



IMPROVEMENT IN CONVERGENT-TYPES OF MICROMIXERS BY THE USE OF PLATES

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IMPROVEMENT IN CONVERGENT-TYPES OF MICROMIXERS BY THE USE OF PLATES

Chin-Tsan Wang and Hong-Chang Zhou

Key words: convergent-type, micromixer, flow mixing, passive micromixer.

ABSTRACT

Micromixers have a wide application in the biomedical engineering and chemical industry. The passive micromixer is now widely studied because it is simple and easy to fabricate. In this study single plates applied in a convergent-type flow channel are utilized to enhance the flow mixing at a lower Reynolds number. Results show that good flow mixing could be achieved in a convergent-type flow channel. The highest flow mixing efficiency, 0.974, is found at the optimal combination of $Re = 80$ and plate dimensions of $J = 45 \mu\text{m}$, $G1 = 15 \mu\text{m}$, and $G2 = 3 \mu\text{m}$. Furthermore, the flow mixing in the case of using plates is found to be better than the case of without them. These findings will be useful in the future design of a micromixer.

I. INTRODUCTION

Micromixers are commonly employed for chemical or biological analysis in the lab-on-a-chip system. Normally, micromixers are categorized as active micromixers and passive micromixers. As for the passive mixer, it has been widely used in complex microfluidic systems because of its simple fabrication technology and easy implementation. Generally speaking, two techniques of convection and diffusion were utilized respectively in passive mixers for enhancing the flow mixing. Considering the facts of low cost and low power consumption, considerable research has been done on the passive mixers.

Liu et al. (2000) indicated that a three-dimensional serpentine flow channel was used to cause the appearance of chaotic advection for enhancing the flow mixing. Another method of using a vortex flow was addressed by Bohm et al. (2001). In addition, Mengeaud et al. (2002) indicated that the strength of vortex flow in a sawtooth flow channel would be strengthened

at a high Reynolds number for improving the flow mixing. Bing et al. (2001) designed a device with multiple intersecting channels of varying lengths and bimodal width distribution, replacing the original Y-shape, and added a fine micro flow channel to the original primary flow channel.

Nevertheless, J-shaped baffles in the T-channel were added to enlarge the flow contacting area to produce a better flow-mixing, but this structure was very complicated (Lin et al., 2007).

Similarly, inner baffle plates embedded in the micromixers were utilized to investigate the flow mixing performance (Wang and Iovenitti, 2004). A branch flow channel added in the main flow channel of the Y-shaped micromixer was designed to increase the flow mixing. The herringbone flutes embedded at the bottom of the flow channel (staggered herringbone mixer) were used to produce a stretching effect of chaotic convection flow. On the effects of vortex and velocity on the flow mixing, it has been proved that the mixing performance could be improved by a variance in vortex and the lateral velocity resulting from obstacles (Wong et al., 2003). A round mixing tank added in the flow channel could result in a better flow mixing than in the case of the general straight tubes (Chung et al., 2004). Jeon et al. (2005) designed a recycling micromixer in a special geometric shape to recycle the fluid and improve the flow mixing. Finally, the technique of photolithography chemical etching was used to stagger the stop blocks and arrange single-sided mixers respectively (Fu et al., 2006). They found that the effect of the stop-block staggered mixer was better than that of a single-sided mixer arrangement (Fu et al., 2006).

It can therefore be seen that many kinds of passive micromixers have previously been designed. In this study a simple convergent-type micromixer with plates, rarely considered before, will be designed. In addition, a three-inlet branch flow channel will also be utilized to enhance the flow mixing.

II. PHYSICAL MODEL AND DESIGN CONCEPT

In order to simplify the design of a passive micromixer and improve its flow mixing effect, the concept of a converging flow channel has been adopted so as to strengthen the flow convection effect of the induced fluid flow. A positive effect

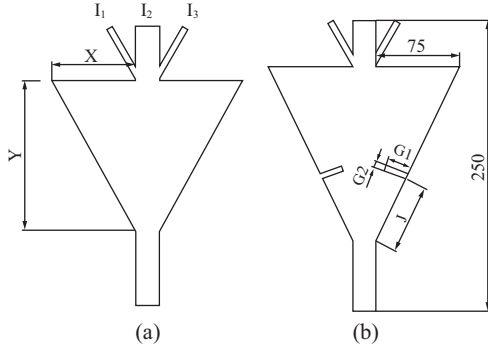


Fig. 1. Prototype of converging flow channel (a) without baffle plates; (b) with baffle plates.

on flow mixing would then be expected.

