paired electrodes</td>
<td>341.77</td>
<td>Stationary</td>
</tr>
<tr>
<td>[4]</td>
<td>Co-planar paired electrodes</td>
<td>35.94</td>
<td>Continuous</td>
</tr>
<tr>
<td>[5]</td>
<td>Meandering co-planar paired electrodes</td>
<td>24.3</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

*Mixing enhancement factor is defined as the ratio of the mixing time by diffusion to that by the micromixer.

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REFERENCES


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