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Numerical Analysis of Fluid Mixing in Three Split and Recombine Micromixers at Different Inlets Flow Rate Ratio

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Abstract **–**Numerical simulation were carried out to study the mixing of miscible liquid at different inlets flow rate ratio (1 to 3) within two existing Chain mixer, Tear-drop mixer and one new "C-H" mixer. The mixing performances of these three split and recombine (SAR) micromixers were predicted by a preliminary numerical analysis of the flow patterns inside the channel in terms of the segregation or distribution of path lines. Afterward, the efficiency and the pressure drop were investigated numerically, taking into account species transport. All numerical calculations were computed at a wide range of Reynolds number from 1 to 100. Among the presented three micromixers, the Tear-drop provides fairly good efficiency except in the middle range of Re numbers but has high-pressure drop. In addition, inlets flow rate ratio has a significant influence on efficiency; especially at the Re number range of 10 to 50. The Chain mixer presents relatively low mixing efficiency at low and middle range of Re numbers ($5 \leq Re \leq 50$) but has reasonable pressure drop. Furthermore, the Chain mixer shows almost no dependence on inlets flow rate ratio. Whereas, the C-H mixer poses excellent mixing efficiency (more than 93%) for all range of Re numbers and on top of that efficiency has slight dependency on inlets flow rate ratio. In addition, the C-H mixer shows respectively about three and two times lower pressure drop than the Tear-drop and the Chain mixers.

Keywords**:** CFD, Micromixing, Passive micromixer, SAR

1. Introduction

Development of efficient micromixers and understanding the mechanism of mixing fluid samples has become a focus of research in the area of micro fluidics (Ansari et al., 2010). Numerous mixers are extensively used in various homogenization processes in industrial operation like, e.g. polymer blending, chemical reaction, food processing, heat transfer, and in cosmetic and pharmaceutics, but also in waste-water treatment (Meijer et al., 2012).

In principle, the mixing of two or more different fluids depends on convection and diffusion (Liu et al., 2013). At micro scale, molecular diffusion becomes dominant while advection components are limited in case of simple mixer under the low Reynolds number. Mixing relay on species diffusion normally needs long time and long channel length (Zhang et al., 2012). To obtain efficient mixing within short residence times, (i) the contact area between regions of higher and lower species concentrations has to be increased (Bothe et al., 2008) and (ii) the fluids has to be repeatedly stretch, compress, split and recombine, which will yield multiple lamination of fluid. In case of high Re number, it is certainly possible to get good mixing performance of micromixer but at a high cost in terms of large pressure drop. Therefore, it is important to design efficient mixer to effectively simulate the flow in microchannel for low as well as high Re numbers.

Micromixers are generally divided into two categories, active and passive (Capretto et al., 2011). The active micromixers require external actuation elements, such as periodic variation of pumping, electrokinetic instability, acoustically induced vibration, electrowetting induced merging of droplets, magneto-hydrodynamic action, small impellers, piezoelectrically vibrating membrane or integrated micro valves (Asgar et al., 2008). In contrast, passive mixers use the flow energy to create multi-lamellae structures, which are stretched and recombined to promote mixing by diffusion (Falk et al. 2010).

Static mixers have been intensively studied in the last two decades not only due to their excellent performance in the field of mixing and two-phase dispersion but also in their ability to redesign a discontinuous process into a continuous process. Most of the studies in the recent past were focused on numerical simulation and experiment measurements of pressure drop, heat transfer, mass transfer and mixing of same or different fluid samples. All these previous numerical or experimental works were done using same inlets flow rate and according to our knowledge, no work has done experimentally or numerically at different inlets flow rate ratio.

In present study two existing split and recombine (SAR) mixers namely, Chain, Tear-drop and a new SAR mixer "C-H" were investigated numerically for Re numbers range of $1 \le Re \le 100$. The large area-to-volume ratio of these mixers gives prospect of better yield and selectivity than conventional designs. In addition to that, these mixers provide less mixing time due to their microstructure. The influence of different inlets flow ratio on mixing and pressure drop in case of water-water mixing at diffusion constant of 1×10^{-9} m^2/s was studied numerically using ANSYS Fluent 15 software. Firstly, the simulation was carried out for different inlets flow rate ratio (1 to 3) to investigate the distribution of path lines of fluid, mixing efficiency and pressure drop dependence on Re numbers. Inlets flow rate ratio is calculated considering the velocity rate of input 1 and input 2 of the micromixer. For example, in case of inlets flow ratio 3, inlet 1 velocity/inlet 2 velocity = 3. Secondly, a comparative analysis of mixing efficiency and pressure drop of Chain, Tear-drop and C-H mixers was performed to predict the most promising prototype for industrial applications.

2. Micromixer Design

In present study, three micromixers based on split and recombine principle with different geometrical configuration were designed and analyze to compute the pressure drop and mixing efficiency. A 3D passive Chain micromixer concept was presented by Viktorov et al. (2013); the basic idea and design of a Tear-drop mixer was presented in (Chen et al., 2009). A slightly modified version of the Tear-drop micromixer consisting of plate symmetrical modules (PSM) was designed and structural detail of the Tear-drop mixer was presented by Nimafar et al. (2012a). The detailed geometrical configuration of the Chain and the Tear-drop mixers is shown in figure 1.

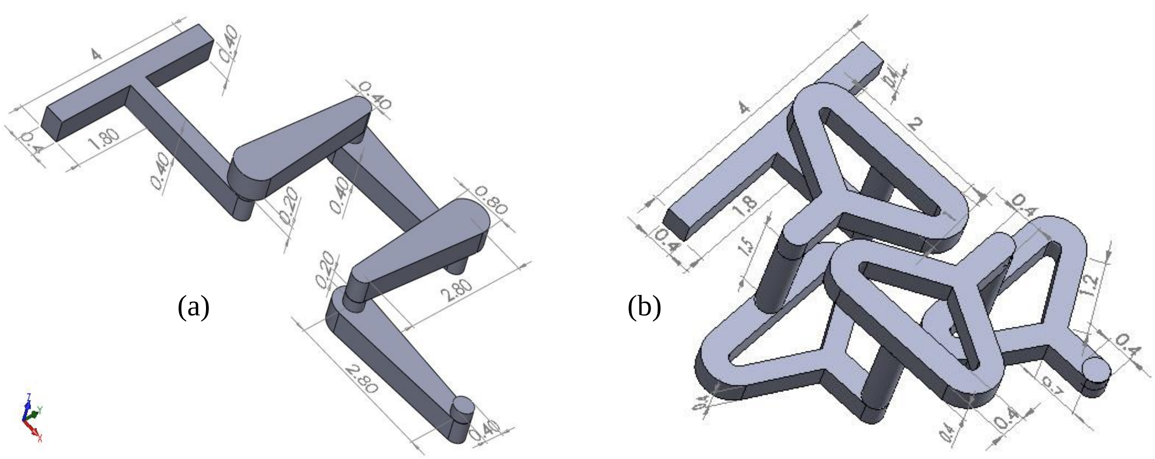


Fig. 1. Design of (a) Chain and (b) Tear-drop micromixer (all dimensions are in mm)

A new SAR micromixer was designed on the fundamental knowledge of a Chain mixer and a H mixer (Nimafar et al., 2012b). It is in fact, a combination of Chain and H mixers. The main working principle of Chain module is to make 90° rotation of a flow, folding the stream and then split and recombine the flow to enhance the mixing. On the other hand, H-shape segment makes it possible to move part of the flow near the wall, in the central zone of the channel along the axial direction and vice versa. Thus, both Chain and H modules contribute to improve the mixing efficiency.

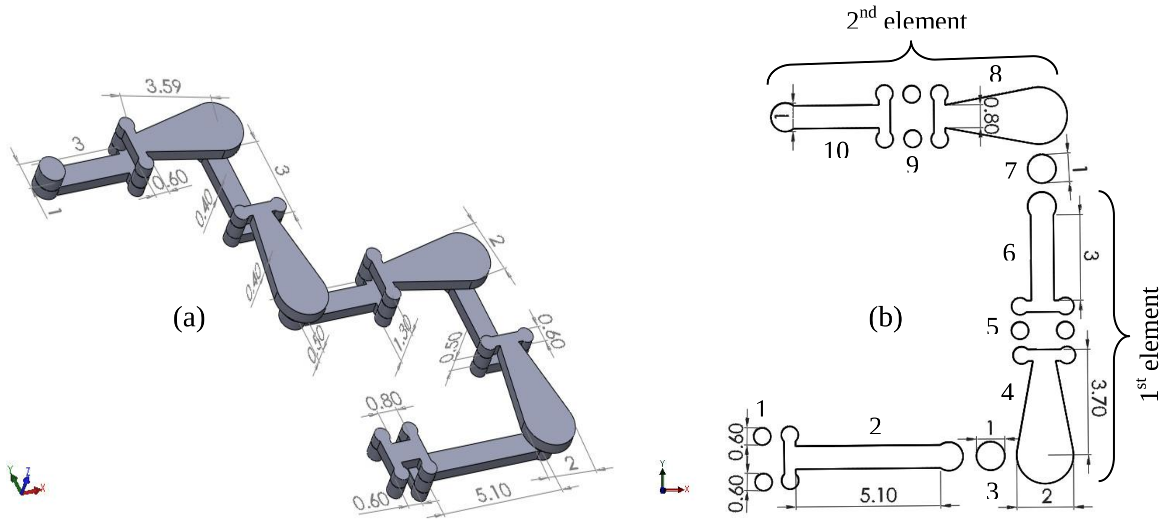


Fig. 2. Design of 3D C-H micromixer (all dimensions are in mm)

Figure 2(a) illustrates the three dimensional geometry of C-H micromixer. The mixer starts with two circular inputs of 0.6 mm in diameter connected with two vertical cylinder of 0.5 mm long along -Z direction as shown in figure 2(b) (segments 1). A rectangular channel of 5.10 mm in length and 0.8 mm in width is linked with a semicircle of 1 mm in diameter (segment 2) that coupled with a circular cylinder (segment 3) of diameter 0.1 mm extended by 0.5 mm (+Z direction). The circular connector passes the flow to the first Chain module that is 0.4 mm in breath (segment 4). In addition, the starting and the end dimension of the Chain module is respectively, 2 mm and 0.8 mm. This characteristic geometry causes the splitting of the flow in the starting part of the Chain and moving downstream, recombination of fluids take place. The H module starts with two new circular sections (segment 5) of diameter 0.6 mm each extended by 0.4 mm (-Z direction). Two cylindrical channels of each 0.5 mm long (along –Z direction) connect these two circular tubes with a horizontal channel of 5 mm long as shown in figure 2(b) (segment 6). When fluid enters into H channel from Chain, it splits into two flows: one moving in the +Y direction and the other one moving in the –Y direction; flows then move to -Z direction. Afterwards, one flow moves in the –Y direction and the other one moves in the +Y direction until they reconnect again. Lastly, the output of H module is connected with a circular connector radius of 1 mm (segment 7), it conveys the flow to the next element and the SAR process starts again.

3. Numerical Methods

Fluent is a comprehensive tool for computational fluid dynamics and is widely used in many engineering fields. ANSYS Fluent 15 was applied in this study to estimate the properties such as flow pattern, pressure drop and mixing efficiency of Chain, Tear-drop and C-H micromixers. Reynolds numbers of the micromixers were calculated using equation (1).

$$Re = \frac{\rho v d}{\mu} \quad (1)$$

where ρ is the fluid density, v is the velocity of fluid, μ is the dynamic viscosity, and d is the characteristic length of the channel. In this study, the minimum depth or dimension of the micromixers is considered as the characteristic length, which is 0.4 mm. Cut cell Cartesian method was used to generate hexahedral cells, which is suitable for complex geometry for computational fluid dynamics (CFD) simulations. Mesh independent solutions were checked for three mixers for different grids; simulations were carried out using number of elements of approximately 5×10^5, 4×10^5 and 3×10^5. For example, the deviation of mixing efficiency of the Chain mixer after four elements was less than 3% as shown in figure 3. So the grid numbers about 3×10^5 was chosen for Chain mixer. Similarly, grid numbers around 4×10^5 and 5×10^5 were assigned for Tear-drop and C-H mixers.

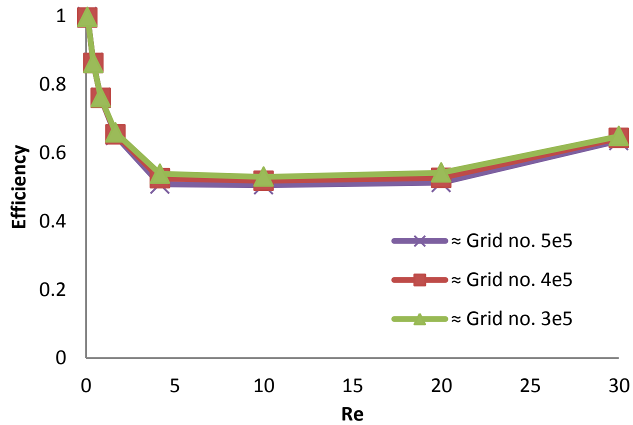


Fig. 3. Grid dependency of Chain mixer: efficiency after 4 elements

In the present numerical calculation, fluids are assumed Newtonian and incompressible. Ignoring the body force and gravity, the governing equations including the continuity equation, Navier-Stokes equation and species convection-diffusion equation can be described as:

$$\nabla . V = 0 \tag{2}$$

$$\rho V . \nabla V = -\nabla P + \mu \nabla^2 V \tag{3}$$

$$V . \nabla C = D \nabla^2 C \tag{4}$$

where V is the fluid velocity vector, ρ is the fluid density, P is the pressure, μ is the fluid dynamic viscosity, C is the species mass concentration and D is the diffusion coefficient of the species.

Firstly, pressure-based and time steady laminar flow was selected in the Fluent solver to compute the overall distribution of fluid particles, initially with same and afterward with different inlets flow rate ratio for the three mixers, which provides a general qualitative idea of fluids blending.

Secondly, pressure-based and time steady laminar flow was chosen with species transport model on, in which fluid concentration of two inlets were set as 1 and 0 respectively. In the boundary conditions, inlets were set as velocity inlets, static gauge pressure of outlet was set as zero, and the wall was set as stationary wall with no slip condition. SIMPLEC scheme was assigned as solution method to calculate pressure velocity coupling. For obtaining more accurate results, the second order upwind of momentum and pressure were employed. In present calculation, the fluid is assumed to have a dynamic viscosity of 10^{-3} Ns/m^2, a density of 10^3 kg/m^3 and a diffusion coefficient of 10^{-9} m^2/s, which is a typical value for an aqueous solution at room temperature. To quantify the mixing performance, the following equations were employed (Engler et al., 2004):

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (C_i - C_\infty)^2} \tag{5}$$

$$MI = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\frac{C_i - C_\infty}{C_\infty}\right)^2} \tag{6}$$

$$\eta = 1 - MI = 1 - \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\frac{C_i - C_\infty}{C_\infty}\right)^2} \tag{7}$$

where σ is the standard deviation of mass fraction at a cross section, N is the number of sample cells in that cross section and C_i is the mass fraction of a sample cells i; C_∞ is the optimal mass fraction which, depends on inlets flow ratio. If the two fluids have same amount in the micromixer (inlets flow rate ratio is 1), C_∞ is 0.5. The value of optimal mass fraction will be 0.33 and 0.25 respectively for inlets flow ratio 2 and 3, when fluid correspond to lower inlet velocity is considered. The mixing indexes (MI) are 0 and 1 for well-mixed case and unmixed case, respectively. Mixing efficiency η is 1 (100%), when the two species are fully mixed; efficiency more than 80% is acceptable for mixing process applications.

4. Results and Discussion

The purpose of this study is to examine the performance of Tear-drop, Chain and C-H micromixers at different inlet flow ratio. As mentioned earlier, the effects of various Reynolds numbers and geometry on mixing efficiency and pressure drop were examined numerically at Re number up to 100 using CFD code.

Firstly, the flow pattern inside the channel was examined in terms of path lines to know the overall distribution of fluids particles. It is possible to get a general idea of mixing of fluids from the segregation of path lines. At very low Re number where the flow is strictly laminar, the mixing is entirely due to molecular diffusion between layers of different concentration. Figure 4(a) shows the path lines distribution for inlets flow rate ratio 1; both streams (red and green) flow side by side inside the all three mixing channels. In case of Chain mixer, there are only 3 distinct layers of path lines at the output when Re = 1, which indicates the non homogeneity of mixing; the layer of path lines decreases at Re = 30, and finally more than 7 layers of stream lines can be found at Re = 100. On the other hand, Tear-drop shows more than 7 layers of fluid except at Re number of 30. On contrary, C-H mixer always presents more than 7 layers of streamlines regardless of Re numbers. Hence, it is highly likely that Tear-drop and C-H mixers will offer higher mixing efficiency than the Chain mixer at low and middle Re numbers. Figure 4 (b) shows the path lines distribution of three mixers when inlets flow ratio is 3; which presents the same scenario as flow rate ratio 1with some minor difference.

