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Simulation of Box-shaped Micromixer with the Variations in Size

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ABSTRACT: In this paper, we have simulated a novel design of Box shaped micromixer. This planar micromixer provides mixing of the fluids with low Reynolds number. Box micromixer is based on converge-diverge mechanism. The numerical simulation of passive Box shaped micromixers was performed with Reynolds number lying in the range between 0.01and 60. The range of flow rates at the inlets has been kept between 0.0135 percent and 81 percent ml/s. The pumping power consumption for each flow rate has also been calculated. The simulation has been carried out by using the software tool COMSOL Multiphysics. The box sizes were varied to find out the acceptable design to attain high mixing performance with low pressure at shortest channel length. It has been observed that the Box micromixer of size 200 µm gave best performance at low Reynolds number and minimum pressure drop.

KEYWORDS: Passive micromixer, micro fluidics, simulation, COMSOL.

I. INTRODUCTION

Micromixing has been studied for last two decades for different fluids. Micromixing is a process through which homogeneity of concentration of two or more fluids is achieved. This is executed through the basic component of microfluidics called as micromixer [1]. Microfluidics has many applications including medical [2] and chemical, etc. and micromixer plays a significant role in many of these. They can be integrated along with the other components such as microvalve and micropump. Micromixer has various applications such as cell separation, chemical synthesis, Micro-Total Analysis (µ-TAS) and Lab-on-chip (LOC), drug delivery, and many more. Micromixer is important component for the functioning of microfluidic systems or devices for various applications.

Micromixers are classified into two types: active and passive. Active micromixer consists of actuators, which require external source of energy. Its fabrication process is complex, difficult to operate and integrate and that leads to high expenses. Because of these reasons passive micromixer, which does not need an external source of energy, is the best option. Unlike the active micromixer, passive micromixers are easy to fabricate, need no external energy, and are easy to operate and integrate. Additionally the absence of actuators makes passive micromixer more preferable.

II. LITERATURE SURVEY

Various designs based on converge-diverge method have been studied to enhance mixing in passive chaotic micromixer. Self-circulating micromixer has been investigated where fluids flow in circular mixing chamber at low Reynolds numbers. It was observed that at high Reynolds number the mixing is effective and mixing performance improves with increase in angle and decrease in width/depth ratio [3]. The sigma micromixer has been designed to study the effects of the laminar velocity profile and variations on the mixing phenomena at the reduced scale [4] and increase in velocity at the interface of co-flowing fluids results in increased diffusive mass flux across their interface [5]. Arshad Afzal and Kwang-Yong Kim, [2015] explored the same sigma design to found that mixing performance increases with higher (major-axis of ellipse/channel width) values and lower values of (minor-axis of ellipse/lag between repeating side walls) and (constriction width/channel width). Simulations were performed on planar micromixer with two different chambers a) hexagonal and b) round corner rectangle with combination of four different obstacles within it. The micromixer with round corner rectangle chamber along with vertical-straight obstacle gives maximum mixing efficiency at low Reynolds number [7]. Numerical simulation assessed an effect of depth variations on wing-shaped micromixer by using COMSOL software tool [8] and variations in wing size gave better results when the wing size is large [9]. Rei-Tang T. and Chih-Yang W., [2012] fabricated curved-straight-curved (CSC) micromixer, which provide mixing in three streams and two inlets. The comparative study was performed on CSC with full stream, internal wall injection and external side-wall injection; from amongst them, CSC with full three streams was found to be the best.

In the present work, we have investigated the Box-shaped micromixer to enhance the mixing of miscible Newtonian fluids. The converging-diverging method assists in mixing at low Reynolds number at a short distance. The simulation has been performed to calculate mixing index with less pressure drop at different flow rates with different box sizes.

In section II, specifications of dimensions of proposed micromixers are presented. In section (III), we discuss the equations used for simulation. In section (IV), shows the characteristics of Box micromixers whereas in the last section, the results of intensive numerical simulations are discussed.

