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Modeling and Simulation of Rhombic Micromixer For Laminar Blood Mixing

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Abstract: In lab-on-chip (LOC) systems, there is often a need to mix fluids. However due to the small dimensions of the microchannels on the chip, turbulences does not occur, and hence a mixing length of up to 2cm is always required, using up valuable space on the chip. To minimize the space usage for mixer on the system, the mixing in Rhombic microstructure was demonstrated by simulation using *CoventorWare2010* software. The fluid mixing is related to the geometry parameters and Reynolds (Re) number of the Rhombic micromixer. The better fluid mixing is attributed to the more rhombi and the higher flow rates. The reagents that will be used are consist of a varied level of viscosity. The main parameters that need to be considered are width, number of rhombi and the fluid properties. In order to get an optimum result, the width and length of the micromixer depends on the mixing of reagent and blood. The fluid's properties that need to be controlled are the density, viscosity, diffusion and Reynolds number (Re). To evaluate the effect of the Reynolds number on the fluid mixing, numerical simulation is used. Simulation results proved that good mixing performance efficiency can be achieved with more number of rhombi in a micromixer. Due to its rapid and good mixing, this micromixer can be applied to the fields in need of rapid mixing, such as drug discovery, binding assay, protein folding analysis and the development of LOC or DNA chip.

Keywords: Reynolds number, micromixer, mixing performance, numerical simulation

1.0 INTRODUCTION

Rapid mixing is essential in many of the microfluidic systems used in biochemistry analysis, drug delivery and sequencing or synthesis of nucleic acids. Biological processes such as cell activation, enzyme reactions and protein folding often involve reactions that require mixing of reactants for initiation.

Mixing is also necessary in lab-on-a-chip (LOC) platforms for complex chemical reactions. Micromixers can be integrated in a microfluidic system or work as stand-alone devices. Furthermore, the investigation of micromixers is fundamental for understanding transport phenomena on the microscale[1,2].

In general, micromixers can be categorized as passive micromixers and active micromixers. Passive micromixers do not require external energy; the mixing process relies entirely on diffusion or chaotic advection. Passive mixers can be further categorized by the arrangement of the mixed phases: parallel lamination, serial lamination, injection, chaotic advection and droplet. Active micromixers use the disturbance generated by an external field for the mixing process.

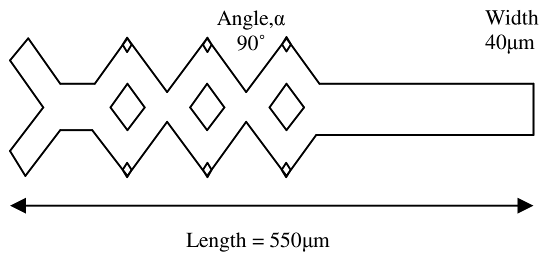
Effective mixing of microfluids is the basic requirement for biochemical analysis. However, this process is extremely slow since it is purely dictated by passive molecular diffusions due to the laminar nature of the fluid flow within the microfluidic channels, as a result of the small dimensions of the channels and slow flow rates of the fluids within the channels.

According to Ficks' law[4], effective mixing on this scale requires that fluids should be manipulated to increase the interfacial surface areas among different fluids for mixing of fluids within a reasonable time. However, the procedures for the macroscale mixing, such as stirring and creation of turbulent flow, are not applicable under this circumstance in that the Reynolds number is below the critical value for transition to turbulence.

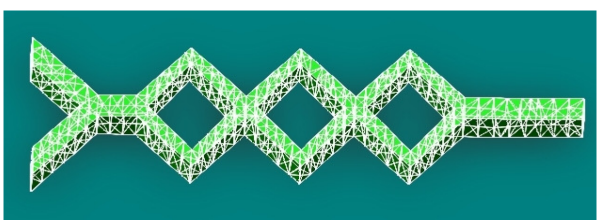
Therefore many mixing technologies, both active and passive in nature, have been developed to overcome this problem in an attempt to achieve complete mixings within a reasonable time and microchannel length scale. The alteration of internal structure and shape of microchannel is a good option since it can increase the interfacial surface areas and then improve the mixing performance[9,11]. In this paper, the mixing performance of rhombic micromixer will be investigated by numerical simulation.

