Study of mixing in circular unbalanced split & recombine micromixer

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Abstract- In the present work, numerical simulation has been performed to analyze the mixing of fluids inside a passive circular unbalanced split & recombine micromixer. The continuity, Navier-Stokes & mass diffusion equations were solved and numerical simulation were performed for aspect ratios of 3.00. The width ratio (w1/w2) was varied for seven different values between 1.90 & 2.20 and numerical simulations were performed for five different Reynolds numbers (10, 20, 40, 60 & 80) at each value of width ratio. The mixing phenomenon was explained with the help of stream lines plots, contour plots etc. The generation of secondary flows across the transverse plane and their contribution in achieving better mixing has been explained. The mixing performance of the micromixer is quantified with the help of mixing index.

1. Introduction
Micromixer is a microfluidic device used to mix fluids in the micro-dimensions. In micromixer, the Reynolds number is low therefore viscous forces dominates rather than the inertial forces. Another important factor for consideration in the micromixers is ubiquity of laminar flow. High surface to volume ratio, smaller size, less energy consumptions, cost effectiveness are some features of micromixers. Based on the source of energy, the micromixer can be classified in two major groups: active & passive micromixer. In active micromixer, the external source of energy is used in the mixing of fluid streams while in passive micromixer, geometrical features of the system are utilized for the same process [1-2].

Ansari et al designed a passive micromixer which is fundamentally based on the principle of unbalanced splits and cross-collisions of fluid streams. In the proposed design the main fluid channel was split into two sub-channels of unequal widths that further recombine after a certain distance and again split and recombine. The proposed design gave best results for width ratio of 2.0 for Reynolds number higher than 20 and poor performance for width ratio of 1.0 [3]. Afzal et al proposed a passive micromixer with convergent divergent walls based on the principle of unbalanced split and recombine. [4]. Changing the inlet and outlet configurations of mixing chambers also improved the performance of the passive micromixer. Alam et al designed a micromixers with four mixing chambers and four different arrangements, for inlet and outlet of fluid streams [5]. Shakawat et al increased the number of splits in split and recombination based rhombic micromixers. The rhombic angle 90° gave the best mixing performance except at the low Reynolds number [6]. Alam et al placed circular obstruction in the path of fluid flow in planer curve micromixer. [7]. In simple straight channel passive micromixer, the mixing was dominated by molecular diffusion only, irrespective of Reynolds number. But in case of curved channel, Dean vortices were generated due to the combined effect of inertial and centrifugal forces. At low Reynolds number, the mixing was dominated by molecular diffusion only but as the
Reynolds number was increased, the inertia effect started to take effect as well due to continuous change in the curvature, the centrifugal effect also came into picture creating secondary Dean vortices in the micromixers, which helps in the improvement of performance of passive micromixer at higher Reynolds numbers [8].

2. Physical model of the micromixer
The schematic diagram of the circular passive unbalanced split & recombine micromixer is shown in the figure 1. The micromixer is consist of T-joint followed by six circular unbalanced and split and recombine (SAR) units. The width of the main channel (W) is kept constant at 300 µm. The diameter of the base circle of each SAR unit is 900 µm. In each SAR unit the main channel is split into two sub channel such that the sum of the width of both sub-channels equal to width of the main channel i.e. \( w_1 + w_2 = 300 \) µm. The total length (L) of the micromixer is equal to 10350 µm. The pitch (\( p_i \)) of the micromixer is equal to 100 µm. The aspect ratio (AR) of the micromixer is defined as the ratio of the width of the main channel (W) to the height (h) of the micromixer.

![Figure 1. Schematic diagram of the micromixer (a) front view (b) side view](image)

For aspect ratio of 2.50, the earlier results showed that mixing efficiency of circular unbalanced split & recombine micromixer was maximum at width ratio (\( w_1/w_2 \)) of 2.0 for Reynolds number (Re) lying between 10 & 80 [3]. In this present work, further study was done in investigating the optimum width ratio (\( w_1/w_2 \))_{optimum} for the aspect ratio (AR) of 3.00.

