Unsteady Flow Mixing Effect in Bionic Micro-Flow Channel

Chin-Tsan Wang*  
C. T. Chang†

Tzu-Yang Hu†  
Tzong-Shyng Leu**

*National Ilan University, ctwang@niu.edu.tw
†National Ilan University, ctchang@niu.edu.tw
‡National Ilan University, hour7593@yahoo.com.tw
**National Cheng Kung University, tsleu@mail.ncku.edu.tw
Unsteady Flow Mixing Effect in Bionic Micro-Flow Channel

Chin-Tsan Wang, C. T. Chang, Tzu-Yang Hu, and Tzong-Shyng Leu

Abstract

Micro-mixers are studied extensively due to their high mixing efficiency. A periodic flow variation at the channel entrance will be used to drive fluids in this study to achieve a mixing effect. Numerical analysis is used and verified by experiment in the study to identify the group of operating factors, such as Reynolds number Re, the driving phase difference $\theta$ and the driving frequency ratio Fr, needed for the fluid to achieve the best mixing result for a bionic micro-mixer. It is found in this study that the mixing efficiency is related to the velocity period distribution; the more even the velocity period distribution becomes, the better the mixing efficiency and the best group of operating factors is found ($Re_2 = 1$, $Re = 0.85$, $Fr_1 = 1$, $Fr_2 = 50$ Hz, $I/A_{in} = 1$, $\theta = 3/4 \pi$). Furthermore, a larger aspect ratio results in a better mixing efficiency. The influence of wall-effect on the flow mixing decreases with AR. It is found that there exists an optimal mixing efficiency at aspect ratio AR = 10. These research results could be used to improve the design of a bionic micro-mixer.

KEYWORDS: bionic micro-mixer, mixing effect, operating factors

*Please send correspondence to: Chin-Tsan Wang, ctwang@niu.edu.tw or Tzong-Shyng Leu, tsleu@mail.ncku.edu.tw; tel. +886-3-9357400, ext 686; fax: +886-3-9311326.
1. Introduction

Microfluidics integration technology, such as fluid transport, metering, mixing, and so on, is one of the important core technologies in Micro-Electro-Mechanical Systems (Burns et al., 1998). Microfluidic devices such as micro-pumps, micro valves, micro-sensors and micro-mixers have been flourishing in the past several years (Shoji and Esashi, 1994). They are used throughout bio-medical technology (Shin et al., 2003; Shiramizu et al., 2008) and industrial production (Loh et al., 2007) and many other fields. Thus, achieving effective mixing is imperative for a microfluidics device in a microfluidic system, especial for chemical system.

Macroscopically, mixing of different fluids relies mainly on turbulence and an internal diffusion effect.

While in a microscopic fluid, it will flow in a laminar fashion under the condition of an extremely small Reynolds number resulting from the characteristics of slow flow velocity and small size and will not mix in a turbulent fashion (Tritton, 1988; Fox et al., 2004).

Micro-mixers can be divided into two types, active and passive, based on their actuation mechanism. Passive micro-mixers rely primarily on changing the channel shape, i.e. adding barriers inside the channel or changing the geometric shape of the channel to increase the contact areas and diffusion time between fluids to enhance mixing, e.g. the partitioned-pipe mixer (Khakhar et al., 1987). Active micro-mixers change the flow field to enhance the mixing efficiency (Wang et al., 2007; Tsui et al., 2008) by placing movable mechanical components in them or exerting external forces on themselves. The active type can be divided into pressure fluctuation types (Glasgow and Aubry, 2003), electro-kinetic instability types (Oddy et al., 2001; Taniguchi et al., 2007), ultrasonic disturbance types (Yang et al., 2001), thermal fluctuation types (Mao et al., 2002), and ferrofluid types (Fu et al., 2010; Affanni et al., 2010) based on the amount of energy input supplied.

