Vane induced two phase flow mixing
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Abstract
Micromixers are used for mixing of multiphase fluids in microchannels. Passive micromixers help in mixing of fluids by having a designed periphery in their structure. In the current study, a Y micro-channel section of 25 mm length with an inlet diameter of 2 mm is considered. Vane shaped micromixers are placed inside the channel to mix fluids of two different concentrations. The vanes are positioned at specific places inside the channel to enhance mixing in the stratified flow stream. The presence of vanes during the flow induces mixing of the stratified fluids without requiring additional components. The study is carried out using COMSOL Multiphysics. The mixing index increases with increase in the number of vanes and no considerable change in velocity is observed downstream of the last vane. Further, when the thickness of the vane is increased, it is found that the mixing index also increases.

Keywords: Passive Micromixer; Mixing Index; Two Phase Flow; Stratified Flow; Vane

1. Introduction
Over the last several decades, the requirement of devices employing microfluidics has drawn increased attention in various applications. The microfluidic devices are used as biosensors in DNA analysis, bio reactors in the process of chemical synthesis and in MEMS technology for various applications including aerospace propulsion [1] [2][3]. Microfluidics has been progressively used in the chemical and biological industries, because of carrying out experiments in precise and controlled manner along with speedy results in an economic way. Significant advantages of microfluidic devices are low cost, ease of handling and carrying, and safer when handling toxic chemical reactions such as nitration reactions. When compared to macro fluidic devices, chemicals and less quantity of sample is sufficient for analysis [4][5]. Because of low inlet velocity, sample flows in micro channels will be laminar till the end at fixed flow condition. Thus, in such flows, mixing of two fluids having different densities does not happen due to stratification. But for consecutive development of microfluidic devices, controlled mixing is necessary. Various microfluidic mixing techniques were formulated and analyzed by various researchers and one important component of microfluidic devices is the micromixer [1]. A micromixer is a device based on mechanical micro parts used to mix fluids and it is having exclusively created structures which give rise to chaotic advection in flow [6][7] by reducing the length of the fluid path when increasing exposure time between fluid streams in streamline flow.
Microfluidic mixing can be classified as active micro-mixing and passive micro-mixing. Both the mixings have their own unique mixing conceptions, mixing potential, mixing rate, and working conditions. Mixing can be done by micromixer in two steps. One is heterogeneous mixing, where mixing takes place by convection of fluid particles. Next is homogenous mixing, but here it is provoked by molecular diffusion between the vicinity domain. In active micro mixing techniques, mixing efficiency can be enhanced by giving external power such as the electro kinetic force, ultrasonic vibration, and magnetic force which increases the pace of action of mixing.[8][9][10] These active micromixers, on the other hand, are made up of a lot of segments, which leads to more difficulties in manufacturing and also during incorporating with microfluidic systems. A passive micromixer is another type of microfluidic mixing device. It does not require any input power to mix fluids other than its designed configuration and mechanism required to maintain constant fluid flow rate. Because of predominating laminar flow on microfluidics, mixing using passive micromixers relies on several mechanisms such as single mixing mechanism which includes molecular diffusion by increasing the engaging surface and exposure time, vortices, split and recombination, recirculation, transversal flow, or deranged advection between the different fluids flows [11]. Hence, passive micro-mixers have the advantages of consistent operation, ease incorporating with microfluidic systems, and cheap manufacturing as they are easy to fabricate. Their only disadvantage is the high pressure drops associated with fluid movement across a geometrical obstruction. Passive micromixers are divided based on their structural dimensions; two- and three dimensional. Two-dimensional passive micromixers are easier to make using lithography than three-dimensional passive micromixers. Various geometries have been studied in passive mixers. Some common ones use obstacles in the flow path, zig-zag channel [12], deformable baffles [13], O-H structures [14], deformable walls etc. Some aspects that have been deemed in experimental and numerical investigations include parallel lamination, multi lamination, obstacle or convergence-divergence based, curved-channel, and asymmetrical. Though there are various experimental and numerical works on passive micromixers with different shapes and obstacles, there is a need to analyze each broad shape of an obstacle with the other.

