SPLIT AND RECOMBINATION MICROMIXER INCLUDING INTERFACIAL ROTATION*

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In this paper, a split and recombination (SAR) micromixer with a polydimethylsiloxane (PDMS) 3-dimensional structure is realized, and the mixing efficiency of the rotation effect in the SAR mixing is evaluated quantitatively. Three types of micromixers are designed to verify the effect of the rotation; these micromixers are called No-R, Co-R, and Count-R. The fabrication process is based on PDMS rapid prototyping and efficiency is estimated by both numerical analysis and experimental observation and is confirmed by quantification of image data. We compare the mixing efficiency for the rotation effect of various Reynolds numbers. In the region of low Reynolds number which SAR is dominant in mixing, the rotation effect decreases mixing efficiency. However, in the region of high Reynolds number more than 12 which the rotation effect is dominant in mixing, the efficiency is increased by the rotation induced by inertia effect. This tendency shows that the rotation type micromixer can be used in wide range of Reynolds number.

1. Introduction

Many types of micromixers have been developed in an attempt to reduce mixing time, dead volume of the mixing channel, and pressure drop [1]. One such micromixer is the 'split and recombination' (SAR) mixing method, which increases interfaces exponentially by laminating interfaces continually along the channel. When solutions that produce an interface between them enter the channel, the interface is doubled in one SAR mixing iteration: once by the 'split' process, which divides interfaces, and once by the 'recombination' process, which laterally reunifies the divided interfaces. After the nth SAR mixing iteration, the number of interfaces increases to 2^{n+1}-1. This mixing method was realized by micromachining based on silicon and laser processes [2,3].

2. Design concept

In this paper, a SAR micromixer is fabricated by PDMS process and mixing efficiency is evaluated for the rotation of interfaces and various Reynolds numbers. Figure1 shows the structure and the concept of the micromixer. When mixing solutions pass through the channel, the split membrane divides interfaces into upward and downward as a 'split' process, and divided interfaces are arranged laterally by curved guiding walls which make the slight rotation of interfaces. At the end of the 1st unit, interfaces are reunified as a 'recombination' process and 2nd split process is started. Thus, after flow passes through the nth unit, interfaces are increased to 2^{n+1}-1. Figure 2 shows the regime of the rotation of the interface at the expanding wall. When

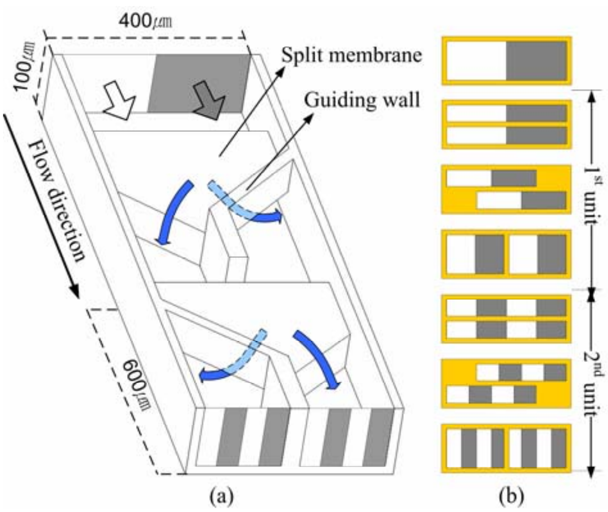

Figure 1. (a) Schematic view of the SAR micromixer, (b) Corresponding cross-sectional view.

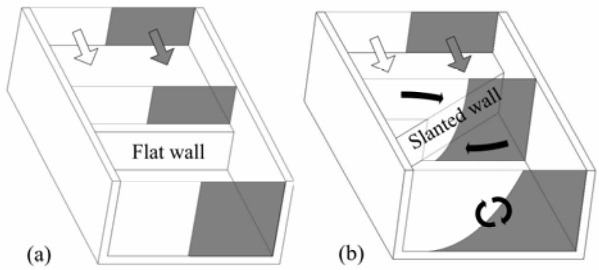

Figure 2. The rotation of interfaces induced by angled wall.

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the flow is expanded after following the guiding wall, an interfacial rotation is induced by the transverse flow generated by the different expanding time along the channel, which does not meet the expanding wall at a 90-degree angle. In contrast, when the channel and the expanding wall are perpendicular, interfaces maintain their own direction without distortion. In order to investigate this effect, three types of micromixers are designed to verify the effect of the rotation of interfaces, called No-R, Co-R, and Count-R defined by the existence and the direction of the rotation.