3. Numerical methodology
The general transport equations in numerical solver poses the following general form:

\[
\frac{\partial (\rho \phi)}{\partial t} + \nabla (\rho \phi V) = \nabla (\Gamma \ \text{grad} \ \phi) + S_\phi
\]

Here, \( \rho \) is the density, \( V \) is the velocity, \( S_\phi \) is the source term, \( \mu \) is the dynamic viscosity, \( p \) is pressure field, \( c \) is the mass fraction & \( D \) is the diffusion coefficient. ANSYS-CFX is cell-vertex based finite volume, coupled implicit pressure based commercial CFD code. CFX is based on finite volume method, the partial differential equations of flow as represented above is integrated over each of the control volume in the computational domain. The pressure velocity decoupling in the CFX is handled by using Rhie-Chow approach [9]. For numerical simulation, hexahedral grids had been generated in the entire numerical domain using ANSYS ICEM 18. For the same amount of cells, hexahedral cells have high accuracy in 3-D space.

Numerical simulations were performed by studying the mixing between water and ethanol. The dynamic viscosity of water & ethanol was taken as \( 1.002 \times 10^{-3} \) Pa-sec & \( 1.187 \times 10^{-3} \) Pa-sec and density as \( 998.20 \) kg/m\(^3\) & \( 789.7 \) kg/m\(^3\) respectively [10]. At 20°C, the diffusivity of water and ethanol was taken as \( 1.2 \times 10^{-9} \) m\(^2\)/s [3]. The flow inside the micromixer is considered as steady, laminar and incompressible. The isothermal condition was maintained in the micromixer. [11]
In the numerical solver, different boundary conditions were specified at both inlets, outlet and wall of the micromixer. There were two inlets and one outlet in the considered design of micromixer. At both inlets, normal inlet velocity and ethanol mass fraction was specified as boundary conditions. At outlet of micromixer, average static pressure was specified as boundary condition. No slip condition was applied at the wall of the micromixer. The numerical solution was converged when the RMS value of the residue at each node points attains a value of $10^{-6}$.

The effectiveness of the micromixer was quantified by calculation of the mixing index. A plane perpendicular to direction of flow inside the micromixer and near the outlet of the micromixer was selected and mass fraction of ethanol has been taken from ample numbers of sample data points. Then, the variance of mass fraction from these data points was calculated using the following equation

$$
\sigma = \sqrt{\frac{\sum (c_i - c_m)^2}{N - 1}}
$$

Here, $\sigma$ is the standard deviation of sample data points, $c_i$ is the mass fraction of ethanol at the $i$th sample point and $c_m$ is the mean mass fraction of ethanol along the sample plane and $N$ is the number of the sample points taken from the micromixer. After calculation of the variance of mass fraction at the sample plane, the mixing was calculated by applying the following equation [3].

$$
M = 1 - \frac{\sigma^2}{\sigma_{\text{max}}^2}
$$

Here, $M$ is the mixing index at the sample plane, $\sigma^2$ is the variance of mass fraction and $\sigma_{\text{max}}^2$ is the maximum value of the variance on the sample plane.

4. Validation & grid independency test

Adopting an efficient and correct numerical strategy does not guaranty the accuracy of the simulation results. The validation of the numerical scheme is very necessary step in order to obtain accurate numerical results. Figure 2 shows the validation of current numerical solutions. The numerical simulations were performed for Re 80 and width ratio ($w_1/w_2$) of 1.0, 1.5, 2.0 and 2.5 at aspect ratio of 2.50 and the results were compared with the earlier published experimental results of Ansari et al [3].

![Figure 2. Validation of numerical result from experimental result [3] at Re 80 for aspect ratio 2.50](image)

![Figure 3. Grid independency test at width ratio 2.00 & Re 80 for aspect ratio 3.00](image)

The refinement of the grid is very important factor in the generation of optimum grid. Therefore, a detailed grid independency test was performed at width ratio of 2.00 & Re 80 for six different grid sizes. The result of grid independency test is shown in the figure 3. On the basis of results obtained
from the grid independence test, grid size of 2.29 million was selected for numerical simulations in the current design of micromixer.

5. Results & discussions
The mixing of fluid streams is better understood with the help of the ethanol mass fraction contour plots. The figure 4 gives a comparison of contour plots of balanced collision ($w_1/w_2=1.00$) & unbalanced collision ($w_1/w_2=1.95$). In case of balanced collision of fluid streams, the different fluid streams came into contact with each other at the junction of two mixing units only and almost flow separately in the sub-channels.