Literature survey implies that a micromixer with enhanced mixing index need to be developed. A vane shaped micromixer is designed in the present work where the mixing performance is increased by increasing mixing index along with reduced pressure drop.. Curvature in the vane geometry will help out in increasing the turbulence required for mixing with minimal pressure drop. Here, the overall performance of the micromixer was evaluated with mixing index and pressure drop. Mixing index is a measure of the degree to which fluid flow will promote the dispersion of dissolved solutes or suspended materials in the fluid, leading to homogeneity. It is an indicator of the quality of the mixing process. In the present work, such mixing index of fluids was calculated by finding the variance of concentration of fluids along the cross section of this mini-channel using the equations (1), (2), (3) as stated in [15].

\[
\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X}_i)^2} \tag{1}
\]

\[
\bar{X}_i = \frac{\sum_{i=1}^{N} X_i}{N} \tag{2}
\]
\[ M = 1 - \sqrt{\frac{\sigma^2}{(\sigma_{max})^2}} \]  

(3)

\( \sigma \) represents standard deviation, \( X_i \) denotes normalized colour intensity; \( \bar{X}_i \) represents average colour intensity and \( \sigma_{max} \) is the maximum standard deviation at the inlet. \( M \) is the mixing index.

In the present work, a vane shaped micro mixer is positioned inside a mini channel in which stratified two phase flow occurs. The developed numerical model is analyzed to determine the effect of number of vanes and thickness of vanes on mixing index and pressure drop.

2. Numerical Method

In the last decade, there have been extensive studies of mixing in the Y-mini channel, which is one of the simplest models available. The total length of the mini channel is 30 mm and has two inlets which are 105° apart. The rectangular section is 24 mm in length and 2 mm in diameter, with curved vanes to enhance mixing in the flow stream that creates vortices. Water and curcumin drug loaded suspension are being injected separately through different inlets at the same velocity, each of which has a cross sectional area of 2.25 mm² [16]. The concentrations of distilled water and curcumin-loaded water were both maintained at 0 mol/m³ and 1000 mol/m³, respectively. The vanes are located at the initial region of the rectangular section because in many cases, stratified flow exists at the entry region itself [17]. Depending on the number, size, and spacing of the vanes, the mixing time and length varies. In the present study, an optimal value for the size, number, and spacing of the vane is sought with the goal of enhancing the mixing and minimizing pressure drop.

The turbulence created by one vane is detrimental to the other if the vane spacings are too small. The spacing between the vanes is carefully chosen so that the circulation created by one vane doesn’t overlap or affect that created by the other vanes. Within the rectangular section, the vanes are maintained at 12.5%, 29.1%, 33.3%, 50%, and 54.166% of its length from the inlet.

2.1 Governing equations

In the present study, all proposed designs were modeled using COMSOL 5.2a to evaluate the performance of the micromixer. COMSOL Multiphysics is a finite element method (FEM) based solver. To carry out the mixing simulation for two-dimensional models, laminar flow and transport of diluted species modules have been implemented. The physics behind the fluid flow is governed by the equations (4) and (5) as mentioned below. The two fluids are allowed to separately flow through the two inlets of Y-microchannel with velocity of 0.00007m/s.

\[ \rho (\mathbf{u} \cdot \nabla) = -\nabla [p + (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \]  

(4)

Continuity equation:

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

(5)

Transport of diluted species:

\[ \frac{\partial C}{\partial t} = \nabla (D \nabla C - u C) \]  

(6)
In this equation, D denotes the diffusivity of the medium, C specifies the concentration of the fluid and u denotes the velocity of the fluid.

Since the flow is solved in 2D rectangular coordinates, the differential and Laplacian operator is written as.

\[
(\nabla) = \frac{\partial}{\partial x} \frac{\partial}{\partial y}
\]  

(6a)

The value of D can be presumed from equation (7).

\[
D = \frac{k_b T_o}{3\pi \eta d_h}
\]  

(7)

\(k_b\) denotes the Boltzmann constant, \(T_o\) denotes the ambient temperature (25°C), \(d_h\) is the hydrodynamic diameter of the nanoparticle (200 nm), and \(\eta\) denotes the viscosity of the fluid.

