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Design of confluence and bend geometry for rapid mixing in microchannels

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ABSTRACT

In micromixers, reactant fluids deform through convection arisen by channel geometries such as channel confluence and bend. This deformation reduces the diffusion length between fluids and thus enhances the mixing performance. This paper discusses the effects of channel confluence and bend geometries in microchannles on mixing rate. The results show that the combination of these geometries enhances the mixing performance under the condition that the channel bend is set after the confluent flow sufficiently develops. Larger confluence angle is also effective for rapid mixing. We also confirmed that the bend geometry has little effect for increasing the pressure drop in microchannels. To achieve a fixed segregation index, which represents the mixing performance, microchannels with a bend requires smaller flow rate and thus lower pressure drop than straight channels. From the experimental results, we have established the design guideline of microchannel for improving mixing performance without channel reduction and pressure drop confirmed the effectiveness of this guideline. Using this guideline, a micromixer with high operability and productivity can be developed.

1. Introduction

Microreactors are miniaturized reactors including microchannels of characteristic dimensions in the submillimeter range [1]. The reactor miniaturization provides improved mass- and heat-transfer rate and thus enables us to proceed with reactions under more precisely controlled conditions than conventional macro-scale reactors, leading to a possibility of improved yield and selectivity of desired products in organic syntheses [2–4] and narrower particle-size distributions and a lower polydispersity in the continuous synthesis of nanoparticles [5,6]. Enhancing mixing performance in microreactors is also an essential issue to produce desired products in high yield and selectivity. Many mixing principles have been derived by focusing on reducing the diffusion length between reactants. This is because mixing in microreactors is mainly driven by molecular diffusion, since reactor miniaturization leads to low Reynolds numbers in reactor channels. One of the main principles is to divide reactant fluids into many fluid segments using channel geometry [7,8]. Examples of micromixers using this mixing method are the interdigital mixer [9,10], and the multi-stream mixer with focusing after confluence [11,12], the split and recombination of microchannel [13,14]. When we use only this mixing principle, to shorten the diffusion length by channel reduction is essential for fast mixing. Mixing enhancement only by channel reduction, however, causes high pressure drop, which decreases the operability and productivity of micromixers. Another principle to enhance mixing performance is, therefore, needed for industrial production where high throughput is needed.

In micromixers, fluid deformation through convection generated by variations in the geometry of a channel, e.g., channel confluence, bend, and twist, also enhances the mixing performance [15–18]. In the channel confluence, fluids deform, and the deformation shortens the diffusion length between fluids. As a result, the mixing performance is improved. Confluence of two fluid streams is the simplest method for this mixing principle. T- and Y-shape microchannels are examples of micromixers using this mixing principle and have been employed in the investigation on the relationship between design factors such as channel sizes and flow rates in the mixers, flow pattern, and mixing performance in the micromixers [19–23]. Moreover, the channel bend also deforms fluids and shortens diffusion length between fluids. Previous investigations based on experiment and simulation reveals that channel geometries of bend and curve after fluid collision enhance mixing performance [24–26].

To leverage the effects of channel geometries for improving the mixing performance, precise design of shape parameters such as the angle of confluence and the distance between points of channel confluence and bends. This paper discusses the effects of confluence and bend geometries in microchannles on the mixing rate and proposes an effective combination of these geometries for improving the mixing performance.

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2. Experimental

2.1. Microchannels including channel confluence and bend

We examined the effect of bend geometry on the mixing performance. The microchannels are illustrated in Fig. 1. For all channels shown in Fig. 1, the channel internal diameter (i.d.) was 500 μm, and the channel length after the confluence was 20 cm. For comparison, the mixing performance of a microchannel with the same channel i.d. and length without bend as shown in Fig. 1(a) was also examined (named "straight"). For the channels with bend (Fig. 1(b)), the distance between the points of confluence and bend was fixed at 18 mm; the bend angle was 90°. The channel was bent in the horizontal or vertical direction as shown in Fig. 1(c) and (d). The channels were named using these directions.

The effect of the confluence angle was also evaluated. Fig. 2 shows a schematic of microchannel. This channel is made of Polydimethylsiloxane (PDMS) and transparent. The transparency is useful for flow visualization. The confluence angle θ was 60°, 180°, or 300°. The channel length after the confluence L was 5 cm. The channel before the confluence was 150 μm width and 150 μm depth, and that after the confluence was 300 μm width and 150 μm depth. At the inlets and outlets of the channel, silicon tubes with 1 mm i.d. and 20 mm length were connected.

The effect of the distance between points of channel confluence and bend was then evaluated. Fig. 3 shows a schematic of microchannel for this purpose. This channel is also made of PDMS. The distance between channel confluence and bend L_1 was 1 mm or 5 mm. The channel length after the bend L_2 was adjusted so that the total channel length $L_1 + L_2$ was 50 mm. The channel size was fixed at 500 μm width and 500 μm depth. At the inlets and outlets of the channel, silicon tubes with 1 mm i.d. and 20 mm length were connected.

