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An Optimal Inlet Flow Angle Design of Vascular-type Micromixer

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Keywords： *Blood-vessel micromixers, mixing index, pressure drop, Numerical Simulation, flow splitting and recombining (SAR)*

ABSTRACT

Micromixers are important modules in medical applications. Novel and excellent biometric micromixers have been designed with an effective mechanism of flow splitting and recombining (SAR). The aim of this study is to modify the prototype of a biometric micromixer by designing the inlet flow channel and generating a better flow geometry in the blood vessel-micromixer. The blood vessel-micromixer was also investigated with different inlet channel angles and various Reynolds number ratios (Re_{I2} and Re_r) for the estimation of their influence on the mixing performance of the micro-mixer. The Re_{I2} is the inlet 2 and the Re_r is the combination of side flow and middle flow effects during the different flow conditions. Results showed that the blood vessel-micromixer with an inlet channel angle of 30° (Ø =30°) can be optimized for future research works. In addition, optimal performance with a Amixing index of 0.88 would be achieved at a condition of Re_{I2}= 1 and Re_r = 0.7. These findings will be definitely useful for the improvement of micromixer applications in the future.

INTRODUCTION

Micromixers are crucial components in biomedical systems and are extensively used in the application of biology and chemical synthesis for sample preparations (Oh et al. 2010; Cheri et al. 2013; Yang et al. 2015; Shamloo et al. 2017). Efficient mixing of substances is very important for these types of applications (Lee and Fu 2018; Hermann et al. 2018; Wang et al. 2012). Therefore, micromixers are worthy for further research and improvement in mixing performance, because they are capable of mixing two or more fluids rapidly (Huang et al. 2017). Micromixer designs can be categorized as active micromixers and passive micromixers. In the active micromixers, the external disturbance will be applied to fluids through different methods like pressure, temperature, electrokinetics, etc (Wang et al. 2014). As far as the passive type of micromixers is concerned, they are dependent on the flow channel design for the mixing process because this will force the flow motion to change and will also produce better flow mixing efficiencies (Ruijin et al. 2017). Considering the passive micromixers, two mechanisms of flow mixing such as molecular diffusion and chaotic advection have been addressed and extensively applied. But the diffusion type of micromixers is quite complex to be understood because a long mixing length is required during the mixing process (Chen and Li 2017). In another type called the chaotic advection micromixer, a series of obstacles will be placed in the flow channel to create a better flow mixing by the mechanism of flow splitting and recombining (SAR) (Hossain and Kim 2015; Nimafar et al. 2012; Viktorov and Nimafar 2013). In addition, a series of numerical simulations of the “OH-shape” micromixers were designed by Hossain and Kim (2015). In their study, the flow chaotic phenomenon was created by the concept of SAR at various operational Reynolds numbers (Re) ranging from 0.1 to 120 and a better flow mixing index of 0.884 was achieved at Re=30. Similarly, a novel micromixer with SAR, called a chain micromixer was addressed and a flow mixing efficiency of 0.98 was obtained at a low Re condition of $0.083 \le Re \le 4.166$ (Nimafar et al. 2012). Another type of “H-shaped” micromixer based on the same SAR mechanism was designed and was reported to have displayed a better flow performance at a low Re

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(Viktorov and Nimafar 2013).

All the above-mentioned studies are related to passive micromixers which were operated based on the SAR mechanism. The advantage of SAR is the ability to enhance mixing at a low Re, while a long mixing length will be required. Therefore, an innovative design of a micromixer known as a biophysical micromixer has been addressed in this research with the aim of reducing the total mixing length. A biophysical micromixer was designed by varying the runner width, such as the vein which changes from major to minor, and then back to major again (Wang et al. 2009; 2011a; 2011b). A biophysical micromixer could provide a simple structure, a short mixing length, and a low-pressure drop but with an efficiently higher flow mixing. This design has been extended to be applied in microbial fuel cells (MFCs) for producing bioelectricity with higher power densities (Wang et al. 2010; 2016a; 2016b). Nevertheless, this prototype biophysical micromixer needs to be further improved since the effect of inlet angles of the flow channel has been neglected in the system. In fact, different inlet angles would influence the mixing performance significantly. In this study, a modified vein shape type of biophysical micromixer, called a blood vessel-micromixer, has been designed according to the principle of the SAR mechanism, which helps us reveal the effects of inlet flow angles. It is concluded that combining SAR and the shape of blood vessels can produce a high flow mixing with low-pressure drop and short mixing length.