Passive mixers use the flow energy to create multi-lamellae structures, which are stretched and recombined to promote mixing by molecular diffusion, such as parallel lamination, serial lamination, injection, chaotic advection, droplet, turbulent mixing by means of collision of jets and specialty flow configurations (e.g. the Coanda effect, relying on a microstructure for redirecting the flow), and so on. In passive micro-mixers no external power is supplied for the stirring, therefore the mixing relies mainly on molecular diffusion and chaotic advection. The molecular diffusion is induced by increasing the contact surface and decreasing the diffusion path between the different fluids (Kumar et al., 2010). As for the operational convenience, the pressure pumping type was applied to investigate the unsteady flow mixing effect in a bionic micro-channel channel in this research.
In this study, an unsteady flow disturbance was imposed at the channel entrance to drive the fluids and achieve the desired level of mixing (Goullet et al., 2005). This driving method was first proposed by Deshmukh et al., (2000), which built a hybrid system using micro-pumps and valves. However, it had a shortcoming of unstable outputs, and therefore Fujii et al., (2003) proposed a model that used external micro-pump devices to produce pressure fluctuations to drive fluids so that they could mix steadily and quickly. Niu et al., (2003) and Glasgow et al., (2003) analyzed this type of pressure-driven micro-mixer using numerical simulation. Among them, Niu et al., (2003) used T-type micro-mixers to induce pressure fluctuation at the entrance and were able to obtain a mixing efficiency of $\varepsilon_{\text{mixing}} = 0.83$. Ma et al., (2006) proposed a model with four inlets to serve as the pressure driving model, which could reach a mixing efficiency of $\varepsilon_{\text{mixing}} = 0.82$ under the condition of a somewhat lower driving frequency. In addition, a small vibration perturbation that occurred at the sidewall of the flow channel was used to arouse the flow vortex at the tip of the channel corner to enhance the flow mixing performance in a short time interval (Chan et al., 1996; Oberti et al., 2009). Knight et al., (1998) verifies the fact that a little amount of reagent could be mixed well by way of folding initiated action (Jones et al., 1993) within a short time interval. The kinematics of mixing including the stretching, chaos and transport was addressed by Ottino (1989). Finally, Neilda et al. (2010) addressed a new design, modified from the original prototype of Oberti et al., A low frequency sidewall flow was injected into the main flow channel and an identical flow mixing to Oberti et al., could be achieved but with a shorter mixing length required.

It can be observed from the above discussion that pressure driving a fluid indeed helps to enhance the mixing efficiency. The bionic micro-mixer can achieve a high mixing effect with a mixing efficiency of $\varepsilon_{\text{mixing}} = 0.897$ (Wang et al., 2009) during a steady state However, the influence on the mixing effect by unsteady flow has not been explored in those studies. Therefore, an unsteady flow will be imposed on the entrance of the bionic micro-mixer to drive fluids and analysis on the mixing effect in a flow field with unsteady flow will be conducted in this study.

2. Numerical Method

2.1. Physical model

The analysis model shown in Figure 1 was used in this work because it can produce a lower pressure drop and a better mixing performance within a limited space (Wang et al., 2009). Its design idea is to mimic the concept that different
blood vessels in different parts of the human body have different flow rates to construct a new type of bionic micro-mixer with an optimal size obtained by the use of the Taguchi optimization analysis. It induces changes in the fluid flow rate through the changes in the flow channel width and induces mixing in fluids through the flow rate exchanges between fluids (Glasgow et al., 2004). The best way for a micro-mixer to enhance its mixing effect is to increase the contact opportunity between two fluids. Therefore, a design of three inlets is adopted in this study to lead the duo-fluid flow through multiple folds using the two-sided inlets in a symmetrical fashion, so that the contact opportunity between the two fluids can be increased to enhance the mixing effect. These system flow channel inlets are labeled as I₁, I₂, I₃ respectively; the two slanting inlet channels are (I₁, I₃) and the central inlet channel is (I₂). Different fluids are injected into these inlets: I₁ and I₃ are injected with the same kind of fluid and have the same flow channel diameter, which is different from the type of fluid and the diameter of I₂. Therefore, I₁ and I₃ have the same Reynolds number.

Figure 1. The optimal bionic mixer model (Wang et al., 2009), unit: μm.