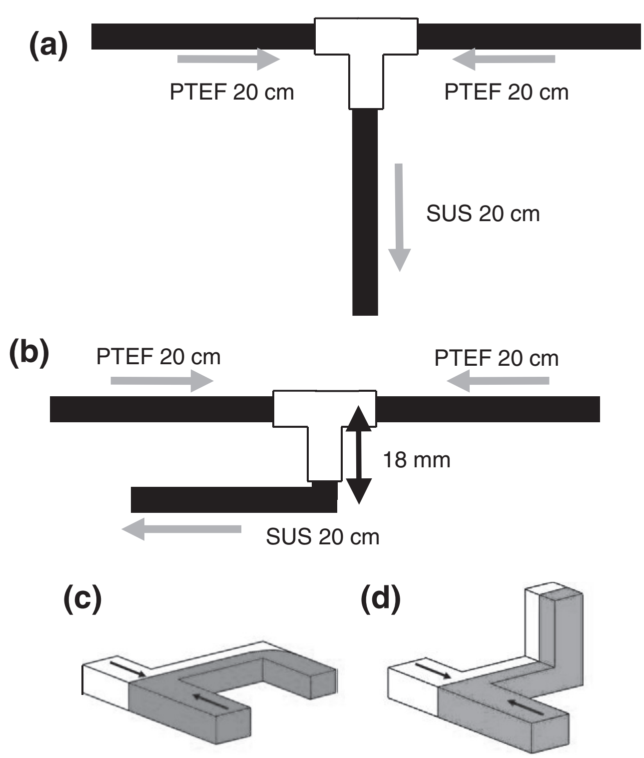

Fig. 1. Microchannels for evaluating the effect of bend and its direction. (a) Straight channel, (b) Channel with a bend, (c) Horizontal bend, and (d) Vertical bend.

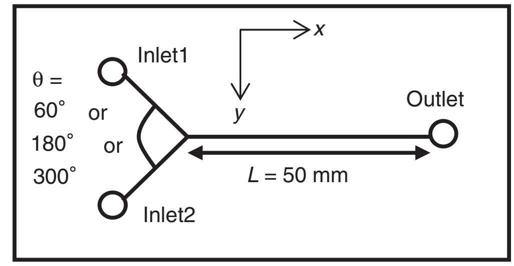

Fig. 2. Microchannel for evaluating the effect of confluence angle.

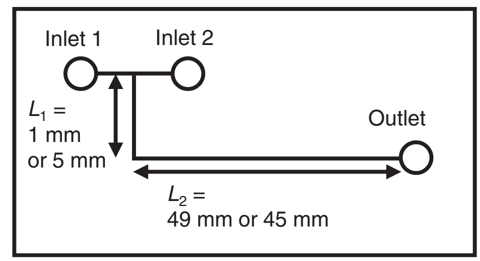

Fig. 3. Microchannel for evaluating the effect of distance between points of channel confluence and bend.

2.2. Evaluation method of mixing performance

We first evaluated mixing performances of the microchannels described in the previous section using parallel-competitive redox and neutralization reactions called the Villermaux/Dushman Reaction [27–30]. The reactions occur by mixing two reactant fluids. One is a solution of diluted strong acid (referred as solution 1); and the other is a buffer solution (mixture of weak acid and strong base) containing KI and KIO_3 (Redox reagents) (solution 2). In our experiments, solution 1 was 0.03 mol/L of HCl, and solution 2 was the mixture of 0.016 mol/L of KI, 0.0032 mol/L of KIO_3, 0.09 mol/L of NaOH, and 0.09 mol/L of H_3BO_3. The two solutions were fed from the two inlets of each microchannel. When boric acid is used as a weak acid for the buffer solution, the reaction formulas are as follows:

$$H_2BO_3^- + H^+ \rightleftarrows H_3BO_3 \tag{1}$$

$$5I^- + IO^{3-} + 6H^+ \rightleftarrows 3I_2 + 3H_2O \tag{2}$$

$$I_2 + I^- \rightleftarrows I_3^- \tag{3}$$

where reaction (2) is fast, but reaction (1) is instantaneous and is much faster than reaction (2). When mixing is slow, the protons of acid are consumed by reaction (2), and I_2 is produced. The iodine then reacts with iodide ions quickly by reaction (3). When mixing is slow, the strong UV light absorbance around 352 nm, which is the peak of I_3^-, is observed. This peak represents the formation of the product of the slower redox reaction. Thus, we can use the UV light absorbance at 352 nm as a measure of mixing performance. We sampled mixed solutions and measured the absorbance of the solutions with a UV–Vis spectrometer (Multispec-1500, Shimadzu Co.). For all experiments, the flow rates of the two solutions were equal and half of the total flow rate. We increased the flow rate until the value of ABS less than 0.1. For the channels made of PDMS, the flow visualization using distilled water colored by red ink was also carried out.

From the measured values of ABS, we quantitatively evaluated the mixing quality. The mixing quality is expressed using segregation index (X_s) that lies between 0 and 1 [23,24,29]: