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Design and characterization of a passive recycle micromixer

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Abstract

A new design was devised for a recycle micromixer, i.e., a passive micromixer with side channels for a recycle flow. The geometry, required to perform a recycle flow and effective mixing, was determined by a simulation based on computational fluid dynamics. A recycle flow of the mixed flow of each unit was introduced to the inlet flow, and a circular flow was generated in the body of the mixer. For complete mixing, five units of the micromixer were connected in series. The simulations were performed at Reynolds numbers of 7, 14 and 28 and channel depths of 100, 150 and 200 μm. Mixing efficiency and direction of recycle flow were significantly affected by both *Re* and channel depth. When channel depth was 150 μm, mixing efficiency of the micromixer increased from 89.3 to 95.6, 98.4 and 98.6% with the increase of *Re* from 7 to 14, 28 and 42, respectively. The increasing channel depth also increased mixing efficiency. The micromixer was fabricated by a conventional photolithography technique using polydimethylsiloxane. Color dispersion in blue ink was compared with simulated flow patterns. The characterization of mixing in the recycle micromixer was verified by using an aqueous NaOH solution and phenolphthalein solution, composed of the same volume of ethanol and water. For both cases, fully mixed profiles were achieved along five micromixers, connected in a series at a flow rate of 0.1 ml min^{-1} for each flow and a short residence time of 0.11 s.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In the study of micro total analysis systems (μTAS) and complicated lab-on-a-chip systems that involve mixing, chemical reaction, separation and detection, micromixers were focused on solving the difficulties of mixing several fluids in micro-scale channels. In micro-scale systems, the Reynolds number is too small for turbulent flow to occur and mixing can only be completed by diffusion. Among the various types of micromixers, active mixers have external power sources for moving components such as micropumps [1, 2]. Because of the moving parts, active micromixers require complicated fabrication steps. Furthermore, the electrical field and heat generated from the actuators can cause damage to the biological samples, although active micromixers can provide rapid mixing. On the other hand, passive micromixers have the advantage of simple fabrication, easy operation and no heating elements. The absence of heating elements is important for applications to biological studies where temperature is a very sensitive parameter. The design of a passive micromixer is based on the increased boundary area of each component, enabling faster mixing [3, 4]. This type of micromixer, however, requires long mixing length or complicated inlet structure patterns to enlarge the mixing time or boundaries respectively. Other types of passive micromixers that have commonly been suggested include micromixers that use the injection of a liquid through a nozzle [5] and chaotic micromixers [6–8]. The nozzle-type micromixers require complex geometry, fabrication and optimization of parameters. The chaotic micromixers have the advantage of reasonable mixing in a short channel at a wide range of *Re*. However, chaotic micromixers need three-dimensional geometry and two-step photolithography in order to generate the chaotic flow.

In the chemical industry, the recycle reactors are widely used to get a high conversion and to reduce the reactor volume at the same conversion [9]. Pumps are used to recycle the flow. A turbulent flow is usually generated to facilitate mixing. In a micro recycle reactor, however, fast mixing is very difficult due to the laminar flow inside the reactor. Hence, to overcome the mixing problem, we devised a recycle micromixer that can be used as a micro recycle reactor.

In this paper, we report on a novel passive micromixer that uses a recycle flow. Gebhard *et al* suggested a design for a micro-oscillator that uses a recycle flow caused by the Coanda effect [10–12]. That design was modified by a simulation based on computational fluid dynamics (CFD) for fast mixing and the induction of a recycle flow. The micromixers were fabricated and characterized by using poly(dimethylsiloxane) (PDMS) by conventional photolithography.

2. Geometry optimization and CFD simulation

To produce a recycle flow, the micromixer body was separated into two parts and one of the inlet flow was divided into two parts before being inserted into the recycle micromixer where it would be introduced to both sides of another inlet flow. For sufficient mixing of two fluids, five units of the micromixer were connected in a series. Figure 1 illustrates the schematic diagram of the micromixer (unit: mm).

