

Numerical Study and Comparison of Passive Mixing in Helical Micromixers

Akash Sinha^{1,*}, M. Zunaid¹, Afzal Husain²

Abstract

A passive mixing inside three micromixers has been studied with water as the mixing fluid. Since the mixing at the micro-level is governed by species diffusion hence it is a time-consuming process that requires an extended length of micromixer for the required amount of mixing. The present study tackles this problem by introducing two helical micromixers, a Three-dimensional helical micromixer (TDHM), and TDHM having four inlets (TDHM-FO). These micromixers need a reduced length of mixing channel while still providing greater efficiency than a simple T-micromixer (STM). A detailed analysis is being presented to analyse the mixing process and performance. Several other parameters have been calculated and presented in this study along with the efficacious Reynolds number. Both the helical micromixers performed better than simple T-micromixer for all values of Reynolds numbers. For low Reynolds numbers ($Re \leq 75$), TDHM-FO is better. TDHM provides the best results for $Re=310$ and 400 which is even better than TDHM-FO and the mixing efficiency for TDHM and TDHM-FO is much better than STM for all ranges of Reynolds numbers. It is concluded that both the helical micromixers provide much better efficiency that too with less mixing length compared to STM. While examining a fluid flow, pressure drop becomes an important parameter to study because it indicates about the amount of energy required to make the fluid flow. Higher the mixing, higher will be the pressure drop and hence more pumping power is needed to drive the flow. Among all three micromixers, STM showed the least value of pressure drop while TDHM-FO showed the highest.

Keywords: Helical passive micromixer, STM, numerical analysis, Newtonian fluid water, mixing index (MI), pressure drop

INTRODUCTION

The branch of science that studies the behaviour, precise control, and manipulation of fluids at the microscopic level is known as microfluidics. At this small scale, surface forces dominate volumetric forces. Micro-scaled devices, ranging from 10 to $100 \mu\text{m}$ come under this field of science and have several applications in mechanical, chemical, and other domains. For example, it has opened a new field of research in biomedical diagnostics, chemical synthesis, lab-on-chip etc. In μTAS biochemical

research domain, a micro-device is being used nowadays which uses the human-derived cell to mimic the actual human body. The device is known as organ-on-chip, and it has been actively pursued considering the unethical medical practices being done on animals. Their advantages can be the use of less reagent consumption, time efficient as computational time is less, low cost, portability etc. The main drawback of this system is the inefficient mixing. Unlike macro-systems, where a desired amount of mixing can be achieved by generating turbulence, but, since the entire flow is mostly laminar in micromixers, so increasing mixing efficiency is a very difficult task. There

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Received Date: August 27, 2022

Accepted Date: November 24, 2022

Published Date: November 30, 2022

Citation: Akash Sinha, Zunaid M, Afzal Husain. Numerical Study and Comparison of Passive Mixing in Helical Micromixers. Journal of Polymer & Composites. 2022; 10(Special Issue 1): S76–S92.

could be instances where it may even require an elongated length of the microchannel to do the desired degree of mixing. In the case of passive micromixers, Molecular diffusion which mainly drives a passive mixing is a very time-consuming process since it requires the movement of molecules through the fluid. Micromixers are generally categorized into two types, Active micromixers and Passive micromixers. Active micromixers are those micromixers that require external energy sources, such as Magneto-thermodynamic, Ultrasonic, electro-kinetics etc. to drive the flow; whereas a passive micromixer has no such moving parts and requires no energy input. The pressure drop between the inlet and outlet section of fluid drives the flow. This pressure drop is generally achieved by making a variation in the geometrical shapes of the micromixers. Active micromixers are costly as compared to passive units [1–8].

T and Y junction type micromixers have a very basic geometrical design. Over the year, a considerable amount of research work, both numerical and experimental, has been done describing various flow regime. Apart from it, several geometrical configurations have also been done to enhance their mixing in T-micromixers [9–11]. Shi *et al.* designed and studied six T-micromixer models with Koch fractal obstacles [12]. His study resulted that the obstacles increased the chaotic advection inside the fluid and improved mixing. Dundi *et al.*, in their study, compared two cases of inlet velocity: one case with swirl velocity and the other without swirl velocity [13]. It was concluded that mixing efficiency increased significantly at both lower and higher values of Reynolds numbers. Farahinia and Zhang presented a numerical study on how the design of micromixers affects the mixing efficiency [14]. Circular and rectangular T and Y micromixers were taken for study. Fluid velocity and diffusion coefficient were among the process parameters which were taken in this study. The results showed that circular T and Y micromixers performed better at low inlet fluid velocity and with a high diffusion coefficient value.

Mixing efficiency can also be enhanced by increasing the interfacial area (which can be defined as the contact layer area between the fluid species) between the mixing fluids. There are several methods to achieve the larger interfacial area and a few of them have already been discussed in the previous paragraphs. Another way to increase the interfacial area is by using curved channels. This type of channel configuration develops a secondary flow which acts perpendicular to the main flow producing an enhanced mixing. Khaydarov *et al.* examined flow regimes, both numerically and experimentally, inside a microchannel having chicane geometry [15]. A much higher fluid mixing was observed due to the involvement of swirling and recirculation which were induced due to the geometry. Lin presented two different micromixers, the first serpentine designed micromixer and the second is a square-wave design micromixer which contained cubic grooves [16]. The computational analysis was done on a series of Reynolds numbers (8–160) and mixing efficiency and pressure drop were studied. The models resulted in better mixing due to chaotic advection, continuous rotation, planar stretching, and 3D stretching. Chaotic advection is a complex behaviour attained by the fluid particles under the effects of fluid flow. Rampalli *et al.* numerically studied a convergent-divergent micromixer by replacing a previously available square-wave channel micromixer [17]. Square-wave convergent-divergent micromixer was studied, and it was found that for higher Reynolds number i.e., for $Re > 10$, mixing efficiency was improved but not much significant difference was observed for lower values of Reynolds number ($Re < 10$). Chen *et al.* numerically studied and analysed flow inside a serpentine microchannel [18]. It resulted in enhanced molecular diffusion and increased mixing index due to the serpentine shape of the microchannel. Square wave microchannel was also studied along with six other types of microchannels and the results showed that among the six types of micromixers, square wave channels performed best. Usefian and Bayareh experimentally and numerically investigated a convergent-divergent micromixer for low Reynolds number [19]. Effects of several parameters which include inlet velocity of the fluid, number of mixing cycles and blockage ratio were studied, and the results showed that the increase in inlet velocity increased the mixing efficiency, number of cycles and blockage ratio. It was also observed that, for $Re > 19$, expansion vortices were the main factor of mixing. Mengeaud *et al.* studied 100 μm wide zig-zag channel [20]. It was observed that mixing

efficiency significantly increased for $Re > 80$, which was due to the recirculation phenomenon of flow. Ziegenbalg *et al.* numerically studied and compared two different types of micromixers, Y and S-form micromixers [21]. S-form micromixer resulted in better mixing efficiency when compared with Y micromixer because of the vortex flow regime in the former. Several experimental works on passive and active micromixers have also been done which can be referred to in the literature [3–5, 15, 19].

