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Numerical Investigation into Mixing Efficiency of T-Micromixers with Elliptic Barriers

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***Abstract*–This paper proposes a numerical study of the heat transfer and mixing properties of two liquid samples in a two-dimensional T- microchannel with and without elliptic barriers. The effects of various parameters such as mixing efficiency and thermal mixing efficiency and performance index, pressure drop have been analyzed and compared, at Reynolds numbers ranging from 5 to 500. The vortical structure of the flow is examined too.**
Modeling was performed for laminar flow using the CFD code with water/Al_2O_3 nanofluid at two volume fractions, base fluid (φ=0%) and nanofluid (φ=0.5%), and Three cases were chosen and simulated. The results indicated that adding elliptic barriers can enhance the mixing efficiency greater than 80%, performed considerably fine andhad a very good quality of performance compared to the standard T-mixer with the cost of a higher pressure drop.
Keywords: T-microchannel; Elliptic barriers ; Mixing efficiency; Performance index; Thermal mixing; Pressure drop.

1. Introduction

Mixing has a significant position in the process industries like food, polymer and chemical industries.
Mixing of fluids in micro-channels can be realized using either passive or active mixers, an external force are used to develop the mixing in the active mixers, [1] beside the passive mixers, they are easy to fabricate and there is no necessitate of external energy with low cost of manufacturing [2],an amount of micromixers have been build including passive or active mixers while the passive type are the most used [3].
To have uncomplicated designs, the typical Y, T shape and L-shaped [4 -7] designs have been experienced to affect the flow structures in the initial contact region of the mixer. A lot of work has been done on liquid mixtures and micromixers with Y and T type [8-10]. Micromixers with T- type have been shown to be ideal for liquid mixing for standard research and validation of blending processes in microreactors and micro mixers. They show a very decent productivity. There are a number of experimental and quantitative studies on the mixing and mixing systems in these micro mixers [11-13], therefore, diverse revisions in design and various processing configurations have been established with the mean of rising the mixing performance, by including obstacles within the channel [14,15].
The mechanism of mass transfer depends on the value of Reynolds, wherefrom low Reynolds (Re <8) mass diffusion is the predominant mechanism which is a very slow, while the advection is the dominant at moderate and high Reynolds numbers [16, 17].
In micromixers, splitting and stretching fluids (increasing the interfacial area) can be reduce diffusion length and enlarge the contact time, thus enhance mixing function. In (SAR) mixers [18,19], the split of fluid into an amount of laminar fluids and recombine them (lamination mechanism) is the principle mechanism used. Through different geometries including obstacles [20-22], ridges [23] grooves, [24,25] and curves [26,27], layers [28], baffles [29], were carried out to generate the chaotic advection by building of the transverse movement of flow through breaking, folding, stretching, the liquid to enhanced the mixing behavior and constructed an optimal design.
Gobby et al. [4] calculated numerically the gaseous mixing in T-shaped micro mixer in 2-D and studied the effect of varying fluid flow and geometric parameters on the implicated mixing length.
Wong et al. [5] numerically and experimentally calculated the flow mixtures into a T-shaped; they reported the effect of creation of secondary flows and vortices in enhancing of mixing performance.
Engler et al. [6] observed that even in small numbers values of Reynolds in T-shaped micromixers the vorticity can be developed in rectangular cross-sections this result was confirmed by experimental measurements and cfd simulation.
Bothe et al. [8] estimated the mixing manners within T-shaped micromixer. They showed that engulfment flow leads to more efficient mixing.
Kim et al. [30] Utilize 3-D barriers set in micromixers to improve microchannel mixing efficiency at low numbers of Reynolds.

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Arash et al [31] used various sizes of CBPs (cylindrical barrier pairs) to investigate the importance of fluid hydrodynamic tortuosity on fluid mixing quality, and reported the impacts of Reynolds numbers and every geometric pattern on the mixing performance.
Nichino et al [32] integrated a couple of anti-symmetric obstructions in the entrance channels close to the junction area of a variety of geometrical designs, the impact of the inlet was significant and mixing efficiency increased.