In this study, when the flow of the three inlet channels converged and entered the main part of the micromixer, a pair of swirling flows would be generated. This is due to the Coanda effect occurring at the point of abrupt change in the geometric shape of the inlet. It is at this point that the first flow mixing was conducted. Then, a simple baffle plate was added to the convergent-type micromixers. This meant that when the fluid passed by the baffle plate, a second flow separation was induced by the appearance of a pressure gradient on both sides of the plate. A pair of swirling flows was then generated with the swirling effect significantly impacting flow mixing. At this time, the flow mixing performance could be strengthened by the coupling effect of that fluid as it moved faster and faster towards the converging outlet. As mixing contacted the surface in the swirling flows it would become enlarged, hence the mixing length was shortened and a high mixing efficiency was achieved.

The basic model of the converging flow channel without the baffle plate is shown in Fig. 1(a). It is a three inlet flow channel, with the width of the main flow channel I_2 at $20 \mu\text{m}$, the widths of the side inlets I_1 and I_3 at $5 \mu\text{m}$, and the width of the outlet flow channel at $20 \mu\text{m}$. To create a positive swirling effect on flow mixing baffle plates were set vertically to the flow wall and are shown in Fig. 1(b). Here, the optimal dimension of the group (G1, G2, J), shown in Fig. 2(b), were found by using Taguchi method technology to attain a better flow mixing.

The Reynolds numbers of the fixed inlet, I_2 , in the micro-mixer ranging from $Re = 10$ to $Re = 85$ were utilized. In addition, an optimal flow condition that exhibited an outstanding mixing performance was set at Reynolds number ratio $Re_r = 0.85$, defined as $Re_r = \frac{Re_1 + Re_3}{Re_2}$ (Wang and Chen,

2011).

Here, the X and Y sizes were set and the relation between the angle inside the flow channel and the flow mixing efficiency was explored by changing the two parameters. It was found that a better flow mixing was achieved at the condition of where the included angle between $I_{1/3}$ and the middle inlet

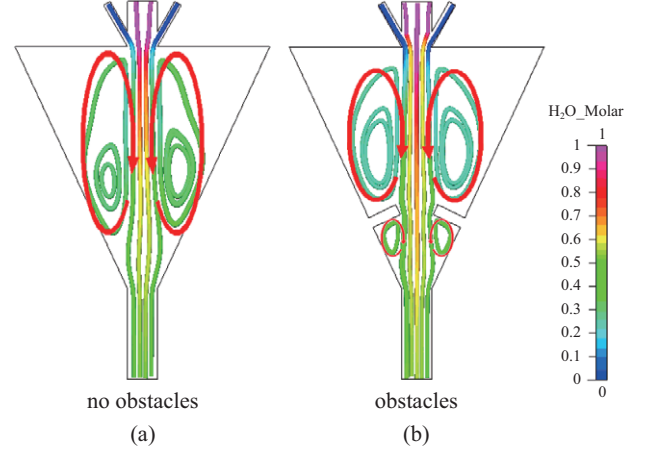


Fig. 2. Fluid flow diagram of the converging flow channel (a) without baffle plates (left) and (b) with baffle plates (right), with a Reynolds number of $Re = 80$.

I_2 was 30 degrees and $Re_r = 0.85$. It has therefore been used in subsequent discussions.

III. NUMERICAL ANALYSIS AND METHOD

In the design of the micromixer, two cases of with and without the addition of baffle plates were investigated by numerical simulation to find the optimal flow mixing. In this case, the fluid in the middle channel, labeled as fluid I_2 , was assumed to contain a species such as protein or DNA, and the dimensionless concentration was set to unity. In addition, the fluids in channels I_1 and I_3 were all the same and the concentrations were assumed to be zero. Some assumptions adopted in order to simplify the calculation of the flow field are as follows: (1) the flow field was at a steady state; (2) the fluids were Newtonian fluids; (3) the fluids had an incompressible flow; (4) the physical properties of fluids such as density, viscosity coefficient, and diffusion coefficient were constants; (5) the influence of gravity, magnetic force, and temperature field were neglected; (6) the two kinds of fluid did not have any chemical reactions, except for a simple concentration change.

The equations that govern the flow mixing process can be obtained by solving the continuity equation in the form of (1), momentum equation shown in (2), and diffusion equation defined in the form of (3):

$$\nabla \cdot \vec{V} = 0 \quad (1)$$

$$-\nabla \cdot P + \frac{1}{Re} \nabla^2 \vec{V} = 0 \quad (2)$$

$$\frac{1}{Re \cdot Sc} \nabla^2 C_m = 0 \quad (3)$$

Here, Re is the Reynolds number and defined as $Re = \frac{\rho V_0 W}{\mu}$; Sc is defined as $Sc = \frac{\mu}{\rho D_{ij}}$ and is the Schmidt number that represents the ratio of viscosity effect to the diffusion effect. W is the width of the outlet channel, \vec{V} is the velocity vector. P denotes pressure, C_m is the molar concentration, V_0 is the characteristic velocity, ρ is the density, and μ is the fluid viscosity. D_{ij} is the mass diffusivity.

