Mixing of fluids in vortex T-mixer with two and four non-aligned inlet microchannels

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Abstract. Mixing of fluids at microscale is an indispensable stage required on the microfluidic systems. Large number of micromixer designs aimed with efficient mixing has been reported by many researchers. In this work numerical study has been executed out on vortex T-mixer. This mixer has two and four non-aligned inlet channels. The inlet channels are aligned tangentially to the main microchannel at one end. The objective was to examine mixing and fluid flow for a broader range of Reynolds numbers. The results were correlated with simple T-mixer (inlet channels in-planar with the main microchannel). Vortex T-mixer with two inlet channels show better mixing performance among the three designs due to vortex flow. Vortex T-mixer with four inlet channels show the formation of vortex flow. However, such flow are depicted at much higher Reynolds number. The study reveals vortex T-mixer with two inlet channels quite promising design as compared to T-mixer with four inlet channels.

Keywords: Mixing, Microchannel, Micromixer, Numerical simulation, Navier-Stokes equation

1. Introduction

Microfluidics technology has shown significant enhancement in the manipulation of fluids at the micro/nano scale in chemical, biological and biomedical applications. A better apprehension of transport processes on the relevant time and length scales is requisite to fully utilize the potential of microfluidics technology. Small channel dimensions in micromixers and lower flow velocities, makes the transport processes dominated by laminar flow. This laminar flow in straight channels limits to diffusion governed mass transfer due to the absence of secondary flows. While in curved channels, transverse velocity components are generate that increases mixing of fluids.
Most microfluidic systems require fast mixing of different fluids. Since fluid flow in microchannels is essentially laminar, mixing becomes difficult due to its reliance on molecular diffusion thus requiring longer mixing channels and mixing times. The two categories of micromixers namely active and passive help overcome this constraint. Both types have been researched[1,2] extensively as the low Reynolds number causes the mixing to occur through diffusion thus the basic problem is elongated mixing length requirement. Thus primarily, the micromixer design objective is to curtail down the mixing length by either incorporating external perturbations such as pressure field [3], electrical field [4], acoustic wave [5], magnetic field [6], etc. as in active micromixers or by modifying the geometry of the micromixer to manipulate the flow path and augment mixing of fluid as in passive mixers.

Though active micromixers are good for mixing but they are complicated and expensive to fabricate and are more prone to failures. On the other hand, passive micromixers are simpler and demand no external power. Also passive micromixers can be combined easily with microfluidic devices. In such devices, chaotic advection and molecular diffusion are two primary types of mixing mechanisms [2,7] which can be achieved by inducing chaotic trajectories in a laminar flow.

The primary design of passive micromixers are straight channeled with either Y-shaped[8,9] or T-shaped inlets[10,11]. Simple straight micromixers have the advantages of simple fabrication, easy integration into the microfluidic device and mass production capability. In a simple channel, mixing process is mainly by diffusion. The Reynolds number influences mixing differently in the two cases. According to the equation, \( L = \sqrt{Dt} \), where \( L \) is the characteristic diffusion length, \( D \) is the diffusion coefficient and \( t \) is the residence time. Increase in velocity reduces the residence time of the mixing fluids thus reducing mixing efficiency.

Higher mixing in straight micromixers with non-aligned inlets was better due to creation of vortex flow at much lower Reynolds numbers and it was considered a prospective design for generating vortex flow at the inlet junction of the micromixer. In the present work, the micromixers with two and four non-aligned inlets were investigated at different Reynolds numbers.

2. Micromixer Design and Numerical methods

2.1. Micromixer Design Concept

A simple T micromixer with main microchannel having depth and width as 200 μm and length as 5 mm is considered as the base case and is compared with vortex T-micromixer (with two and four non-aligned inlet channels) with area of the inlet channels i.e. (100μm x 100μm). The basic concept implied in the present is study is vortex based design (See Figure 1). The schematic diagram for the micromixer is shown in Figure 2. The inlets of the simple T-mixer was taken as 50μm x 200μm. The dimension of vortex T-mixer is same for both the designs. The numerical simulations have been carried out at different Reynolds numbers. Here the Reynolds number is representative of the main channel dimensions and working fluid as water.
2.2. Mathematical Model and governing equations

The flow and mixing in the microchannel for the present work is numerically simulated using a ANSYS CFX-16.0 software. It solves the governing equations (1-3) namely continuity, momentum and species convection diffusion.

\[ \nabla \cdot \vec{V} = 0 \quad (1) \\
\rho \vec{V} \cdot \nabla \vec{V} = -\nabla P + \mu \nabla^2 \vec{V} \quad (2) \\
(\vec{V} \cdot \nabla) C = D \nabla^2 C \quad (3) 
\]

Where \( \rho \) and \( \mu \) are the density and viscosity of the fluid respectively. \( \vec{V} \) is the velocity vector, \( P \) is the pressure, \( C \) is the mass fraction or concentration of the mixing fluids and \( D \) is the mass diffusivity. The three equations must be solved simultaneously to obtain the simulation results.

2.3. Numerical methodology
The CFD software ANSYS CFX-16.0 was used to carry out the simulations by finite volume method. Visualisation of mixing profiles of the two fluids was done by solving the convection-diffusion equation. ANSYS Design Modeler and ANSYS ICEM have been utilised for the creation of CAD design and unstructured hexahedral meshing of the micromixer geometry.

Navier-Stokes equations were discretized into a system of algebraic equations and solved numerically. The numerical simulations are susceptible to numerical diffusion due to discretization terms and these errors are larger for coarse grid systems. The deconstructed equations gives more numerical diffusion effects in the results. A commendable computational solution having high accuracy much closer to the true solution of governing equations can be obtained by making a good representation of the governing equations and refining the grid. But computer resources and error accumulation during iteration restricts the additional refinement. To avoid this, grid test is performed and an optimized grid size is chosen and applied to obtain sufficient accuracy. A good mesh is crucial in getting accurate results.