The simulation was performed using CFD-ACE+^{TM} software (ESI Group, USA). The diffusion, velocity and pressure were calculated in the user scalar module by using a finite element method and three-dimensional structured grids, as shown in figure 2. Both the diffusion coefficients of the inlet fluids were 10^{-9} m^2 s^{-1}. The inlet boundary condition was set to have a constant velocity for both fluids, and the outlet was assumed to have a constant pressure condition. When the flow rates of both inlets were 0.2 ml min^{-1} and channel depth was 150 μm, the calculated *Re* was about 28. The simulation as a function of *Re* was performed at *Re* of 7, 14, 28 and 42. Further simulation for dependence on the channel depth was calculated for 100 μm and 200 μm deep micromixers at various Reynolds numbers.

Mixing efficiencies were calculated for quantitative analysis of the micromixers. The cross-sectional images of outlets obtained from the CFD simulation were converted to portable graymap (pgm) formats and standard deviations of the pgm files were calculated.

3. Fabrication and experiments

The master mold for the microstructure was fabricated by using conventional photolithography technology with a negative

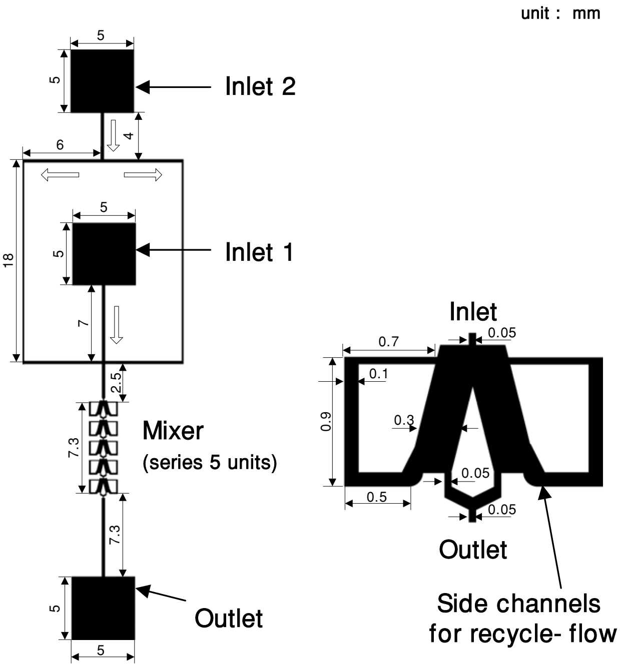

Figure 1. Schematic diagram of the recycle micromixer (unit: mm).

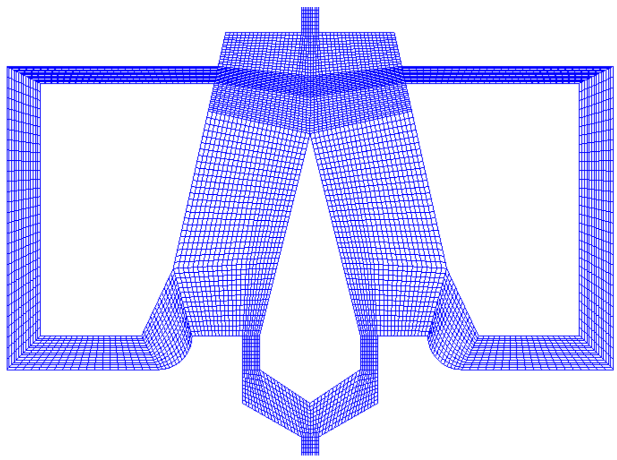

Figure 2. Top view of the mesh used for CFD simulation.

photoresist (MicroChem Corporation XP SU-8) on silicon wafers. A curing agent and PDMS prepolymer (SYLGARD 184 Silicone Elastomer Kit, Dow Corning, Midland, MI) were mixed in a weight ratio of 1:10. The PDMS prepolymer mixture was then poured onto the master. The prepolymer mixture was degassed with a mechanical vacuum pump over 2 h to remove air bubbles in the mixture. The PDMS prepolymer was then cured for 30 min at 90 °C in a convection oven and the PDMS replicas were peeled off from the masters. The inlet and outlet holes were punched in the fabricated PDMS replicas. Finally, the PDMS channels were bonded to slide glasses by using oxygen plasma treatment. Figures 3(*a*) and (*b*) show a whole photograph of the fabricated micromixer and a cross-sectional image of the micromixer body. The depth of the micromixer was adjusted before the experiments for several times of fabricating the SU-8 molds.

