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Comparative Analysis of Mixing Performance of Three Types of Passive Micromixers for Laminar Blood-Reagent Mixing

I.S.L. Abdul Hamid[1], M.S.L. Ishak[1], S. W. Kamaruzzaman[1] & M.M. Abdul Jamil[2]
[1]Department of Computer Engineering
[2]Department of Electronic Engineering
Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia,
86400 Parit Raja, Batu Pahat, Johor, Malaysia.

Corresponding email: liana@uthm.edu.my

Abstract: Micromixers are the most important components in the biomedical and chemical investigations since efficient and effective mixing of two or more different fluids in a micro-scale region is the basic requirement for biochemical analysis. In this paper, we used *CoventorWare2010* software to investigate fluid mixing of three types of micromixers with different structures. The alteration of internal structure and shape of microchannel can increase the interfacial surface areas and then improve the mixing performance. A 550μm long mixing channel with 40μm width was taken as a reference for channel length. Meanwhile, the mixing performance of these micromixers was compared. According to the results of the numerical simulations, the mixing performance of the Z-shaped micromixer surpasses the other two types of micromixers. Over 95% mixing efficiency had been achieved at Re=0.05 and Re=0.005. The Z-shaped micromixer meet the requirement of microfluidic chips which may be applied to the fields in need of rapid mixing, such as drug discovery, binding assay, protein folding analysis and the development of Lab-on-chip (LOC) or Deoxyribonucleic acid (DNA) chip.

Keywords: Micromixer, mixing performance, numerical simulation, reynolds number

1.0 INTRODUCTION

Lab-on-a-chip is an application of micro total chemical analysis system (µTAS). The concept of µTAS is to integrate some instruments needed in traditional biochemical analysis, such as micro-pump, micro-actuator, micro-valve, micro-sensor and micro-mixer which are fabricated by using the Micro-Electro-Mechanical-Systems (MEMS) techniques, and then the pretreatment, transmission, mixing, reaction, separation and detection of the sample can be proceeded on a single chip. The advantages of using the Lab-on-a-chip on biochemical analysis are strong system stability, reduced reagent amount and the savingof manpower and time [1].

At a macro-scale level, mixing is conventionally achieved by a turbulent flow, which makes possible the segregation of the fluid in small domains, thereby leading to an increase in the contact surface and decrease in the mixing path. The Reynolds number is small in micro-fluidic systems, implying that hydrodynamic instability does not develop. Therefore, the flows cannot be turbulent. Owing to this limitation, mixing in micro-fluidic devices is generally achieved by taking advantage of the relevant small length, which dramatically increases the effect of diffusion and advection. Micro-mixers are generally designed with channel geometries that decrease the mixing path and increase the contact surface area.

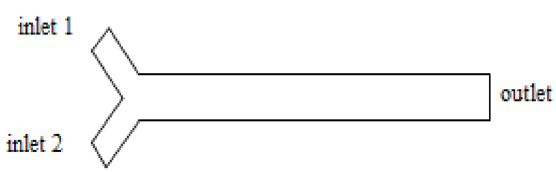
According to the two different basic principles exploited to induce mixing at the micro-scale, micro-mixers are generally classified as being passive or active. Active micro-mixers use external energy input as well as fluid pumping energy to introduced time-dependent perturbations that stir and perturb the fluid for accelerating the mixing process [2]. The type of external force employed by active micro-mixers can be further categorized as pressure field-driven, acoustic (ultrasonic)-driven, temperature-induced or magneto-hydrodynamic. Most of the active mixer is difficult to integrate into microfluidic systems due to the requirement for an external power source and controller [3].

In contrast, passive mixers have the advantages in ease of integration with microfluidic devices and no complex control units or additional power input. Most passive mixers take advantage of specific configurations in microchannels, such as multiple levels of fluid channel structures to repeat the lamination or splitting process. Passive mixing using geometric variations, which includes the shape of a microchannel and other obstacle structures inside the microchannel, provides a versatile solution to simplify the design and fabrication of microfluidic device, and is totally compatible with the current microfabrication techniques. Hence, it is a cost-effective mixing method and has great potential in a practical μTAS [4].