The fabrication of micromixers is a challenging issue and requires unconventional manufacturing methods. Generally, the soft photolithography technique is used to fabricate two-dimensional micromixers. Mondal *et al.* studied fabrication processes and evaluated a quick method to manufacture the micromixers with poly-di-methyl-siloxane (PDMS) [22]. The method was used to produce two micromixers, first one is raccoon type and another one is serpentine type. Tachibana *et al.* fabricated a helical micromixer using micro-scale low-wax casting [23]. The moulds for lost wax casting were manufactured by the 3D printing of wax resin. Taheri *et al.* experimentally and numerically investigated a passive three-dimensional split and recombined structure micromixer based on lamination of fluid layers [24]. These micromixers provide increased contact surface by increasing molecular diffusion that helps in achieving faster mixing. This device was manufactured using the Xurography method. It was concluded that this method is simple and low-cost to fabricate three-dimensional micromixers. Literature can be referred for more work on the various fabrication techniques [25–27].

Another way to enhance the mixing is by placing obstacles in the microchannel. The obstacle helps in increasing mixing efficiency by introducing chaotic advection. Also, due to the now-increased length of the micromixer, the residence time of the fluids also increases and hence the fluid particles got more time to diffuse which ultimately increases mixing efficiency. Mahmud numerically studied a variant of T-micromixer [28]. Obstacles of two shapes were placed inside the path (circular and hexagonal). Water was taken as the active fluid and the research was performed on a series of Reynolds numbers. The result indicated that modified T-micromixer with obstacles had better efficiency than modified T-micromixer without obstacles. Mondal *et al.* numerically analysed a rectangular microchannel with obstacles, having aspect ratios of 4:1, 1:1, and 1:4, placed in the walls [29]. Both the conditions (with obstacles and without obstacles) were studied and compared for two parameters (mixing efficiency and pressure drop). The analysis resulted in higher mixing efficiency on the microchannel with obstacles. The results were best for obstacles with an aspect ratio of 1:4. Hossain *et al.* numerically and experimentally analysed the effect of different obstacles (diamond, rectangular, and circular) on the mixing efficiency of a tesla structured micromixer [30]. Tesla structure produced transverse dispersion by splitting and recombining the fluid streams which enhanced the mixing and the sporadically positioned obstacles further enhanced the mixing due to the presence of chaotic advection. Literature can be referred for more work on the same [31–34].

The research gap lies in the mentioned literature review above. Many studies and research exist for micromixers of various shapes but on contrary, only a few for helical micromixers. In this study, the mixing of three micromixers has been numerically studied: simple T-micromixer (STM), 3D Helical Micromixer (TDHM) with rectangular cross-section and TDHM with four inlets at offset (TDHM-FO). Few of the works on the spiral channel of different shapes and sizes have been listed in references [35–37]. This 3D helical geometry of the microchannel creates a vortex in the fluid which helps in enhancing the mixing and providing inlets at an offset to each other and creates rotation in the fluid. A comparative analysis of mixing index and drop in pressure, between inlet and outlet, has been numerically studied using Computational Fluid Dynamics simulations.

GEOMETRICAL AND NUMERICAL MODELLING

Geometrical Description of the Systems

All the micromixers that have been chosen for the study have been presented in Figure 1(a–c). simple. The dimensions of the inlet channel of STM,

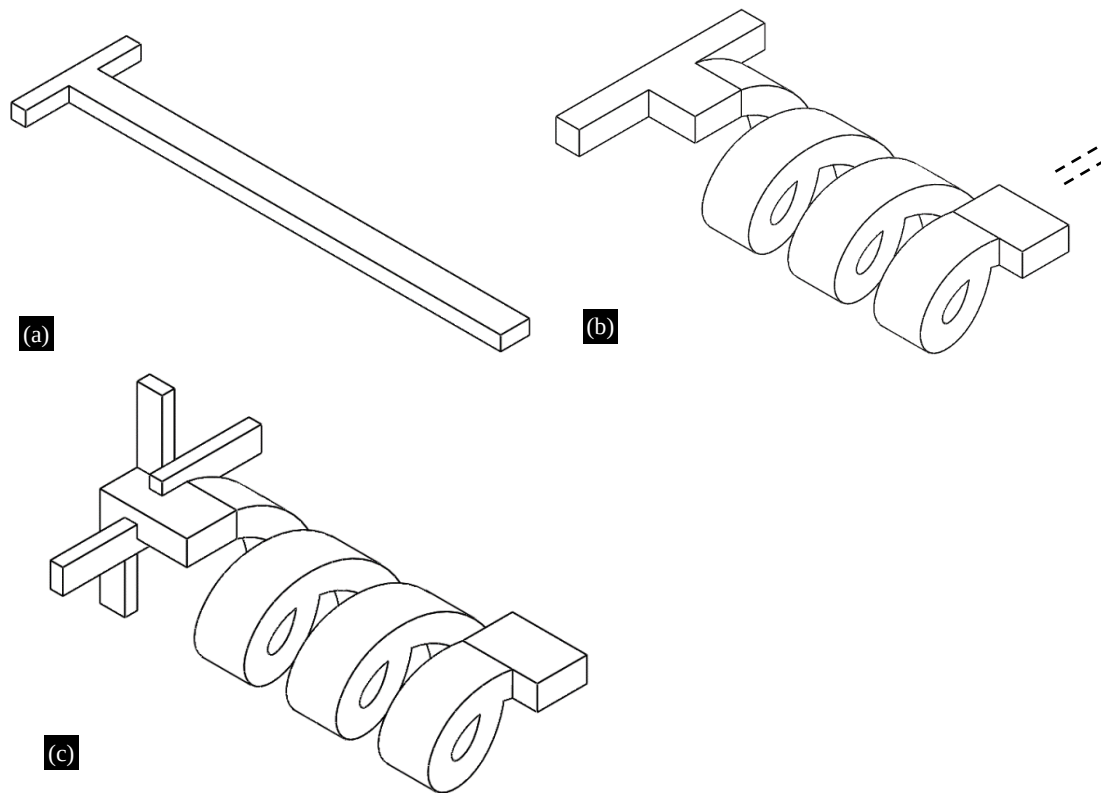


Figure 1. (a) Simple T-micromixer; (b) three-dimensional helical micromixer (TDHM); (c) TDHM with four inlets at offset.

TDHM micromixer has a cross-section of $100 \times 100 \mu\text{m}$, whereas, to maintain the same mass flow, the inlet channel of TDHM-FO has half cross-section when compared with the other three i.e., $100 \times 50 \mu\text{m}$. The outlet has a rectangular cross-section of $200 \times 100 \mu\text{m}$ for all geometries. The channel length of STM is $3000 \mu\text{m}$ (L_a). The unfolded length of rest of the micromixers L_m is kept equal to the sum of the microchannel length of the STM and length equivalent to one extra spiral. Figure 2 shows all the geometrical specifications required to design both the helical micromixers. Curve Pitch (P_h) and helical curve diameter (d_m) of the helix curve are the same for both the helical micromixers with values of 0.3705 and 0.38 mm , respectively.

Detailed dimensions are mentioned in Table 1. The Hydraulic diameter of the mixing channel and velocity has been used for the calculation of Reynolds numbers.

