Numerical Investigation of the Mixing Performance of a Novel Hepatic Sinusoids-Based Micromixer

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***Abstract*— Recently, microreactor technology has been considered for carrying out reactions in different fields of application. A microreactor can be divided into three main parts; micromixer, reactor, and separator. The micromixer is the most important part of a microreactor as the reaction performance is highly dependent on the mixing performance. In this paper, an innovative hepatic sinusoids-based (HS) micromixer is introduced and numerically investigated for mixing performance. A 3-dimensional model is constructed to conduct the study. The mixing performance is described by both the mixing quality and the pressure drop across the micromixer. The study is conducted for low Re numbers ranges from 0.1 to 50, where the flow is considered stratified. Results show that the use of the developed micromixer enhanced the mixing performance over the studied range of Reynold numbers compared with regular micromixer.**

***Index Terms*— passive micromixer, hepatic sinusoids, mixing performance**

I. Introduction

Recently, microreactor technology has been considered for carrying out reactions in different fields of application, such as chemical industry, biotechnology, the pharmaceutical industry, clinical and environmental diagnostic, and food industry. It becomes a breakthrough technology on which the new concept of production and research are built upon. The use of microchannel in fabricating different micro processing units helps in enhancing mass and heat transfer rates which directly leads to better effectiveness. The small channel size also has many advantages. Besides the great increment in surface area to volume ratio, the unit becomes cheaper due to the low material, transportation, and energy costs. The unit is easier to be numbered up which makes it more flexible to withstand the market demands. For researcher, it is faster in transferring research results [1].

A microreactor can be divided into three main parts; micromixer, reactor, and separator. The micromixer is the most important part of a microreactor as the reaction performance is highly dependent on the mixing performance. The mixer function is to ensure a high mixing quality between interactive fluids by enhancing mass transfer due to both diffusion and convection. In general, micromixers are usually classified as active and passive. Active type uses an external energy source to produce turbulence to enhance the mixing process. On the other hand, in passive type, there is no need for external energy source and basically, it depends on different geometrical parameters to guide the flow during the mixing process. Over the years, both types of micromixers have been frequently reviewed [2-8]. Different proposed configurations of passive micromixers have been introduced. They depend on either multilamination principle [9-16] (i.e. creation of multiple

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interfaces) to increase molecular diffusivity or shape optimization to increase convective mixing [17-25].

Mixing quality can be described as a function of Reynolds Number (Re) through three different flow regimes [26, 27]. Stratified flow regime at which no eddies are prevailed, and molecular diffusion is the dominating mixing mechanism. This is usually found at low Re numbers. Through this region, the mixing quality decreases with Re because the residence time decreases. At moderate values of Re number, some eddies start to appear which balances the decrease in residence time. Thus, mixing quality remains almost constant. This is called vortex flow. At higher Re, flow instabilities become significantly stronger resulting in an increase of mixing quality with Re [28].

The objective of this paper is to introduce an innovative hepatic sinusoids-based micromixer and investigate its performance using computational fluid dynamics simulations. A 3-dimensional model is constructed to analyze the mixing performance of the proposed configuration. The mixing performance is described by both the mixing quality calculated at the mixer outlet and the pressure drop across it. The study is conducted for low Re numbers ranges from 0.1 to 50, where the flow is considered stratified.

II. Computational Model

An innovative hepatic sinusoids-based (HS) micromixer configuration is introduced in fig.1. The micromixer has two inlets for entering of two different fluids as shown in fig.1 (b). The mixture then diffuses in the hex-shaped configuration described in fig.1 (a) at which it meets circle obstructions in a staggered arrangement that helps in the destruction of the boundary layer and thinning the diffusion film which in turns enhances mass transfer by diffusion. Afterwards, the main stream is divided into six sub-streams located at the hex shape walls in which every three sub-streams are gathered in a divergent channel. Finally, the created two streams meet each other in a T-junction to reach the mixer outlet. For the numerical study, water and ethanol enter the micromixer from inlet 1 and inlet 2, respectively, with a mass ratio equals 1:1 and a constant temperature of 20 ^{o}C. The density and viscosity of water and ethanol are 999.8 kg/m^3 and 0.0009 Pa.s, and 789 kg/m^3 and 0.0012 Pa.s, respectively, with 1.2 X 10-9 m^2/s diffusivity.

