Enhancement of mixing efficiency of multilamination micro mixer by adding recirculation zones

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Abstract

This paper describes the method of improving the mixing efficiency of multilamination micro mixers, i.e. adding a number of recirculation zones downstream of the mixing zone. The recirculation micro mixer of the present study consists of 8 micro feed channels to periodically create liquid multilamination and the recirculation zone to assist the mixing with the convection mechanism that arise with vortices inside those zones. The effectiveness of this addition in mixing performance was evaluated by experiment and numerical simulation. Six layers of glass wafer were fabricated individually and bonded together to form a mixer structure. Performance of micro mixer was measured by using color intensity variation of the fluid. As Reynolds number increased, significant enhancement of the mixing performance was observed. Mixing performance of more than 90 % was available for Re greater than 400.

Keywords: Micro mixer, Recirculation zone, Multilamination, Photosensitive glass

1 - INTRODUCTION

Micro mixers are essential components of a micro chemical plant. The mixing performance of a micro mixer affects the overall performance of the micro plant such as a μTAS and lab-on-a-chip. The flow rate of a typical micro mixer ranges from sub ml/hr to a few hundreds of ml/hr. Micro mixers are classified into active type and passive type depending on whether external action is applied for the mixing. External action can be supplied through periodic change of flow rate, micro impeller with the mixing cavity, ultrasonic excitation of flow, and so on. Micro mixers with external action generally require complex structure and fabrication process. In a passive micro mixer, mixing is achieved by the flow action inside the channel. The design and fabrication are simple for micro mixers of this type. Many ways to enhance mixing performance of passive micro mixers have introduced: interdigital multilamination, split and recombination, vortex generation, and chaotic mixing [1~3].

In this paper, a method to enhance the mixing efficiency of a micro mixer is presented. Conventional micro mixers that were used as a component in μTAS and lab-on-a-chip operated at very low Re, typically less than 10. Micro mixers for a micro plant application typically operate in hundreds to thousand ml/hour, with Reynolds numbers in the range of hundreds to thousand. Fluids used in such a plant are strong acids in general, requiring substrate material with high chemical resistance. In this paper, we developed micro mixers that were adequate for micro plant application and proposed the method to enhance the mix efficiency of a multilamination micro mixer by adding a number of recirculation zones downstream of mixing zones. Figure 1 illustrates the schematic of the micro mixer of the present study.
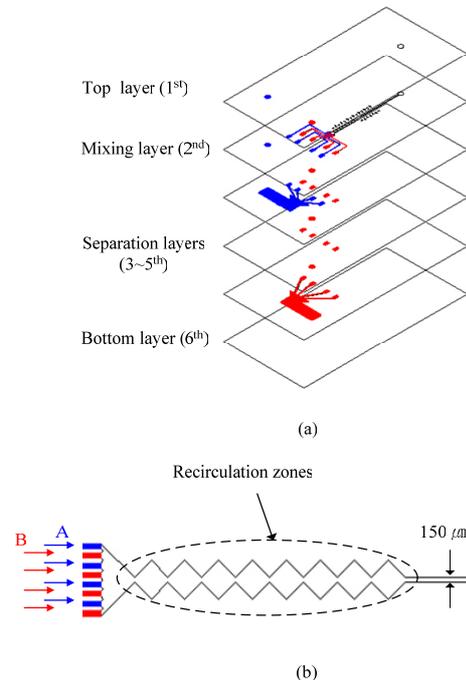

(a)

(b)

Figure 1 – (a) Schematic view of Multilamination micro mixer including recirculation zones (b) Detail view of mixing layer

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The mixing zone is fed by two fluids that are divided into 4 substreams respectively, which constitute the conventional multilamination type micro mixer. This configuration, however, solely depends on molecular diffusion for the mixing of the two fluids. The addition of 8 recirculation zones downstream of the mixing zone is to assist the mixing with the convection mechanism that arises with vortices inside zones. The width and height of micro channel are 150 μm and 500 μm respectively, with the hydraulic diameter is 230 μm . In this study, we named the proposed micro mixer a recirculation micro mixer.

We simulated the mixing process in the conventional multilamination micro mixer and the recirculation micro mixer to verify the enhancement. Micro mixers were fabricated to validate the prediction. Photosensitive glass was used as the substrate, considering its low thermal conductivity and high chemical resistance. The performance of the fabricated micro mixer was measured by visualization of the mixing process and analyzing the color intensity.