To compare the simulation results with the experimental results, the fabricated mixers were characterized by using

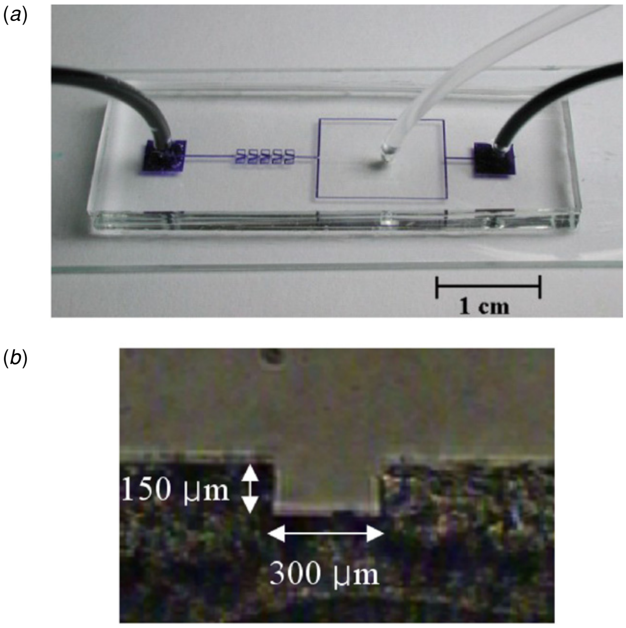

Figure 3. Photographic images of the fabricated PDMS recycle micromixer: (*a*) the whole shape, and (*b*) cross section of the micromixer body.

commercial ink and distilled water for each inlet. To see the color change in the mixed volume through the mixers, an aqueous NaOH solution and a phenolphthalein solution were used to characterize the fabricated micromixer. The ink was filtered before use through syringe filters of 0.2 μm pore diameter and distilled water was used for another inlet fluid. The color change profile in the mixed volume was observed by mixing two flows of aqueous NaOH (0.3 M) and a solution of phenolphthalein dissolved in the same volume of ethanol and water (0.01 M). Phenolphthalein is a pH indicator that changes its color from transparent to red when the pH is higher than 8.

4. Results and discussion

Simulation results are shown in figure 4 as a function of flow rates when channel depth was 150 μm with 13 contours and directions of recycle flows. Regardless of our expectation, when the flow rate was 0.05 ml min^{-1} ($Re \approx 7$), the recycle flow ran along the opposite direction. Recycle flow began to flow in the expected direction when the flow rate increased to 0.1 ml min^{-1} ($Re \approx 14$) and a detailed flow pattern is shown in figure 5. Internal circulation flow was observed in the corners where the outlet of recycle flow meets the body. However, the amount of recycle flow was only 0.2% of the inlet flow. The amount of recycle flow increased to 2% and 3% of the inlet flow when flow rates increased to 0.2 ml min^{-1} ($Re \approx 28$) and 0.3 ml min^{-1} ($Re \approx 42$), respectively. Here Re should be larger than 7 to induce recycle flow when channel depth is 150 μm and this result can be explained by a pressure drop. Points A and B are marked in figure 6 to compare the pressure in the side channels for recycle flow. The difference in pressure between points A and B ($P_A - P_B$) was −3, 0.5, 30 and 69 N m^{-2}, when Re numbers were 7, 14, 28 and 42 respectively. The critical Re of 13.6, where the pressure at A and B was same, was interpolated by using a polynomial equation. For high Re, which is equal to (inertia force)/(viscosity force), inertial force