**Figure 1**: Mesh of Y-microchannel

The model is validated by comparing the simulation results with Y channel containing cylindrical obstacles [16]. In paper [16] Y channel with the interacting fluids being water and a nanofluid with two different concentrations; 0 mol/m\(^3\) and 1000 mol/m\(^3\) were used. As a result of cylindrical obstacles being introduced into the flow stream, the flow separates at the top and bottom surface of the obstacle, resulting in chaotic flow. Two fluids are mixed, and this mixing was analyzed through the use of surface plots of concentrations. The concentration plot was derived, which is shown in figure 2b, along with a calculation of the percentage of increase in pressure drop. There was a 113% of increase in pressure drop observed, which is similar to the results obtained in [16]. Thus, the model for the Y channel is validated, and the numerical results for vane as passive mixers are compared to the simulation results for the Y channel with cylindrical obstacles. The dimensions of Y channel are altered in the model and vanes are introduced to provide mixing with less pressure drop. The number of vanes and their thickness are varied to obtain the optimum Mixing Index. For each vane, thickness is changed and is in the range of 0.025 to 0.46 mm.
3. Results and Discussion

A Y-shaped smooth circular mini channel is designed with an internal diameter of 2mm. Due to the low Reynolds number and absence of obstacle makes that the flow through mini channel is laminar, and mixing occurs only by diffusion. The laminar flow is disrupted and mixing is improved by creating chaotic advections.

A stratified flow is created using two fluids (curcumin drug loaded suspension and water) with specified inlet conditions and geometry of the Y-mini channel. The vanes are placed inside the mini channel at specific locations which obstruct the flow and act as a passive micromixer. The vanes are placed in the frontal region of the rectangular section because stratified flow is observed in the initial region itself. The presence of these obstructions causes flow separation at the obstacle interface which leads to chaotic motion that gives rise to mixing of two fluids. Numerical simulations for various mixed sets of parameters are carried out and the results are presented in the following sections.

3.1 Thin Vane Analysis

Initially a single vane with thickness of 0.025mm is placed at 12.5% length of the rectangular section from inlet. A numerical study is performed in the Y channel and the mixing index is found downstream of the microchannel. The concentration plot obtained for increasing the number of thin vanes is illustrated in figure 3.
3.2 Moderately Thick Vane Analysis

In the flow field, mixing is enhanced by the separation of flow at the interface when vanes are introduced, as shown in figure 4. The mixing increases with the increase in the number of vanes from one to five, thereby increasing the mixing index. The study extends the analysis of mini channel mixing to examine the influence of the thickness of vanes. Vane thickness is used as a parameter to gauge its effect when mixing. Vanes that are moderately thick have a thickness of 0.3mm, and the mixing index is measured by varying the number of vanes from one up to five. It was found that increasing the thickness of the vane enhanced mixing as shown in figure (4) irrespective of the number of obstacles and it was due to the separation of flow in the flow stream which induced chaotic mixing. It has been demonstrated that both an increase in the number of vanes as well as its thickness affect the mixing index.

Later, the study was extended to a much higher vane thickness in order to determine its efficacy.
Figure 4: Concentration plot for moderate thick vanes as passive micromixers

3.3 Maximum Thick Vane Analysis
Figure 4 clearly shows that the thickness of obstacles has a significant impact on mixing. As the vane thickness expands, a greater obstruction in the flow stream is generated, resulting in a higher mixing index.

Figure 5: Concentration plot for maximum thick vanes as passive micromixer
A plot of the mixing index with vanes number and thickness can be found in figure 6. It has been determined that higher mixing index values are observed as the vane thickness and number of vanes are increased. Thus a larger mixing index is achieved for more vanes kept at maximum thickness value when compared to other vane configurations.

**Table 1:** Comparison between Vane and Cylindrical Obstacles

| Passive micromixers     | Mixing Index (mol/m³) | Pressure Drop (Pa) |
|-------------------------|-----------------------|--------------------|
| Cylindrical obstacles   | 496.35                | 0.086              |
| Vanes                   | 502.00                | 0.028              |

As part of the validation study, we compare the cylindrical obstructions to five maximum thick vanes. Analyzing the data, implies that the pressure drop is lesser for five vanes with maximum thickness, compared to cylindrical obstacles in the flow field as shown in table (1). Hence it can be inferred that vanes as obstacles serve mixing more effectively with less pressure drop as compared to cylindrical obstructions.