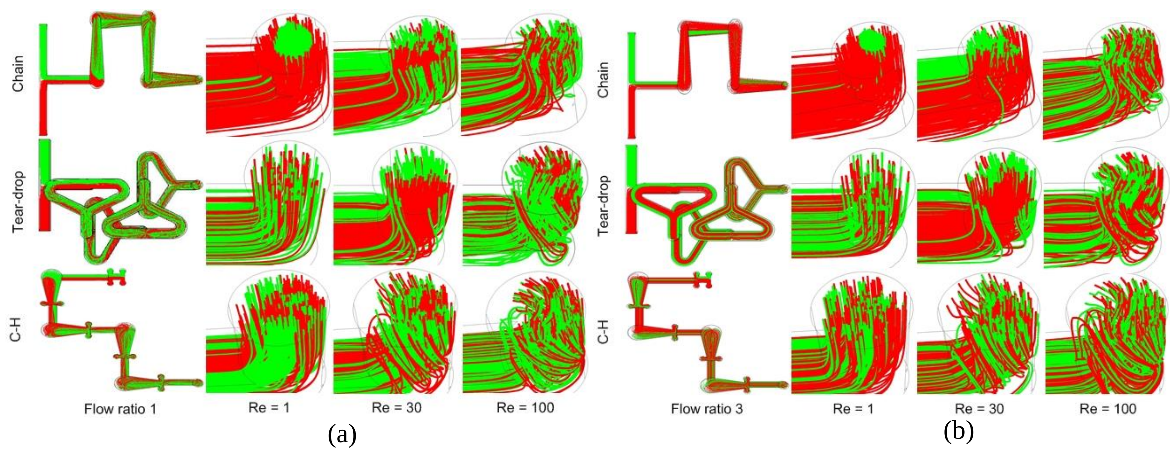
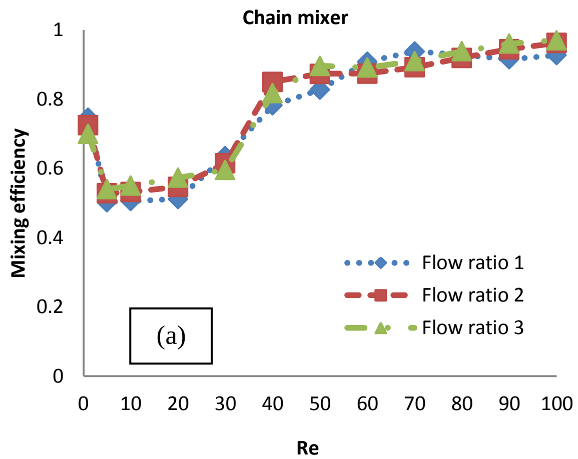


Fig. 4. Path lines inside the micromixers for inlets flow ratio; (a) one (b) three

Secondly, mixing efficiency of Tear-drop, Chain and C-H mixers was evaluated at a wide range of Re numbers (1 to 100) for inlets flow rate ratio 1 to 3. Figure 5(a) compares the mixing efficiency of Chain mixer obtained numerically at inlets flow ratio from 1 to 3 after four elements; as shown, all numerical data have the same trend. At very low Re number (Re≥1) efficiency is about 70%; afterward efficiency decreases sharply and efficiency varies slightly in the Re number range of 5 to 20. Mixing efficiency increase considerably at Re = 30 and finally efficiency exceed 80% when Reynolds number reaches 50. It is also clear that mixing efficiency depends strongly on the value of inlets flow rates rather than inlets flow ratio.

The mixing efficiency of Tear-drop mixer for inlets flow ratio 1 to 3 is plotted in the figure 5 (b). It is clear that, all three efficiency curves show the same progression. In contrast to the Chain mixer, the efficiency of Tear-drop mixer depends strongly on inlets flow ratio and interestingly the efficiency increases for higher inlets flow ratio, especially in the middle range of Re number. In case of inlets flow ratio 1, the efficiency is less than 90% in the Re numbers range of 10-60. This range of Re number decreases with the increase of inlets flow rate ratio and becomes 20-50 in case of inlets flow ratio 2. Moreover, efficiency is about 90% for all range of Re numbers at inlets flow rate ratio 3.



