Performance Investigation of T-Shaped Micromixer with Different Obstacles

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Abstract. Mixing of fluids is an essential process of most of the microfluidic systems. Usually, passive micromixers are employed for this purpose. In the case of creeping or flow having low Reynolds number, the mixing process is dominated by diffusion and shows lower mixing efficiency with higher mixing length. To enhance the mixing efficiency and decrease the mixing length, T-micromixers are analyzed in the present work with different types of obstacles. Here, the effect of a single obstacle with different shapes and positions in T-micromixer is analyzed. Basic shapes such as circle, ellipse, triangle, and rhombus (diamond) are used for the obstacle. To define at par dimensions, all selected shapes for the obstacle are inscribed through a common circle. The flow simulations are created in multiphysics software COMSOL. The best obstacle is selected based on mixing efficiency and mixing length. The obtained results will be helpful to design micromixers with high performance.

1. Introduction

In microfluidic channels, usually flow occurs at a very low Reynolds number (Re). It results in co-laminar flow, which does not allow proper mixing of fluid through the convection process. In such a situation, mixing of two fluids can be achieved through tailoring flow parameters such as concentration, velocity, and pressure. The micromixers in which mixing of fluid is enhanced through external methods are active micromixer. Few common methods for inducing the mixing through active methods are, dielectrophoretic ultrasonic, electro-kinetic acoustic, electro-hydrodynamic force, thermal actuation, periodic electro-osmotic flow, magneto-hydrodynamic methods etc. [1]. On the other hand, better mixing can also be achieved through enhancing the convection process by varying the shape and size of micromixer. This method does not involve any externally added mechanism, hence termed as passive micromixer [2]. In past, different attempts are made to increase the mixing performances. These attempts are made by either varying the shape and size of the channel or inducing the flow using external methods. A spiral microchannel is used in a standalone system with chaotic advection technique to enhance the mixing [3]. A multi-layer planner obstacle micromixer is proposed for low-pressure drop. The study was validated through experiments at Re value of 20 [4]. For Y-micromixer, the effect of circular obstacles is studied for low to medium range of Re (i.e. 0.5-60), based on diffusion path and mixing [5]. Li and Chen used topology optimization method to generate optimal obstacle shape for increasing mixing performance [6].
They analyze the mixing performances are different Re values. For chemical and bioengineering applications, Chen and Zhao analyzed T-micromixer using multi tiny obstacles. They showed the effect of shape, size, height, and number of obstacles in the microchannel for effective mixing [7]. Wangikaret al. studied mixing lengths in a serpentine shaped mixer with semicircular obstacles at different Re values. They used soft lithography process for fabrication of microchannel with obstacles, to validate the results [8]. To enhance the mixing, array of thin curved ribs are also analyzed for varying dimensions i.e. chord length, thickness [9]. Recently, T-micromixers are also examined with active mixing method such as periodic frequency of electro-osmotic effect [10]. However, passive micromixing is considered as more suitable methods for device development because of their fabrication simplicity.

The available methodologies are based on complicated designs for fabrication. One of the simplest methods to attain passive micromixing is to introduce flow obstacles, which are easier to fabricate at small dimensions and provide better mixing performance. In this paper, a simple T-shaped micromixer is analyzed with different types of shapes for obstacles such as circle, rhombus (diamond), ellipse, and triangle. The performance of mixing is compared for different values of Re. From the literature it is evident that T-micromixer gives better mixing efficiency at very low and high Re values (Re≤1, 100≤Re); whereas at intermediate Re values, the mixing efficiency is comparatively inferior [3]. Hence, the present study is focused upon obstacles introduced in this range of Reynolds number. Also, the mixing length is attempted to minimize in the present study.

2. Numerical Model

In this section, a fundamental model for T-micromixer is introduced. Further, different obstacles are added to the fundamental model to achieve better mixing efficiency. The numerical simulations are performed using COMSOL Multiphysics software.

2.1. Geometry

A basic T-micromixer has two inlet channels for different fluid to be mixed. The channels are straight and the mixing junction is in form of T, as shown in figure 1(a). In figure 1(b), the location of the obstacle is shown with dimension values given in table 1.

![Figure 1](image)

**Figure 1.** (a) Geometry of T-micromixer and (b) Diamond Obstacle at the junction of T-micromixer

**Table 1.** Dimensions and obstacles of T-micromixer

| Parameter | Values |
|-----------|--------|
| Dimensions (T-Mixer) | Length=10400µm, width=200µm, depth=200µm |
| Different Obstacles at the junction | Circle, Diamond, Ellipse, Triangle inside, Triangle outside |
2.1.1. T-micromixer with obstacles

In T-micromixer different obstacles at the junction are introduced. The shapes of different obstacles are shown in figure 2. These shapes are generated through a common inscribed circle. Practically, these obstacles can be placed within the microchannel at any location. However, the mixing performance will be different corresponding to these locations. These possible locations of the obstacle along the length of the channel are simulated and it is observed that mixing is highest when the obstacle is placed at the junction point (figure 1(b)). In order to keep this manuscript short, those results are not included here; and for further simulations, the location of the junction is selected for different obstacles.