Chen et al. [33] used the fractal theory and global Murray's law to examine 2D T-type micromixers and Y-type micromixers and evaluated the impact of geometric factors on mixing performance and pressure loss.

Lee et al [34] proposed a numerical and experimental study of mixing efficiency through various geometries of barriers in micro-channels; they compared and reported the mixing performance of leaking side-channels with the elliptic-shape barriers.

The objective of this study is to examine the mixing performance in the micromixer of Lee et al. [34]. The Navier-Stokes equation is used in CFD (ANSYS-Fluent) codes with Reynolds numbers from 5 to 500 to study hydrodynamic, thermal mixing and flow structures. The effects of mixing performance with two working fluids water (φ=0) and nanofluid (φ=0.5), respectively in two different temperatures in the T-mixer with elliptic barriers are computed. Based on the results presented, the effects of sample concentration on the used fluids and design are discussed

2. Micromixer geometries

This micro-mixer was suggested by Lee et al [34], the micromixer is planned on the straight T-type channel, with 11 sets of elliptic barriers in the main channel, and its geometric characteristics are revealed in Fig. 1.
The axial length of all micromixers,), channel width (W), and height (H),are 15mm, 0.2mm, and 0.8 mm, in that order.

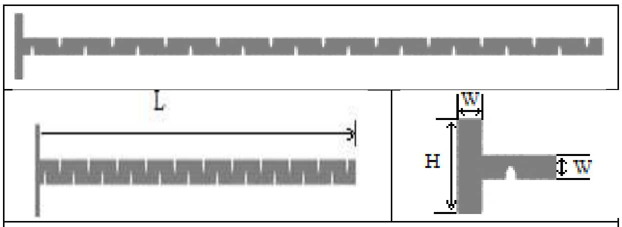

Figure 1: The geometric configuration of the T-micro mixer

3. Formulation and numerical method

The flow field of the micromixer is governed by the incompressible Navier-Stokes equations, the equations of the conservation of mass, conservation of momentum and species can be listed in the following types:

$$\nabla\vec{V} = 0 \quad (1)$$

$$(\vec{V}\cdot\nabla)\vec{V} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{V} \quad (2)$$

$$(V\cdot\nabla)C_i = D_i\nabla^2 C_i \quad (3)$$

Where, p, and ρcorrespond to the static pressure, and the fluid density,ν the kinematicviscosity. $C_i$and$D_i$representin that order the mass fraction and the coefficient of diffusion of the species"i"

Reynolds number is defined as:

$$Re = \frac{\rho v D_h}{\mu} \quad (4)$$

Dh: represents the hydraulic diameter of the channel.

The MI (mixing index) is calculated in the area of each part of the micromixer as follows [35, 36]:

$$M = 1 - \frac{\sigma}{\sigma_0} \quad (5)$$

Where σ is the SD (standard deviation) of the mass fraction of the mixture in the sampling area:

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(C_i - \bar{C})^2 \quad (6)$$

Where n indicates the whole number of sampling,C_i: the mole fraction at a measured position on the selection plane and $\bar{C}$: the average value ofC_i.$\sigma_0$is the SD at the inlet.

To quantify the thermal mixing we use the thermal mixing index (TMI) of the hot and cold fluids which is calculated as follows:

$$TMI = 1 - \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_i - \bar{T})^2}}{\sigma_0} \quad (7)$$

Where,$T_i$represents the temperature on node I,$\bar{T}$is the average temperature at the selection plane, and$\sigma_0$is the SD at the inlet.

3.2. Performance index (PI):

The performance index is an important measure that helps to evaluate the general performance in micromixers [37]:

$$PI = \frac{MI}{\Delta P} \quad (8)$$

To simulate the Newtonian fluid flows, pure water, dye-water and Water- Al_2O_3 Nanofluid were used. The nanofluid used is composed of 0.5 wt%, water as base fluid and 40 nm particles of Al_2O_3, the physical properties of the nanofluid are according to measures achieved by Ting et al. [38].