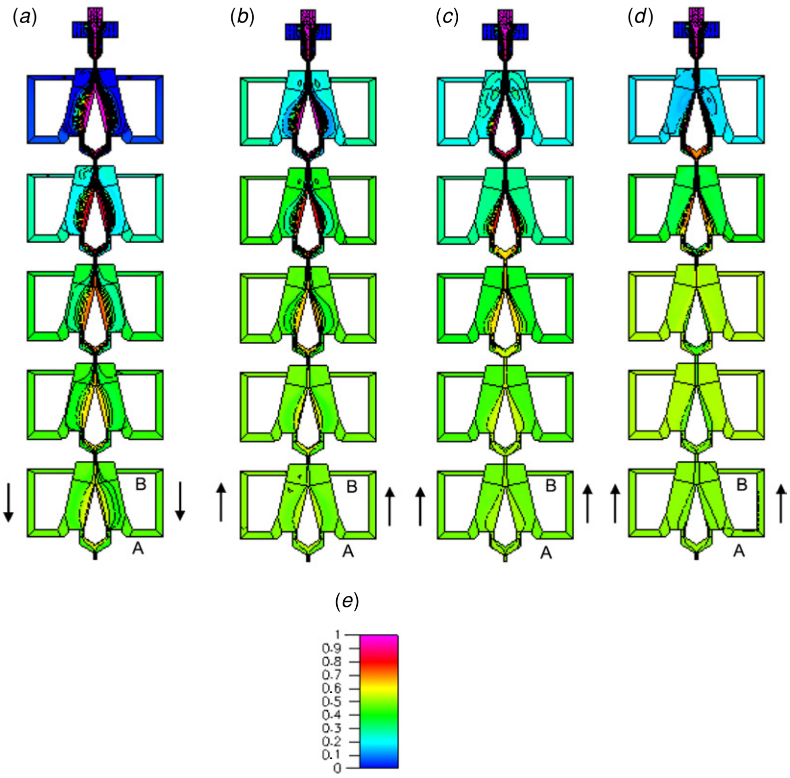

Figure 4. CFD simulation results as a function of Reynolds number when channel depth was 150 μm. (*a*) $Re = 7$, (*b*) $Re = 14$, (*c*) $Re = 28$ and (*d*) $Re = 42$. The mixing bar is shown in (*e*).

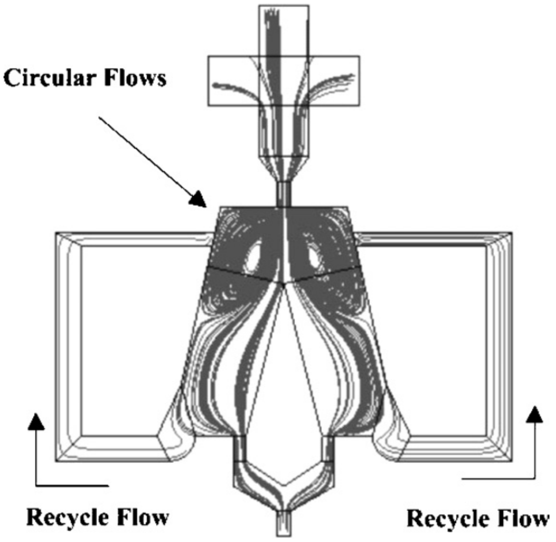

Figure 5. Flow pattern of the first unit of the recycle micromixer when Reynolds number is 14 and channel depth is 150 μm.