![Figure 2. The geometry of various obstacles used to enhance mixing](image)

2.2. Governing equations

For numerical analysis, Navier Stokes equation of continuity and convection-diffusion are used (Eq. 1, 2 and 3) [11].

\[ \rho \nabla \cdot \mathbf{u} = 0 \]  
(1)

\[ \rho \frac{du}{dt} + \rho \mathbf{u}(\mathbf{u}, \mathbf{V}) = -\nabla p + \mu \nabla^2 \mathbf{u} \]  
(2)

\[ \frac{dC}{dt} + (\mathbf{u}, \nabla)C = D \nabla^2 C \]  
(3)

where \( \mathbf{u} \) is the velocity magnitude, \( \rho \) the density of the fluid, \( t \) is time, \( p \) the pressure of fluid, \( \mu \) absolute dynamic viscosity, \( C \) and \( D \) are species concentration and species diffusion coefficient, respectively. Reynold number is defined as,

\[ Re = \frac{\rho ul}{\mu} \]  
(4)

Here, \( l \) is the characteristic length, which is hydraulic diameter in the present case [12]. At the low Reynolds number, inertial forces are negligible at comparative to viscous force. For simulation, the assumptions made are,

1. Incompressible Newtonian fluid
2. Laminar flow
3. Miscible liquid flow with uniform properties
4. Gravity and temperature are negligible
5. The micromixer walls are smooth, no slipping of fluid
6. Along depth of the channel, flow properties are uniform
For co-laminar flow, mixing dominates by diffusion, which is defined as a process of molecules spreading in the channel from higher concentration to lower concentration region by Brownian motion as explained by Fick’s law. To investigate the degree of mixing, the mixing efficiency of the fluids at any cross-section in the channel is computed as,

\[ M = 1 - \frac{1}{N} \sum_{i=1}^{N} \left( \frac{C_i - C'}{C} \right)^2 \]  

(5)

where, \( C_i \) and \( C \) are normalized and expected concentrations, respectively. \( N \) is the number of mixing samples in the micromixer. \( M \) value varies between 0.00 (0% mixing) to 1 (100% mixing, completely mixed).

2.3. Boundary conditions for numerical simulation

T-micromixer is considered in standard conditions, i.e. two different liquids are provided at the inlets and exit through a single channel. The various values of parameters used in the simulation are shown in table 2.

| Parameter                              | Values                                      |
|----------------------------------------|---------------------------------------------|
| Reynolds’s number                      | 0.1 to 100                                  |
| Diffusion Coefficient                  | \( 3.23\times10^{-10} \) m²/s               |
| Concentration                          | \( C_0=1, C_1=0 \)                          |
| Chemical Diluted species               | DI water, Ink                               |
| Viscosity (kg/m-sec)                   | Fluid1= 0.001, Fluid 2=26.46×10⁻³           |
| Fixed flow velocity at the inlet (m/s) | \( 5\times10^{-4}, 5\times10^{-3}, 0.025, 0.05, 0.125, 0.25, 0.375 \) |
| Density (kg/m³)                        | Fluid1= 998, Fluid2=1000                    |
| Channel walls                          | No slip                                     |

2.4. Grid independence investigation

For an efficient numerical simulation, good mesh structure and low computation time are desired. The grid independence test was performed to ensure convergence of result. It was performed at different number of elements at Re value of 100. Different grid sizes starting from 2959 to 135135 is chosen to simulate T-micromixer at Re of 100. The performance curve is shown in figure 3(a) for velocity profile along the middle line at the outlet. Figure 3 (b) shows the grid structure for the same. For better accuracy grid of 135135 elements is chosen.
3. Result and Discussions
This paper is mainly focused on the mixing efficiency at various locations along the channel length, pressure drop, velocity profile, and concentration distribution. Simulations are performed for T-micromixer with different obstacle at different conditions of flow. The obtained results are presented and discussed in this section. In figure 4(a) & (b) pressure drop and velocity for T-micromixer with different obstacles at different Re values are shown. The flow nature is strongly dependent on the micromixer geometry, especially the obstacles that alter the nature of flow. From figure 4(a) it is observed that the pressure drop is highest for circular obstacle and minimum for triangle inside. Lowest pressure drop is observed for the case of no obstacle, which is in the agreement of basic theory. Figure 4(b) shows the maximum velocity for different obstacle conditions. It is seen that up to Re=25, the maximum velocity remain the same for all conditions, later it shows a slight change. Highest and lowest velocity is observed for diamond and triangle outside shaped-obstacle, respectively.