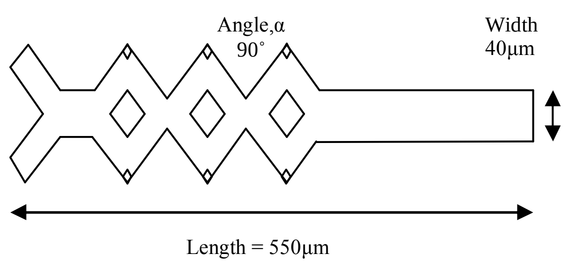
In this paper, a comparison of the mixing performance of 3 types of micromixers will be investigated by numerical simulation. In our work, we focus on the laminar mixing between blood and reagent and to conclude, we obtain an improved micromixer with excellent mixing performance.

2.0 MATERIALS AND METHODS

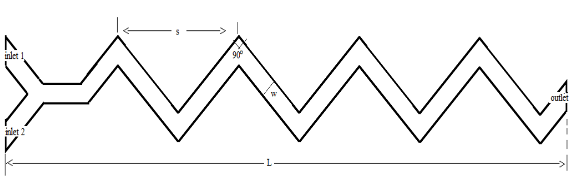
A. Geometric Model



(a) Y-shaped micromixer



(b) Rhombic micromixer



(c) Z-shaped micromixer

Figure 1 The geometric model of 3 types of micromixers

A 3D solid model of the micromixer was built and named in the preprocessor for *CoventorWare2010*. The dimension of the Y-micromixer is illustrated in Figure 1(a). The two inputs will flow through the mixer. The input 1 is blood and input 2 is the reagent. The mixing product will flow through the corner and will provide the results of completely mixing fluids. Only the flow field in the microchannels starts from the junction of the micro Y-mixer to the outlet was simulated since the flow field is the main area of interest.

Figure 1(b) illustrates the geometric models of the rhombic micromixer, which consists of 2 inlets, 1 outlet and 1 mixing channel. The two inlets are symmetrically distributed, with the inlet angle of 90˚. The turning angle of the Rhombic micromixer is 90˚.

The geometry for a Z-shaped micromixer is schematically represented in Figure 1(c). The microfluidic system features two perpendicular and 40 μm wide (w) feeders that are ended by a zigzag channel having the same width and integrating 90° angles. The linear length of one zigzag pattern is defined as a variable periodic step (s).

All three designs of micromixer use the same effective channel length (L) and width (W) which are 550µm and 40µm respectively. The liquid of inlet 1 and 2 are blood and reagent, respectively. In this paper, a varied level of reagent's viscosity is considered. A compact but efficient model allowed a finer mesh to be used while remaining the simulations manageable. Fluid 2 consists of two different reagents which have various viscosities. These reagents were categorized into two groups; fluid A and fluid B, where each group has a lower and higher viscosity compared to blood. They are summarized in Table 1.

Table1 The Boundary Conditions Specified For The Two Types Of Simulated Mixing.

Fluid A : Lower viscosity compared to blood			
Reagent	Density,ρ kg/m³	Viscosity, µ (kg/ms)	Reynolds number
Toluene	866	$0.68e^{-3}$	0.05
Fluid B : Higher viscosity compared to blood			
Reagent	Density,ρ kg/m³	Viscosity, µ (kg/ms)	Reynolds number
Benzyl	1079	$5.51e^{-3}$	0.005

B. Working Principle

Fluids are composed of molecules that collide with each other. The continuum assumption fluids to be continuous which is the property such as density, pressure, temperature and velocity are well-defined at infinitely small points and are assumed to vary continuously from one point to another. The discrete molecular nature of fluid is ignored. Fluid is such a material which is a composed molecule separated by an empty space.

