Simulation and evaluation of the performance of the proposed micromixer with particular obstacles

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ABSTRACT

Microfluidics is a relatively new field that has a significant effect on various applications, particularly in biology, biomedical, and biotechnological research. Micromixers are important components of microfluidic systems that help to mix two or more fluid species. In this paper, a new micromixer with particular obstacles is designed and its performance in terms of mixing and pressure drop is compared with a simple y-type micromixer through computational fluid dynamics (CFD) simulations using COMSOL Multiphysics software. The results showed that the simple y-type micromixer has a low mixing efficiency in the Reynolds number range, while the proposed micromixer shows significantly higher mixing efficiency. In the proposed micromixer, the mixing index is initially reduced by increasing the Reynolds number from 0.5 to 1, and then continuously increasing by further increasing the Reynolds number to more than 10. In general, the proposed micromixer using special barriers leads to the formation of vortices and the dominance of the chaotic advection term over the molecular diffusion, and by using it, it is possible to achieve relatively complete mixing at Reynolds numbers above 50.

Keywords: Microfluidics, Micromixer, CFD

1. INTRODUCTION

Microfluidics is an emerging interdisciplinary field that employs the principles of physics, chemistry, biology, fluid dynamics, microelectronics, and materials science to manipulate small quantities of fluids. This technology has been recognized as a powerful tool for conducting experiments with high efficiency and low consumption of reagents, and it finds wide applications in the areas of pharmaceutics, biology, and chemistry. Micromixers, microreactors, and lab-on-a-chip devices are some of the microfluidic devices that perform operations such as reactions, separations, or detection of various compounds. Microfluidic devices have diagnostic applications in the medical field that can be used to diagnose cancer, pathogens, and infectious diseases such as HIV, coronavirus, and various types of hepatitis A, B, and C. [1],[2],[3].

Mixing is a physical process that aims to achieve uniform distribution of different components of a mixture in a short time [5]. Micromixers play an important role in microfluidic systems, by allowing the mixing of two or more fluid species. When constructing micromixers, it is important to consider practical applications, ease of construction, and mixing efficiency. In microfluidic systems, molecular diffusion is the dominant phenomenon for mixing, which is a time-consuming process [4],[5]. However, diffusion can be improved by making changes to the channel geometry. Mixing efficiency can be enhanced through the use of obstacles to the formation of vortexes, particularly at high Reynolds numbers [6]. Micromixers are classified into two categories: active and passive. Active micromixers use external energy sources, such as magnetic fields or electric fields, to achieve complete mixing in a short time [6],[7],[8]. On the other hand, passive micromixers do not require external energy and only use fluid-pumping energy. They have many advantages over active micromixers, including ease of construction, relatively low cost, and ease of integration with microfluidic systems [6],[7],[9].

In this paper, we first look at designing a new type of micromixer with specific obstacles. We then evaluate its performance according to the mixing index and pressure drop in the Reynolds number ranging from 0.1 to 100 and compare it with the simple y-type micromixer of similar dimensions. For simulations, COMSOL Multiphysics 6 software has been used.

2. MICROMIXER DESIGN AND MESHING

The design of the micromixers is shown in Figure 1. In both designs, the length of the micromixers is 15000 µm, and the width of the microchannels is considered to be 800 µm.