Computational fluid dynamics (CFD) simulations are performed to investigate the flow and mixing behavior within the micromixer. A 3-dimentional model is constructed assuming multicomponent, steady, laminar, isothermal, Newtonian and incompressible flow. the three-dimensional mass, momentum, and species conservation equations are solved with the commercial CFD software ANSYS Fluent 19.0. Dilute approximation is used to model species transport due to diffusion. The SIMPLE algorithm is used to solve the pressure-velocity coupling with 10,000 iterations that give scaled residuals less than 10-6 for all cases.

Mass flow inlet conditions are used for both inlets, while the mass flow rates are calculated based on Re number, water properties, and the area of the T-junction end (1000 x 50 µm). Zero-gauge pressure outlet is used for exit face, and no-slip wall condition for the rest.

The mixing performance is described using both the mixing quality (M) at the exit section and the pressure drop (Δp) across the micromixer. The mixing quality and the pressure drop are calculated using the following equations:

$$M = \left(1 - \frac{1}{2}\sqrt{\sum_{i=1}^{N} \frac{\left(c_i - 0.5\right)^2}{N}}\right) \quad (1)$$

$$\Delta p = p_1 - p_o \quad (2)$$

where N is the number of nodes inside the cross section, c_i is water mass fraction at node, p_1 is the gauge pressure at inlet 1 in Pa, and p_o is the gauge pressure at exit section in Pa.

Unstructured mesh was created using ANSYS Meshing 19.0 software to discretize the domain. A mesh dependency study is performed to investigate the effect of mesh size on both mixing quality and pressure drop at Re=10 as listed in Table I. For the selected mesh sizes, both the mixing quality and the pressure drop slightly change. The case of 1,506,211 was selected for simulation.

The reactor was then fabricated from Polydimethylsiloxane (PDMS) using photolithography in order to validate the model. fig.2 shows the fabricated chip and its dimensions as observed under digital microscope (Keyence Digital Microscope VHX 1000). To examine the performance of the mixer, the mixer was loaded with two solutions, pure distilled water and 200 ppm congo red-water solution, through syringe pump, two 60 ml syringes and connecting tubes, as shown in fig.3. The pump was used to attain the required flow rates in the micromixer. Starting from Re of 50 to Re number of 1, real time images were captured at the outlet using a digital microscope. Then, they were converted to 32-bit images and examined using the open source image processing software (ImageJ 1.52a, NIH) by calculating the standard deviation in color intensity and comparing it with the mean intensity to calculate the mixing quality.

TABLE I. Effect of Number of Mesh nodes on Mixing Quality and Pressure Drop at Re=10

No. Of Nodes	M	%error	Δp (Pa)	%error
609,703	99.78%	0.29%	5076.56	8.36%
1,506,211	99.83%	0.35%	5292.51	4.46%
4,588,315	99.77%	0.29%	5471.42	1.23%
10,470,706	99.48%	0.00%	5539.41	0.00%