In this analysis, the liquid flow was taken as considerations. The flow of the fluids is treated as incrompressible with the density is constant with respect to pressure as well as temperature. Reynolds Number is use to characterize the flow of fluids. Reynolds Number can be simply defined as the number of different situations of fluid flow in microscale laminar mixing. All the parameter use to determine the Reynolds Number is the fluid properties of density, viscosity, velocity and the length characteristics. Flow of fluids can be classified in to the two types which are turbulent and laminar. Whenever the friction exists, turbulent flow is dampened by frictional forces and the flow is laminar. For higher velocities, where the disturbances due to inertial forces are larger than frictional forces the flow will become unstable and form the turbulence flow. The ratio between the inertial and forces and frictional forces is called Reynolds Number. The Reynolds number is defined as:

$$R_e = \frac{\text{Inertial Forces}}{\text{Viscous Frictional Forces}} = \frac{\rho u D_h}{\mu} = \frac{u D_h}{v} \quad (1)$$

Where ρ is the density of the fluid, u is the mean fluids velocity, D_h is the hydraulic diameter or another characteristics dimension while μ is dynamic viscosity and v is kinematic viscosity.

C. Computer Simulation

Numerical simulations of the micromixers proposed in this paper were conducted with *CoventorWare2010* software running on a personal computer. A pre-processing was employed for geometric modeling, mesh generating, and boundary conditions defining. In order to model the mixing in micromixer, the related equation and the computational domain must be discretized. A computational domain is an enclosed three-dimensional volume. Domain is discretized into a finite set of control volumes or cells. General conservation equations are discretized into algebraic equations. Then the appropriate boundary conditions must be specified for the simulated mixing.

The Navier-Stokes equation describes the dynamics of fluids. A navier-Stokes equation is a partial differential equation which describes the conservation of linear momentum for a linearly viscous (Newtonian), incompressible fluid flow. In vector form, this relation is given by:

$$\rho\left[\frac{\partial V}{\partial t} + (V \cdot \nabla)V\right] = -\nabla p + \rho g + \mu \nabla^2 V \quad (2)$$

where V is the fluid velocity, t is time, p is pressure, ρ is the density of the fluid, $\vec{g}$ is the gravitational acceleration and μ is the dynamic viscosity of the fluid. ∇ is the del or grad operator, and ∇^2 is the Laplacian operator.

The finite volume method (FVM) and the structured grid were employed to solve the governing equations, consisting of continuity equation, Navier-Stokes equation and convection-diffusion equation.

D. Evaluation Criterion of Mixing Performance

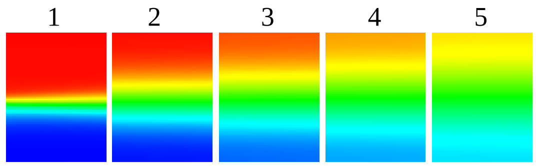
From the image cross-section of mixing visualization, the information on fluids mixing is extracted. Different colour represents different value of viscosity. Thus, when the two fluids have been completely mixed, only one value of viscosity will represent at the outlet of the micromixer. The image standard deviation is used to measure the difference of the value of viscosity that was taken along the five sections at the channel length. The smaller the standard deviation means the smaller the different value of viscosity. The fluids can be considered as mixed when the same value of viscosity represent at the outlet of the micromixer and the standard deviation is reaching zero. Thus, it can be conclude that the higher standard deviation indicates poor mixing while the lower standard deviation indicates better mixing.

3.0 RESULTS AND DISCUSSION

A. Mixing of Blood with Low Viscosity Reagent

Laminar mixing and the influence of shape of micromixers were studied. Simulations were first done on the mixing of blood with low viscosity reagent which is Toluene. The value of the Reynold number, Re had been fixed to its optimized which is Re=0.05. Same Reynolds number for the fastest mixing performances was taken into consideration to observe the differences of laminar mixing performance at different types of micromixer. For this laminar mixing, the viscosity of the Toluene is 0.68e-^{3} kg/ms while the viscosity of the blood is 3.006e-^{3} kg/ms. The density for Toluene that had been used in this simulation is 866 kg/m^3 while for the blood is 1e-9 kg/m^3.