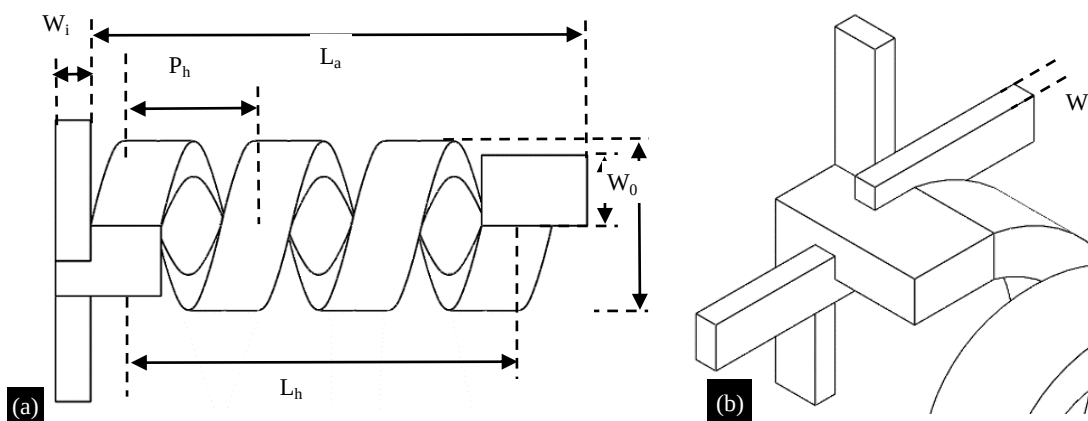


Figure 2: (a) and (b) Parameters of the 3D helical micromixer geometry.

Table 1. Dimensional parameters of 3D helical micromixer geometry.

Specifications	Lengths (μm)
Inlet width of micromixers (except TDHM-FO)	100
Inlet width of TDHM-FO (W_i)	50
Outlet width (W_o)	200
Curve pitch (P_h)	370.57
Length of the curved helical microchannel (L_a)	1411.71
Helical curve diameter (d)	380

Mathematical Modelling

Numerical analysis is used to study various contours and streamlines of flow and to get the values mixing index (MI) for a series of Reynolds numbers. Pressure based model has been used since the flow is incompressible and water is a Newtonian fluid. The Navier-Stokes equation, continuity equation and the convection-diffusion equations for species transport are being numerically solved to get the solution of the flow field.

(Continuity Equation)

$$\nabla \cdot \vec{V} = 0 \quad (1)$$

Here, ‘V’ denotes the velocity vector of the flowing fluid.

(Navier-Stokes equation)

$$\rho \cdot \nabla V = - \frac{1}{\rho} \nabla P + \nu \nabla^2 V \quad (2)$$

‘ρ’ represents the density of the fluid, ‘P’ denotes pressure and ‘ν’ represents the kinematics viscosity. ∇ is the Del operator and is given by:

$$\nabla = \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k}$$

Mixing index is a parameter which denotes the degree up to which mixing has been taken place. The value of mixing index is calculated according to the following Eq. (3):

$$Mi = \left(1 - \sqrt{\frac{\sigma^2}{\sigma_{max}^2}} \right) \times 100 \quad (3)$$

$$\sigma^2 = \frac{1}{n} \sum_{j=1}^n (c_i - c_{avg})^2 \quad (4)$$

Where σ^2 represents the summation of variance in the mass fraction at any specific plane of the species, whereas σ_{max}^2 is the maximum possible variance at the plane. ‘ c_i ’ denotes the species mass fraction at point ‘i’ in that plane, and ‘ c_{avg} ’ denotes the mean value of species mass fraction at that plane. A total of 500 such sampling points have been taken on every selected plane to get better results. 0% of MI represents no mixing between the fluid species has taken place, whereas, 100% MI denotes complete mixing among the species.

Numerical Modelling and Boundary Conditions

The Advection-diffusion scalar transport equation has been utilized for the modelling of the mixing of two fluid species. The equation is given by:

$$(\vec{u} \cdot \nabla)c = D_m \nabla^2 c \quad (5)$$

Here, ‘c’ is the concentration of the fluid species ‘a’ and ‘b’, D_m is the molecular diffusivity. Viscosity, density, and diffusivity are considered at 20°C as 0.01 g/cm s, 0.9982 g/cm³ and 900 cm²/s respectively.

The boundary conditions, that have been unitized to solve the above-mentioned equations, are same for the STM and TDHM whereas, to maintain the symmetry, there is a slight difference in the species

concentration of TDHM-FO. Two fluids, 'water' and 'water-dye', have been selected at inlet 1 and inlet 2 respectively. Water is fed into inlet 1 with a species concentration of '1' and water-dye into inlet 2 with a species concentration of '0' for STM and TDHM, whereas for TDHM-FO, the species concentration is kept at 0.5 for two inlets which are fed 'water', whereas, for other two inlets, it was kept 'zero'. 'Stationary wall', 'No slip' and 'zero heat flux' condition is given to the wall of the micromixer in all three geometries. 'Gauge Pressure' at the outlet is provided to be 'zero'.

METHODOLOGY

All three geometries of micromixers are modelled using SolidWorks software. The models are then imported to Ansys Workbench for further simulation. Ansys Mesher is used to generate the mesh having tetrahedral elements which are good for complex geometry as it can fit better in complex geometry (Figure 3).

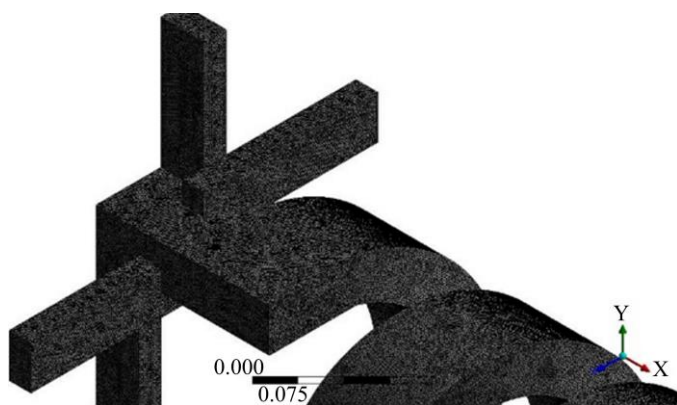


Figure 3. Mesh of TDHM-FO with tetrahedral elements; no. of elements: 3.5 M.

Since the flow is assumed to be laminar and steady states, hence, “steady-state laminar model” was used during the simulation. Also, since the temperature is assumed to be constant, the energy model was utilized. To deal with various species, the species transport model was utilized. All the mentioned equations have residual values of 10^{-15} .

Numerical Modelling and Boundary Conditions

Optimized mesh element size is needed before moving for the simulation. This is done to minimize the cost and time of the simulation. This is done by doing a “grid independence test”. As can be visualized from Figure 4, which shows the variation of the mixing index with mesh element numbers for TDHM, there is a saturation in the value mixing index after 3.45 M mesh elements. No significant change was found in the value of the mixing index between 3.45 and 4.0 million mesh elements. This variation of the mixing index was obtained for $Re = 230$. Similarly, grid independence tests were carried out for all other geometries as well before running the actual simulations.