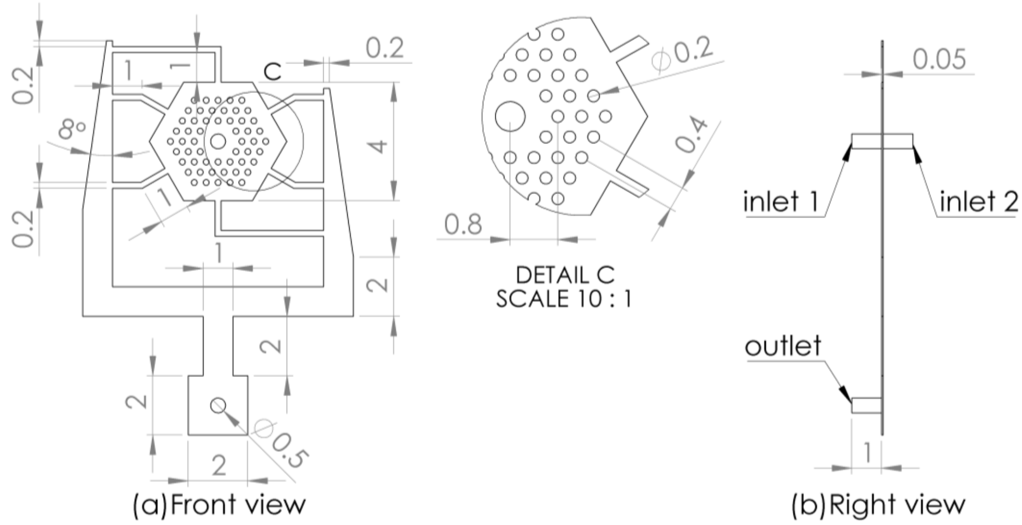


Figure 1. Different views of the hepatic sinusoids-based micromixer configuration describing inlets and outlets of the micromixer

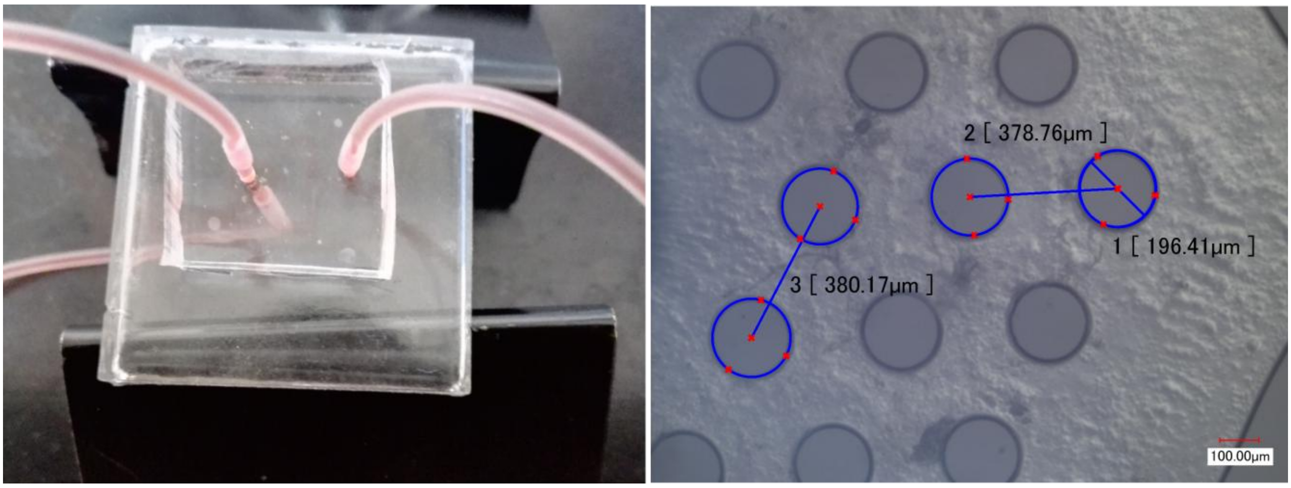


Figure 2. Fabricated micromixer and its dimensions

III. Results and Discussion

A. Model Validation

Validation of the model was done by comparing the results obtained from simulations with experimental results and with Soleymani et al. [26] for a regular T-Shaped micromixer as shown in fig.4. Both validation methods showed good agreement with satisfactory variance.

B. HS Micromixer Performance Compared with Regular Micromixers

Mixing qualities and pressure drops were calculated for the HS micromixer over a range of Re numbers from 0.1 to 50 and compared with that calculated from the T-shaped and the Cross-shaped micromixers shown in fig.5. The T-shaped and The Cross-shaped micromixers dimensions were chosen to ensure that the mixing channel has the same volume of the HS micromixer with a cross sectional area at the micromixers end of end 1000 x 50 µm. Comparison results are shown in fig.6 which indicates that the developed configuration has improved the mixing performance compared with the two regular configurations. Mixing qualities of more than 90% with relatively low pressure drops were obtained.

The high mixing qualities achieved result from the enhancement in mass transfer by diffusion and convection due to the existence of obstructions and the creation of multilaminated sub-streams afterwards as illustrated in fig.7. In addition of creating turbulence in flow, obstructions help in the destruction of the boundary layer and thinning the diffusion film which in turns enhances mass transfer by diffusion.