2 - NUMERICAL SIMULATION

Prior to fabrication and experiment, numerical simulations were carried out to predict and evaluate the performance of systems over a wide range of parameter. The flow field inside the micro channel was obtained by the Navier-Stokes equation. The mixture fraction field was obtained by the convective-diffusion equation. For pressure-velocity coupling, SIMPLE algorithm was used. To minimize numerical diffusion, the QUICK scheme with a high order discretization was adopted [4]. To evaluate the mixing quality, the numerical mixing efficiency was defined as

$$\eta_N = \left(1 - 2 \times \sqrt{\frac{1}{A} \sum (c_i - 0.5)^2 A_i}\right) \times 100\% \qquad (1)$$

Where A_i is the cross sectional area of the ith element, c_i is the mass fraction of the species of the ith element, A is the cross sectional area and η_N is the numerical mixing efficiency [5, 6]. Transport properties of water were used in the calculation and the diffusion coefficient was set 10^{-9} m^2/s. The volume flow rate was set from 5.85 ml/hour to 585 ml/hour for both inlets. The Reynolds number at mixing channel varied from 10 to 1000.

Mixing efficiency for various Reynolds numbers are presented in figure 2. In the conventional multilamination micro mixer the mixing performance decreased while Reynolds number increased, as the mixing depended in molecular diffusion only. The increase of the flow rate caused the reduction of the allowed time for diffusion as Reynolds number increased. Contrary to the multilamination micro mixer, the mixing performance of the recirculation micro mixer was improved as Reynolds number increases, except below a Reynolds of 20. In these conditions, vortices did not exist and mixing was mainly achieved by diffusion. On the other hand, vortices showed up in recirculation zones beyond a Reynolds number of 40 and mixing was significantly aided by the convection mechanism. Mixing performance was as
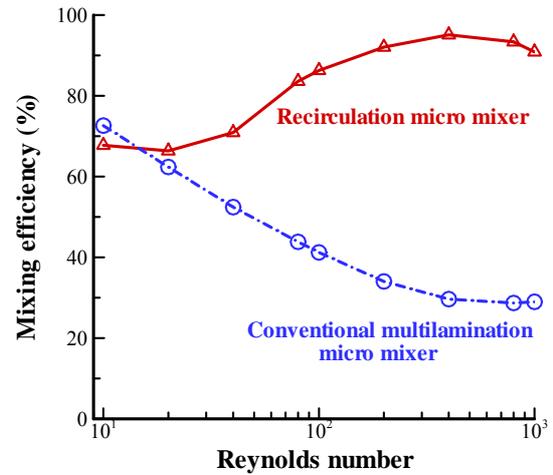

Figure 2 – Numerical mixing efficiency as a function of Reynolds number

high as 90% from a Reynolds number of 200. Mixing efficiency of the recirculation micro mixer re-decreased beyond a Reynolds number of 400. The effect of reduction of the mixing time was stronger than the effect of vortices. But more than 90% of mixing was still achieved at a Reynolds number of 1000. In addition, the recirculation micro mixer had lower pressure drop below a Reynolds number of 400 owing to the fact that the width of recirculation zones had larger than that of the mixing channel.

According to the numerical results, we could confirm the performance of the proposed micro mixer and understand the physical phenomena which took place in the device. Numerical results indicated that more than 90% of mixing efficiency of the recirculation micro mixer was achieved for a Reynolds number ranging from 200 to 1000.

3 - FABRICATION

Photosensitive glass wafer was used as the substrate material. Photosensitive glass does not have preferred orientation. As a result, the glass can be etched isotropically and difficult to get fine structure with a high aspect ratio. When it was exposed to ultraviolet (UV) light, the exposed parts of glass crystallize during heat treatment while the non-exposed areas stay in vitreous form. The processing steps of the photosensitive glasses are shown figure 3.

In order to transmit the UV light, a quartz mask with a chromium absorber pattern were prepared. The substrate was exposed to UV light at the wavelength of approximately 310nm. For precision exposure, a mask aligner was used. Photosensitive glass was illuminated by UV light with an energy density of approximately 2.5 J/cm^2. During UV exposure step, silver atoms were formed by a photochemical process in the illuminated parts. The UV exposed wafer was then heat treated in a furnace with automatic temperature control. The furnace was heated up to 500 °C with a rate of 2 °C/min and stayed constant for one hour. Then it was heated up to 585 °C with a rate of 1 °C/min and stayed constant for one hour. Finally, it was cooled at a rate of