2.2 Numerical simulation method

As for the fact that some important physical effects in micro-mixers can be addressed a multi-scale method, a review of state-of-the-art computational strategies for micro and nanofluid dynamics and materials in the framework of
hybrid molecular dynamics, plus the continuum fluid dynamics method was addressed by Kalweit et al., (2008). In addition, an interface capture in dual-flow microfluidics addressed was utilized extensively in microfluidics applications, especially for the microfluid mixer. In addition, an important effect addressed (Shapiro et al., 2006; Shapiro et al., 2007) is the displacement of the contact distinctness between the carrier liquids due to the difference in carrier liquid viscosities pumped in with the same volume. In computer simulations, numerical diffusion could lead to a more diffused displacement of the interface. Therefore, the only solution to a microfluidic system is to rely on a micro-mixer with high efficiency and stability, the design of which is currently one of the more important topics in the research of microfluidics.

In this study the mixing performance was numerically simulated using a commercial package, CFD-ACE+. A multi-physics package based on the Finite-Volume Method (Giuseppe, 2007; Robert Cook et al., 1989) was applied. The equations that govern the mixing process can be obtained by solving the continuity equation in the form of (1), momentum equation shown in (2), and advective diffusion equations based on the combined effect of diffusion and convection in a medium and defined in the format of (3):

\[ \nabla \cdot \vec{\nu} = 0 \]  
\[ \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\nabla p + \frac{1}{Re} \nabla^2 \vec{V} \]  
\[ \frac{\partial C_i}{\partial t} + \vec{V} \cdot \nabla C_i = \frac{1}{ReSc} \nabla^2 C_i \]

These three laws can be used to develop a set of equations (known as the Navier-Stokes equations) for CFD-ACE+ to solve numerically.

Here, the diffusion coefficient, set as \( \frac{1}{ReSc} \), is the proportionality between the molar flux due to molecular diffusion and the gradient in the concentration of the species. Re is the Reynolds number and is defined as \( Re = \frac{\rho V_0 D_0}{\mu} \). Sc is defined as \( Sc = \frac{\mu}{\rho D_{ij}} \) and is the Schmidt number to represent the ratio of the
viscosity effect to the diffusion effect. $D_0$ is the inner diameter ($D_0=20 \, \mu m$) at the entrance of the central main flow channel ($I_2$). $V_0$ means the average velocity at the entrance of the central main flow channel ($I_2$). $\mu$ is fluid dynamic viscosity coefficient. $\rho$ indicates the density of fluid. $\vec{V}$ stands for the velocity vector; $t$ is time; $p$ denotes pressure; $C_i$ represents mole concentration and $D_{ij}$ is the mass diffusivity.

The program was run on a 2.4 Ghz Pentium IV processor with 1GB of RAM memory. On the mesh-independent tests, four numbers of $N=2\times10^4$, $2.5\times10^4$, $3.0\times10^4$ and $3.5\times10^4$ were used to test before the studies and are shown in Figure 2. A good multi-block unstructured grid number selected was $N=3.5\times10^4$ and $9\times10^5$ for 2D and 3D numerical simulation, respectively. An algebraic multi-grid method (AMG) method was applied to accelerate the convergence. The convergent criterion was assumed to be $\pm 10^{-4}$ for the residual of the governing equation applied in the simulation. For the boundary condition of the simulation process, a no-slip condition at the channel wall was assumed. In addition, the pressure was set to zero atm at the outlet flow channel and the 3 inlet Reynolds number ratio was $Rer = 0.85$ (Wang et al., 2009). Although the valve flow was laminar, a rather fine mesh was needed to account for the detailed features of the sorting mechanism. The simulation time interval for each run spanned from 24 hours to 48 hours for the two dimensional simulations and from one week to three weeks for the three dimensional simulations.

The inlet fluids were all set at a water temperature of 25 degrees, a density of $997\, \text{kg/m}^3$ and viscosity coefficient of $8.91\times10^{-4}\, \text{kg/ms}$. For the ease of classification in this study, “water A” and “water B” were used to represent the fluid in the central main flow channel and that of the side-flow channels, so that the experimental concentration changes could be represented.