Although some techniques[12] exist which help reduce numerical diffusion errors, it is hardly possible to completely eliminate them in the simulations. The boundary conditions involved considers normal inlet velocities. The outlet was assigned zero static pressure, while the walls were assigned no slip condition. The solution is considered converged for the solution when rms residual value is less than 10^-16.

2.4. Mixing Index
Qualitative and quantitative assessment of mixing performance of the designs of micromixer was carried out. Numerous statistical models have been preferred for the quantitative assessment of mixing quality by various researchers for both macro and micro scale mixers. In the present work, Danckwerte’s intensity of segregation [13] concept is applied for calculation of mass fraction variance at a given plane normal to the flow direction.

It is defined as

\[
\sigma = \sqrt{\frac{1}{N} \sum (c_i - \bar{c})^2}
\]  

(4)

Where, \( N \) is the number of sampling points (computational nodes) on the plane, \( c_i \) is the mass fraction at those points, \( \bar{c} \) is the optimal mixing fraction and \( \sigma \) is the variance of the mass fraction. To ensure high accuracy, the number of sampling points \( N \) on each plane is taken more than 400 while locating the sampling points equidistant. Finally, for appropriate indication of mixing performance, Mixing Quality or Index is calculated using the equation,

\[
MI = 1 - \frac{\sigma^2}{\sigma_{\text{max}}} 
\]

(5)

Where, \( \sigma_{\text{max}} \) is the maximum variance which indicates completely unmixed fluids. The minimum value signifies completely mixed fluids. Mixing efficiency varies from 0 to 1.

3. Results and Discussion
The mixing and fluid flow in vortex T-mixer were determined using numerical methods. The grid test was performed before carrying out these simulations. Similar mesh density and number of nodes were considered in this work. For details about grid independency test and mesh refer to paper [14]. Figure 3 shows the mesh for the three designs of the micromixer. In both the cases the fluid stream were tangential flow path to the main microchannel as expected to create vortex flow. Such vortex flow can be harnessed to increase mixing of fluids. The results were compared with the simple T-mixer. Figure 4 shows the mass fraction distribution on \( yz \)-plane at various Reynolds numbers. In simple T-
mixers, the interface of the fluid streams shows almost no mixing at Re = 10, 40 and 100. A little bend in interface of the fluid streams can be observed at Re = 200. The vortex T-mixers with two inlet channels shows vortex flow due to the tangential fluid streams into the main channel. The vortex flow increases with Reynolds number that directly enlarges the interface area (see Fig. 5). Understanding the effect of the vortex flow on mixing performance, the idea of the two non-aligned inlet channels was extended to four non-aligned inlet channels. Here, we were expecting stronger vortex flow and better mixing performances. However, the results were against our expectation, as the flow induced by four non-aligned inlet channels is not efficient in creating strong vortex flow (see Fig. 6). On comparing with the mass fraction distribution for two non-aligned inlet channels, it is able to provide some mixing only at very high Reynolds number (Re=200). Increasing Reynolds number (Re = 300), increases the vortex flow which increases the mixing of fluids. Here we can say that the concept of four non-aligned inlet channels as not effective.

**Figure 3** Representative mesh for Vortex T-mixer.
Figure 4. Mass fraction distribution; (a) Re = 10  (b) Re = 40 (c) Re = 100 (d) Re = 200 (e) Re = 300.

Figure 5. Mass fraction distribution; (a) Re = 10  (b) Re = 20 (c) Re = 40 (d) Re = 80 (e) Re = 150
Figure 6. Mass fraction distribution; (a) Re = 20  (b) Re = 40 (c) Re = 100 (d) Re = 200 (e) Re = 300.

(a) Vortex T-mixer with two non-aligned inlets
(b) Vortex T-mixer with four non-aligned inlets

Figure 7. Projected streamlines at different Reynolds numbers

The projected streamlines for vortex T-mixer can be investigated to check the formation of the secondary flow with two and four non-aligned inlet channels (See figure 7). For simple T-mixer, the flow is well ordered without any secondary flow (Streamlines not show here). Such flows are
ineffective in mixing enhancement. Vortex T-mixer with two inlet channels creates vortex flow. The vortex flow is increasing with Reynolds number. At Re = 40, vortex T-mixer is creating vortex flow that can cover the full cross-sectional area of the microchannel. Such flows desirable as it helps in increasing the mixing of fluids. On contrary, the design with four non-aligned inlet channels is not able to create vortex flow in the microchannel. As can be observed at Re = 200, vortex flow can be observed. However for Re = 40, 80 and 100, no vortex flow is observed. The design of the micromixer with two non-aligned inlet channels is creating vortex flow at Re = 40, while with four inlet channels, it creates a very high Reynolds number (Re = 200).

4. Conclusion

Numerical study was performed on three different designs of the micromixer. The designs are basic simple T-mixer, mixer with two and four non-aligned inlet channels at different Reynolds numbers. In simple T-mixer, the height of the full domain is same. In vortex T-mixer, the height of the inlet channels is not same as that of the main microchannel. It joins at tangential positions at microchannel other end. The fluid streams entering the microchannel create vortex flow. As expected, simple T-mixer shows lowest mixing performance among the three designs. Vortex T-mixer with two inlet creates vortex in the channel at Re = 40, which is found to be very effective in mixing. Vortex mixer with four non-aligned inlet channels is not capable of creating vortex flow at lower Reynolds numbers. Vortex formation begins at much higher Reynolds number for micromixer with four inlet channels. Among the three, vortex mixer with two non-aligned inlet channels is best suited for mixing applications.

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