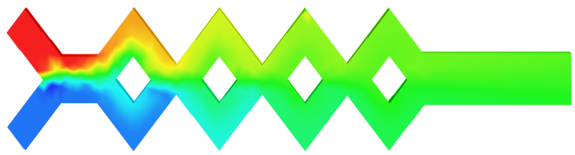
Section:



(a) Y-shaped micromixer

Section:

1 2 3 4 5



(b) Rhombic micromixer

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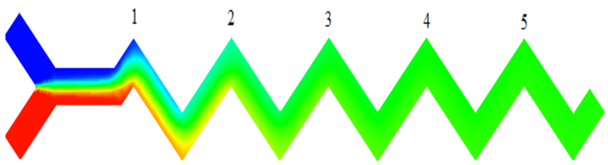


(c) Z-shaped micromixer

Figure 2 Cross-section mixing visualization of 3 types of micromixer for blood and Toluene.

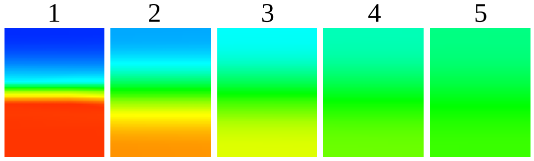
Figure 2 shows the cross section mixing visualization of 3 types of micromixer for blood and Toluene. Apparently the Y-shaped micromixer did not achieve a complete mixing within the 550μm channel length. This is indicated by the different colors in the mixing visualization. The mixing process starts when the two fluids with different viscosity which are differentiate by color in the mixing visualization, is entering the channel from both inlets and started to mix in the mixing channel.

B. Mixing of Blood with High Viscosity Reagent

The second analysis was done on mixing between blood and Benzyl. Benzyl has higher viscosity than the blood which is $5.51e^{-3}$ kg/ms while blood's viscosity is $3.006e^{-3}$ kg/ms. The different level of viscosity will affect the performance of the mixing. In order to perform a good mixing efficiency for high viscosity reagent, a lower Reynolds number needed to be used in the simulation. This is because, high viscosity reagents like Benzyl needs longer mixing timing to produce laminar mixing compared to low viscosity reagents like Toluene. For this simulation, the optimized Reynolds number used is Re=0.005. For this laminar mixing, the density of the Benzyl is 1079 kg/m^3

Section:

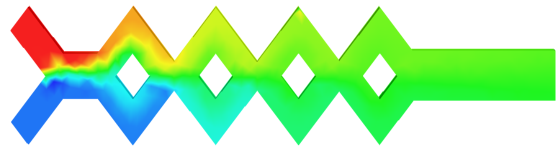
1 2 3 4 5



(a) Y-shaped micromixer

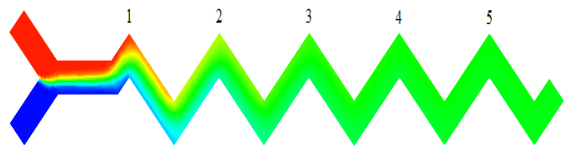
Section:

1 2 3 4 5



(a) Rhombic micromixer

Section:



(b) Z-shaped micromixer

Figure 3 Cross-section mixing visualization of 3 types of micromixer for blood and Benzyl

Figure 3 presents the visualization and quantification mixing results at Reynolds number 0.005 for mixing of blood and Benzyl for three types of micromixer. The mixing visualizations are obtained by using the *CoventorWare2010* software. In this study the visualization for field of viscosity is taken into consideration. The visuals outcomes are then analyzed statistically to characterize the mixing performance.

C. The Comparison of Mixing Performance of 3 types of micromixers

From the image cross-section of mixing visualization, the information on fluids mixing is extracted. The image standard deviation is used to measure the difference of the value of viscosity that was taken along the five different sections. The fluids can be considered as mixed when the same value of viscosity represent at the outlet of the micromixer and the standard deviation is reaching zero. Thus, it can be conclude that the higher standard deviation indicates poor mixing while the lower standard deviation indicates better mixing. The comparisons of the mixing performance of different micromixers are conducted at five different sections.

