EXPERIMENTAL AND NUMERICAL CHARACTERIZATIONS OF BARRIER EMBEDDED MICROMIXER

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Abstract
In this paper, we present experimental and numerical mixing characterizations of a chaotic micromixer, Barrier Embedded Micromixer (BEM). Mixing performance was experimentally characterized in two ways: i) with respect to an average mixing intensity by means of color change of phenolphthalein as a pH indicator and ii) in terms of mixing patterns via a confocal microscope. Finite element analysis of flow field in micromixer also clearly showed the mixing enhancement mechanism via chaos. Mixing performance of BEM was found to be quite efficient, in particular for Reynolds number (Re) < 5.

Keywords: Chaotic Mixing, Barrier Embedded Micromixer, Microfluidics, Numerical Analysis

1. Introduction
Mixing plays an important role in μTAS [1,2]. Chaotic mixing could remarkably enhance the mixing efficiency. We presented the concept and primitive experimental results of BEM in μTAS2002 [2]. Figure 1 shows the schematic of BEM with corresponding cross-sectional velocity fields. Alternating velocity fields of Figure 1(b) and (c) result in the chaotic mixing [2]. In this paper, the characterization of the mixing performance of BEM was carried out experimentally and numerically.

2. Experimental
Mixing experiments were performed using three different microchannels, all made of PDMS: T-channel, slanted grooved microchannel (SGM) and BEM. For the first kind of mixing experiment, phenolphthalein and NaOH (pH = 13) ethanol solutions were injected to microchannels by a syringe pump. The effect of the flow rate was investigated while the flow rate is kept constant for each experiment. Since phenolphthalein changes its color from colorless to red if pH becomes greater than eight, the mixing performance can be quantified by measuring the change of red color along the downstream. For the second kind of mixing experiment, rhodamine B dissolved in ethanol and pure ethanol were used.
as two inlet streams. In this case, cross-sectional mixing pattern was observed by means of a confocal microscope along the downchannel direction.

3. Results and Discussion

Figure 2 shows the first kind of mixing experimental results for three different microchannels at several positions along the downchannel direction. For this experiment, BEM was designed to have one barrier per two grooves and no barrier over the next two grooves in a periodic manner. Measured intensity of red color is normalized as follows:

$$I = \frac{1}{I_{\text{max}}} \frac{I_{\text{REF}}}{I_{\text{ref}}} \sum_{n=1}^{N} \frac{I_n}{N}$$

where $I$, $I_{\text{max}}$, and $N$ represent the normalized average intensity, intensity at pixel $n$ and total number of pixels in the mixing zone, respectively. $I_{\text{ref}}$ and $I_{\text{REF}}$ represent mean local reference intensity and representative mean reference intensity, respectively, for compensation purpose. $I_{\text{max}}$ is the maximum intensity amongst pixels in mixed zone in the whole experiments for normalization purpose. Figure 3 shows the normalized average intensity change along the downchannel direction for several values of $Re$.

Making use of data in Figure 3, we defined a characteristic required mixing length, $\lambda$ as a length that appears as an exponent when the intensity data are fitted in terms of an exponential function as follows:

$$I = 1 - \exp \left( -\frac{z}{\lambda} \right)$$

Plotted in Figure 4 is so obtained $\lambda$ as a function of $Re$. As $Re$ increases, $\lambda$ increases for all microchannels as shown in Figure 4(a) and (b). According to Figure 4(c), the characteristic required mixing length of BEM increases logarithmically with $Re$. 
Figure 2. Mixing experimental results of: (a) T-channel, (b) SGM and (c) BEM at the indicated positions at the flow rate of 10.0μl/min (Re = 0.457).

Figure 3. Normalized average intensity changes along the downchannel direction of three microchannels, T-channel, SGM and BEM, for Re of (a) 0.228, (b) 0.457 and (c) 0.685.

Figure 4. Characteristic required mixing length of (a) all three microchannels as a function of the Reynolds number (Re), and (b) and (c) enlarged plots of characteristic required mixing length of only SGM and BEM as a function of Re and ln (Re), respectively.

Figure 5 shows cross-sectional mixing behaviors in BEM (one barrier per ten grooves) at several locations which were observed by means of a confocal laser scanning microscope. Almost complete mixing at the exit zone was observed as shown in Figure 5.

A numerical analysis system was also developed based on Finite Element Method. After solving the velocity field of creeping flow in the microchannel, a particle tracking method was utilized to predict mixing patterns in microchannel. Figure 6 shows predicted
cross-sectional mixing patterns in BEM at the entrance, 1st-, 5th-, 9th-, 13th- and 15th-cycle along the downstream. Stretching and folding behavior caused by barrier in BEM is easily observed. This stretching and folding mechanism exponentially induces interfacial area growth, resulting in the chaotic mixing in BEM as presented in [2].

4. Conclusions

In this paper, the mixing performance of BEM was successfully characterized experimentally and numerically. Experimental and numerical results showed stretching and folding mechanism of BEM which results in quite efficient mixing performance, in particular for Reynolds number \( (Re) < 5 \).

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References