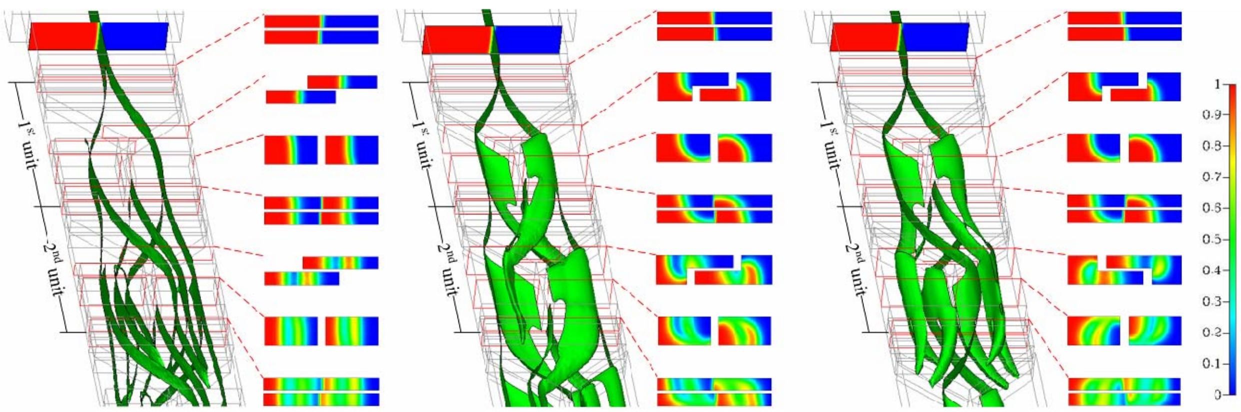
3. Numerical anlaysis

In order to evaluate each type of micromixer, the flow and diffusion between the two solutions are numerically analyzed by CFD ACE+ (ESI group). Figure 3 (a) shows the result of No-R type. The interface is increased in accordance with the manner of the SAR mixing and is not disturbed by rotation. A corresponding cross-sectional view shows the three-step process of the SAR mixing: splitting, guiding, and recombining. Figure 3 (b) and (c) show the results of the Co-R and Count-R types, respectively. In these types, interfaces are increased by the SAR mixing and stretched by the rotation. The difference between these two types is the direction of the rotation. In the Co-R type, interfaces are not folded but are stretched continuously and their distribution is expanded because the direction of the rotation is simply counter-clockwise (CCW), without alternation. In the Count-R type, interfaces are folded but are also stretched due to the direction of the rotation, which alternates between clockwise and counter-clockwise. This effect results in intense mixing because of the stretching and folding at the rotated region, but the unmixed void region is larger than in the Co-R type because interfaces are not expanded by continuous stretching and are somewhat confined.

4. Experiment and results

The fabrication process of the micromixer consists of the lower and upper PDMS layers. PDMS patterns are replicated on SU-8 master patterns. Curing PDMS with clamping process makes holes and membranes on the lower layer. The micromixer is completed by bonding of two PDMS layers[4]. In the mixing experiment, black dye and water are used for mixing solutions in order to measure mixing efficiency.

Figure 4 (a) shows the experimental result in the 1st unit of the No-R type SAR micromixer. The flow rate is 50 $\mu\ell$/min (Re 6) for each fluid. Water and blue dye are split into upper and lower flow by the PDMS membrane. The upper flow is directed along the downside of the figure by the upper guiding wall, and the lower flow is directed along the upside of the figure by the lower guiding wall. After the 1st unit, the disposition of mixing fluids is changed from black-clear to black-clear-black-clear. This result shows clearly that SAR mixing increases the interface from one to three at the 1st unit. In the expanding region, the significant contrast between the clear water and black dye means that rotation does not occur in the No-R type and the interfaces are parallel. The parallel interfaces seen in the cross-sectional view of the numerical analysis at the corresponding position of the channel support the experimental result. Figure 4 (b) shows the



(a) No-R type (b) Co-R type (c) Count-R type

Figure 3. Numerical analysis for three types of the SAR micromixer. A contour of the interface and cross-section.