Basic assumptions:

1. The fluid is incompressible and it is a Newtonian fluid.
2. Fluid properties such as viscosity, density and diffusion coefficient are all constant.
3. The effects of gravity, magnetic field, and temperature field are ignored.
4. Concentration changes without the occurrence of chemical reactions for mixing only.
5. The channel wall does not slip.

In order to analyze the mixing efficiency of the bionic flow channels, the mixing indicator $\varepsilon_{\text{mixing}}$ is adopted in this study for quantitative analysis (Hung et al., 2005) and its definition is shown in (4):

$$
\varepsilon_{\text{mixing}} = 1 - \frac{1}{L_0} \left| \int_X \frac{X_{A,\text{outlet}} - 0.5}{X_{A_{\text{max}}} - 0.5} \, dx \right|
$$
$\varepsilon_{\text{mixing}}$: The mixing efficiency  
$X_{\text{A max}}$: The maximum mole fraction for A fluid (its value is always 1)  
$X_{\text{AX outlet}}$: The mole fraction for A fluid at the outlet  
$L$: The width at the outlet is 20 $\mu$m

![Figure 2. Mesh-independent tests.](http://www.bepress.com/ijcre/vol9/A14)

In order to investigate the pressure drop and the mixing efficiency of the bionic micro-mixer under different inlet flow rate conditions, Reynolds number $Re$ was used to represent the flow rate in this study.

In addition, the pressure drop and the mixing efficiency of the bionic micro-mixer under different driving frequency ratios would be investigated, the driving frequency ratio $Fr$ for the flow channel is defined as in (5):

$$Fr = \frac{F_1}{F_2}$$  \hspace{1cm} (5)

$F_1$: The driving frequency for the side inlet flow channel $I_1$  
$F_2$: The driving frequency for the central main flow channel inlet $I_2$

In order to investigate whether the shear flow effect caused by the difference in flow rates in inlet flow channels will impact mixing, Reynolds number ratio $Rer$ is defined as in (6) to serve as a factor for analysis:

$$Rer = \frac{Q_1}{Q_2}$$  \hspace{1cm} (6)
\[
\text{Rer} = \frac{\text{Re}_{1(3)} + \text{Re}_2}{\text{Re}_2} 
\]

\text{Re}_{1(3)} : \text{Reynolds number for the side-way inlet flow channel } I_{1(3)}

\text{Re}_2 : \text{Reynolds number for the central main flow channel inlet } I_2

2.3 Boundary settings

A periodic flow velocity variation, as in (7), is imposed at the entrance of the flow channel to drive fluids through the control of operating factors to enhance the mixing effect:

\[
U = U_m \left[ I + A_m \sin (\tau \omega + \theta) \right] \tag{7}
\]

\(U_m\) = the average velocity of the inlet flow

\(A_m\) = the amplitude of the sinusoidal periodic variation

\(\tau\) = Time constant

\(\omega\) = Angular velocity

\(\theta\) = Phase difference

\(I\) = Unit inflows

The average velocity of the inlet flow \(U_m\) is varied to investigate the change of the mixing effect under different Reynolds numbers in this study. However, the objective of maintaining the fluid flowing forward must be ensured even under periodic driving variations. Therefore, the amplitude \((A_m)\) is set to 0.01.

When varying different parameters, in order to find the stable mixing efficiency value under periodic driving variations, the simulation conditions are set to: Reynolds number \(\text{Re}_2=1\) for inlet \(I_2\), Reynolds number ratio \(\text{Rer} = 0.85\), and frequency \(F=50\) Hz. The fluid driving frequencies for the three inlets are fixed and there are no phase differences. The results are shown in Figure 3, in which the mixing efficiency approaches \(\varepsilon_{\text{mixing}} = 0.904\) when the fluids are driven at the 60th cycle, thus showing that the fluid mixing has reached a stable condition.
3. Discussions and Results