In this study, the physical model of blood vessel-micromixer was analyzed with different inlet flow angles as illustrated in Fig. 1. Here, five different channel angles (Ø) between inlet 1 and inlet 3 (I1 and I3) and inlet 2 (I2) (Ø=15°, 30°, 45°, 60°, 75°) were investigated for realizing the impact of inlet flow channels on the mixing performance at various operational Reynolds number ratios (Re_r) ranging from 0.1 to 1 and Re_{I2}=1.

MATERIALS AND METHODS

Numerical Method

For evaluating the physical design of the blood vessel-micromixer, the SAR mechanism was followed by modifying the inlet flow channel angles. Three inlet flow channels marked in red and blue and one outlet flow channel marked in green were set (Fig. 1). In addition, the bifurcate channels with an angle of split (θ) marked in purple and orange respectively were used for indicating the function of splitting and recombining of fluids. In this study, a blood vessel-micromixer with a mixing length of 370 μm and a lateral width of 217.5 μm was designed and investigated.

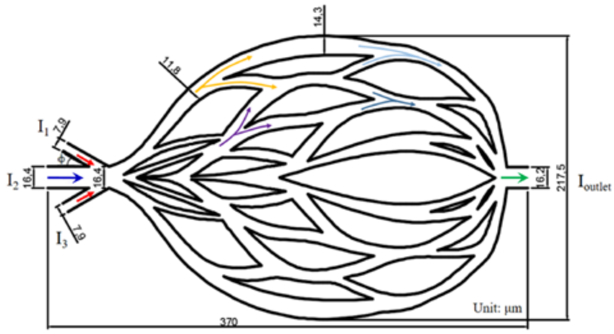

Fig. 1. Physical model of blood vessel-micromixer

Numerical Simulation Method

For demonstrating the mixing efficiency in the micromixer by numerical simulation technique, two kinds of water A (H_2O Molar=1) and B (H_2O Molar=0), were employed to represent two different fluids. Here, constant viscosity (μ=8.91×10^{-4} kg/ms) and density (ρ=998 kg/m^3) values were assigned. The flow mixing performance was numerically simulated using a commercial Computation Fluid Dynamics (CFD) software package, CFD-ACE+, and a multi-physical package based on the Finite-Volume Method (FVM) was applied. The program was on a 2.4 GHz Pentium IV processor with 1GB of RAM memory. Mesh-independent tests were performed prior to the experiments. An upwind method for solving the multi-block unstructured grid of 1.28×10^6 cells was used as the 2D computational domain inside the micromixer. The convergent criterion was assumed to be $\pm10^{-8}$ for the residual of the discrete governing equations in the simulation.

Some assumptions were followed in order to simplify the calculations of the flow field as follows:

(1) Flow field was in steady-state.
(2) Fluid was Newtonian fluid.
(3) Flow was incompressible and in a no-slip condition.
(4) The influence of gravity, magnetic force, and temperature field were neglected.
(5) The two kinds of fluids did not undergo any chemical reactions.
(6) The physical properties of fluids such as viscosity coefficient, diffusion coefficient, and density were all set as constant.

The equations that governed the flow mixing process were obtained by solving the continuity equation (1), momentum equation shown in (2), and diffusion equation (3) as follows:

1. continuity equation

$$\nabla \cdot V = 0 \tag{1}$$

2. momentum equation

$$\vec{V} \cdot \nabla \vec{V} = -\nabla p + \frac{1}{\mathrm{Re}} \nabla^2 \vec{V} \tag{2}$$

3. diffusion equation

$$\vec{V} \cdot \nabla C_i = \frac{1}{\mathrm{Re}\, Sc} \nabla^2 C_i \qquad (3)$$

Here, Re is the Reynolds number and defined as $\mathrm{Re} = \frac{\rho v_0 W}{\mu}$; 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_i 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.