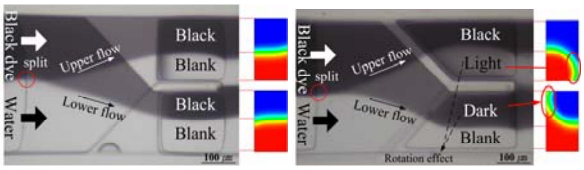


Figure 4. Mixing experimental results of the 1st unit of the No-R micromixer (a) and the Co-R micromixer (b).

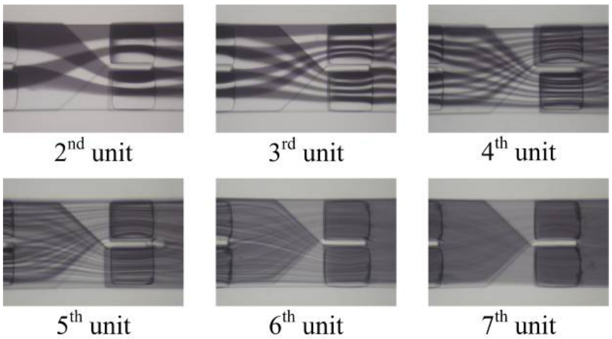


Figure 5. Mixing experimental results of the 1st unit of the No-R micromixer (a) and the Co-R micromixer (b).

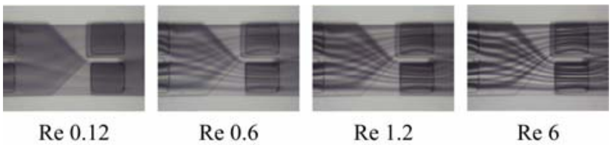


Figure 6. Comparison of mixed states with various Reynolds numbers in the 4th unit of the No-R micromixer.

experimental result in the 1st unit of the Co-R type SAR micromixer. The flow rate is 50 $\mu\ell$/min (Re 6) for each fluid. The Co-R type performs SAR mixing in the same manner as the No-R type, but it also includes rotation. In the expanding region of the Co-R type, the contrast between clear water and black dye is not obvious. In regions where the rotation occurs, the colors are gray and dark gray instead of the unmistakably clear or pitch-black colors in the No-R type, because here the water and blue dye have merged. This theory is supported by a cross-sectional view of the numerical analysis at the corresponding position of the channel. Alternative transverse flows at both ends of the interfaces induce the rotation of interfaces and the result is that the two colors have merged into gray and dark gray by the penetration of black dye into the clear water region and the penetration of clear water into the black dye region, respectively.

Figure 5 shows the results of mixing experiments for No-R types of SAR micromixers. The flow rate is 5 $\mu\ell$/min (Re 0.6) for each fluid. Increasing interfaces that maintain the contrast between the black stream and clear stream are observed in the figure. Because rotation does not occur, the stream is so distinct that the number of lines can be counted. After the 6th unit, when mixing is almost complete, the lines become too dense to be counted.

Figure 6 shows the mixing results of the 4th unit in the No-R type SAR micromixer for various flow rates, from 1 $\mu\ell$/min to 100 $\mu\ell$/min. The blended light color that is seen through the whole 4th unit of the channel means that mixing is almost complete at the low flow rate. The contrast between black and clear increases as the flow rate increases because the diffusion time at one position is smaller at a higher flow rate, although the number of interfaces at the same unit is independent of the flow rate. In order to mix fluids completely at a higher flow rate, more units are needed.

In order to quantify of the degree of mixing in each type of the SAR micromixer, a standard deviation (Stdev.) of the distribution of intensity in the image data is measured. In the first step the intensity value is addressed I_{max}=1 and I_{min}=0 for white pixel and black pixel of the image data, respectively. In the second step, we define the intensity value of every pixel of the image data between 0 and 1 as I_n and the number of pixels, 'N'(Figure 7). Finally, stdev. is obtained by following equation.

Figure 8 compares the mixing efficiency for the rotation effect in various Reynolds numbers with Stdev. at the end of each unit for the three types. Before the 1st unit, Stdev. is almost 0.5, which is the ideal value for complete mixing, without regard to Reynolds numbers and types. In early units, the Stdev. of the Co-R and Count-R types decreases rapidly compared with that of

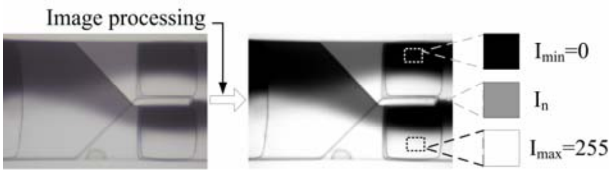


Figure 7. Normalization of pixel intensity of the image from the experimental results.