(a) Cr pattering on Quartz wafer

310 nm UV

(b) UV exposure

(c) Heat treatment

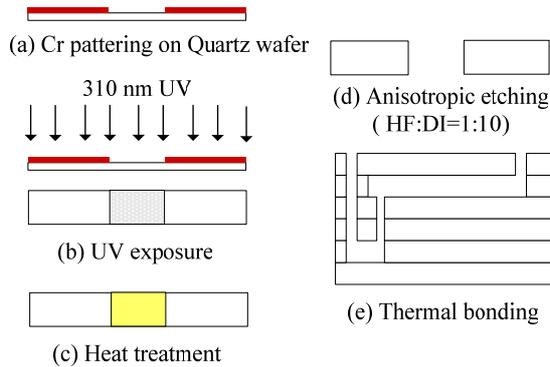(d) Anisotropic etching (HF:DI=1:10)

(e) Thermal bonding

Figure 3 – Process sequences of the fabrication of photosensitive glass
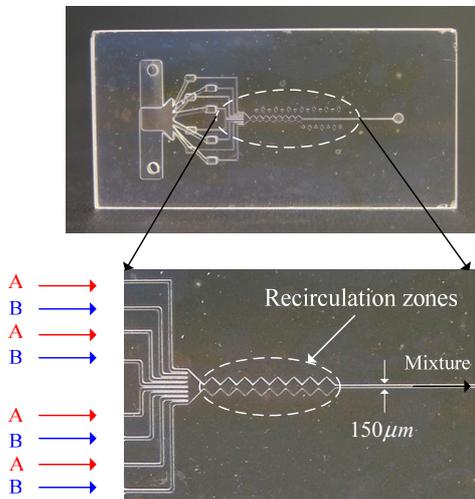

Figure 4 – Recirculation micro mixer made by etching and bonding processes of photosensitive glass

-3 °C/min. During heat treatment, photosensitive glass crystallized around silver atoms. The crystallized part had physical properties that are different from the glass. When etched in a 10% hydrofluoric acid, the UV exposed part was washed out. Generally, the ratio of etching rate of crystallized glass to vitreous glass is 20:1 [7]. After individual substrate was fabricated, each layer of photosensitive glass was polished and cleaned in piranha solution ($H_2SO_4:H_2O_2$=3:1) for 10min. Six layers of fabricated glass wafers were then carefully aligned and pressed together under 1 kPa at 500 °C for 12 hours. During this process, diffusion of atoms took place at the interfacial surface of bonded glass, leading to the formation of new chemical bonds. Figure 4 shows the fabricated micro mixers.

4 - EXPERIEMENT

Mixing in the micro scale devices is examined by measuring color intensity variations. In this paper, we chose to use diluted black dye and DI water. CCD camera connected to zoom lens was used to record the image (figure 5).
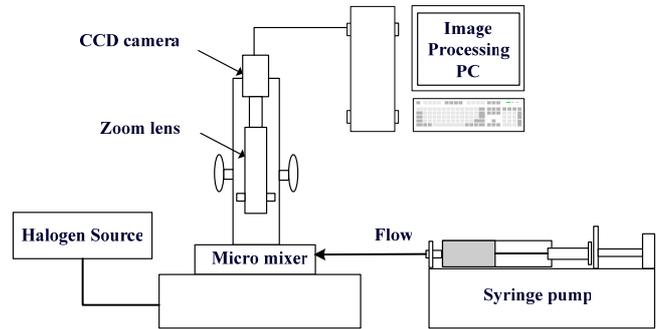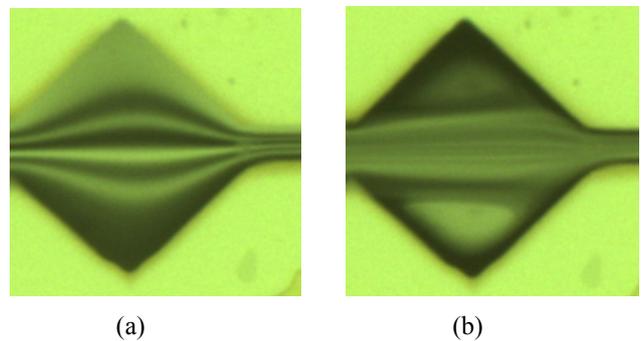

Figure 5 – Experimental setup

Figure 6 – Experimental flow pattern at 8th recirculation zone (a) Re 10 (b) Re 100

The captured images were then analyzed using a image data processor. The mixing efficiency was calculated by

$$\eta_E = \left(1 - 2 \times \sqrt{\frac{1}{n} \sum \left(I_{nor,i} - I_{nor,avg}\right)^2}\right) \times 100\% \qquad (5)$$

where $I_{nor,i}$ is the normalized intensity of the ith pixel; $I_{nor,avg}$ is the average of normalized intensity; n is the number of pixel; η_E is the numerical mixing efficiency [5,6].