In order to analyze different inlet channel angle conditions for the flow mixing effect, the mixing efficiency has been defined as shown in equation 4

$$\varepsilon_{mixing} = 1 - \frac{1}{W} \int_0^W \left\| \frac{X_{Ax,Outlet} - 0.5}{X_{A\max} - 0.5} \right| dx \qquad (4)$$

Here, X_{Amax} has described as a maximum concentration of the solution. $X_{AX,outlet}$ is the concentration of the solution in the outlet. W is outlet width of the micromixer and 16.2 μm was set in this study.

Similarly, another significant parameter of pressure drop called the coupling mixing index (M_{idx}) is defined with factors of mixing efficiency and pressure drop as shown in equation (5). It is important in the design of the micromixer and can be used as a criterion for discussing mixing performance:

$$M_{idx} = \varepsilon_{Mixing} \times \frac{\Delta P_{\max}}{\Delta P} \qquad (5)$$

Here ε_{mixing} is mixing efficiency; ΔP_{max} represents the maximum value of the pressure drop.

On the setting of Re_r in form of (6), this parameter defined will be combined with a side flow effect and middle flow effect during the different flow conditions.

$$\mathrm{Re}_r = \frac{\mathrm{Re}_1 + \mathrm{Re}_3}{\mathrm{Re}_2} \qquad (6)$$

Here Re_1, Re_2, and Re_3 in (7) are the Reynolds numbers of I_1, I_2, I_3 at the inlet channel, and in order to explore the influence of the velocity I_1 and I_3 have the same values.

$$\mathrm{Re} = \frac{\rho v D}{\mu} \qquad (7)$$

Here ρ is density of flow, $V_{1(2)(3)}$ is average velocity of the inlet channel $I_{1(2)(3)}$, D is the hydraulic diameter of the inlet channel, $I_{1(2)(3)}$, μ is the dynamic viscosity coefficient of the flow.

RESULT AND DISCUSSION

This modified type of biometric micromixer has originated from the biophysical micromixer demonstrated in the previous publications of our research group (Wang et al. 2009; 2011a). They reported that the inlet channel angle of the side channels had definite effects on the mixing and pressure of the fluids. Therefore, the present study has been focused on investigating the effects of different inlet channel angles ranging from Ø=15° to 75° as shown in Fig. 1. This was determined for finding a better design of inlet channel angle in flow systems with a high mixing index. Fig. 2 clearly indicates that the conditions of Re_{I2}= 1 and Rer= 0.7 displayed that when the inlet channel angle was larger than Ø=30°, the tendency of mixing efficiency decreased with pressure drop. In addition, when the inlet channel angle was set at Ø =30° mixing efficiency was better because it produced a higher flow mixing efficiency of 0.85 and a lower pressure drop at a low inlet Reynolds number. These findings were similar to the reports of Wang et al (2009), but the pressure drop of 1.5 kPa that occurred in this modified type of micromixer was less than the original biophysical type of micromixer, with a reduced amount of pressure drop of 17 % at the same operational condition. These results clearly indicated that the modified type of blood vessel-micromixer was better than the original type.

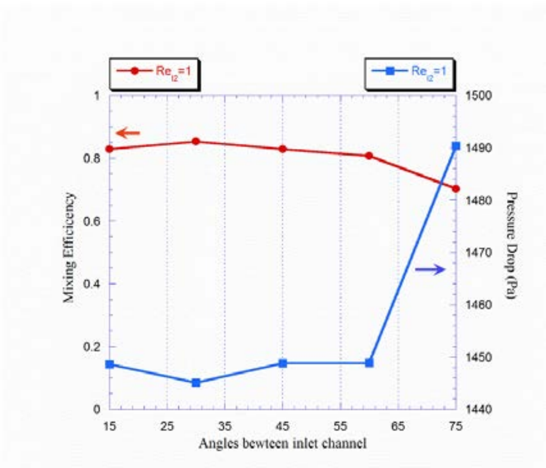

Fig. 2. Mixing efficiency and pressure drop versus different inlet flow channel angles (Ø=15°, 30°, 45°, 60°, 75°) at ReI2= 1 and Rer= 0.7