The flow mixing performance was numerically simulated using a commercial Computational Fluid Dynamics (CFD) software package, CFD-ACE+ and a multi-physics package based on the Finite-Volume Method (FVM) was applied. The program was run on a 2.4 GHz Pentium IV processor with 1 GB of RAM memory. Mesh-independent tests were performed before the studies took place. An upwind method for solving the multi-block unstructured grid of 2×10^4 cells was used as the 2D computational domain inside the micromixer. The convergent criterion was assumed to be $\pm 10^{-18}$ for the residual of the discrete governing equations in the simulation. The flow mixing effect under the different conditions was studied, and the equation of mixing efficiency (Wong et al., 2003) cited is shown as (4).

$$\epsilon_{\text{mixing}} = 1 = \frac{1}{W} \int_0^L \left| \frac{X_{A_x, \text{outlet}} - 0.5}{X_{A_{\text{max}}} - 0.5} \right| dx \quad (4)$$

Here, the ϵ_{mixing} is the mixing efficiency, and $X_{A_{\text{max}}}$ is the maximum mole fraction of substance A; this value is fixed at 1. $X_{A_x, \text{outlet}}$ is the mole fraction of substance A in a certain position at the outlet, and W is the outlet width.

The mixing efficiency was calculated according to the mole fraction distribution at the outlet, where the closer ϵ_{mixing} was to 1, the better the mixing effect was found to be.

IV. RESULTS AND DISCUSSION

In this study, the mixing effect of a converging flow channel would be challenged to improve by using vortices. Here, baffle plates (Fig. 1(b)) would be applied. The appearance of vortices was induced by the pressure gradient when the flow passed through the plates. Previous literature (Hing et al., 2005; Howell et al., 2005; Fu et al., 2006) indicated that when additional non-equip phase stop blocks were placed in the flow channel, or the geometric shape of the flow channel was changed to cause chaotic flows in the flow field. These flow stretching and folding effects would make the flow swirl and the fluid contacting area to be enlarged (Jeon et al., 2005; Lin et al., 2007) for quick flow mixing. Therefore, this study discussed the optimal flow channel's geometric factors and the flow field operating conditions for improving the flow mixing based on the generation of rotational flow.

Numerical simulation executed in the cases of convergent-types of micromixers with/without plates was carried out at a

Table 1. Variations of mixing efficiency at different downstream locations in respect to Fig. 3.

position	without baffle plates	with baffle plates
	ϵ_{mixing}	ϵ_{mixing}
1	0.68	0.57
2	0.70	0.63
3	0.87	0.81
4	0.91	0.89
outlet	0.92	0.96

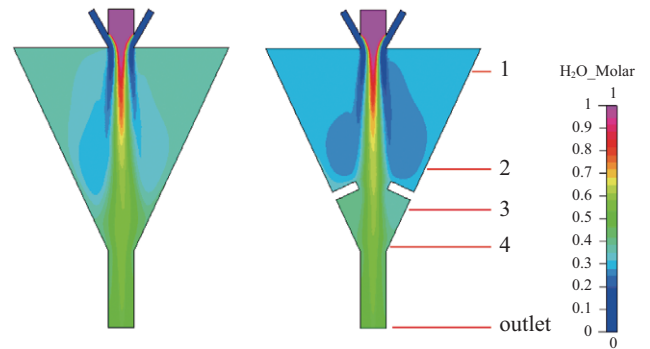


Fig. 3. Molar distribution of H₂O in convergent channel with/without plate cases.

flow condition of $Re = 80$. Results show that the outlet flow mixing efficiency in the case of without plates was 0.925, but 0.963 in the case of those whose plate dimensions were ($G1 = 15 \mu\text{m}$, $G2 = 3 \mu\text{m}$, $J = 50 \mu\text{m}$). It showed that the role of plates added in the micromixer would provide a positive effect on the flow mixing performance.

As for the distribution of the flow mixing shown in Fig. 2, it is clear to see that a pair of rotational vortex flows generated behind the baffle plates. Therefore, the mixing length could be enlarged by the appearance of the vortex flow. The flow in the case of with baffle plates had a better mixing performance expected and is confirmed in Fig. 3.

This resulted from the two coupling effects- the converged flow and vortex flow. The variation of flow mixing would change with the location and different flow mixings downstream. Some locations are shown in Table 1. From the results shown in Table 1, the higher flow mixing, with $\epsilon_{\text{mixing}} = 0.92$ at the outlet, could be achieved in the case of without baffle plates in a convergent-type flow channel. This evidence shows clearly that a converged flow effect with a flow tilting or swirling feature, by using a convergent-type channel, would create a significantly positive effect on flow mixing in this study. In addition, a vortex flow generated by using single plates can be seen as a multiplication factor of flow mixing.