2.0 MATERIALS AND METHODS

2.1 Geometric Model



(a)



(b)

Fig. 1 The diagrams shows the dimensions of the (a) 2D model and (b) 3D solid model used in the computer simulation of mixing.

Fig. 1 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 effective channel length (L) and width (W) are 550μm and 40μm respectively.The turning angle of the Rhombic micromixer is 90˚. Fig. 1(c) shows the dimension of the 3D solid model used in the computer simulation of mixing.

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. Blood was specified to enter from the inlet on the right while fluid 2 was specified to enter from the inlet on the left. Fluid 2 consists of three 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.

Table 1: 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

2.2 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.

The governing equations in the continuum model are derived from the fundamental physical laws of conservation of mass, momentum and energy. From the basic principle that matter can neither be created nor destroyed, we obtain the continuity equation, and from the conservation of momentum, the Navier-Stokes equation and the conservation of energy, the energy equation is derived. The parameter of concern in this study is the calculation of Reynolds number which involved the volume flow rates of the devices and this is carried out by using the continuity equation and the Navier-Stokes equation. Since temperature is not taken into consideration, the energy equation is not used.

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:

$$\rho\left[\frac{\partial V}{\partial t} + (V \cdot \nabla)V\right] = -\nabla p + \rho g + \mu \nabla^2 V \qquad (1)$$

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.

Governing equations are discretized based on cells. Consequently, the governing equations are transformed into set of ordinary differential equations (ODE) solely dependent on time.

The discretization of ODEs using either an implicit or an explicit scheme eventually leads to the final product of the discretization of governing equations: an algebraic system of equations, which are in turn solved by either direct or iterative methods. Iterative methods are necessary when the problem is nonlinear.

With FVM, the governing equations are expressed in the form of the integral forms of the conservation laws, and such integral equations are then directly discretized on cells. FVM works with both structured cells and unstructured cells.

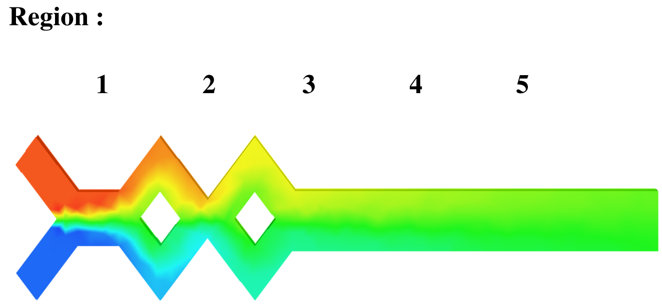
2.3 Evaluation Criterion of Mixing Performance

Standard deviation, a term in the discipline of probability statistics, has been widely used in error analysis. In this paper, the quantification of standard deviation of the data was used as an index indicating the degree of uniformity of the fluid medium distribution. We extract the viscosity value of the liquid of all nodes in a certain cross section from the simulation visualized to an excel file, and then calculated the standard deviation.