Boundary conditions:
The boundary condition of T-microchannel wall is no-slip condition and zero flux of sample concentration, and atmospheric pressure at the outlet, and all walls are considered adiabatic. Equal flow rates were considered at both inlets.
In case of thermal mixture: hot and cold liquid temperatures are separately 330 and 300 K.

Grid independency test:

Several meshes were made to validate the numerical results, so the grid of 441173 was chosen (Table1).in this analysis, the distinction among the mesh grids of 441 173and 1 060 459 doesn't surpass 2.01%. In calculation of mixing index using the standard deviation the difference does not exceed 0.34%.

Table1: Mesh independence test

Mesh	Standard deviation
140223	0.06136
218363	0.06499
388503	0.06817
441173	0.06918
514295	0.0693
552679	0.06932
1060459	0.0706

4. Results and discussion
4.1. Validation

A quantitative comparison has been realized for Newtonian fluids in order to ensure the numerical solutions obtained by the CFD code, the mixing performance was confirmed with numerical simulations of mixing value in a T-junction micro channel with Elliptic Barriers from Lee et al. [34]at Re=8 with2, 5, and 8 barriers. It is obvious from the table 2 that our results are very consistent with the results of Lee et al.

Table.2: Comparative mixing efficiency with Lee et al. [34].

	Mixing efficiency%		
Re=8	2br	5br	8br
Lee et al.	50.79	60.80	82.07
Present study	49,09	60.72	81,38
error	3.3%	0.13%	0.84%

4.2. Hydrodynamic behavior of the mixing evolution

4.2.1. Micromixer mixing performance

Numerical simulation is carried out for compared the mixing efficiency of pure water and nanofluid at the T-junction micromixer with elliptic barriers. On the mixing performance in Fig. 2, note that the lowest value of Reynolds takes the highest values of the mixing index where the molecule diffusion dominated with priority to the alumina nanofluid .In the range of Re between50and 500 in the mix channel, it can be seen that the mixing performance is affected by the advection and concentration level for moderate and high numbers of Reynolds. This figure shows that the (MI) rises as Reynolds number augments, with best mixing rates for water fluid compared to the nanofluid.

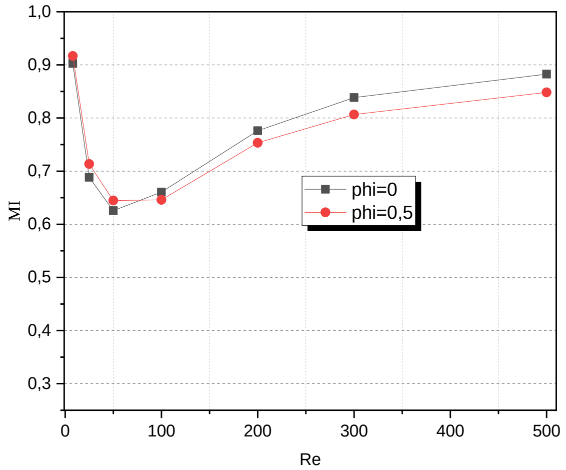

Figure 2: Development of mixing performance of water vs.nano (φ =0.5) with several Reynolds numbers.

A quantitative comparison was made. The mixing performance of T-micromixer with elliptic barriers was compared with kurnia micromixers with solid

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tape (Wt/D=0.8) [39]. As shown in Fig.3. The mixing indices were compared using the range of Reynolds number between 0.1 to 500. The T- micro mixer illustrates a superiority mixing performance compared to the other of kurnia et al.