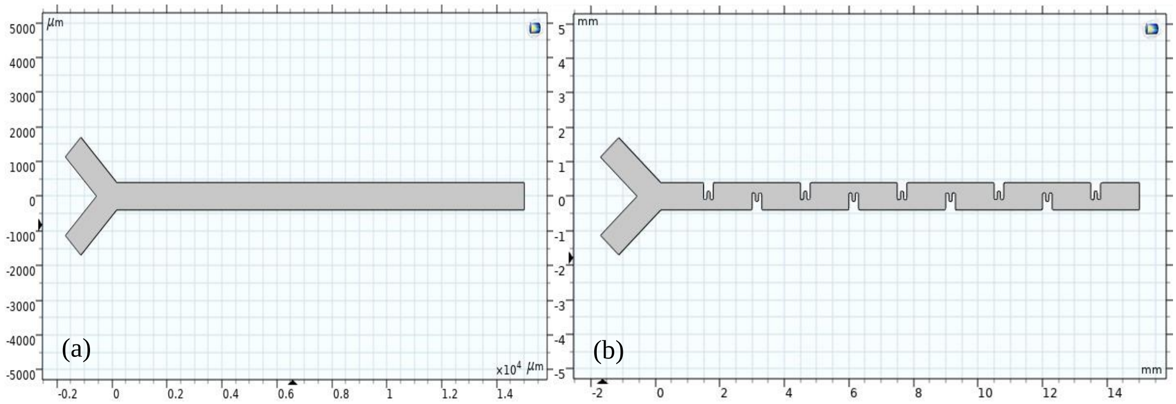


Fig. 1. Schematics of the (a) simple y-type micromixer and (b) micromixer with particular obstacles

To determine the optimal number of elements, the mesh independency test was performed for both micromixers at Re=10. The result of the mesh independency test is shown in Figure 2.

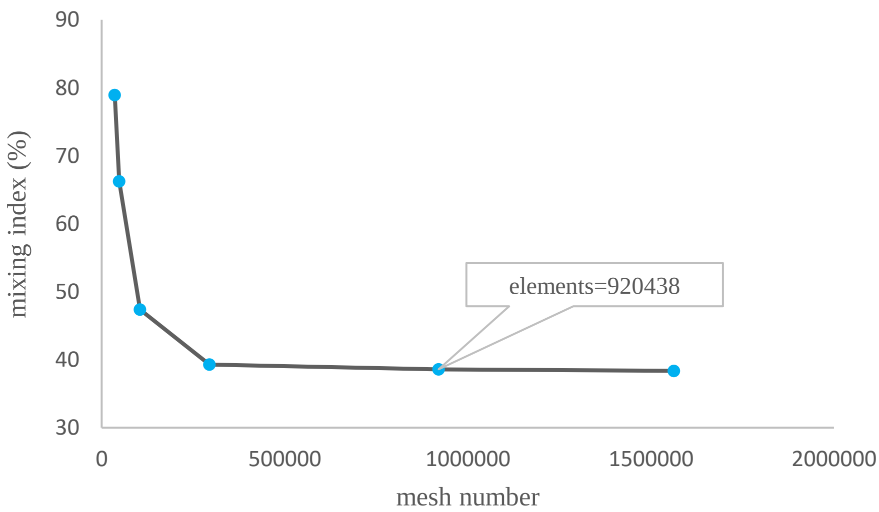


Fig. 2. Mesh independency test at Re=10.

3. NUMERICAL ANALYSIS

In this paper, COMSOL Multiphysics software version 6 is used to evaluate mixing efficiency and pressure drop in micromixers. The governing equations, which neglect gravitational force, include continuity, Navier-Stokes, and convection-diffusion equations (Equations 1-3). We assume that both fluids are steady, incompressible, and Newtonian.

$$\nabla, V = 0 \quad (1)$$
$$\rho\,(V, \nabla)V = -\nabla P + \mu \nabla^2 \mathrm{V} \quad (2)$$
$$(V, \nabla)C = D\nabla^2 C \quad (3)$$

Where ρ and V are density and velocity of the fluids, respectively. μ is the dynamic viscosity, P is pressure, c is the concentration of species, and D is the diffusion coefficient of the species. The mixing index (MI) is defined as a criterion for evaluating the performance of micromixers in Equation 4. The MI value ranges from 0 to 1, where 0 indicates no mixing and 1 indicates complete mixing.

$$MI = 1 - \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\frac{Ci-\bar{C}}{\bar{C}})^2} \quad (4)$$

Where n is the number of nodes in the meshed geometry, Ci is the concentration of the combined component in each node and $\bar{C}$ is the concentration in complete mixing conditions, assumed to be equal to 0.5. Reynolds number is also defined using Equation 5:

$$Re = \frac{\rho\, V\, Dh}{\mu} \quad (5)$$

Where Dh is the hydraulic diameter of the microchannel.