The analysis in this study for the impact to the fluid mixing by the unsteady flow will be divided into 6 parts for the sake of discussion. The first part investigates the impact of the Reynolds number effect on the mixing efficiency. The second part investigates the mixing efficiency when the main flow channel and the two side-way channels are at the same fluid driving frequency but with a phase difference ($\theta$). The third part investigates the impact on the mixing when the main flow channel and the two side-way channels are at the same phase, but under a different driving frequency ratio $Fr$. The fourth part investigates the impact of the ratio ($I/A_m$) between the inflows (I) and the driving amplitude ($A_m$) to the mixing efficiency. The fifth part investigates the impact of the aspect ratio (AR) to the mixing efficiency. Finally, some experiments are executed to confirm the simulation results in the final part.

First, the fluid mixing scenarios under different Reynolds numbers were analyzed to find the best Reynolds number that could produce the maximum mixing efficiency. Under the condition of setting all the fluid driving frequencies for the three inlets to $F = 50$ Hz and the Reynolds number ratio to $Re_r = 0.85$ (Glasgow and Aubry, 2003) in this study, the Reynolds number for the $I_2$ inlet flow channel was set to $Re_2 = 0.5, 1, 5,$ and $10$ to perform fluid mixing analysis through the change in the inlet Reynolds number for the central main flow channel. The results are shown in Table 1. It was found from the table that the mixing effect at $Re_2 = 1$ is better than that at any other $Re_2$ and that it also has a
better mixing efficiency $\varepsilon_{\text{mixing}} = 0.905$. Therefore, $Re_2 = 1$ was used in this study as the flow field condition for subsequent analyses.

Here, some cases of experimental verification will be made by way of the disposable apparatus for the numerical results in this study. The experimental flow condition of the micro-mixer shown in Figure 1 with an aspect ratio $AR=1$ and Reynolds ratio $Rer=1$ is as follows:

The constant flow velocity of the side inlet channel $I_1$ and $I_3$, which were pushed by an injector (KDS 220), was set as $1.52\times10^{-4}$ m/s and the corresponding Reynolds number $Re_1(3)$ was $0.05$. The middle channel $I_2$, which was pushed by a digital wriggle syringe pump (77920-30L/S), and corresponding to Reynolds number $Re_2 = 0.1$, had a flow velocity of $8.97\times10^{-5}$ m/s and a pumping frequency of $f = 0.125$Hz for the digital wriggle. The dye flow visualization was made and a gray-scale technology was used and applied for the quantitative mixing coefficient of the outlet channel. The estimated value of the mixing coefficient was 0.904 for the experiment of studied cases. In addition, another experimental case of the operational frequency $f = 0.333$ Hz and in phase applied for the two identical digital wriggle syringe pumps were executed at an optimal flow condition of $Rer = 0.85$ and $Re_2 = 1$ for comparison with the same flow condition of the simulation. The estimated value of the mixing coefficient was 0.925 for the experiment of studied cases. These verifications show a small difference between the experiment and simulation because the deviation is only about 2%.

Table 1. Table for the relationship between Reynolds number $Re_2$ and the mixing efficiency.

<table>
<thead>
<tr>
<th>$Re_2$</th>
<th>0.5</th>
<th>1</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{mixing}}$</td>
<td>0.864</td>
<td>0.905</td>
<td>0.871</td>
<td>0.869</td>
</tr>
</tbody>
</table>

In order to investigate the impact of different phase differences for the fluid driving at the inlet on the fluid mixing, phase angle ($\theta$) was varied from $\{0\sim2\pi\}$ at $Re_2 = 1$, $Rer = 0.85$, and all the fluid driving frequencies for the three inlets set to $F = 50$ Hz, to analyze its mixing efficiency. The result from Figure 4 indicates that the distribution of the mixing efficiency is extremely irregular, among which the mixing efficiency $\varepsilon_{\text{mixing}} = 0.929$ at phase difference $\theta=3/4\pi$ is somewhat better than the rest (See Figure 4A). In addition, it was found in the study that the smaller the standard deviation of the velocity is, the more even the velocity distribution is and the better the mixing efficiency becomes (See Figure 4B).
Figure 4. The relationship between the mixing efficiency, $\varepsilon_{\text{mixing}}$, (A), and the standard deviation of the velocity, $V_{SD}$, (B) at different phase differences.