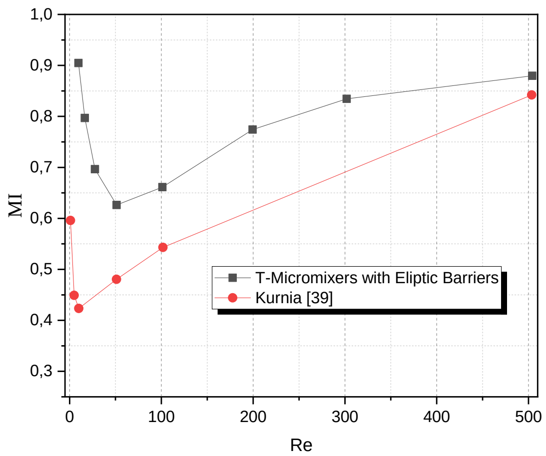

Figure 3: Variation of mixing index (MI) of Re compared with Kurnia et al. [39].

Fig.4 illustrates the mass fraction distribution in T-micromixer of the water fluid in several Reynolds numbers, which the liquid gradually splits into several thinner layers as the flow continues, thus, the inter-liquid interface area is enlarged to homogeneous the mixture.

For low and high Reynolds numbers the mixing arises after a short distance traversed by the fluid. It was observed that mass fraction profiles were developed greatly and this effect can be seen up to 33% of the mixer with elliptic barriers length. In later 67% of the element length, mass fraction was uniform and there is not much signifying mixing in the fluid for low Reynolds. For moderate Reynolds a homogeneous mixture less than for low and high Re is obtained, beside for all ranges studied the performance of the mixture is clearly improved.

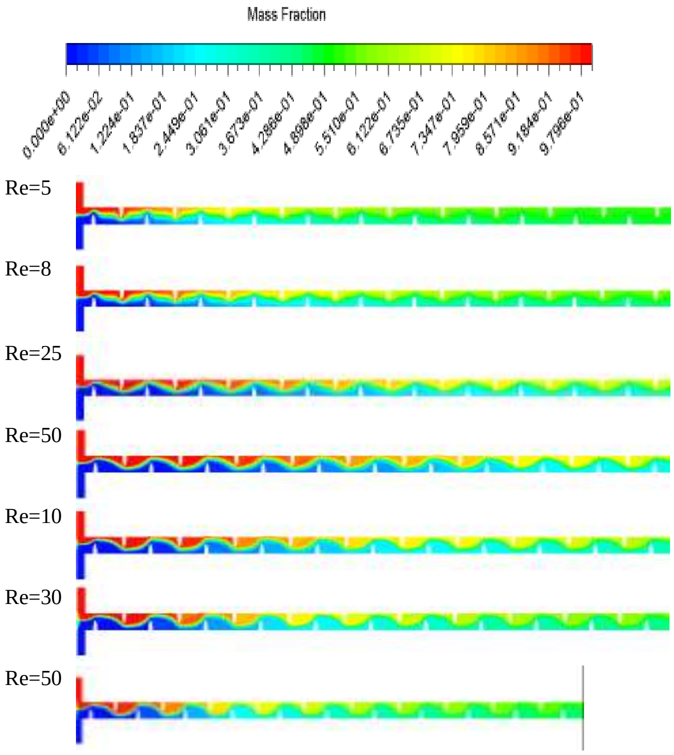

Figure.4: mass fraction distributions of the water fluid in T-micromixer

4.3. Thermal mixing performance:

Fig.5 demonstrates the difference in thermal mixing index (TMI) at the outlet, depending on the Reynolds number, it is clear that the transition interval between the diffusion manner for very low Reynolds numbers and the advection regime for medium and high Reynolds numbers is very small for that the geometric with elliptic barriers improves the thermal mixing performances. Thermal mixing promotes any raises in Reynolds numbers. Where the highest thermal mixing index is obtained in the nanofluid (φ = 0.5) with a small change in value after a large escalation of Reynolds.

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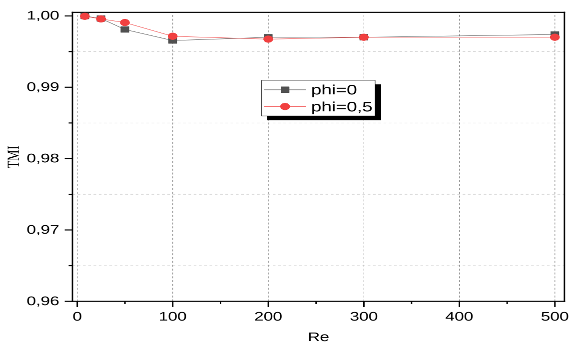

Figure .5: Evolution of thermal mixing performance of water vs. nano ($\varphi = 0.5$).