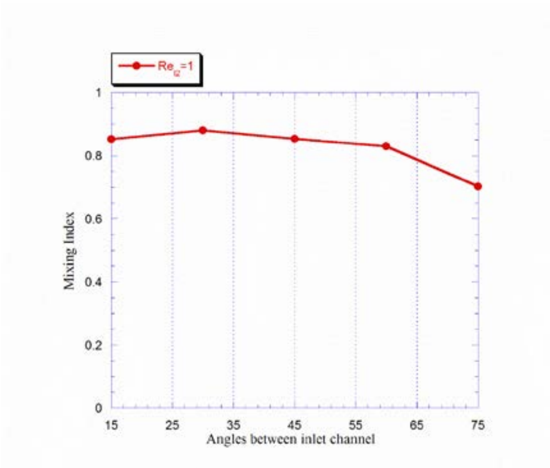

Fig. 3. Mixing index versus different inlet flow channel angles (Ø=15°, 30°, 45°, 60°, 75°) at ReI2= 1 and Rer= 0.7

Regarding the coupling effect of mixing performance and pressure drop cited in the micromixer design, the mixing index was used at Re_{I2}= 1 and Rer= 0.7 and the results are shown in Fig. 3. A mixing index with a larger value than 0.7 was achieved for all different inlet flow channel angles at Re_{I2}= 1 and Rer= 0.7 in this study. Experimental studies were performed after the confirmation of scale-effect at the same condition for identifying the validation of the numerical results. When the inlet channel angle of a flow channel system was set at Ø =30°, an optimal mixing index of 0.88 was obtained and was confirmed by using the gray level imaging technique at the same operational conditions as shown in Fig. 4. The experimental results were further confirmed by the flow images in Fig. 5. They indicated that different inlet flow channels with (Ø =30°, 45°, 75°) yielded similar images. This was due to the fact that they all originated from the same main flow channel of the SAR mechanism when an inlet flow channel angle of Ø =30° was set. In addition, a spiral flow with an organized flow structure appeared clearly and also induced a better flow mixing. Finally, Fig. 6 displays the images of H_2O-molar at Re_2 =1 and Rer= 0.7. It can be incurred from the figures that the inlet flow channel angle and the SAR mechanism cited in the design of the blood vessel-micromixer obviously benefited the flow mixing performance. Thus, the inlet flows channel angle was set at Ø =30°and the flow area of better flow mixing with a fluid molar of 0.5 is shown in green color. These operational conditions can be applied in micromixers and it will enhance the design and performance of the blood vessel-micromixer.

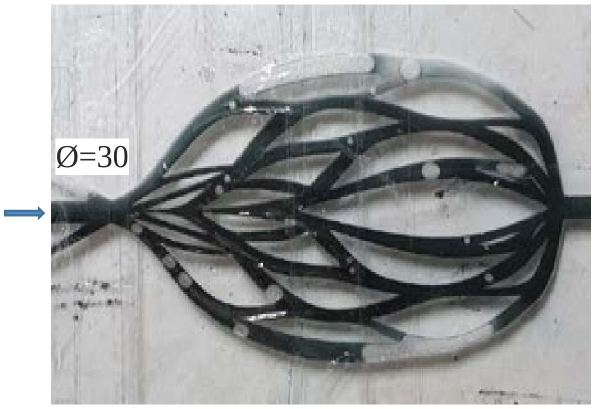

Fig. 4. The optimal performance with mixing index of 0.88 was confirmed by using the technique of gray level image at case of operational conditionals of (Re_{I2}= 1 and Re_r= 0.7).