Next, the impact of a different fluid driving frequency ratio $Fr$ to the mixing efficiency was investigated. The inlet frequency ratio $Fr$ was varied as follows: the fluid driving frequency, $F_2$, for the central main flow channel, $I_2$, was set as $Re_2 = 1$, $Re_r = 0.85$, and $\theta=3/4\pi$, while the frequency ratio was varied from
Fr=0.5-100 Hz. The results are tabulated in Table 2; when Fr=1 and 50, the mixing efficiency is the same, $\varepsilon_{\text{mixing}} = 0.929$, and when Fr=1 and 50, the standard deviation for the velocity is $6.1 \times 10^{-5}$ m/s, which is somewhat smaller than other results. Thus, it validates the previous result again: Fr=1 is the best driving frequency ratio.

Table 2. Fr value versus mixing efficiency.

<table>
<thead>
<tr>
<th>Fr</th>
<th>0.5</th>
<th>1</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V_{SD}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>$4.2 \times 10^{-4}$</td>
<td>$6.1 \times 10^{-5}$</td>
<td>$4.2 \times 10^{-4}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$6.1 \times 10^{-5}$</td>
<td>$3.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>1</td>
<td>0.917</td>
<td>0.929</td>
<td>0.918</td>
<td>0.911</td>
<td>0.929</td>
<td>0.911</td>
</tr>
</tbody>
</table>

Next, the relationship between constant inflows (I) and the driving amplitude ($A_m$) was investigated. The experiment settings in this study were: $I/A_m = 1, 5, 10, 20$, amplitude ($A_m$) fixed at 0.01 and Re2 = 1, Re = 0.85, Fric=1, F2=50 Hz and $\theta = 3/4\pi$. The results are tabulated in Table 3: When the $I/A_m$ value is equal to 1, mixing efficiency $\varepsilon_{\text{mixing}} = 0.929$; the larger the $I/A_m$ value is, the worse the mixing efficiency becomes.

Table 3. Table for the relationship between $I/A_m$ and the mixing efficiency.

<table>
<thead>
<tr>
<th>$I/A_m$</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{mixing}}$</td>
<td>0.929</td>
<td>0.873</td>
<td>0.869</td>
<td>0.869</td>
</tr>
</tbody>
</table>

A group of optimum operating parameters (Re2 = 1, Re = 0.85, Fr=1, F2=50 Hz, $I/A_m=1$, and $\theta = 3/4\pi$) was obtained in this study based on a series of analyses and discussions mentioned above for a mixing efficiency $\varepsilon_{\text{mixing}} = 0.929$. This result was compared with the results published by Glasgow et al., (2004) and Ma et al., (2006), which are shown in Table 4. The flow model used in Glasgow et al., (2004) was a T- type micro-mixer. The length of the model was 3 mm with two inlets, a vibration frequency of 10 Hz, Re = 0.3 and the phase difference was $\pi$, with a mixing efficiency of $\varepsilon_{\text{mixing}} = 0.83$. In addition, the flow model used in Ma et al., (2006) was a model with four inlets. Its length was 3 mm, vibration frequency was $f = 3$Hz, Re = 0.119 and there was no phase difference, with a mixing efficiency of $\varepsilon_{\text{mixing}} = 0.82$. The length of the model in this study was 350 $\mu$m, which differs from that of the two models by a factor of roughly 8.5. However, the mixing efficiency for the micro-mixer designed here can reach $\varepsilon_{\text{mixing}} = 0.929$, which shows that a bionic micro-flow channel with unsteady flow can enhance the mixing efficiency significantly.
Table 4. Comparison table for different mixers.