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4.4. The pressure drops:

The pressure drops of the mixing channel were computed as a difference between area-weighted averages of total pressure. In fig. 6, we compare the pressure drop results of water in microchannel without barriers and water and nanofluid in micromixer with barriers, the pressure loss increases with Renumber in all cases. We can see that the micromixer containing the nanofluid has higher pressure drops in all Reynolds numbers used than the other two liquids.

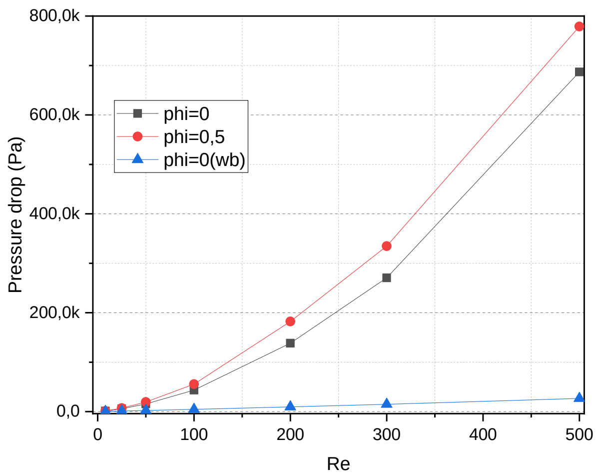


Figure .6: Evolution of the pressure drop with the different Reynolds number

The pressure drop obtained from simulations of T-micromixer with and without barriers was compared with the CSC micromixer and CSC without baffles [40]. As remarked in Fig. 7, the pressure loss with our simulation with elliptic barriers is more than that from CSC micromixer.

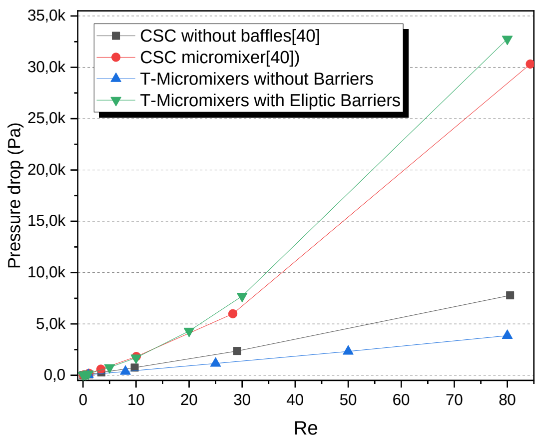


Figure .7: Pressure drop vs. Reynolds numbers compared with the micromixers of Tsai et al. [40]

The secondary flow and the vorticity amplified quickly with the Reynolds number, the effect of the escalating of Reynolds numbers on the vortex intensity of the fluid within three cases of nano with $\varphi = 0.5$ and water in elliptic barriers and without barriers (wb) are offered in Figure 8. When the Reynolds increases, the vorticity increases for all microchannels, it was evident that for $\varphi = 0.5$ the flows were strong, which was leading to elevated kinematic energy. Hence, for a specified value of Re, the dynamic flow is moreover influential for the chaotic flow inside micro channel with barriers.