### 4. Conclusion

The present work focuses on the numerical analysis of micromixers with vanes as obstacles. These passive micromixers are added to enhance mixing efficiency by creating chaotic advections. Introducing vanes enhances the mixing index along with variations in pressure
drop. The effect of vane parameters, i.e. vane numbers is studied and the maximum mixing index is observed when five vanes are placed as obstacles. Further the effect of vane thickness is studied and maximum mixing index is obtained for highly thick vanes as compared to moderately thick and thin vanes. Furthermore, increasing the number of vanes can also result in a higher pressure drop. When compared to cylindrical obstacles the pressure drop is lower for vane shaped micromixers. Hence vanes serve as a better passive micromixer by the way of increasing mixing index with lesser pressure drop is concluded in this analysis.

5. References

[1] Meijer HE, Singh MK, Kang TG, Den Toonder JM, Anderson PD. Passive and active mixing in microfluidic devices. In Macromolecular symposia 2009 May (Vol. 279, No. 1, pp. 201-209). Weinheim: WILEY-VCH Verlag.

[2] Bayareh M, Ashani MN, Usefian A. Active and passive micromixers: A comprehensive review. Chemical Engineering and Processing-Process Intensification. 2020 Jan 1;147:107771.

[3] Sia SK, Whitesides GM. Microfluidic devices fabricated in poly (dimethylsiloxane) for biological studies. Electrophoresis. 2003 Nov;24(21):3563-76.

[4] Nguyen NT, Wu Z. Micromixers—a review. Journal of micromechanics and microengineering. 2004 Dec 8;15(2):R1.

[5] Kumar V, Parashivou M, Nigam KD. Single-phase fluid flow and mixing in microchannels. Chemical Engineering Science. 2011 Apr 1;66(7):1329-73.

[6] Vijayanandh V, Pradeep A, Suneesh PV, Babu TS. Design and simulation of passive micromixers with ridges for enhanced efficiency. In IOP Conference Series: Materials Science and Engineering 2019 Nov 1 (Vol. 577, No. 1, p. 012106). IOP Publishing.

[7] Huang MZ, Yang RJ, Tai CH, Tsai CH, Fu LM. Application of electrokinetic instability flow for enhanced micromixing in cross-shaped microchannel. Biomedical microdevices. 2006 Dec;8(4):309-15.

[8] Yang Z, Goto H, Matsumoto M, Maeda R. Active micromixer for microfluidic systems using lead-zirconate-titanate (PZT)-generated ultrasonic vibration. ELECTROPHORESIS: An International Journal. 2000 Jan 1;21(1):116-9.

[9] Lu LH, Ryu KS, Liu C. A magnetic microstirrer and array for microfluidic mixing. Journal of microelectromechanical systems. 2002 Dec 10;11(5):462-9.

[10] Asfer M, Prasad Prajapati A, Kumar A, Kumar Panigrahi P. Visualization and motion of curcumin loaded iron oxide nanoparticles during magnetic drug targeting. Journal of Nanotechnology in Engineering and Medicine. 2015 Feb 1;6(1):011004.

[11] Li D, editor. Encyclopedia of microfluidics and nanofluidics. Springer Science & Business Media; 2008 Aug 6.

[12] Mengeaud V, Josserand J, Girault HH. Mixing processes in a zigzag microchannel: finite element simulations and optical study. Analytical chemistry. 2002 Aug 15;74(16):4279-86.

[13] Madhumitha R, Arunkumar S, Karthikeyan KK, Krishnah S, Ravichandran V, Venkatesan M. Computational modeling and analysis of fluid structure interaction in micromixers with deformable baffle. International Journal of Chemical Reactor Engineering. 2017 Jun 1;15(3).

[14] Hong CC, Choi JW, Ahn CH. A novel in-plane passive microfluidic mixer with modified Tesla structures. Lab on a Chip. 2004;4(2):109-13.

[15] Cheri MS, Latifi H, Moghaddam MS, Shahraei H. Simulation and experimental investigation of planar micromixers with short-mixing-length. Chemical engineering journal. 2013 Dec 1;234:247-55.

[16] Seetharaman S, Madhumitha R, Venkatesan M, Balakrishnan AR. Layout Optimization Of Passive Micro Mixers With Cylindrical Obstacles. In International Heat Transfer Conference Digital Library 2018. Begel House Inc..

[17] Bhagat AA, Papautsky I. Enhancing particle dispersion in a passive planar micromixer using rectangular obstacles. Journal of micromechanics and microengineering. 2008 Jul 4;18(8):085005.