III. GEOMETRY OF THE BOX SHAPED MICROMIXER

The Box shaped micromixers examined by us have different length viz. 200 µm, 300 µm, and 400 µm. These micromixers have two inlets and the width of both the inlets is 300µm and length is 1300 µm. The depth of inlets and that of the micromixer is 150 µm. For our simulation studies, we have considered different widths of the Boxes viz. 300 µm, 250 µm, 200 µm, 150 µm, and 100 µm but have kept the Box length constant. We have also created micromixing units which comprise of several box micromixers of different widths. The structure of these units is shown in Fig. 1. The overall dimensions of these units vary with the length of box micromixers comprising it. For instance, the units made by using box micromixers of width 200, 300, and 400 are 1600, 2400, and 3200 µm long respectively. The entrance length is taken as half of the length of the Box in each micromixer. Due to the variations in the unit size, the total length of each micromixer would become 11600 µm, 12450 µm, and 13300 µm. The detail structure along with the dimensions of Box micromixer of width size 300 µm are illustrated in Fig 1. In further discussions, we will address these designs as Box-200, Box-300, and Box-400 to avoid the long name.

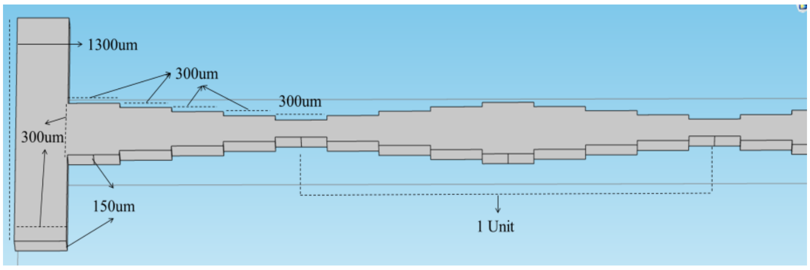

Fig. 1. Box shaped micromixer of with 300 µm showing the full unit.

All the three variations of the box micromixer are displayed in the Fig 2 with the count of units present in all three micromixers. Box-200 (Fig. 2a) consists of six complete units plus a half unit at the start of the main mixing channels and another half at the end of the channel. Box-300 (Fig. 2b) consists of four complete units plus a half at the start and a half at the end of the main channel. Box-400 (Fig. 2c) consists of three complete units plus a half at the start and another half at the end of the main mixing microchannel.

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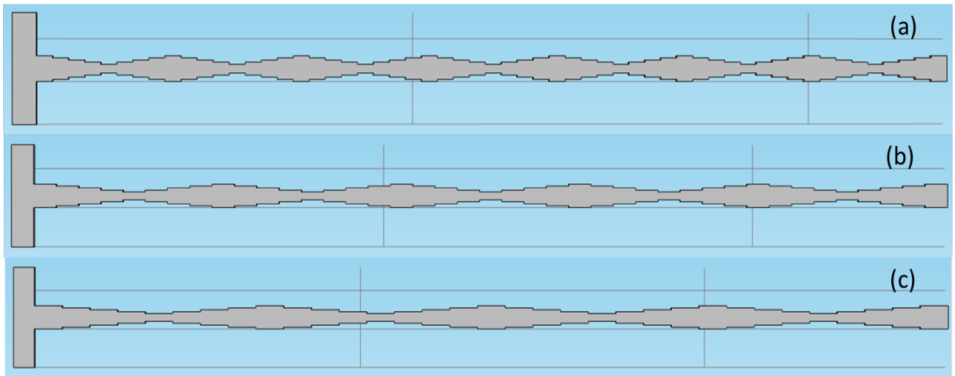

Fig. 2. Box micromixer of width (a) 200 µm consist of 6 full units and 2 half units; (b) 300 µm consist of 4 full units and 2 half units; (c) 400 µm consist of 3 full units and 2 half units.

IV. GOVERNING EQUATIONS

Reynolds number is a dimensionless parameter, which is defined as the ratio of inertial force to viscous force. It is denoted by Re. When the value of Re is < 2000, the flow is laminar where viscous effects dominate inertial force and thus the fluid motion is smooth and constant. When the value of Re is > 2000, the flow will no longer remains laminar; it becomes turbulent. Inertial forces are dominated over the viscous effects in turbulent flow. Because of this, the fluid exhibits motion that is random in both space and time, and convection causes mass transport in all directions [11]. The Reynolds number is defined as:

$$Re = \frac{\rho v D_H}{\mu} \tag{1}$$

where ρ is density, *v* is velocity, µ is dynamic viscosity of the fluid, and D_H is the hydraulic diameter of the channel.