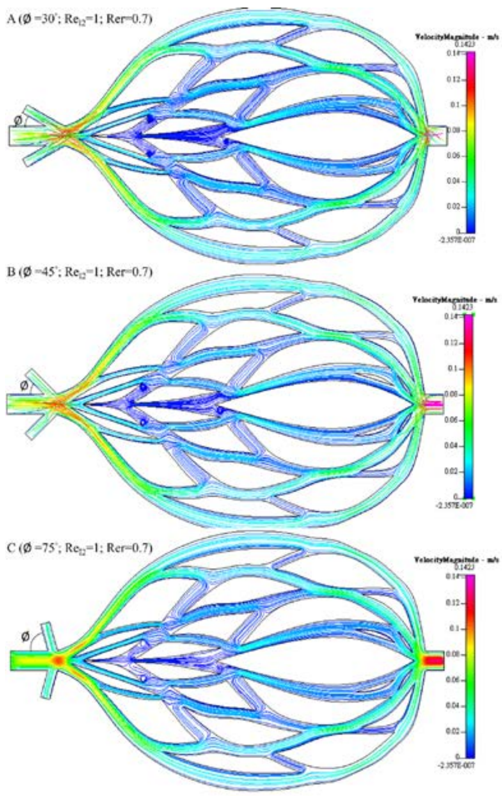

Fig. 5. Velocity flow images at Re_{I2} =1 and Re_r= 0.7

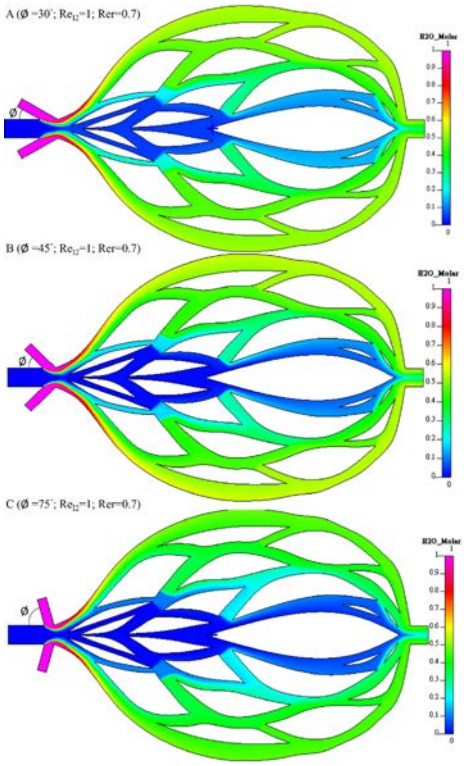

Fig. 6. Images of H_2O-molar at Re_2 =1 and Re_r= 0.7

CONCLUSIONS

An optimal design of biometric micromixer, capable of possessing a better mixing performance and lower pressure drop was reported in this research study. The modified type of biometric mixer that originated from the concept of blood-vessel type was addressed according to the flow splitting and recombining (SAR) mechanism as it could provide a better flow mixing, a lower pressure drop, and a shortened mixing length at low inlet Reynold numbers. The angle of the inlet flow channel of Ø =30° was set and the optimal performance with a mixing index of 0.88 was confirmed and was achieved at Re_{I2}= 1 and Rer= 0.7. These prominent findings will be definitely feasible for the improvement of micromixers applications in the future.

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NOMENCLATURE

μ	Viscosity of fluid
ρ	Density of fluid
Re	Reynolds number
Sc	Schmidt number
W	Width of the outlet channel
$\vec{V}$	Velocity
P	Pressure
C_i	Molar concentration
V_0	Characteristic velocity
D_{ij}	Mass diffusivity
X_{Amax}	Maximum concentration of the solution
$X_{AX,outlet}$	Concentration of solution at the outlet
M_{idx}	Mixing index
ε_{mixing}	Mixing efficiency
ΔP_{max}	Maximum pressure drop
D	Hydraulic diameter of the inlet channel

血管型仿生微混合器最佳入口流角設計

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摘要

微混合器是目前醫療應用中重要模組，透過新型及優化仿生被動式微混合器設計，將具有效流動分裂和重組（SAR）機制。本研究目的將針對入口流道設計一血管型仿生微混合器並透過修正原型仿生混合器幾何形狀，達到產生更好流動混合效果；另研究探討具不同入口通道角度和各種雷諾數比（Re_{12}和Re_r）血管型仿生微混合器，以估算其對微混合器混合性能影響，結果表明，入口通道角為30°（Ø = 30°）的血管型仿生微混合器具優化效果；另在Re_{12} = 1及Re_r = 0.7條件下，可達流體混合效能指標為0.88，相關本研究發現將對未來微混合器應用改進提供有