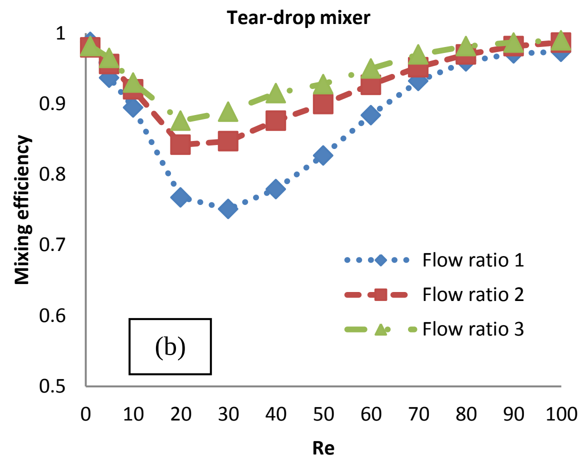


Fig. 5. Numerical mixing efficiency of (a) Chain mixer and (b) Tear-drop mixer at different inlets flow rate ratio, varying Re numbers ($1 \leq Re \leq 100$)

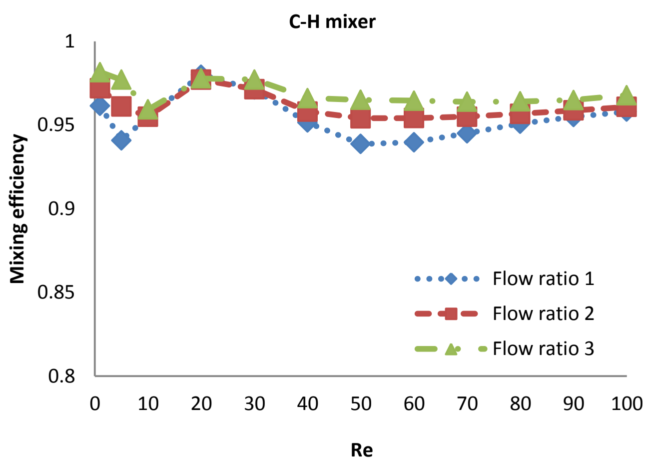


Fig. 6. Numerical mixing efficiency of C-H mixer at different inlets flow ratio, varying Re numbers

The mixing efficiency of C-H mixer for different inlets flow ratio is presented in figure 6. Efficiency curves show same trend for different inlets flow ratio and efficiency slightly increases for higher inlets flow rate ratio especially at Re number range of 40 to 90. In case of Chain and Tear-drop mixers, efficiency is relatively low in the middle range of Re numbers ($10 \leq Re \leq 40$), whereas C-H shows considerably high efficiency. The overall mixing efficiency is more than 93% for all Re numbers regardless of inlets flow rate ratio.

Comparing figures 5 and 6 it is evident that at very low Re number ($Re \leq 1$) all three mixers provide good mixing efficiency at inlets flow rate ratio 1 to 3. It is also obvious that at middle range of Re number ($10 \leq Re \leq 40$), Chain mixer shows low mixing efficiency ($\eta \leq 65\%$) regardless of inlets flow rate ratio and Tear-drop also presents relatively low efficiency but efficiency increase with the increase of inlets flow ratio. All three mixers show efficiency more than 90% at high Re number ($Re \geq 70$) for inlets flow rate ratio 1 to 3. Moreover, inlets flow ratio has no influence on Chain mixer and has slight influence on C-H mixer. In contrary, Tear-drop has significant dependence on inlets flow ratio especially in Re number range of 10≤Re≤70.