![Figure 4. (a) Pressure drop and (b) Velocity for T-micromixer with different obstacles at different Re values](image)

The mixing efficiencies are simulated and shown for different obstacles conditions. The results for mixing efficiency are presented in Figure 5, for three different locations along the length namely, at the middle of the channel length, end and at the obstacle surface. The mixing efficiency of T-micromixer without obstacle is validated with the present results available [13]. Among the differently shaped obstacle, it is observed that diamond is performing best at the end and middle of the micromixer figure 5(a) & (b). However, near to the obstacle surface, it shows intermediate values. The least performance is shown by triangle outside obstacle.
Figure 5. Comparison of Mixing Efficiency at various locations and at different Re value at (a) 10.4 mm, (b) 5.2 mm & (c) at obstacle surface

For a better understanding of diamond-shaped obstacle, simulation results are presented for concentration distribution. These results are compared with a no-obstacle condition at Re=100 as shown in figure 6. It is evident that the mixing is dominated by the diffusion process. Also, mixing is achieved a long way before (before 5.2 mm) in the case of a diamond obstacle compared to that of without obstacle. The analysis of mixing length is also provided with central isosurface, shown in figure 7. In case of the mixer with no-obstacle, the co-laminar flow dominates and restrict the mixing of fluid along the length. Here, mixing takes place through diffusion only. In the case of diamond-shaped obstacle chaotic convection phenomenon of flow is observed, which helps in better mixing.
Figure 6. Concentration distribution in diamond obstacle micromixer at various locations (at the obstacle, middle, and end of channel) (a) with diamond obstacle (b) without obstacle

Figure 7. Mixing path variation in T-micromixer with the diamond obstacle
4. Conclusions
In this work, a numerical simulation was carried out using the COMSOL Multiphysics software. At different Reynolds number, T-micromixer with different obstacles were investigated and compared. Based on pressure drop, concentration distribution, mixing efficiency and mixing path or length, it was found that diamond shaped obstacle gives the best performance compared to other obstacles. Through these simulations, the characteristics of other obstacles are also observed, which are easier to fabricate. Presented work will be helpful for the development of simple and efficient micromixer.

5. References
[1] N T Nguyen and Z Wu 2005 Micromixers—a review. Micromechanics Microengineering vol 5 no 2 pp R1–R16.
[2] L Capretto W Cheng M Hill and X Zhang 2011 Micromixing within microfluidic devices Top Curr Chem pp 27-68.
[3] C P Jen C Y Wu and Y C Lin and C Y Wu 2003 Design and simulation of the micromixer with chaotic advection in twisted microchannels Lab Chip vol 3 no 2 pp 77-81.
[4] C K Chung T R Shih Y S Chen and C H Wang 2008 Mixing process of an obstacles micromixer with low pressure drop 3rd IEEE Int Conf Nano/Micro Eng Mol Syst NEMS pp 170–172.
[5] C T Wang and Y C Hu 2010 Mixing of liquids using obstacles in Y-type microchannels Tamkang J SciEng vol 13 no 4 pp 385–394.
[6] T Li and X. Chen 2017 Numerical investigation of 3D novel chaotic micromixers with obstacles Int Heat Mass Transf vol 115 pp 278–282.
[7] X Chen and Z Zhao 2017 Numerical investigation on layout optimization of obstacles in a three-dimensional passive micromixer Anal Chim Acta vol 964 pp 142–149.
[8] S S Wangikar P K Patowari and R D Misra 2017 Numerical and experimental investigations on the performance of a serpentine microchannel with semicircular obstacles Microsyst Technol vol 24 no 8 pp 3307–3320.
[9] P Borgohain A Dalal G Natarajan and H P Gadgil 2018 Numerical assessment of mixing performances in cross-T microchannel with curved ribs Microsyst. Techno vol 24 no 4 pp 1949–1963.
[10] Y Cheng Y Jiang and W Wang 2018 Numerical simulation for electro-osmotic mixing under three types of periodic potentials in a T-shaped micro-mixer Chem Eng Proces Process Intensif vol 127 pp 93–102.
[11] M Rasouli 2015 Numerical Study on Low Reynolds Mixing of T-Shaped Micro-Mixers with Obstacles Transp Phenom vol 3 no 2 pp 68–76.
[12] Sharp K V and R J Santiago and Molho 2019 Liquid flows in microchannels In The MEMS Handbook-3 Volume 215-267 CRC press.
[13] G Orsi M Roudgar E. Brunazzi C Galletti and R Mauri 2013 Water-ethanol mixing in T-shaped microdevices Chem Eng Sci vol 95 pp 174–183.