<table>
<thead>
<tr>
<th>Inlet number</th>
<th>Model size</th>
<th>Frequency</th>
<th>Re</th>
<th>$\theta$</th>
<th>$\epsilon_{\text{mixing}}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 inlet</td>
<td>3 mm</td>
<td>10 Hz</td>
<td>0.3</td>
<td>$\pi$</td>
<td>0.83</td>
<td>Ma et al (2006)</td>
</tr>
<tr>
<td>3 inlet</td>
<td>250 μm</td>
<td>50 Hz</td>
<td>$1(\text{Re}_2)$</td>
<td>$3/4\pi$</td>
<td>0.929</td>
<td>This study</td>
</tr>
<tr>
<td>4 inlet</td>
<td>3 mm</td>
<td>3 Hz</td>
<td>0.119</td>
<td>0</td>
<td>0.82</td>
<td>Glasgow et al (2004)</td>
</tr>
</tbody>
</table>

Fifth, the impact of the unsteady flow aspect ratio $\text{AR}$ on the mixing efficiency was investigated. The settings were $\text{Re}_2 = 1$, $\text{Fr}=1$, $f=50$ Hz, $l/A_m=1$, and $\theta=3/4\pi$. The results for the changes in the mixing efficiency when the aspect ratio is changed to $\text{AR}=1$, 2, 4, 10 are shown in Table 5. It is found that the larger the depth to width is, the better the mixing efficiency becomes, which indicates that the impact of the wall effect on the mixing efficiency exists with decreasing with AR. There exists a better mixing efficiency at an aspect ratio of $\text{AR}=10$.

Table 5. Table for the relationship between aspect ratio and the mixing efficiency.

<table>
<thead>
<tr>
<th>AR</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>10</th>
<th>2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{mixing}}$</td>
<td>0.691</td>
<td>0.801</td>
<td>0.849</td>
<td>0.925</td>
<td>0.929</td>
</tr>
</tbody>
</table>

Finally, some cases of experimental verification will be made at AR=1 with a flow condition of $\text{Re}_2=2$ and $\text{Fr}=0.85$ by way of disposable apparatus for the numerical results in this study. In addition, a CO2 laser-engraving machine made the flow channels of a mixer, whose substrate material was Polymethylmethacrylate (PMMA).

Owing to the fact that the dimensional scale effect of the mixer had an unobvious appearance upon the flow mixing at same inlet flow condition, the experimental framework is shown in Figure 5. The flow velocity of the inlet channel was pushed by a digital wriggle syringe pump (77920-30L/S) at the operational condition of operation frequency $f_2=0.333$ without any phase difference and an amplitude of $A_m=2.5\times10^{-3}$ ml. The dye visualization was captured by high speed CCD camera and a gray-scale technology for the quantitative mixing coefficient of the outlet channel.

Figure 6 shows the flow mixing images at a different phase for the numerical simulation and experiment. The result shown in Figure 6 indicates a
similar tendency between numerical simulation and experiment. Further, an error value between experiment and simulation for the flow mixing coefficient whose value is 0.925 and 0.904 respectively is about 2%. This evidence could further interpret the validity of numerical simulation.

Figure 5. Experimental framework.

Figure 6. Flow mixing image at different phases (T/4, 2T/4, 3T/4, T) for numerical simulation and experiment.

4. Conclusions

In the bionic micro-flow channel unsteady flow analysis, in order to find the best flow driving operating parameter group, so that the bionic micro-mixer will produce a better mixing performance, a series of numerical studies were
conducted and verified by using specified experiments. Some useful results are described respectively as follows:

(1) The more the velocity distribution is, the better the mixing efficiency becomes.
(2) \((\text{Re}_2 = 1, \text{Rer} = 0.85, \text{Fr}=1, \text{F}_{2}=50 \text{ Hz}, \text{I/Am}=1, \text{ and } \theta=3/4\pi)\) is the best flow driving operating parameter group.
(3) The unsteady flow effect can enhance the mixing effect of the bionic micro-mixer significantly.
(4) The larger the aspect ratio is, the better the mixing effect becomes, which indicates that the impact of the wall effect on the mixing efficiency exists with decreasing AR. Also, there exists a greater mixing efficiency at AR=10, which is found to be the best aspect ratio.

These observations will be useful for a design of a microfluidics device in a microfluidic system.

References


http://www.bepress.com/ijcre/vol9/A14