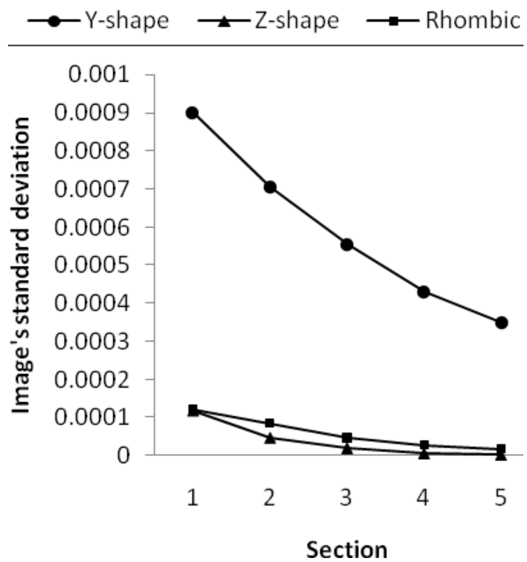


Figure 4 Graph of image’s standard deviation for laminar mixing of blood and Toluene for three types of micromixer

Figure 4 shows the standard deviation curve for blood and Toluene mixing. As shown in Figure 4, for Y-shaped micromixer the standard deviation curve did not reach zero. This curve theoretically indicates that the two fluids were not completely mixed within the specified channel length. However, Z-shaped and rhombic micromixer show excellent mixing performance where the fluids are completely mixed in Z-shaped and the value of standard deviation for rhombic micromixer at section 5 are far smaller than that of Y-shaped micromixer.

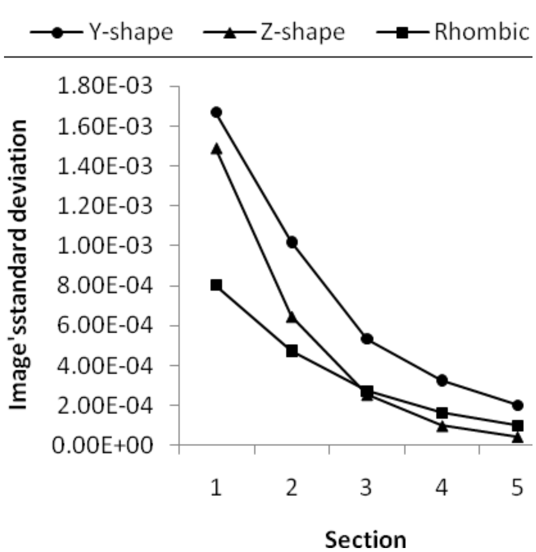


Figure 5 Graph of image’s standard deviation for laminar mixing of blood and Benzyl for three types of micromixer

Figure 5 shows the standard deviation curve for blood and Benzyl mixing. As shown in Figure 5, the mixing performance of the Z-shaped micromixer surpasses the other two types of micromixers with the same channel length. From this comparison, it is clearly shows that Z-shaped micromixer is the best type of micromixer to produce the fastest mixing. When the two fluids in the channel was stretched and folded, the interfacial area within the fluids in the mixing channel is increased. Thus, the two fluids will be easier to mix and will results in reducing of time and the length of the micromixer required for the channel to complete the mixing process.

4.0 CONCLUSION

Fluid mixing of the micromixer is closely related to the geometries and Reynolds number. Through the comparison of mixing performance of 3 types of micromixers, the mixing performance of Z-shaped micromixer is superior to the other two micromixers. The simulation results reveal the difficulty of mixing of blood with high viscosity reagent. The mixing is better if the reagent is smaller in viscosity compared to blood. It was also found out that the enhanced mixing from larger recirculation was due to the increased interfacial contact area between two reagents and enhanced fluidic convection. This micromixer can be applied to the fields of drug discovery and protein folding analysis in need of rapid mixing in future.

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