In case of unbalanced collision of fluid streams, the ethanol stream entering from inlet 1 was flowed through major sub-channel and water stream entering from inlet 2 was flowed through both major and minor sub-channels. In case of unbalanced collision, the major sub channel has large area compare to minor sub-channel, therefore, the water streams were split into two sub streams, one entered in to the major sub-channel and other entered into the minor sub-channel of the first mixing unit. While in the other hand the ethanol stream entering from inlet 1 flowed through only major sub-channel. In the first mixing unit, the ethanol streams had higher mass flow rate in the major sub channel therefore it pushed the water stream towards the inner wall of the unit resulting in the collision at the junction of second mixing unit. Due to this, ethanol stream entered in the both sub channel of the second mixing unit. This process was repeated during the entire mixing length of the micromixer and leads to better mixing compared to the balanced collision.

![Figure 4. Comparison of contour plots of ethanol mass fraction in xy-plane at Re 80 & aspect ratio of 3.00 for balanced ($w_1/w_2=1.00$) and unbalanced ($w_1/w_2=1.95$)](image)

![Figure 5. Velocity vector at plane A & B at Re 60 & 80 for aspect ratio (AR) of 3.00 & width ratio ($w_1/w_2$) of 1.95](image)

At low Reynolds number (Re=10), the mixing is achieved due to the high residence time of fluid flow inside the micromixer as velocity was less at low Re. As the Reynolds number increases further
(Re=20), the inertia forces began to dominate the viscous forces. Therefore, when the fluid streams flowed across the circular sub-channels, the combined effect of centrifugal forces and inertia forces generated the secondary flows in the transverse plane. The counter rotating pair of dean vortices started to form in the both sub-channels and can clearly observed in the figure 5 for Re 60 & Re 80. The dean vortices caused in the increase of the interfacial area between the mixing streams along the length of the circular channel symmetrically. Therefore, the mixing interface became more and more distorted along the middle axis of transverse plane. As the Reynolds number increased further, the secondary flows played an important contributing factor in achieving good mixing efficiency.

![Figure 6](image_url)

**Figure 6.** Ethanol mass fraction profile at various cross section along yz- plane at different axial positions along the x-axis at width ratio (w1/w2) of 1.95 and aspect ratio (AR) of 3.00

From the figure 6 we can see that the interface between the mixing streams played an important role in the understanding of mixing phenomenon inside the micromixer. For aspect ratio 3.00, at low Reynolds number 10, 20 & 40, the interface was straight at the beginning and became to deform from plane B in the major sub-channel and it became developed from plane E. While in case of Re 60 & 80 it started to deform from starting and became developed in the plane B of major sub-channel. For minor sub-channel, the mixing interface did not form and no mixing took place in the entire length for Re 10 & 20. While in case of Re 40 the interface was formed from the plane K and in case of Re 60 & 80, it formed from plane C and became developed from plane G for minor sub-channel. Therefore, the effect of major sub-channel was also propagated in the minor sub-channels from Re 40. As the Reynolds number was increased, the influence of transverse flow in the circular channel also increased resulting in the development of secondary flows inside the micromixer. The mass fraction profile was symmetric about the middle plane due to the formation of counter rotating pair of dean vortices. Therefore, for aspect ratio 3.00, the micromixer gave a poor performance at Re 10 and its performance was improved from Re 20.
The overall performance of micromixer was evaluated with the help of mixing index. Form the figure 7, it is quite evident that the performance of the micromixer was improved with the increase in the Reynolds number. The results of the mixing index indicate that the mixing performance of the circular unbalanced split & recombine passive micromixer become maximum at a width ratio \((w_1/w_2)_{\text{optimum}}\) of 1.95.

6. Conclusion

The present work was aimed to investigate the mixing inside the passive circular unbalanced split & recombine micromixer. The numerical simulations were performed to calculate the optimum width ratios for five different values of Reynolds numbers (10, 20, 40, 60 & 80). The mixing performance of the unbalanced split & recombine micromixer is better compared to the balanced collision micromixer. At low Reynolds numbers (Re=10), the fluid mixing is due to the high residence time of the fluids inside the micromixer. In such case, mixing is mainly due to the diffusion of the fluid particles, which is quiet slow process. When the Reynolds number was increased further the secondary flows were established in the form of counter rotating pair of Dean vortices resulting in the better mixing performance. For aspect ratio (AR) of 2.50, the mixing performance is reported to be highest at width ratio \((w_1/w_2)\) of 2.00 but in our study we found for aspect ratio (AR) of 3.00, the optimum width ratio \((w_1/w_2)_{\text{optimum}}\) comes out to be 1.95.

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