During the simulation in COMSOL software, the physics of fluid flow and transport of dilute species are used. Uniform velocity at inlets and zero static pressure at the outlet are considered as boundary conditions. Additionally, no-slip boundary conditions are considered for the walls. The fluid used in the simulation is considered similar to water with $\rho = 1000\frac{mol}{m^3}$, μ=0.001 Pa.s and $\mathrm{D} = 10^{-10}\,\frac{\mathrm{m}^2}{\mathrm{s}}$. The upper inlet and lower inlet of micromixer have the molar concentration of $1\,\frac{mol}{m^3}$ and $0\,\frac{\mathrm{mol}}{\mathrm{m}^3}$, respectively.

4. RESULTS AND DISCUSSION

The concentration profiles obtained for the simple Y-type micromixer and the micromixer with particular obstacles, within the Reynolds number range of 0.5 to 100, are shown in Figures 3 and 4, respectively. As shown in Figure 3, the simple y-type micromixer exhibits low levels of mixing across all Reynolds numbers, because mixing is done only by molecular diffusion, and due to the short contact time and the short length of the microchannel, molecular diffusion and as a result, mixing not performed well.

On the other hand, as shown in Figure 4, for the proposed micromixer with particular obstacles, a high mixing is observed, especially at high Reynolds numbers. For this micromixer, the mixing index first decreases with the increase of the Reynolds number from 0.5 to 1 and then increases continuously with the increase of the Reynolds number. Because in the range of low Reynolds numbers (0.5 to 1), the phenomenon of molecular diffusion is dominant and with the increase of Reynolds number and fluid velocity, the residence time and diffusion time decrease. At Reynolds numbers higher than 10, due to the formation of vortices due to the presence of obstacles, the chaotic advection term dominates for mixing, and the mixing index increases. As the Reynolds number and fluid velocity further increase, the mixing index also increases due to the strengthening of formed vortices. Using the proposed micromixer, complete mixing can be achieved in a short time at Reynolds numbers higher than 50.

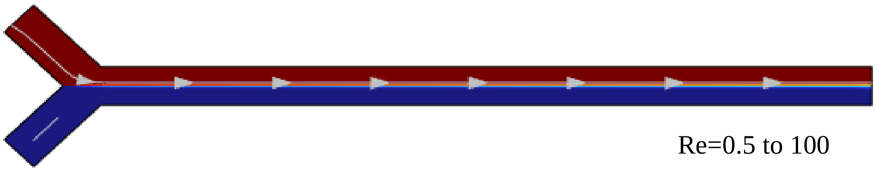
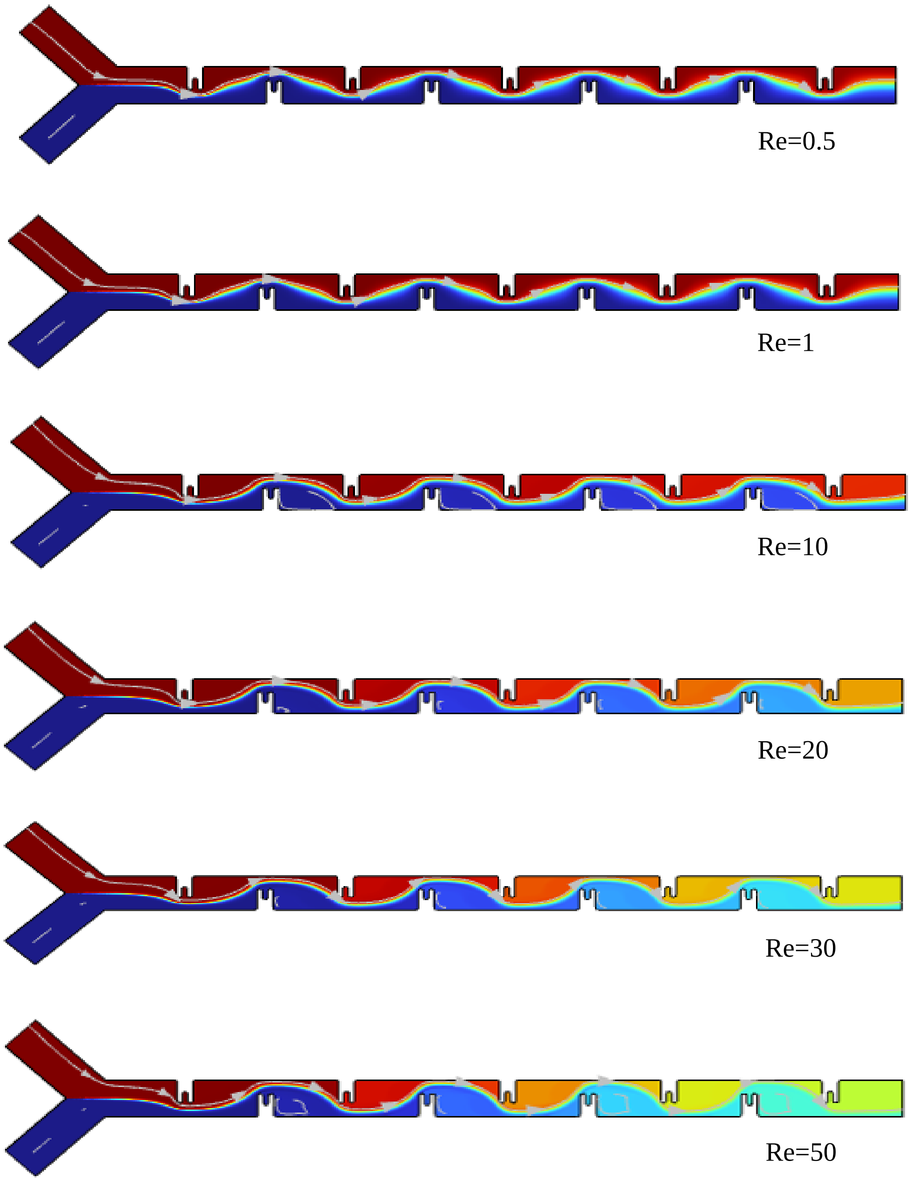