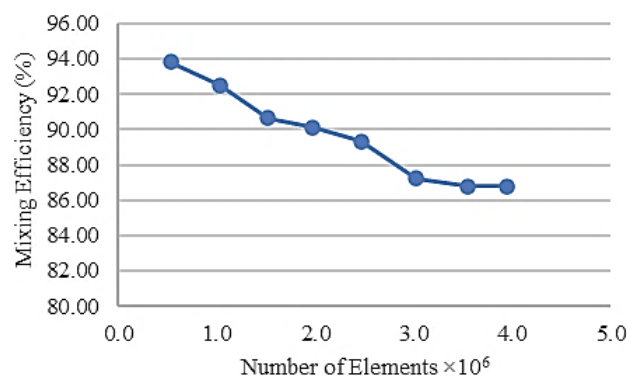


Figure 4. Grid independence test.

Numerical Validation of the Computational Method

The numerical study was firstly done for STM, and the results were compared with existing literature of Dundi *et al.* [13]. This is done to validate the computational model that has been created for this particular study. Figure 5 shows the graph of MI in the present study and the existing study for $Re=266$. The maximum difference of 4.78% was observed at 0 μm . The results were considered satisfactory and hence the computational method is validated. A visual comparison can be made from Figure 6.

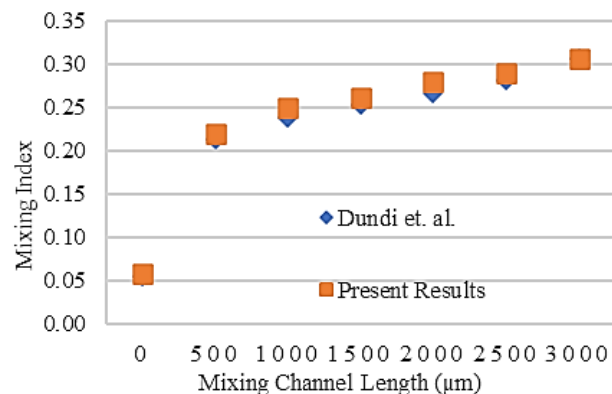


Figure 5. Numerical Validation of The Current Study with Existing Literature [13].

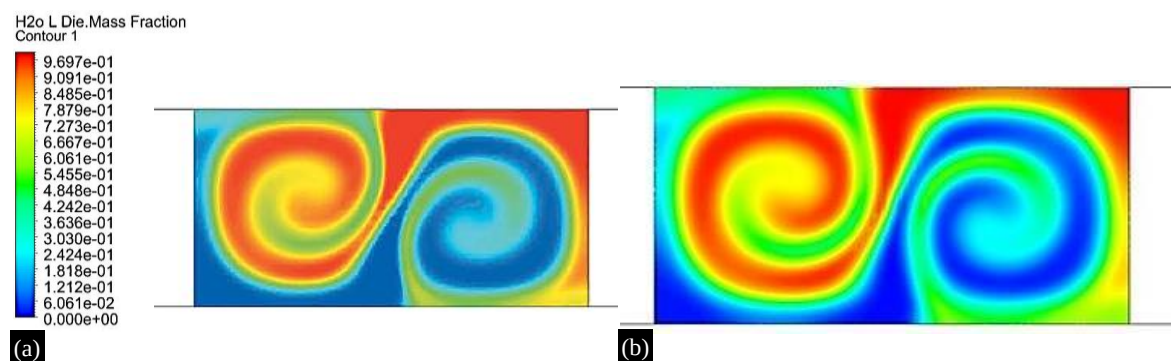


Figure 6. Contours Based on Species Concentration at the Outlet of (a) Existing Literature, and (b) Present Study.

RESULTS AND DISCUSSIONS

This analysis deals with the presentation of mixing index and pressure drop and the reason behind the phenomenon inside three different geometries of micromixers: STM, TDHM and TDHM-FO. These three micromixers are compared based on the value of their mixing index at the outlet and pressure drop between the inlet and outlet sections. The study is done on a wide range of Reynolds numbers (from 8 to 400). Considering three different geometries, this section is divided into three parts each explaining one micromixer.

Analysis of STM with Water as Fluid

This section will deal with the computational analysis of STM using ANSYS Fluent. The parameter mixing index has been calculated on the outlet section of STM for a series of Reynolds numbers (8–400). The pressure drop between the inlet and outlet section has also been evaluated. The values of the mixing index were calculated and plotted on a graph as a function of Reynolds number. It was observed that there are three types of flow regimes which can be divided based on the value of the mixing index for various Reynolds numbers (Figure 7). These flow regimes are the laminar diffusion flow regime, laminar vortex flow regime and the engulfment flow regime. The same has been observed in previously done studies. In the present work, it was observed that for lower values of

Reynold numbers, for $Re \leq 75$, the two flow species seemed to be parallel, and the flow was separated. The same can be visualized in Figure 8(a) which represents the streamlined contour for $Re=20$. Since the flow is parallel and straight, this regime is called the straight laminar flow regime. Here, a vortex is not generated, and only molecular diffusion is driving the flow.

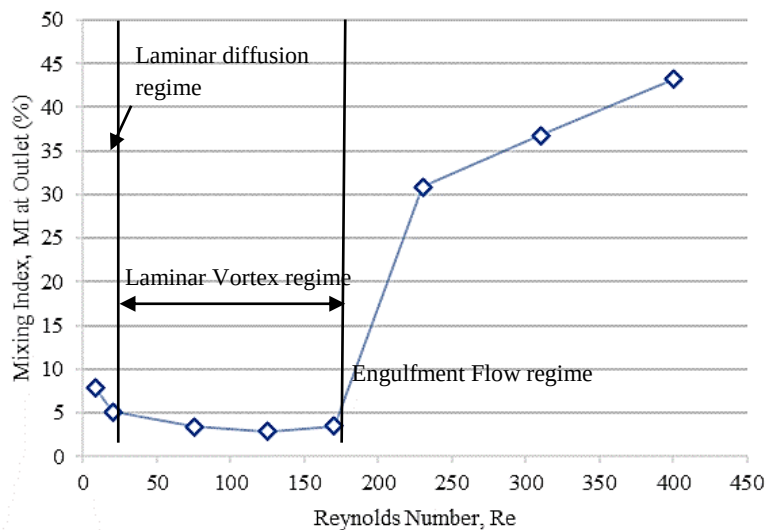


Figure 7. Flow Characterization Inside STM.