The molecular diffusivity is also enhanced due to the creation of multiple interfaces. Regarding the pressure drop, it is noticed that for all studied cases the pressure drop is about 4 times lesser than the values obtained from the T-shaped and the Cross-shaped micromixers. This may be because of the increment of the overall cross-sectional area of the created HS micromixer.

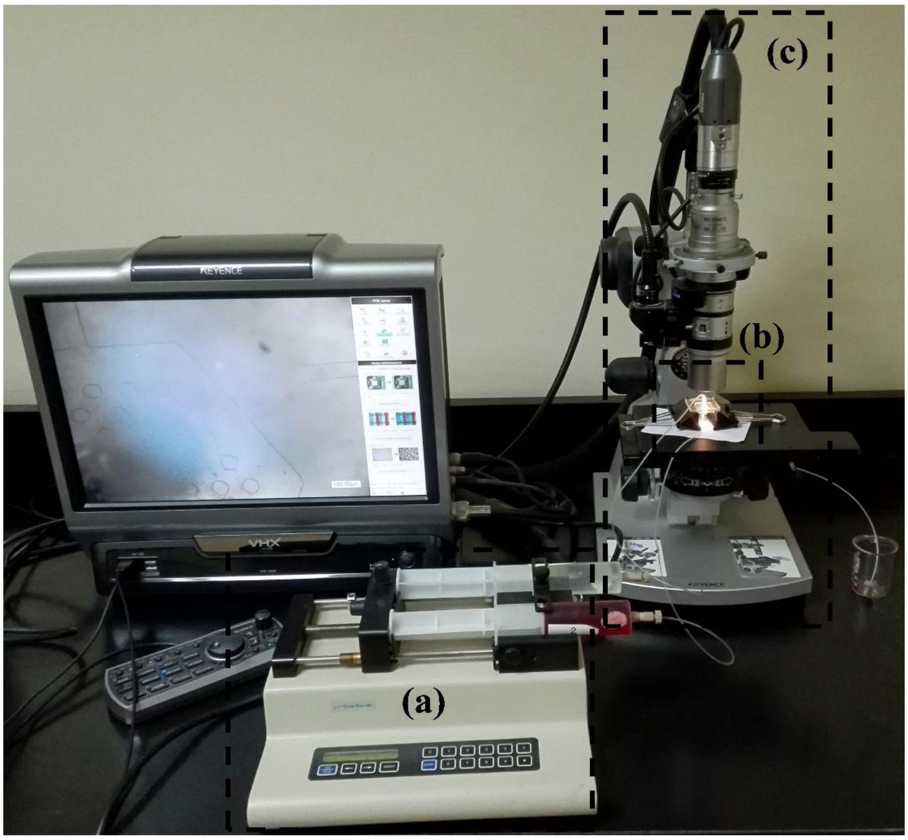
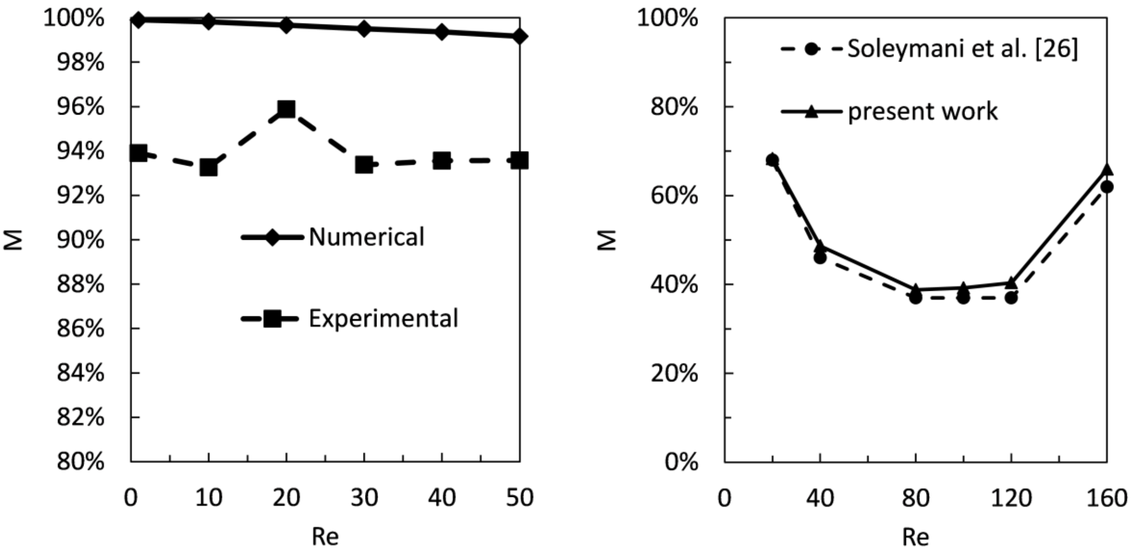