Fig. 3. Concentration profile of a simple y-type micromixer in the range of Reynolds numbers from 0.5 to 100.



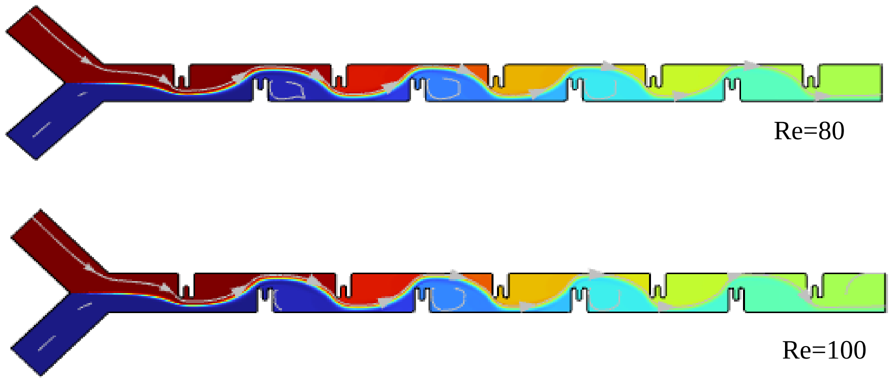


Fig. 4. Concentration profile of a proposed micromixer with particular obstacles in the range of Reynolds numbers from 0.5 to 100.

As shown in Figure 6, no vortex is formed in the flow velocity profile of the simple y-type micromixer even at high Reynolds numbers such as Re=100.

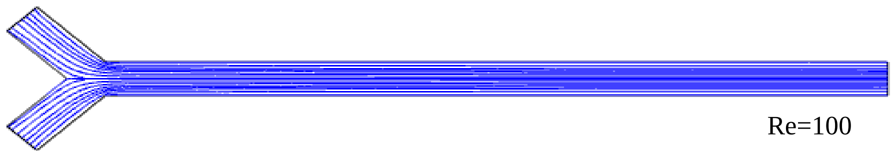


Fig.5. Flow velocity profile of a simple y-type micromixer at Re=100.

However, in the proposed micromixer with particular obstacles, vortices are created at high Reynolds numbers due to the presence of obstacles, which ultimately leads to improved mixing. For example, the flow velocity profile of the proposed micromixer at Reynolds numbers 50, 80 and 100 is shown in Figure 6. As can be seen, with the increase of Reynolds number and fluid velocity, the formed vortices are strengthened and help to improve mixing.