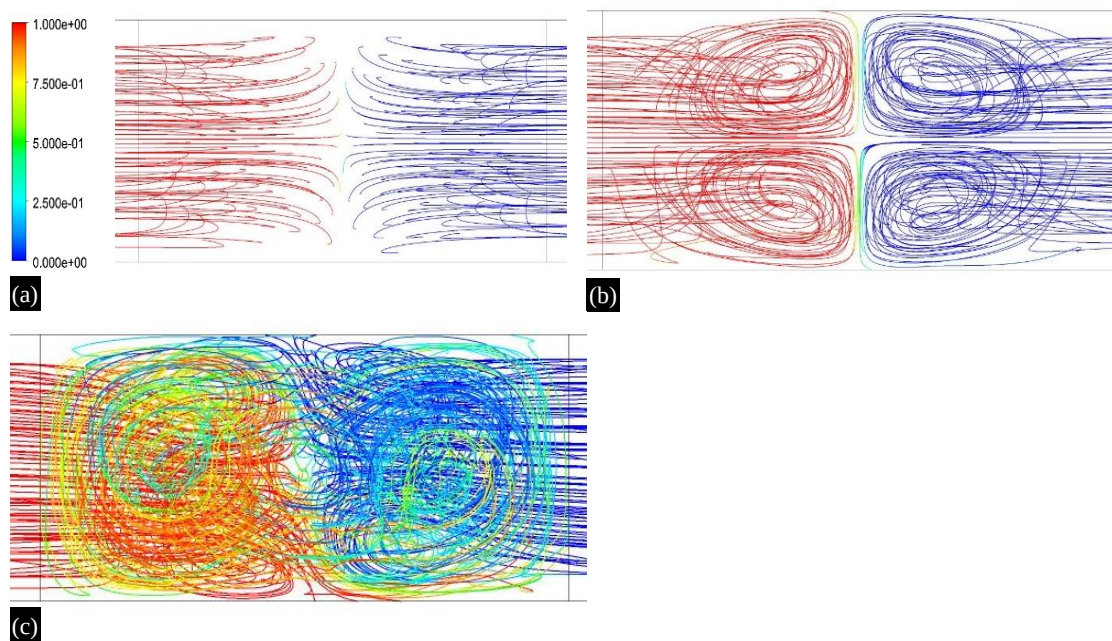


Figure 8. Streamlines of Water Based on Species Concentration at the Outlet of STM For (a) $Re = 20$; (b) $Re = 70$; (c) $Re = 400$.

When the Reynolds number is increased up to $Re = 70$, small and weak vortices can be observed in Figure 8(b). The vortices appeared to be uniform about the vertical plane. We called this regime the laminar vortex regime due to the formation of a small vortex. Although these vortices should have increased the mixing index, they decreased it as can be seen in Figure 9. Figure 9 shows the variation of the mixing index with Reynolds numbers. This is because of the low residence time of the fluid species and hence molecular diffusion could not occur. Residence time is defined as the time spent by fluid particles inside a controlled volume. The mixing index of STM was observed to show this

behaviour till $Re=170$. As the Reynolds number further increased, the strong vortices were observed in the streamline which we called the engulfment flow regime. A significant improvement in the mixing index was observed in this regime mainly due to chaotic advection. The streams have broken the symmetry and are no longer symmetrical about the vertical plane (Figure 8(c)). Eqs. (3) and (4) have been used to calculate the mixing index for a series of Reynolds numbers and the corresponding graph has been presented in Figure 9.

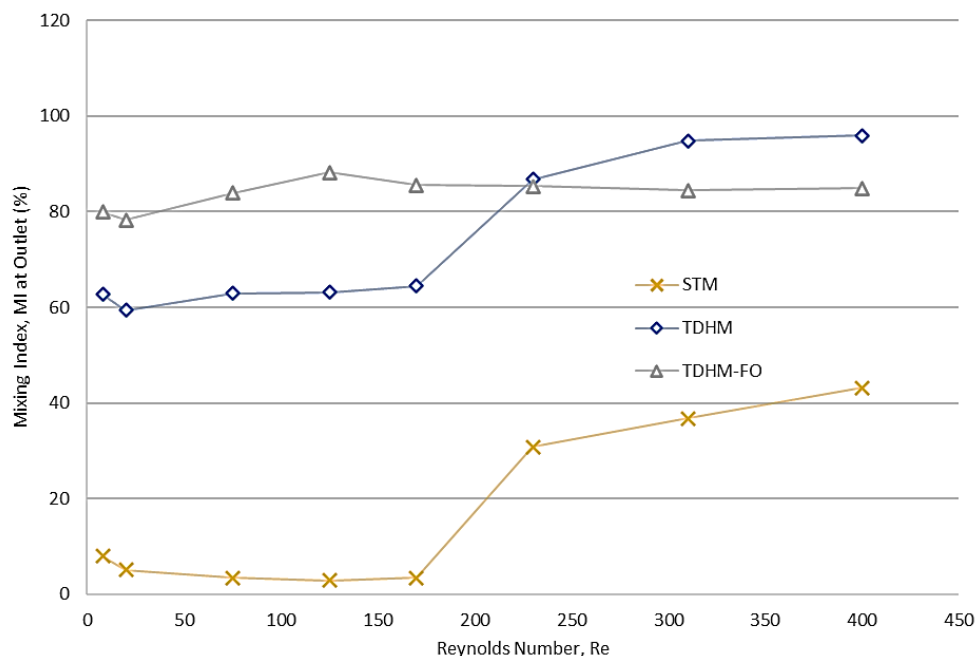


Figure 9. Variation of mixing index of various micromixers with Reynolds number.

Analysis and Comparison of TDHM and TDHM-FO with Water as Fluid

In the same way, computational simulation was done for the rest of the helical micromixers, i.e., for TDHM and TDHM-FO. The mixing index was calculated for a series of Reynolds numbers and pressure drop between inlet and outlet was also obtained. The variation of the mixing index at the outlet plane and Reynolds number can be seen in Figure 9. As was observed from the simulation results, STM showed very poor results for lower values of Reynolds numbers. This is due to the absence of chaotic advection, slow process of mass diffusion and straight laminar flow. As the Reynolds number increases, the mixing index is observed to be reduced (Figure 9). The corresponding value of the Reynolds number for the lowest mixing index is called the 'critical Reynolds number' after which, an increase in the mixing index can be observed due to the presence of chaotic advection.

Analysis and Comparison of TDHM-FO with TDHM with Water as Fluid

As shown in Figure 9, TDHM-FO provides the best mixing index for lower values of Reynolds numbers i.e., for up to $Re = 75$ when compared with the other two micromixers. At a low Reynolds number, TDHM-FO provides a larger interfacial area between the fluid species which causes stretching of the fluid and hence mixing index is increased. This is also due to the enhancement in mass diffusion. Vortex flow is being generated at the junction of four inlets due to its design which is the primary reason for the higher mixing index. This can be visualized by the streamlines of TDHM-FO which is based on the concentration of species for $Re = 310$, as can be seen from Figure 10(c). The mixing efficiency for TDHM-FO was 31.9% more than that of TDHM for $Re = 230$ at the outlet.

To get the variation of the mixing index at various locations inside the microchannel, an in-depth analysis was done and the mixing index at several various locations inside the microchannel of TDHM-FO was calculated. These sections are considered along with the flow directions and the

mixing index is calculated on these planes for each Reynolds number considered for the simulation (Figure 11). The curve for very low Reynolds ($Re = 8$), the curve seemed to be linear in nature and the value of the mixing index was almost linearly increasing as the distance of the plane increased. At $Re=8$, the mixing index is 52.52% at plane A which then increased to 78.68% at plane G, which is an increase of 26.16%.