Figure 3. Experimental setup with; (a) the syringe pump, (b) the micromixer, and (c) the digital microscope



(a) (b)

Figure 4. Model validation; (a) comparing the mixing quality obtained from numerical simulations with experimental results, (b) comparing the present model with the model constructed by Soleymani et al. [26]

IV. Conclusion

The mixing performance of an innovative hepatic sinusoids-based micromixer was numerically investigated over a range of Re numbers from 0.1 to 50. Three different configurations were considered for this study; the first was the introduced micromixer and the other two were a T-shaped and a Cross-shaped micromixers with the same volume of the introduced micromixer. The results showed that use of the introduced micromixer enhanced the mixing performance regarding mixing qualities and pressure drops compared with the values calculated when using other regular micromixers. Mixing qualities of more than 90% with relatively low pressure drops (about 4 times lesser than the values obtained from the T-shaped and the Cross-shaped micromixers) were obtained.

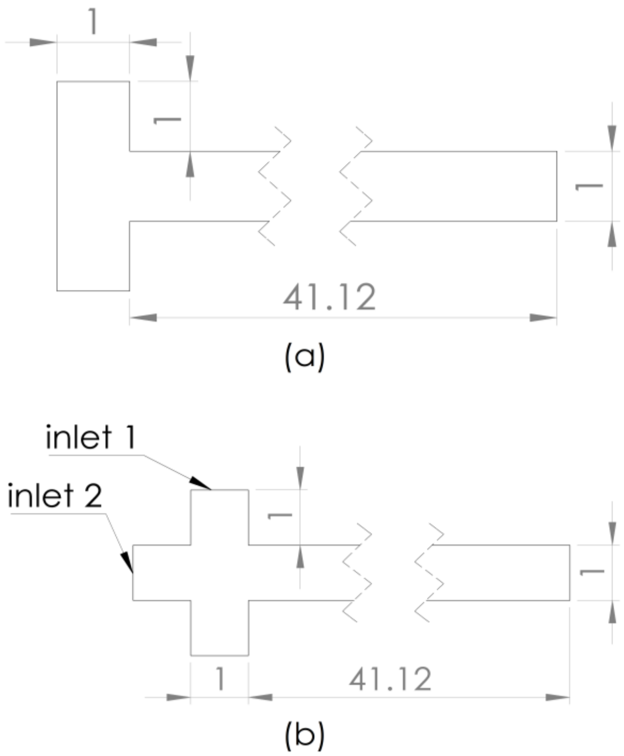


Figure 5. (a) T-shaped micromixer, (b) Cross-shaped micromixer

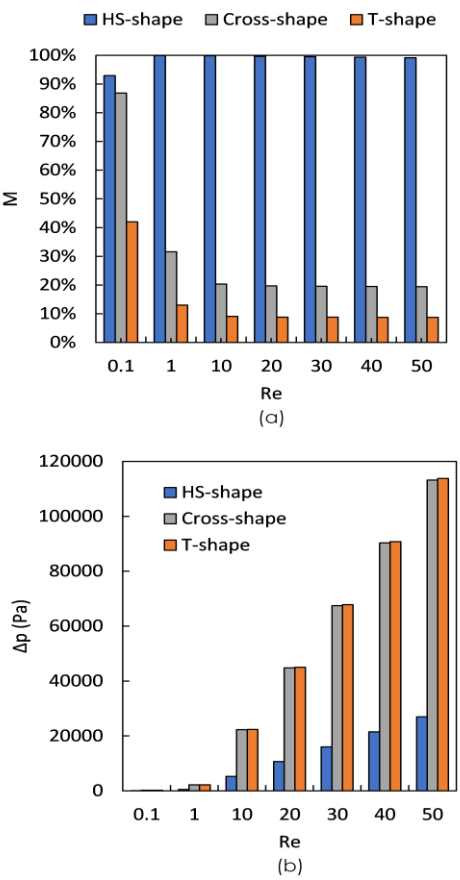


Figure 6. Mixing performance of HS micromixer compared with T-shaped and Cross-shaped micromixers

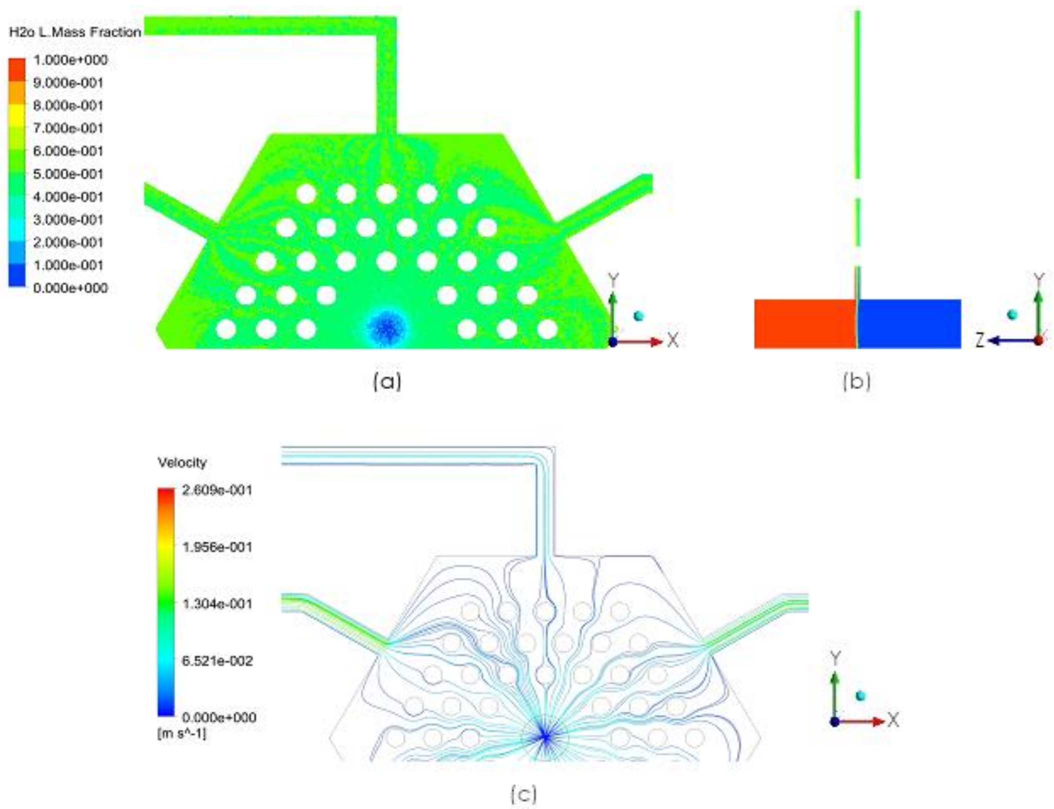


Figure 7. (a) Filled water mass fraction contour drawn at mid plane parallel to the streamlines, (b) filled water mass fraction contour drawn at mid plane perpendicular to the streamlines, (c) streamlines drawn at mid plane parallel to the flow direction

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mahmoud A. Shouman is a PhD student and the corresponding author which conducted the majority of the research and wrote the manuscript while the rest of the authors reviewed it. Ahmed H. El-shazly and Mohamed Nabil Sabry assisted Mahmoud A. Shouman to come out with the idea of the microreactor. Marwa F. Elkady helped throughout the experimental work.

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