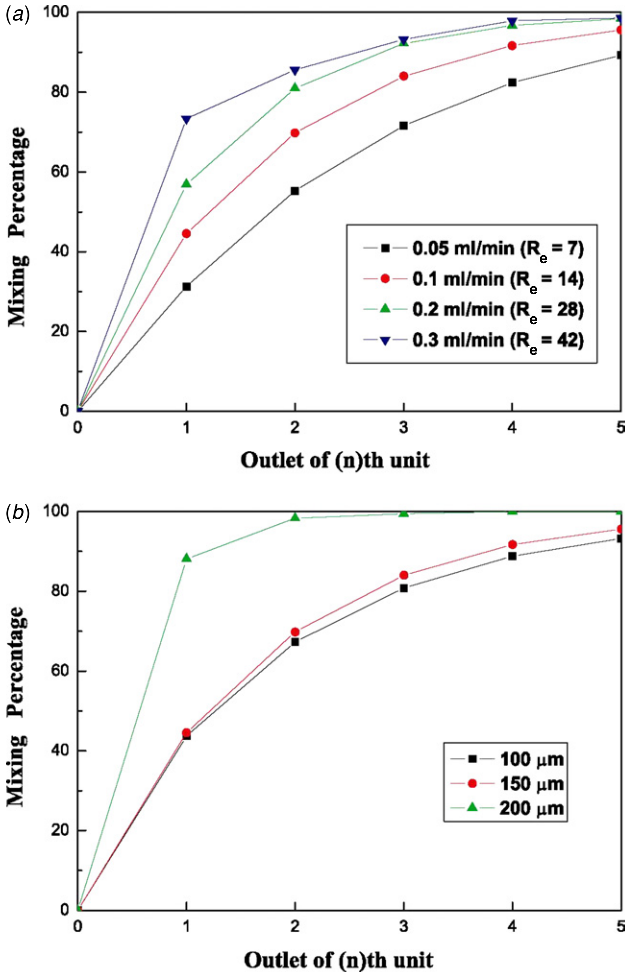

Figure 6. Mixing efficiencies calculated from the cross-sectional images of the simulation results: (*a*) as a function of Reynolds number with a channel depth of 150 μm, and (*b*) as a function of channel depth with a Reynolds number of 14.

seems to cause high pressure at the inlet of the recycle channel (point A) which generates recycle flow. Mixing efficiencies in the final outlet also increased from 89.3 to 95.6, 98.4 and 98.6% with increasing *Re* from 7 to 14, 28 and 42, respectively. The differences were clearly shown in the outlets of the first units where the mixing efficiencies increased dramatically from 31.3 to 44.6, 56.9 and 73.4 with increasing *Re* from 7 to 14, 28 and 42 respectively. The mixing efficiencies are shown in figure 6(*a*) as a function of *Re* and outlet of each unit.

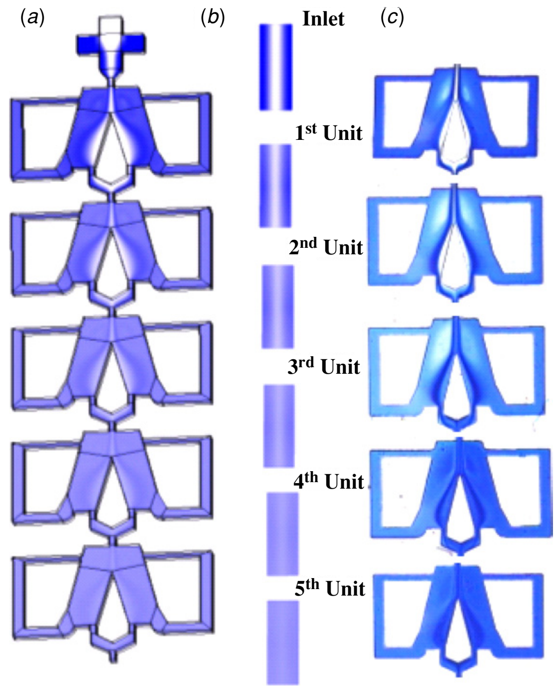

Figure 7. (*a*) CFD simulation mixing results of five units of the recycle micromixer connected in series with (*b*) cross-sectional images of the outlet of each unit, and (*c*) experimental results using blue ink and distilled water.

Further simulations were carried out for channel depths of 100 and 200 μm at *Re* of 7, 14 and 28. The pressure difference ($P_A - P_B$) was -12, -5 and 36 N m^{-2} for Reynolds numbers of 7, 14 and 28 respectively when the channel depth was 100 μm. The critical *Re* for the recycle flow was 16.7. In a 200 μm deep micromixer, the pressure difference ($P_A - P_B$) was -2, 0.7 and 20 N m^{-2} for Reynolds number of 7, 14 and 28 respectively. The approximate critical *Re* was 12.9. The critical *Re* values decreased from 16.7 to 13.6 and 12.9 with increasing channel depth from 100 to 150 and 200 μm. Mixing efficiency increased with increasing channel depth at the same *Re* and in the case of a 200 μm micromixer, 100% mixing was obtained in the outlet of the fourth unit. Mixing efficiency as a function of channel depth is shown in figure 6(*b*).