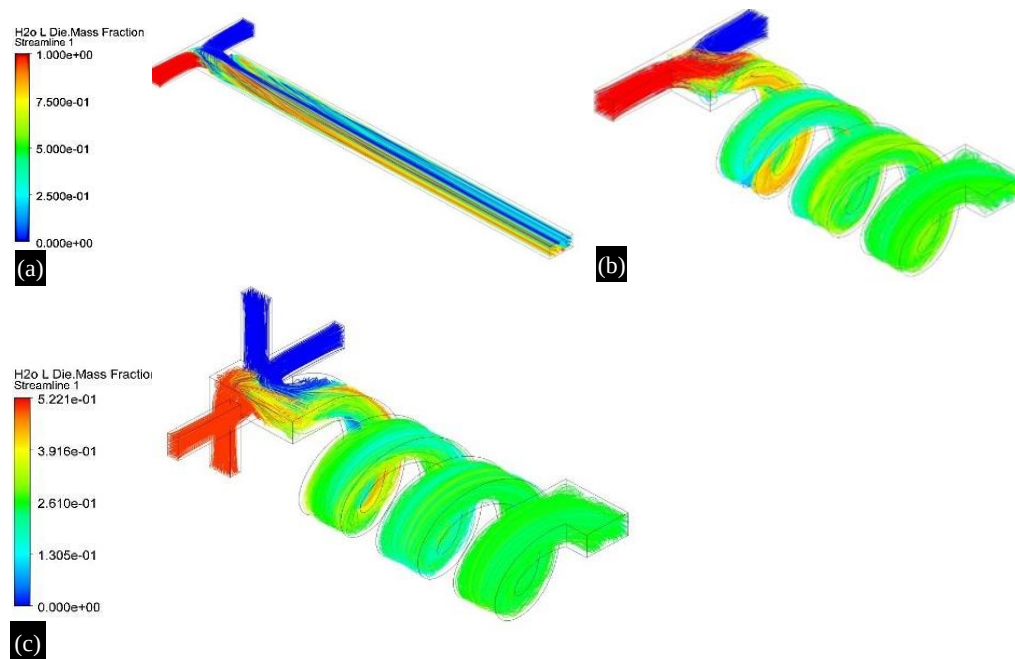


Figure 10. Streamline Based on Species Concentration For (a) STM, (b) TDHM, and (c) TDHM-FO For $Re=310$.

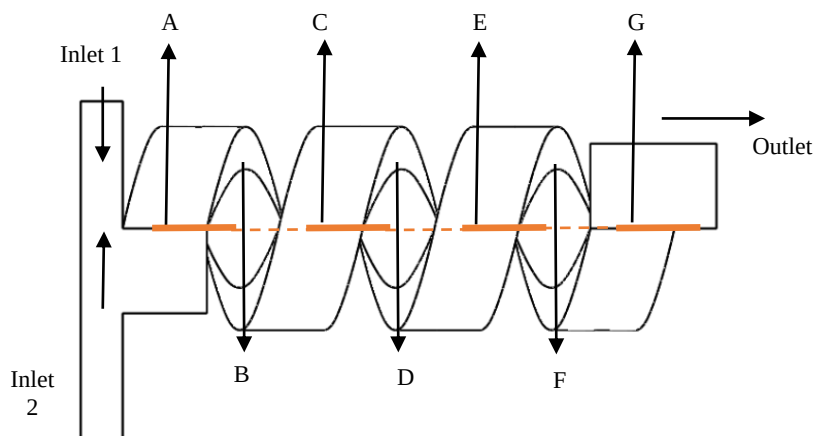


Figure 11. Location of Various Planes at Different Sections in Top View.

For higher Reynolds numbers, this mixing of the increased within a short distance. For $Re=400$, the mixing index is 72.34% at plane A which increased to 95.71% at plane D, which is a sharp increase. Species concentrations for $Re=20$, 230 and 400 have been represented respectively in Figure 12(a), (b) and (c) at planes A, B, C, D, E, F and G. As can be interpreted by the Figure 12, mixing interface between the fluid streams in thin at the starting (at plane A) and slowly starts the increase till plane G which has thicker mixing interface zone. But as can be observed from the streamlined Figure 10(c), the fluid flow separates and hence we get a low value of mixing index at the outlet when compared with plane G. This is due to the comparatively high speed of the flowing fluid and sharp turn at the exit section of the micromixer.

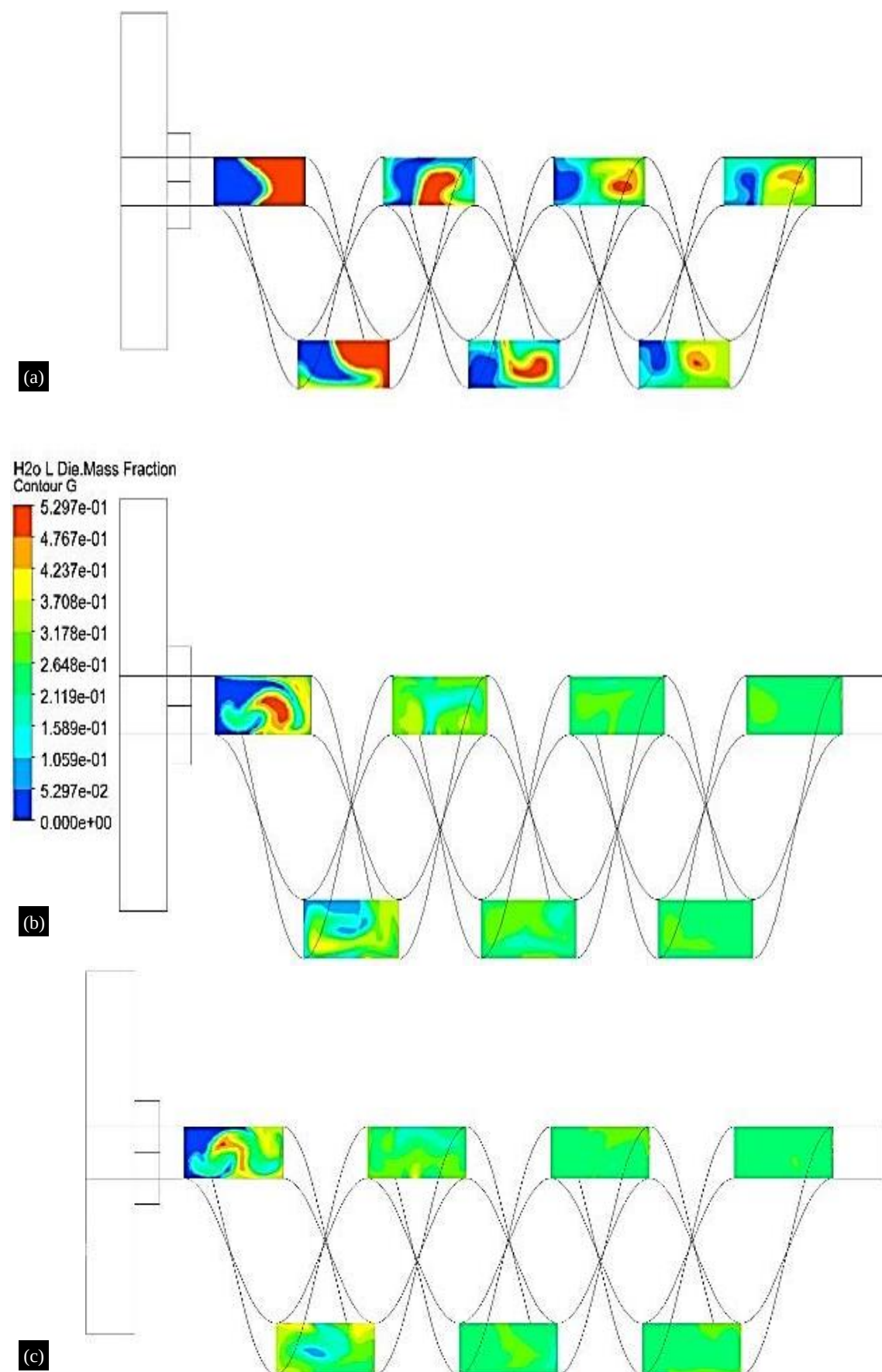


Figure 12. Species concentration at different sections of TDHM-FO for Re=(a) 20; (b) 230; (c) 400.