Figure 6 presents the experimental flow patterns of the recirculation micro mixer at 8th recirculation zones. At a Reynolds number of 10, the vortices did not develop in the recirculation zones. Mixing of the two fluids only depended on molecular diffusion. The vortices inside a recirculation zone, however, generated at a Reynolds number of 100. Mixing was enhanced by the convection mechanism.

Figure 7 shows the mixing efficiency of the recirculation micro mixer and the conventional multilamination micro mixer as a function of the Reynolds number. Around the Reynolds number of 40~80, a critical Reynolds number could be defined. When the Reynolds number was less than the critical Reynolds number, recirculation zones were not effective. The multilamination micro mixer displayed higher mixing efficiency. In this flow regime, Vortices in recirculation zones was weak and the molecular diffusion was dominant. When the Reynolds number was more than this

Reynolds number, recirculation zones downstream of the mixing region significantly enhanced the mixing efficiency because vortices became stronger. We also observed that mixing efficiency of the recirculation micro mixer re-decreased beyond a Reynolds number of 800 different from numerical results. We could identify two significant results from figure 7. First was chaotic flow behavior. For the recirculation micro mixer, the mixing performance was improved rapidly over a Reynolds number of 400. We suggested that this phenomenon was concerned chiefly with the chaotic flow. As the Reynolds number increased, vortices become stronger. When the Reynolds number further increased, the flow tended to be instable, causing chaotic flow. The mixing performance was improved rapidly by chaotic mixing. Second was the appearance of the transition regime at low Reynolds number. For the multilamination micro mixer, the mixing performances were different from the numerical results over a Reynolds number of 200. Numerical results showed that the increase of Reynolds number brought about the decrease of the mixing performance. In the contrary to numerical results, the slope of the mixing efficiency fluctuated at experimental results. We thought that this phenomenon was related to the occurrence of transition regime Mixing was enhanced by convection mixing in the transition regime. These values were significantly different from conventional fluid theories. It was the characteristics of micro rectangular channel.

5 - CONCLUSION

In this paper, we proposed enhancement of mixing efficiency of the conventional multilamination micro mixer by adding a number of recirculation zones downstream of the mixing zone. 8 micro feed channels created multilamination which increased the diffusion surface. And the recirculation zones generated vortices which assisted the mixing with the convection mechanism. The micro mixer was fabricated by anisotropic wet etching of photosensitive glass, which had a number of advantages that made it attractive for use in the micro plant applications. We demonstrated the mixing performance and flow characteristic of the recirculation micro mixer by means of numerical method. The numerical results indicated that the recirculation micro mixer was more efficient in the mixing performance than conventional multilamination micro mixer. More than 90% of mixing was achieved for a Reynolds number ranging from 200 to 1000. We characterized the performance of fabricated micro mixers through the flow visualization technique using diluted black ink solution and DI water. Flow visualization experiments also confirmed that the recirculation micro mixer mixed better than the multilamination micro mixer beyond the critical Reynolds number. The experimental results indicated that More than 85% of mixing of recirculation micro mixer was achieved for a Reynolds number ranging from 200 to 1000.
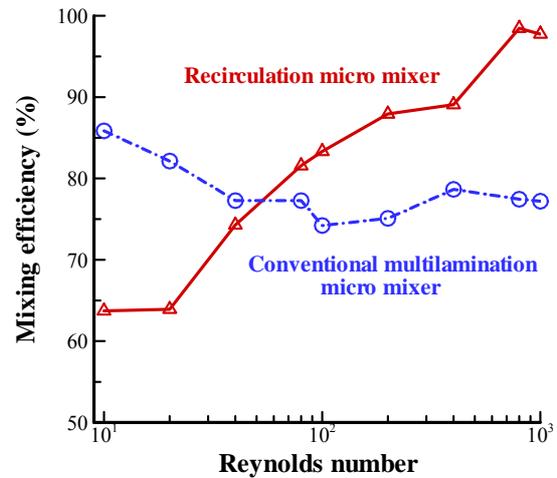

Figure 7 – Experimental mixing efficiency as a function of Reynolds number

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