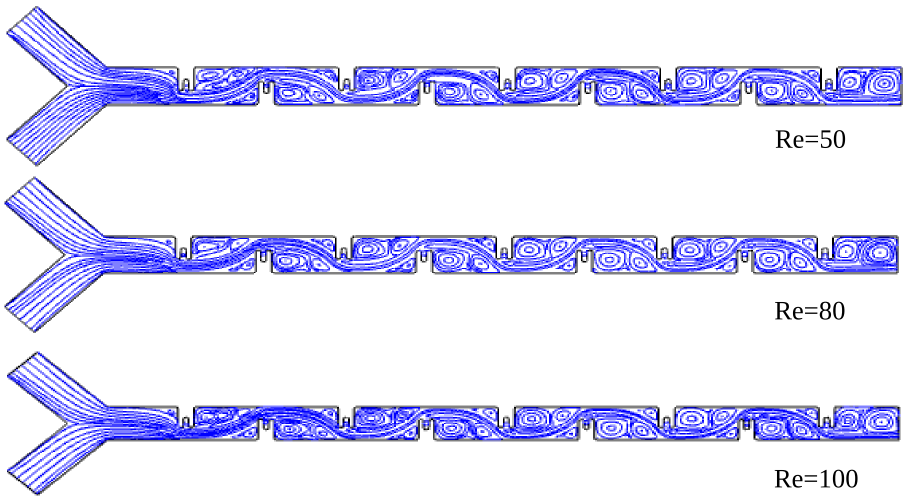


Fig.6. Flow velocity profile of a proposed micromixer with particular obstacles at Re=50, 80, and 100.

On the other hand, as shown in Figure 7, the pressure drop in the proposed micromixer within the considered Reynolds number range is significantly higher than the simple y-type micromixer, and for instance at a Reynolds number of 100 it can reach up to 75,100 pa. This high pressure drop is one of the disadvantages of this type of micromixers with particular obstacles due to the possibility of leakage.

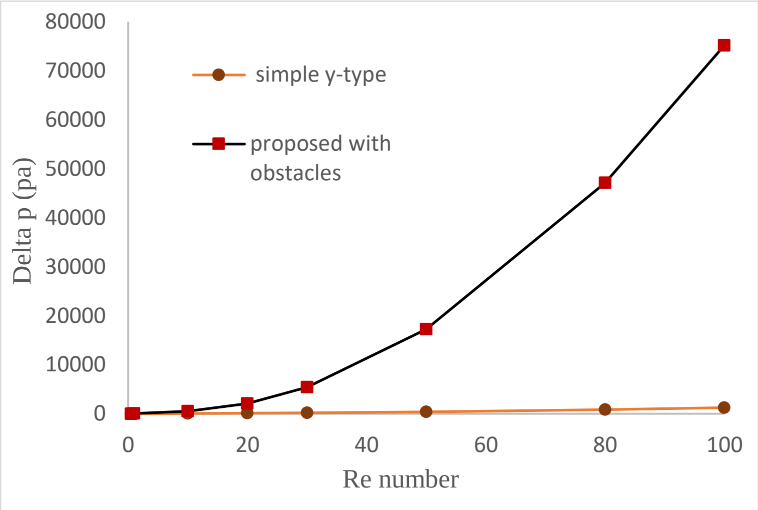


Fig.7. Pressure drop in micromixers in the range of Reynolds numbers 0.5 to 100.

5. CONCLUSION

Considering the important role of micromixers in microfluidic systems, this paper discusses the design and simulation of a proposed micromixer with particular obstacles using COMSOL software. The mixing index and pressure drop for the simple y-type micromixer and the proposed micromixer were calculated and compared. At all Reynolds numbers, the simple y-type micromixer showed a low amount of mixing according to the obtained results. In contrast, within the range of considered Reynolds numbers, the proposed micromixer showed a much more efficient mixing. This is due to the dominance of the advection term and the formation and strengthening of vortices, especially at high Reynolds numbers. In general, the obtained results indicate the superiority of the proposed micromixer with particular obstacles compared to the simple y-type micromixer, so that by using the proposed micromixer at high Reynolds numbers, almost complete mixing can be achieved.

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