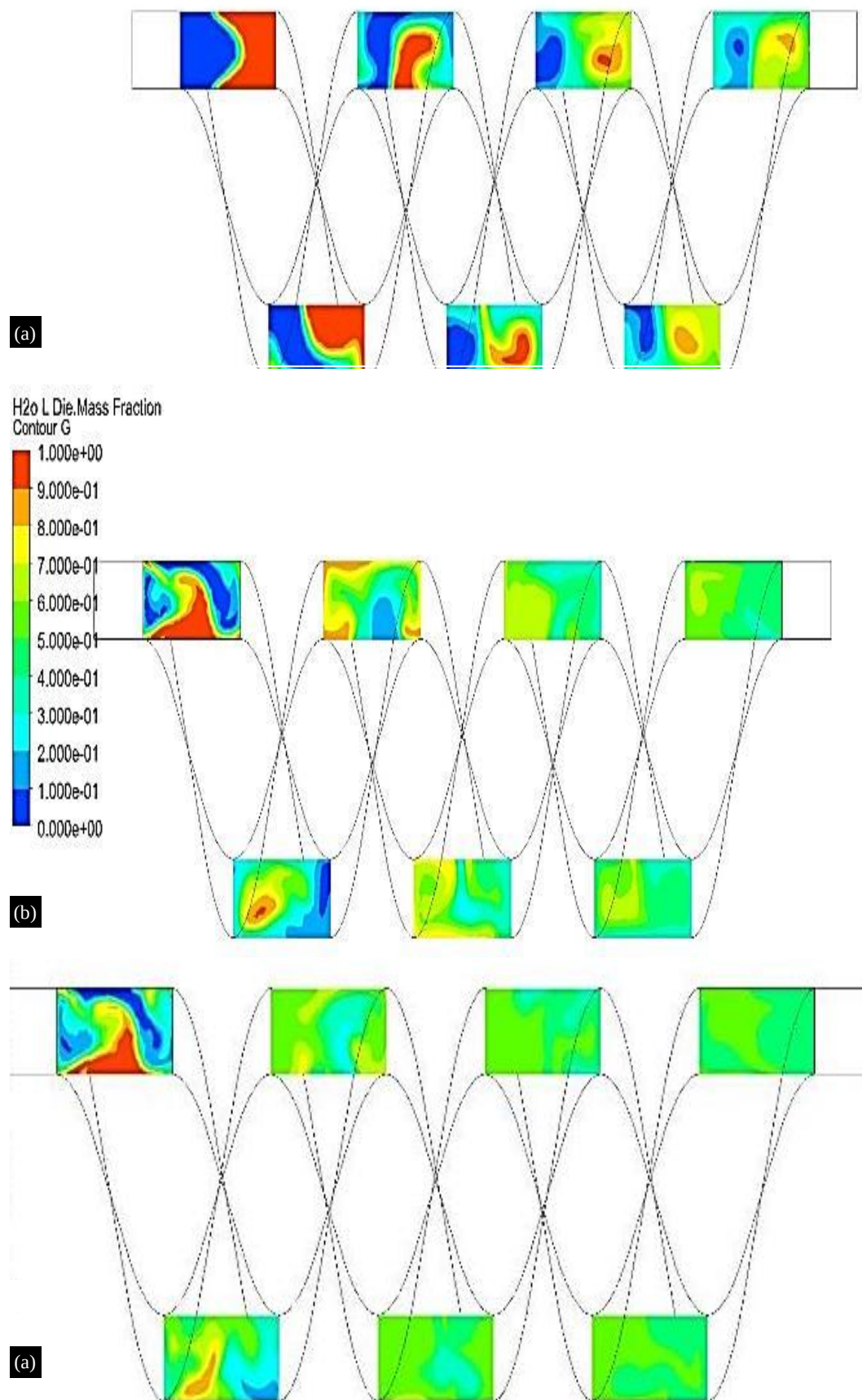


Figure 13. Species concentration at different sections of TDHM for Re=(a) 20; (b) 230; (c) 400.

A similar analysis was done for TDHM as well. TDHM provides better results at high Reynolds numbers, i.e., for $Re=310$ and 400 . The mixing index was found to be more in TDHM compared to STM for all cases of Reynolds Number. At a lower value of the Reynolds number, TDHM provides a larger area between the layers of fluid species and stretching of fluid happens hence the enhanced mixing index than STM.

As the value of Reynolds number increased, the mixing index got also increased. This is because of the formation of secondary flow which dominates the flow in the mixing channel at a higher Reynolds number i.e., for $Re \geq 125$. Another reason is the centrifugal force which is being imparted due to the 3D curvature structure of both the micromixers and this introduces chaotic advection in both the micromixers. Visual representation of the same can be seen in Figures 9(a and b) which show streamlined formation in STM and TDHM. For Reynolds number greater than 170, TDHM even performs better than TDHM-FO because flow did not get separated after plane G and hence the mixing index at the outlet is higher compared to TDHM-FO. Similarly, Figures of species concentrations for $Re=20$, 230 and 400 has been shown in Figure 13(a), (b) and (c) respectively at planes A, B, C, D, E, F and G. From the Figures, similar interpretations can be made as done in the case of TDHM-FO (Figure 14, which represents the change in the mixing index at different locations along the path of the TDHM-FO microchannel for all values of the Reynolds number) and same can be visualized graphically from Figure 15 which represents the change in the values of mixing index at different locations along the path of TDHM microchannel for all values of Reynolds number.

As explained earlier, passive micromixers are micromixers which do not require an external energy source to drive the fluid flow. In the case of a passive micromixer, a pressure drops between the inlet and outlet of the microchannel is needed to drive the flow hence it becomes an important parameter to evaluate. Also, since pumps are used to deliver the fluid inside the micromixer and the idea of power consumption is obtained from the value of pressure drop, it becomes necessary to calculate it. Figure 16 shows the graph between the pressure drop and Reynolds number for all the three micromixers considered in the study. As can be observed from the graph, very less change in the value of pressure drop is there for low Reynolds number ($Re=8$). But, as the value of Reynolds number increased, pressure drop of the helical micromixers deviated exponentially from that of STM. TDHM-FO can be seen to have the highest deviation from STM, and highest values of pressure drop among the three micromixers. In most of the cases, TDHM showed a higher pressure drop than that of TDHM-FO but for other cases, the results were otherwise. STM showed the least pressure drop among all three cases. This is an obvious result because STM is providing the least mixing efficiency as well. Higher values of pressure drop signify high power consumption.