We performed numerical simulation for the three dimensional laminar flow which is considered incompressible and time independent. The governing equations used are Navier Stokes equation "(2)," continuity equation "(3)," and convection diffusion "(4)," in order to acquire the concentration, pressure of the two liquids and their mixing index. These are as follows:

$$\rho\left[\frac{\partial u}{\partial t}(u.\nabla)u\right] = -\nabla p + \mu\nabla^2 u \tag{2}$$

$$\nabla u = 0 \tag{3}$$

$$\frac{\partial c}{\partial t} = D\nabla^2 c - u \cdot \nabla c \tag{4}$$

where ρ is the density, u is the velocity, p is the fluid pressure, µ is the fluid viscosity, c is the species concentration and D is the diffusion coefficient of the species.

Mixing Index is a measure of the effectiveness of mixing process. It is denoted by M. The mixing index range is 0 to 1, where 0 stands for no mixing at all and 1 stands for complete mixing.

$$M = 1 - \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{c_i-\bar{c}}{\bar{c}}\right)^2} \tag{5}$$

where M is the mixing index, N is the total points at the cross-sectional plane, c_i is the molar fraction values at the sample point i and $\bar{c}$ is the mean molar fraction value in the case of complete mixing.

V. EXPERIMENTAL WORK

For the simulation of Box-shaped micromixers, the COMSOL software tool has been used [12 and 13]. The values used for various characteristics of water are density as 1000 kg m^{-3}, dynamic viscosity as 10^{-3} kg/m s and diffusion coefficient as 1.2×10^{-9} m^2/s. The fluid is Newtonian and flow was assumed to be laminar. The temperature was kept constant at 298.15 K. The microchannels consist of two inlets and an outlet. The concentration at one inlet is 1 mol/m^3 and at the other inlet, the concentration is 0 mol/m^3. A wide range of Reynolds number viz. 0.01, 0.1, 1, 2, 3,…, 10, 20, 30,…, 60 has been considered. The flow rates at the inlets range between 0.0135% and 81% of ml/s. The fluid flow has been assumed as steady, with no-slip boundary condition at the wall. The pressure at the outlet was fixed at 0 Pa. P2+P1 is the element order for fluid flow interface and selected for the discretization of the fluids. P2+P1 is second order elements for the velocity and linear elements for the pressure, which gives better solution for low velocities.

Mesh divides the computational domain structure into small regions called elements. We have defined a 3D discretization mesh, because of the limited memory. Free triangular meshes are generated with different sizes in separate subdomain portions. The main channel mesh is generated with fine mesh. The constricted areas consist of extra fine mesh. And the remaining of the geometry consists of free tetrahedrons as shown in Fig. 3.

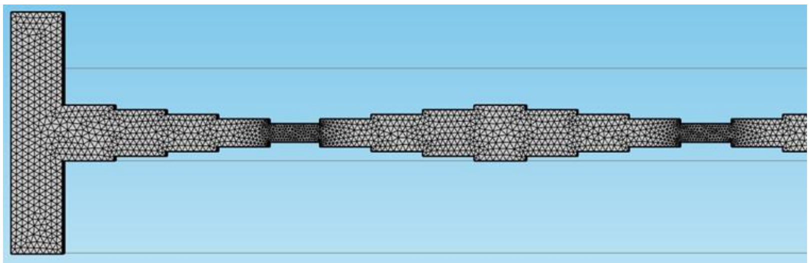

Fig.3. Meshing of the Box micromixer of 300 µm

VI. RESULT AND DISCUSSION

The proposed design of Box-shaped micromixer is based on chaotic advection type of converge-diverge mechanism. It has been created with different size of boxes which is already discussed in section III. Due to the variations in the size of the boxes, the numbers of constrictions present in the microchannel vary. This can be seen in Fig. 2. Box-400 has large dimensions and that is why the numbers of constrictions in it are only four. As the size of the box decreases, the numbers of constrictions increases. Therefore, the Box-300 and Box-200 has five and seven constrictions respectively.