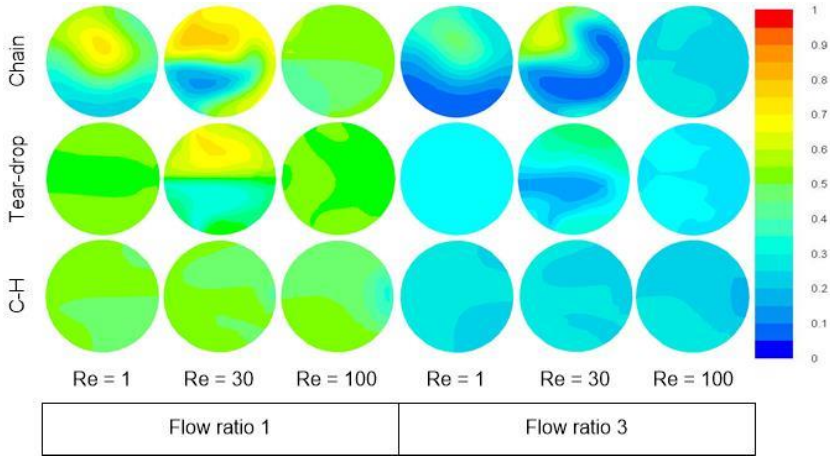


Fig. 7. Contours of mass fraction at the output of Chain, Tear-drop and C-H micromixers, when Re = 30

The mass fractions of water at inlets flow rate ratio 1 and 3 is presented in figure 7. In case of inlets flow ratio 1, the expected maximum mass fraction is 0.5. On the other hand, when the inlets flow ratio is 3, the expected maximum mass fraction is either 0.25 or 0.75 depending on which inlets fluid was considered. In this study, the lower velocity inlet fluid is taken into calculation, so the expected mass fraction is 0.25. It is possible to get an idea of blending of fluids from the contours value of water from the figure 7, which matches the numerically calculated results.

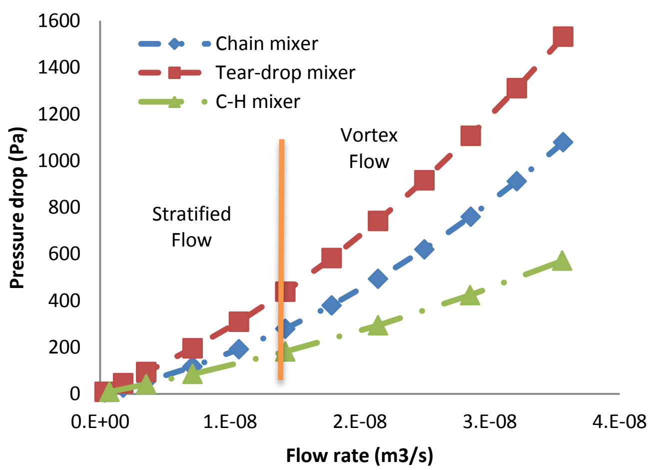


Fig. 8. Numerical pressure drop of Tear-drop, Chain and C-H mixers

Finally, the pressure drop of the three micromixers was computed numerically and pressure drop dependence on the corresponding flow rate is presented in figure 8. It is evident that the pressure drop is linearly dependent on the flow rate up to 1.5×10^{-8} m^3/s due to the stratified flow of fluid. As the flow rate increases, the vortex introduces in the fluid stream and consequently pressure drop increases exponentially. Tear-drop and C-H mixers have consequently the highest (1540 Pa) and the lowest (571 Pa) pressure drop, whereas Chain has moderate (1070 Pa) pressure drop at the highest flow rate (3.57×10^{-8} m^3/s). Furthermore, C-H mixer shows respectively about three and two times lower pressure drop than Tear-drop and Chain mixers.

5. Conclusion

The mixing performance of miscible fluid (water-water) was numerically modelled for three SAR micromixers: Chain, Tear-drop and C-H. Water with diffusion coefficient of 10^{-9} m^2/s was chosen to test the mixing behaviour and pressure drop on the variation of Re numbers range from 1 to 100 at three different inlets flow rate ratio (1 to 3).

Among the presented three micromixers, Tear-drop provides fairly good efficiency except in the middle range of Re numbers but has high-pressure drop. In addition to that inlets flow rate ratio has a significant influence on efficiency especially at the middle range of Re number and maximum increase of efficiency is almost 10% when inlets flow rate ratio is increased by 1. Chain mixer presents relatively low mixing efficiency at low and middle range of Re numbers ($5 \leq Re \leq 50$) but has reasonable pressure drop. Contrary to Tear-drop mixer, efficiency of Chain mixer shows almost no dependence on inlets flow rate ratio. Whereas, C-H mixer poses excellent mixing efficiency for all range of Re numbers and causes the lowest pressure drop. C-H mixer also has slight dependence on inlets flow rate ratio at high Re numbers. In addition, C-H mixer shows respectively about three and two times lower pressure drop than Tear-drop and Chain mixers. Therefore, C-H is the most potential mixer for practical/industrial application.

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