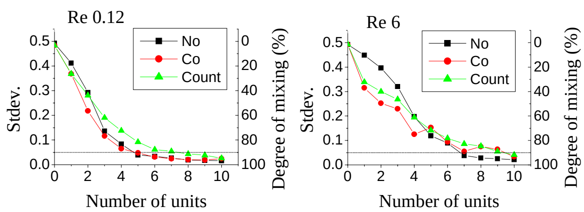


Figure 8. Evaluated degree of mixing of three types of mixers for various Reynolds numbers.

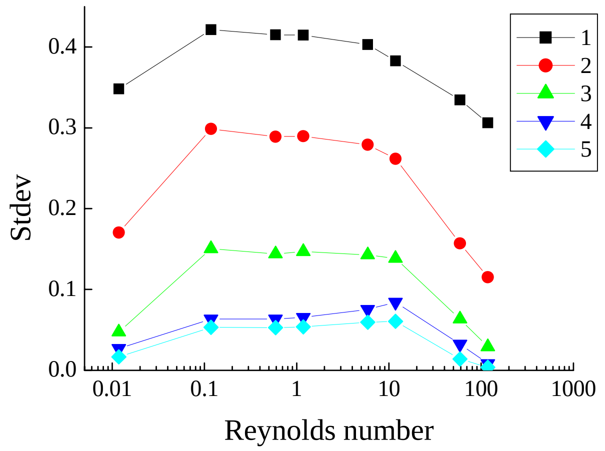


Figure 9. Stdev. of each units of Co-R type for various Reynolds number.

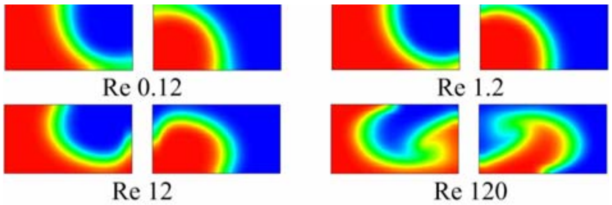


Figure 10. Cross-sectional view of numerical analysis for the 1st unit of the rotation type.

the No-R type. However, the Stdev. of the No-R type decreases first to 0.05, 90% degree of mixing, at the latter units because severe distortion of interfaces by repeated rotation decreases the mixing efficiency of the rotation type. This tendency is significant at higher Reynolds numbers evaluated in the experiment because the interface disturbed by the severe rotation is not split completely. In this range of Reynolds number it is considered that SAR is dominant mixing parameter rather than the rotation induced by inertia effect of flow. However, in much higher Reynolds number more than 10 estimated by only numerical analysis, the efficiency of the rotation type is increased by the rotation as shown in Figure 9. This figure shows the Stdev. of each units of Co-R type for various Reynolds number. In the region of low Reynolds number considered SAR dominant region, efficiency is decreased by reducing diffusion time as flow rate increases. In the region of high Reynolds number considered the rotation dominant region, efficiency is increased by increasing inertia effect of flow as flow rate increases. Figure 10 shows the cross-sectional view of numerical analysis for the 1st unit of the rotation type. In the high Reynolds number more than 12, the dominant mixing parameter is changed from SAR to the rotation because the interface is distorted by severe rotation[5].

5. Conclusion

This paper presents a microfabrication method for a split and recombination (SAR) micromixer based on PDMS. The mixing efficiency of the SAR micromixer is investigated by quantification of image data compared with the rotation effect in SAR mixing. We design three types of SAR micromixers, No-R, Co-R, and Count-R, as defined by their rotation effect and the direction of the rotation. Their efficiency is estimated by a numerical analysis and experimental observation and is confirmed by quantification of image data. In the region of low Reynolds number which SAR is dominant in mixing, the rotation effect decreases mixing efficiency because a severe distortion of interfaces caused by repeated rotation decreases the efficiency of the SAR mixing and produces an unmixed void. However, in the region of high Reynolds number which the rotation effect is dominant in mixing, the efficiency is increased by the rotation induced by inertia effect. This tendency shows that the rotation type micromixer can be used in wide range of Reynolds number.

Acknowledgments

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