When two fluids enter the microchannel through separate inlets and with different concentrations, their flow get turned by fan angle of 90º and enter the main channel. The two streams get constricted, because of the constant decrease in the width of the channel. When they reach the most constricted area, their velocity becomes very high. First of all, the streams get diffused and again the flow diverges as the width of the channel increases. Likewise, the streams get converged and diverged at every constriction, which promote mixing of the fluids and delivers a mixture of homogenous concentration at the outlet.

The concentrations gradient at the outlet of all the three box micromixers has been calculated and these can be viewed in Fig. 4a. It has been found that the concentrations gradient at the outlet of Box-200 and Box-300 are almost similar. However, the curves of their variations intersect at around Reynolds no. 35. Box-200 showed better results than the other two at the outlet as it has maximum constrictions. The concentration obtained from Box-400 showed poorer mixing performance as it has fewer constrictions within the micromixer. Box-400 showed constant decrease in the mixing performance with respect to Reynolds number.

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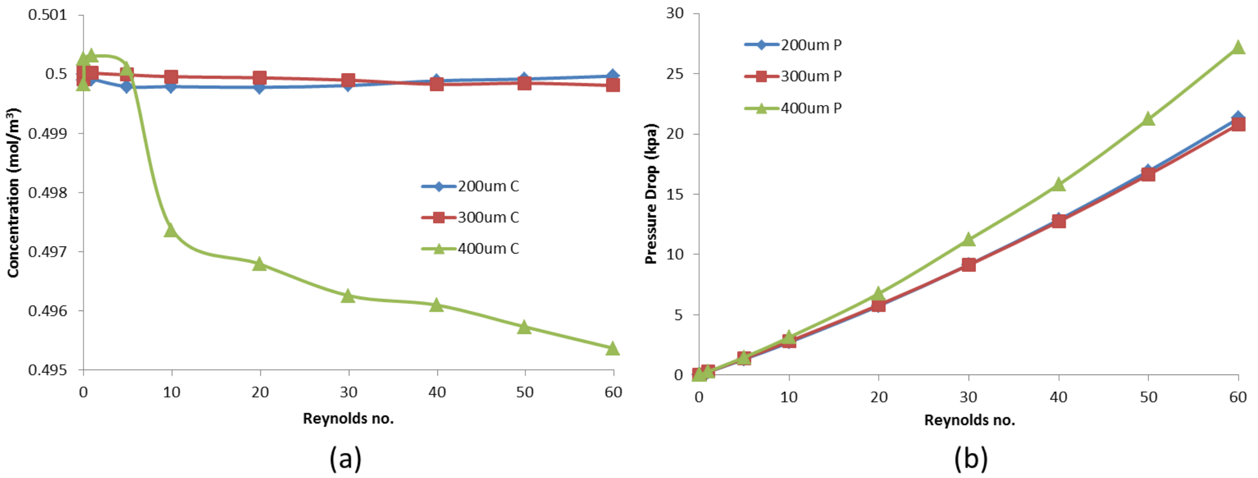

Fig. 4. a) Concentrations at the outlet of Box micromixer 200µm, 300µm, 400µm; b)Pressure drop at the outlet of Box micromixer 200µm, 300µm, 400µm.

The performance of pressure drop is similar that of the concentration. The pressure drop is large in Box-400 than in Box-300 and Box-200. The variation of pressure drop with increasing Reynolds number for Box-200 and Box-300 are almost similar as revealed in Fig. 4b. The velocity always remains high at the middle of the microchannel and lower near the walls.

