RAPID MIXING BY MICRO-VORTEX IN A CONTRACTION-EXPANSION ARRAY MICROCHANNEL
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ABSTRACT
This paper reports vortex generation in a contraction-expansion array micro-channel and its application to a novel micro-vortex mixer. The evolution of the micro-vortices through the expansion and contraction regions, and their influence on mixing of fluid streams have been studied as a function of Reynolds number ($Re$).

KEYWORDS: Micro-vortex, Micro-mixer, Contraction-expansion microchannel

INTRODUCTION
In microfluidic systems, efficient mixing of fluids in a microchannel is required for chemical and biochemical applications. A number of mixing methods have been proposed to achieve this requirement in a microchannel [1, 2]. Such methods employed stirring effects by alternating electrokinetic flows and by Dean vortex flows in a curved channel [3, 4]. In this paper, we studied vortex generation in a contraction-expansion channel and developed micro-vortex mixer for high-throughput and high-efficient mixing.

EXPERIMENTAL
In order to form serial vortices, we fabricated contraction-expansion microchannels in the shape of a semicircular array by using standard poly(dimethylsiloxane) (PDMS) molding techniques. The width of the expansion channel was 550 μm, that of the contraction channel was 50 μm and the radius of the semicircles was 500 μm. The height of the channel was 42 μm (Figure 1). To discover the critical Reynolds number ($Re$) for vortex generation and measure the size of vortices, the 1 μm-sized fluorescence beads which can be neglected for inertia effects were introduced into the channel by using a syringe pump. For the mixing application of the micro-vortex, we introduced two parallel streams of different types (FITC solution and deionized

Figure 1. Optical micrograph of the micro-vortex mixer in the shape of semicircular array fabricated by using standard PDMS molding techniques.
water) into the contraction-expansion channel. The mixing processes were visualized by using a fluorescence microscope equipped with a charge-coupled device camera.

RESULTS AND DISCUSSION

Figure 2 shows the schematic of the vortex formation in a contraction-expansion channel. The dash line and straight line at the vortex area represent trajectories of the two streams of different types. When the fluids flow through the contraction region between a semicircular structure and channel wall, the flow separation occurred at the top of the semicircle structure in the microchannel. It causes the rotational flow at the rear of the semicircular structure. By using this flow separation, we can generate micro-vortices and use them to mix liquids.

In order to quantify the vortices relative to $Re$, the vortex area was determined with a closed area starting from the onset of flow separation to the flow reattachment region on the channel wall. When $Re$ exceeds a critical value, vortices begin to be generated in the contraction-expansion array channel. At $Re > 24.4$, vortices begin to be formed and becomes larger as $Re$ is increased more than 24.4 (Figure 3).

Mixing of two fluids was performed with two different microchannels: a linear channel and contraction-expansion array channel which has a semicircular array (Figure 4 a, b). The two fluid streams were mixed by serial vortices induced by flow separation at the rear of the semicircular structures. The mixing efficiency was evaluated by measuring the fluorescence profile of the captured images at the outlet. From the measurements, we calculated the standard deviation of the intensity distribution (Figure 4c).

![Figure 2. Schematic of vortex formation in a contraction-expansion channel.](image)

![Figure 3. (a) Fluorescent micrographs of vortices formed though the expansion region. (b) Plot of vortex area as a function of Reynolds number (Re).](image)
The value of standard deviation, $\sigma$, is 0.5 for completely segregated streams and 0 for completely mixed streams. We found that mixing efficiency at relatively high $Re$ conditions is much better than that of low $Re$ conditions because the size of vortex area becomes large as increase of $Re$. With the micro-vortex mixer, we achieved the mixing efficiency of 85% at $Re = 37.5$.

CONCLUSIONS

We have studied vortex generation in a contraction-expansion array microchannel and developed a micro-vortex mixer with high-throughput and high-efficient mixing, which can be useful for chemical and biochemical applications.

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