The flow distribution with baffle plates generated two pairs of rotational vortex flows, where their positions were between 1 to 2, and 3 to 4. Hence, the flow contacting area was enlarged, and the flow mixing performance was significantly improved

Table 3. Comparison between the mixing effect of the mixer in this study (convergent-type) and that of other micromixers.

Mixer Type	Channel Type/Obstacles (number)	Mixing length (mm)	Re	ϵ_{mixing}
Y type	Zigzag channel	2	267	0.986
T type	J-shaped baffles (6)	9.5	350	0.706
T type	Rectangular Obstacles (9)	5	NA	0.9
Y type	Feedback side channel (6)	14.1	30	0.968
Double type	Square Obstacles (2)	0.67	4.7	0.984
Converged type	Plates (2)	0.25	80	0.97

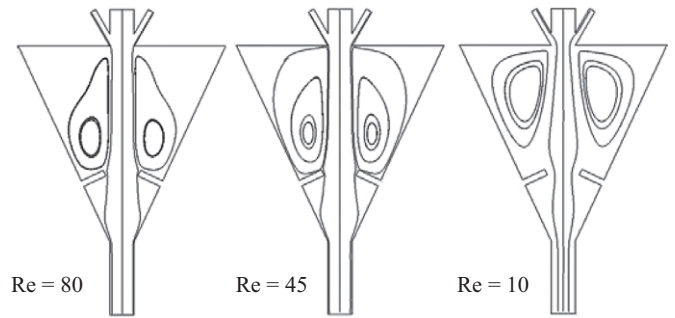
Table 2. Comparison between the optimal combination and mixing efficiency of different Reynolds numbers with baffle plates in the flow channel.

Re	Mixing Efficiency
10	0.924
45	0.94
80	0.97

between positions 2 and 3, where ϵ_{mixing} was increased from 0.63 to 0.81. The increment of mixing efficiency at position 4 still showed a significant increase in spite of being less than in the case of without baffle plates. However, the outlet itself was larger than that of the case of without baffle plates. This indicated that the baffle plates in the converging flow channel could really recombine the rotational flows at the vortices on both sides, thus enlarging the fluid contacting area and improving the flow mixing performance (Liu et al., 2000; Wang and Hu, 2011).

Figs. 2 and 3 show that the flow mixing effect can be strengthened by using baffle plates in a convergent-type flow channel. Therefore the optimal dimension of the group (G1, G2, J) shown in Fig. 2(b) were found by way of the Taguchi method to attain a better flow mixing. Here, the distance J, from the baffle plates to the necking position, and the baffle plate sizes G1 and G2 were defined. According to the analytic results, an optimal flow mixing efficiency, of 0.974, was obtained when $\text{Re} = 80$, $J = 45 \mu\text{m}$, $G1 = 15 \mu\text{m}$, and $G2 = 3 \mu\text{m}$. The effect of the Reynolds number would be worthy of investigating because it seems to have an important effect on the flow mixing. Different Reynolds numbers, $\text{Re} = 10, 45$ and 80 , were executed and are shown in Table 2. A positive effect of the Reynolds number on flow performance can be seen. Roughly speaking, the larger the Reynolds number used, the better the flow mixing.

Literature has indicated that the increase in obstacles in the flow channel will help to improve flow mixing, but a simple convergent-type flow channel with baffle plates in the flow channel has rarely been addressed previously and will be verified in this study. The vortex structure at the corner inside the flow channel was strengthened and more organized as the Reynolds number increased (Fig. 4). When the flow mixing increased as the strengthened convection enlarged the flow contact area, the outlet had a better mixing efficiency.

**Fig. 4. Flow contour with different Reynolds numbers.**

The results of this study were compared to previous studies on Y-shaped micromixers (see Table 3). Table 3 shows that a high mixing efficiency can be achieved, even when the Reynolds number is small, by using a simple baffle plate design. In addition, the mixing length in this study was shorter than that of other passive mixers, with the results illustrating that this design provided a small overall size and relatively simple structure. Due to its converging flow channel, the overall flow mixing performance was better than that of the general, more complicated micromixers.

V. CONCLUSION

In this study single baffle plates applied in a convergent-type flow channel enhance the flow mixing at a lower Reynolds number. Some useful conclusions can be addressed from this outcome.

Results show that good flow mixing can be achieved in a converged-type flow channel. The vortices generated by baffle plates mounted in the converging flow channel improved flow mixing. As the Reynolds number increased, the swirling flow structure became stronger, and the flow mixing at the outlet rose. In addition, the highest mixing efficiency was 0.974 at the optimal combination of $\text{Re} = 80$, $J = 45 \mu\text{m}$, $G1 = 15 \mu\text{m}$, and $G2 = 3 \mu\text{m}$. These findings would be useful to improve the flow mixing of micromixers in the future.

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