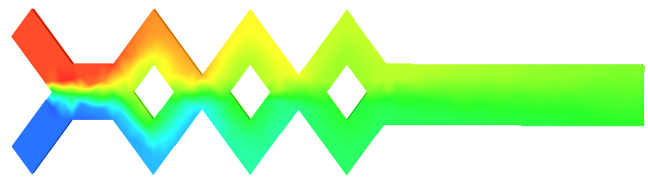
3.0 RESULTS AND DISCUSSION

3.1 Mixing of Blood with Low Viscosity Reagent

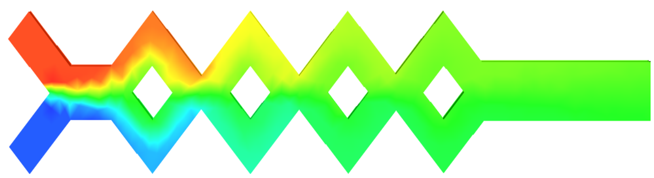
Laminar mixing and the influence of the number of rhombi were studied. Simulations were first done on the mixing of blood with low viscosity reagent which is Toluene. The value of the Reynold number, Re had been fixed to its optimized which is Re=0.05. Same Reynolds number for the fastest mixing performances was taken into consideration to observe the differences of laminar mixing performance at different number of rhombi existed in a micromixer. The number of rhombi used in the micromixer is two, three and four. 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. The flow rate used for each simulation for mixing of blood and Toluene is the same which is 1.5335e^6 m^3/s, since the width of the micromixer does not changed which is 40μm. Fig. 2 shows the cross section mixing visualization of Rhombic micromixer for blood and Toluene for three different micromixers which has two, three and four rhombi each. Increasing number of rhombi will result in better fluid mixing due to the occurrence of larger recirculation. The mixing time for the two-rhombi micromixer is longer than the three-rhombi micromixer. The same goes to the three-rhombi micromixer, which has a longer mixing time compared to the four-rhombi micromixer.



(a) Two-rhombi micromixer



(b) Three-rhombi micromixer



(c) Four-rhombi micromixer

Fig. 2 Cross-section mixing visualization of Rhombic micromixer for blood and Toluene.

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 channel length. The smaller the standard deviation illustrated the smaller the different value of viscosity. The fluids can be considered as mixed when the same value of viscosity represented at the outlet of the micromixer and the standard deviation is reaching zero. From the progressive changes of the standard deviation as a function of channel length, the mixing's performance is evaluated. Higher value of σ indicated poor mixing while a perfect mixing will be achieved at σ=0. The results from Fig. 3 shows that, the curve for two-rhombi micromixer has the highest value of standard deviation followed by the three-rombi micromixer curve. The four-rhombi micromixer has the lowest value of standard deviation. From this comparison, it is clearly shows that increasing number of rhombi in a micromixer will also increase the mixing performance.

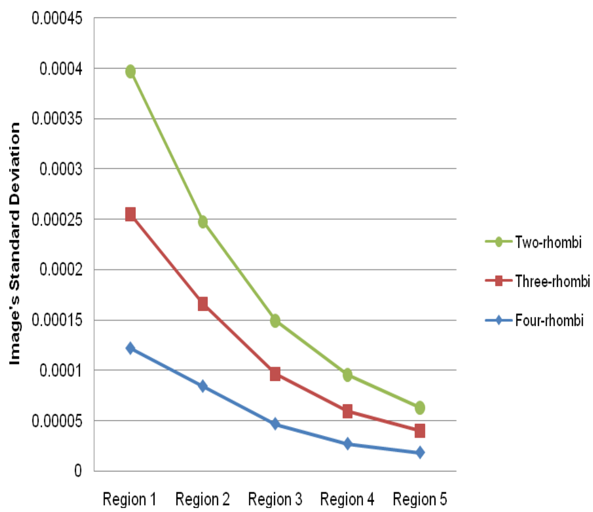
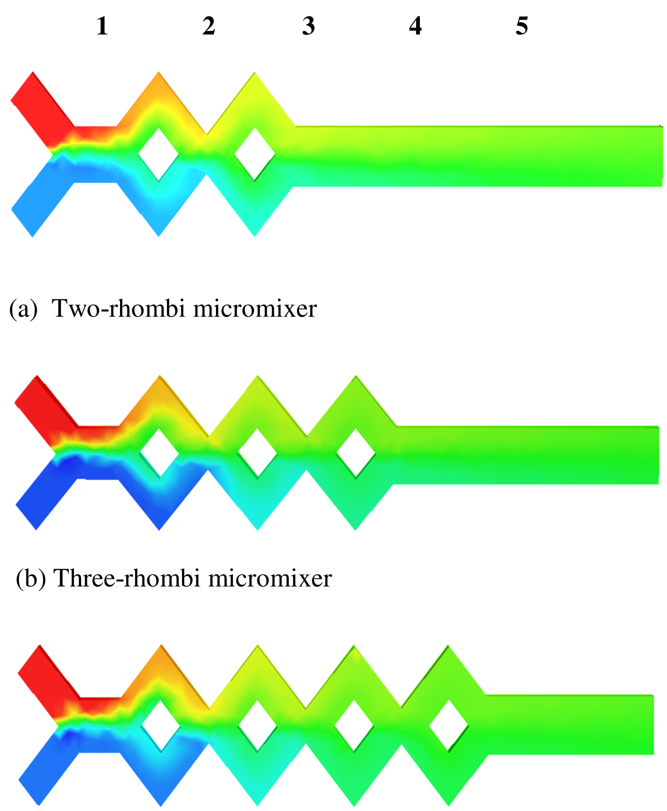