Figure 7 shows the mixing of five recycle micromixers in series, with cross-sectional views of the outlets of each unit when *Re* is 14 and the channel depth is 150 μm. The simulation results were compared to the experimental images, obtained from the microscope image of the color dispersion of commercial blue ink. The outlet of the fifth mixer shows fully mixed profiles for both the simulation and experiments. The mixing profiles and flow patterns of the internal circular flow in the body are also presented, along with a recycle flow similar to the simulation results for each unit of the recycle micromixer. Although the surface roughness and hydrophobicity of the

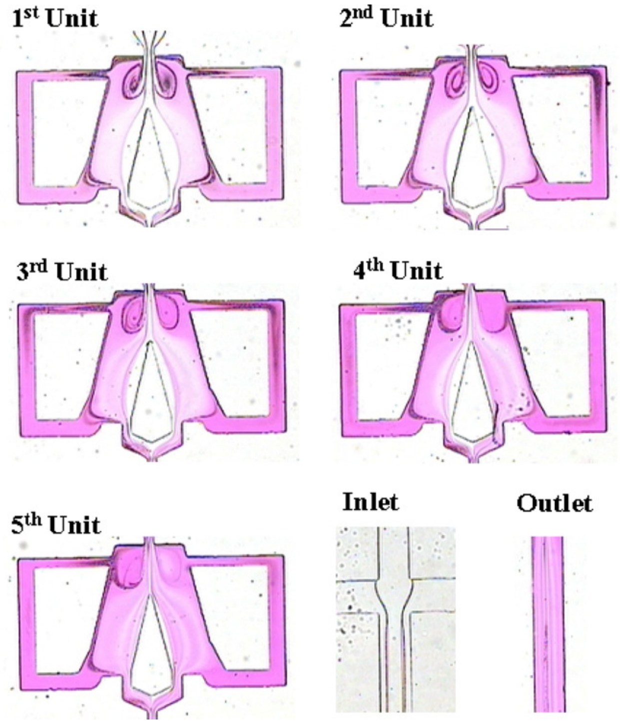

Figure 8. Microscope images for characterization of five units of the recycle micromixer connected in series using NaOH and phenolphthalein solutions ($Re = 14$).

PDMS channels are not included in the simulation, the flow patterns matched the simulation results very well.

The mixing experiments were carried out by using NaOH and phenolphthalein solutions at a flow rate of 0.1 ml $\min^{-1}$ for each flow ($Re = 14$). Figure 8 shows the CCD camera images of each unit of the recycle micromixer, connected in series. Similar flow patterns to the previous results were observed from the color change.

5. Conclusions

A new model of a passive micromixer, which uses a recycle flow, was designed by using CFD calculation for the optimization of geometry and flow patterns. Simulation was carried for channel depth of 100, 150 and 200 μm at various Reynolds numbers. The critical *Re*, where the inlet pressure and outlet pressure of the side channel become the same, decreased with increasing channel depth. Reynolds number should be larger than the critical *Re* to induce the recycle flow along the opposite direction to the main stream of the micromixer body. The micromixer showed 95.6% mixing in the outlet when *Re* was 14 and channel depth was 150 μm. In the case of a 200 μm deep micromixer, 100% mixing was obtained in the outlet of the fourth unit. Fabricated using PDMS, the micromixer showed fast mixing at a short residence time of 0.11 s at a flow rate of 0.1 ml $\min^{-1}$ for both inlet fluids. The micromixer has a limitation of critical *Re* and special inlet structure. However, as the mixing time of the mixer is very short and the mixer can be operated without any heat or electric fields, the recycle micromixer has possibilities for many applications in biological analysis, chemical reaction kinetics, lab-on-a-chip systems and micro recycle-reactors.

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