Fig. 5a shows the variation of the mixing efficiency of the fluids flowing through Box-400 micromixers with increasing Reynolds number. For Box-400 micromixer, the mixing index drops quickly with increasing Reynolds number till mixing index reaches to 90% at Reynolds no. 30. Then it rises very slowly to 91% at Reynolds no. 40. Box-300 offers 100 % mixing at very low Reynolds number. Its performance decreases and remains constant from Reynolds no. 1 to 40 providing 97% mixing indices with trivial fluctuation at Reynolds no. 5. At Reynolds no. 50, the performance increases to 98% and remain constant till Reynolds no. 60. Although, mixing index is same for Reynolds no. 50 and 60, the associated drop in pressure is for them is different. It is 16.63 kPa and 20.80 kPa respectively. Box-200 micromixer exhibits a performance which is quite akin that of Box-300, but its mixing index has no fluctuations and it goes on increasing till Reynolds number reaches 40. Thereafter its performance remains unchanged till Reynolds number becomes 60. The maximum mixing of 98% is attained at Reynolds number 40 and the associated pressure drop is 12.88 kPa.

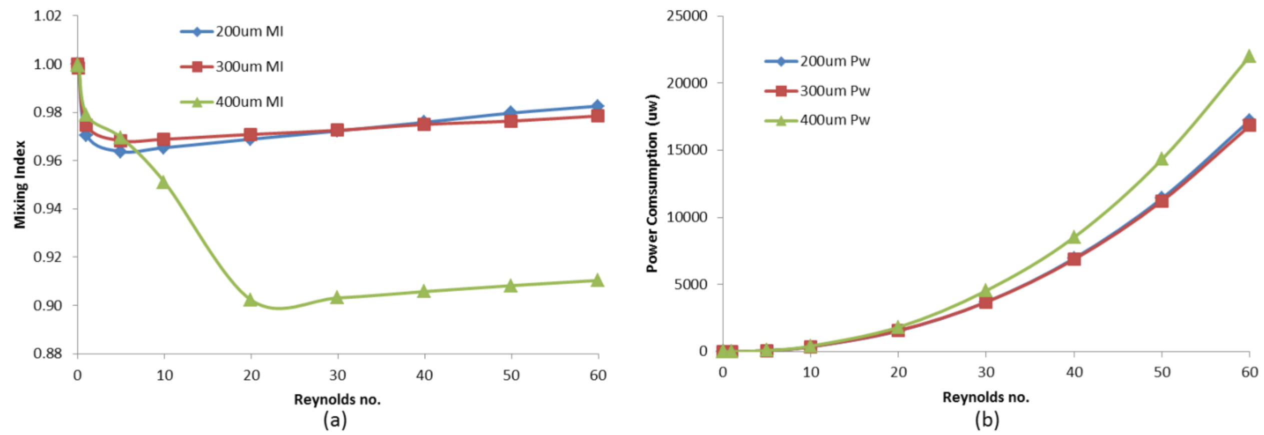

Fig. 5. a) Mixing Index produced by Box micromixers of width 200µm, 300µm, 400µm; b) Power consumption of Box micromixer 200µm, 300µm, 400µm

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The pumping power is the product of the pressure and the volumetric flow rate. For Box-400, 22024.71 µw/min pumping power is required to attain maximum mixing whereas Box-300 requires a pumping power of 11228.62 µw/min. Box-200 required 6956.82 µw/min pumping power to achieve maximum mixing, depicted in Fig. 5b.

VII. CONCLUSION

We have investigated the mixing efficiency, pressure drop and power consumption of the proposed model. In our designs, the converge-diverge based Box micromixers helps to intermix the fluids to achieve a state of uniform concentration with minimum pressure drop at low Reynolds number as well as minimum required power consumption. Among the three different Box micromixers viz. Box-400, Box-300, and Box-200; the Box-200 gave best performance. The maximum mixing index attained is 98% at Reynolds number 40 and a corresponding pressure drop of 12.88 kPa and the required pumping power is 6956.82 µw/min. The Box-200 consists of maximum constrictions among others. We have observed that mixing index depends on number of the constrictions present in the flow. The smaller the size of box, better the mixing efficiency.

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BIOGRAPHY

Arshiya Anjum Khan received the M.Sc. degree in Computer Science from Department of C.S. and I.T., Dr. Babasaheb Ambedkar Marathwada University, in 2007. From 2007 to 2012, she was lecturer. She is currently pursuing the Ph.D. degree in Computer Science at Department of Computer Science and Information Technology, Dr. Babasaheb Ambedkar Marathwada University, Aurangabad (M.S.) India. Her research interest includes MEMS, BioMEMS, Microfluidics and Drug delivery devices.

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