Fig. 3 Graph of image's standard deviation for laminar mixing of blood and Toluene for micromixer which consists of two, three and four rhombi.

3.2 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 while the flow rate used for each simulation for mixing of blood and Benzyl is the same which is 1.0213e^5 m^3/s, since the width of the micromixer does not changed which is 40μm. Fig. 4 shows the cross section mixing visualization of Rhombic micromixer for blood and Benzyl for three different micromixers which has two, three and four rhombi each. Like the previous analysis, the simulation results for the high viscosity reagent are still directly proportional to the number of rhombi in the micromixer. Meaning that, the increasing number of rhombi will lead to the increasing mixing efficiency as well. The difference between the two analyses can be determined by referring to Fig. 5.

Fig. 5 has proved that the more rhombi in the mixer, the more efficient the mixer will be. This is due to lowest value of image's standard deviation for four-rhombi micromixer obtained in the graph compared to the value of two-rhombi micromixer value which has a higher value. The final value of the standard deviation did not reach zero which theoretically indicates that both reagents were not completely mixed. However, this situation is negligible after considering the noise in the colors of the mixing visualizations.



(a) Two-rhombi micromixer

(b) Three-rhombi micromixer

(c) Four-rhombi micromixer

Fig. 4 Cross-section mixing visualization of Rhombic micromixer for blood and Benzyl.

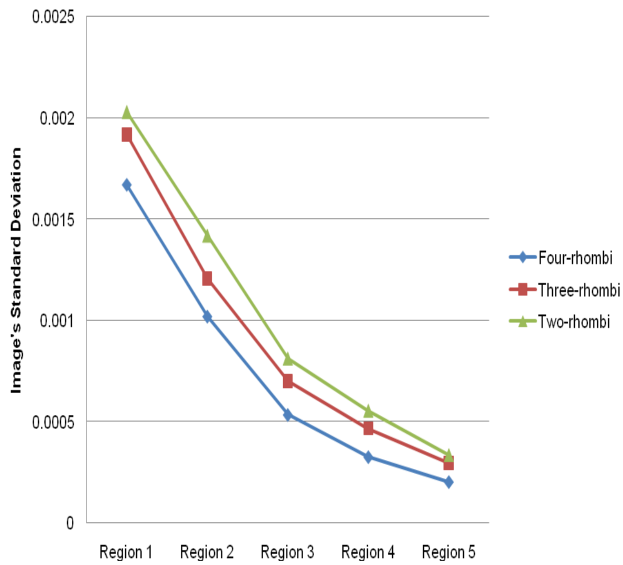


Fig. 5 Graph of image's standard deviation for laminar mixing of blood and Benzyl for micromixer which consists of two, three and four rhombi.

4.0 CONCLUSION

Numerical simulation and mixing experiment demonstrated the design of rhombic micromixer with simple structure design. Fluid mixing of the rhombic micromixer is closely related to the rhombic geometries and Reynolds number. 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. In this design, the recirculation phenomenon enhances the fluid mixing. The better fluid mixing is obtained at the higher rhombus number. In the adaptive design by simulations, four-rhombi mixer with an angle of α=90˚, has the highest mixing effieciency. 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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