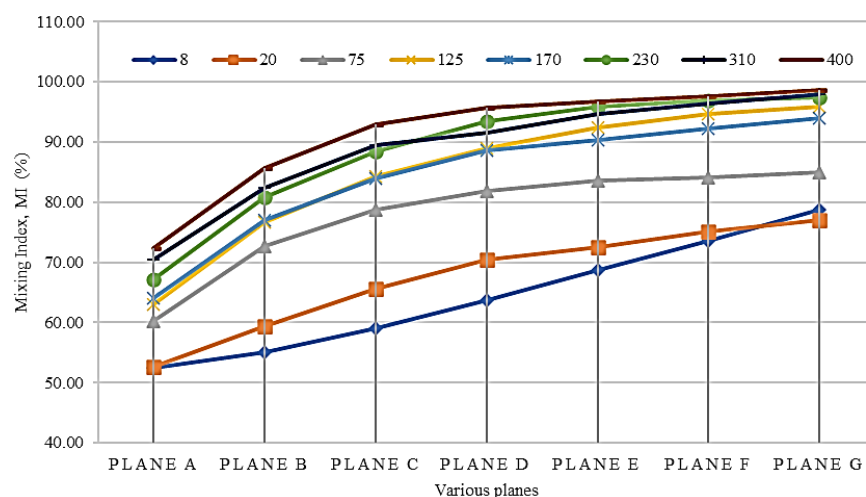


Figure 14. Change in Mixing Index at Different Locations Along the Path of TDHM-FO Microchannel for all Values of Reynolds Number.

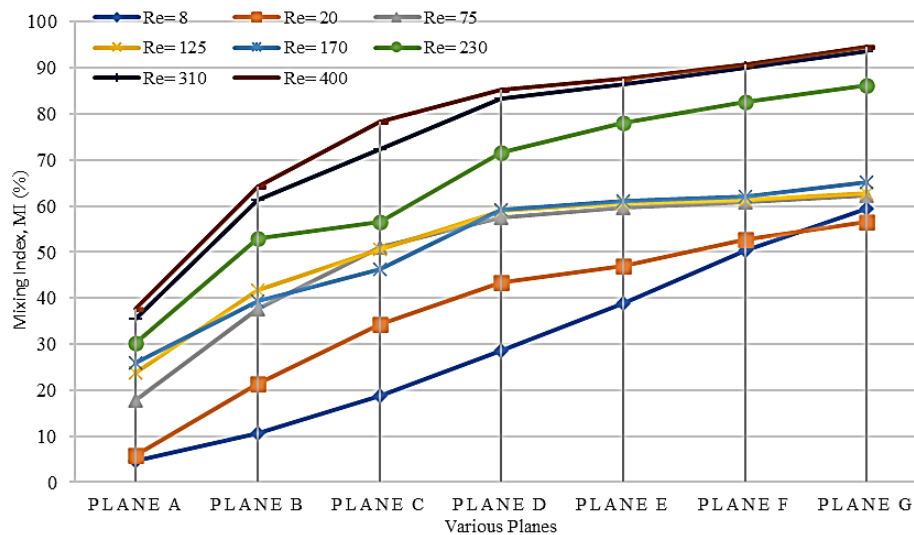


Figure 15. Change in Mixing Index at Different Locations Along the Path of TDHM Microchannel for all Values of Reynolds Number.

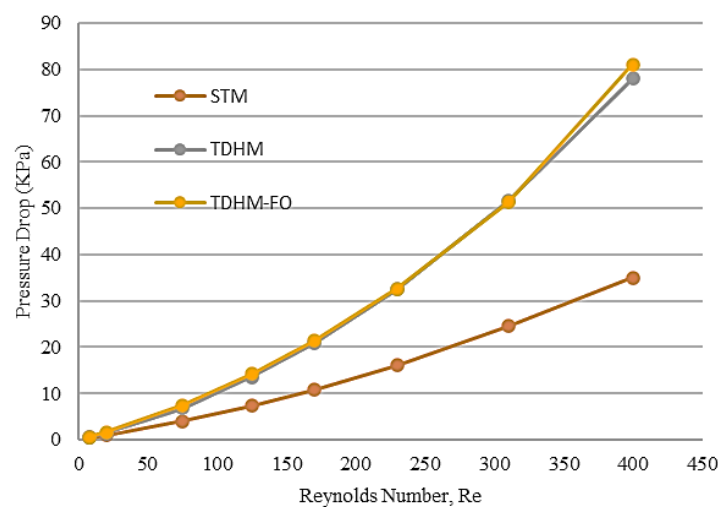


Figure 16. Change in Pressure Drop with Reynolds Number for STM, TDHM, and TDHM-FO.

Ngo *et al.* evaluated the mixing performance of dean flows in a spiral microchannel [35]. Effects of various flow parameters like Reynolds number (Re), Peclet number (Pe), diffusion coefficient (β) and flow rate ratio between two species (α) were studied on mixing efficiency. The analysis was done on a series of Reynolds numbers, ranging from 0.1 to 200. It was observed that mixing efficiency increased with a decrease in Peclet number (Pe) and increased with an increase in the values of Reynolds number. The mixing improved due to the formation of Dean vortices in the curved channels. The maximum mixing efficiency observed was 33.75% at Re 165 when β is 0.5, Pe is 104 and α is 1.0, Whereas the maximum mixing efficiency achieved in the current proposed designs are 95.97 and 88.21% for TDHM (for $Re = 400$) and TDHM-FO (for $Re = 125$) respectively. The reason for this is the presence of high intensity of chaotic advection because of the curved design of micromixer and vortices formation at the intersection of inlets whose axes are not coincident but offset to each other.

CONCLUSIONS

The present study deals with the examination of three micromixers. These micromixers are named STM, TDHM, and TDHM-FO. TDHM-FO has four non-aligned inlets. Computational simulation using ANSYS 20.2 was unitized to perform the analysis. Below are the conclusions drawn from the computationally analysed result:

1. For lower Reynolds number, TDHM-FO performed better than the other three micromixers due to the comparatively larger interface between fluid species that a helical surface provides, and the flow vortices created by the inlet design. This low Reynolds number can be considered up to 75. When compared with STM and TDHM, the mixing index was found to be larger by 80.47 and 20.93% respectively for $Re = 75$. For high values of Reynolds number ($Re \geq 125$), the mixing index value increased from 62.97% at plane A to 88.97% at plane D which corresponds to a 26% increase for $Re = 125$. The significance of this result lies in the fact that for specific cases and applications, the length of the microchannel can also be reduced which ultimately makes the process cost-effective.
2. Similar conclusions can be made in the case of TDHM also. TDHM provided the best results for high values of Reynolds numbers, i.e., for $Re = 310$ and 400 . The mixing index is higher for all the values of Reynolds number when compared to STM because of the formation of secondary flow and centrifugal force imparted due to the 3D curvature structure which introduces chaotic advection. When compared with STM, the increase in mixing index is 54.74, 60.25 and 52.74% for $Re = 8, 125$, and 400 respectively. Other similar conclusions can be made as done in the points above.

Another advantage of these 3D curved micromixers is that they require a shorter length ($1411.71 \mu\text{m}$) compared to STM ($3000 \mu\text{m}$) while still providing better efficiency. These high-performance micro-devices become very helpful whenever high precision is required. For instance, in the production of vaccines and antibody development, in the field of chemical engineering for the study of chemical reaction research. It uses fewer reagents, saves time, is inexpensive and easy to carry. But, due to the higher value of the mixing index, the drop in pressure, between the inlet and outlet of the micromixer, is also having relatively higher values in the case of helical micromixers than that of straight T-micromixer.

Funding and/or Conflicts of Interests/Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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