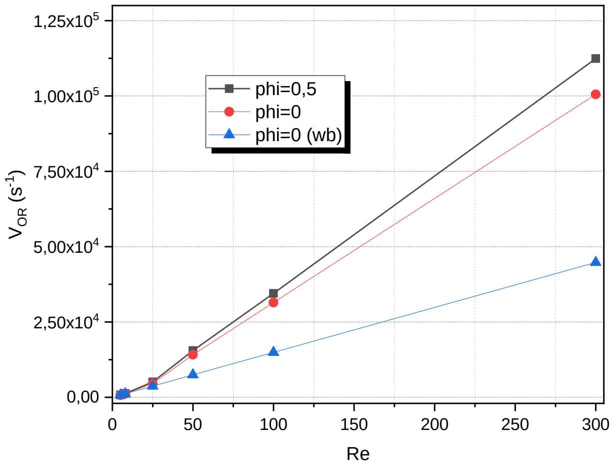
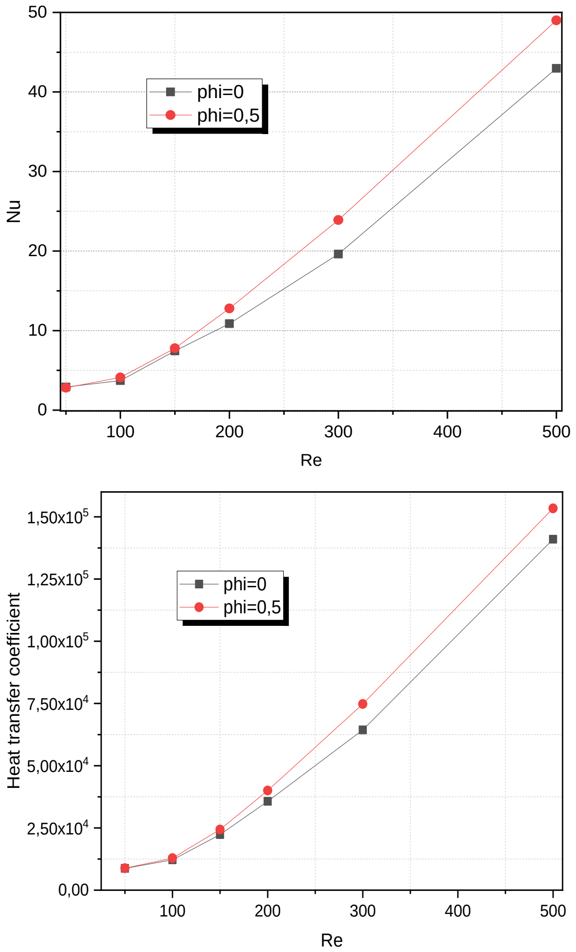


Figure .8: Variation of the vorticity with the different Reynolds number.

4.5. Convection coefficient and Nusselt number:

Fig. 9 shows the evolution of Nusselt number and Heat transfer coefficient in terms of Reynolds number with the change of (φ) in T-mixer with elliptic barriers. We notice that when the Reynolds number is approximately 100, the Nu and h accented their escalation.
Heat transfer coefficient and Nusselt augments with increasing of Reynolds, and the main values of (φ) carry the largest values of the Heat transfer coefficient and Nu number in the order.



(b)

Figure .9:The evolution of Nu number (a) and Heat transfer coefficient (b)as a function of the Re with different values of (φ)

4.6. Performance index

The comparison of the performance index with diverse Reynolds numbers for the 3 cases of micromixers is presented in Table 3.
From the results shown in Table 3, the PI decreases as the Reynolds number increases, for all simulated cases, it is evident that the micromixer with pure water shows more PI compared to that with nanofluid ($\varphi = 0.5$). However, the micromixer without barriers shows a better performance index; this is due to the low pressure loss in T- channel without obstacles.

Table 3. The performance index vs. Reynolds numbers

Re	PI (Performance index)		
	$\varphi = 0$	$\varphi = 0.5$	φ=0 (without barrieres)
8	7.22E-04	5.95E-04	2.03E-03
25	1.21E-04	1.01E-04	3.42E-04
50	4.03E-05	3.31E-05	9.82E-05
100	1.51E-05	1.16E-05	3.03E-05
200	5.6E-06	4.13E-06	9.7E-06
300	3.09E-06	2.4E-06	5.01E-06
500	1.28E-06	1.09E-06	3.22E-06

5. Conclusion

In this study, the mixing performance of a T- mixer with and without elliptic barriers in the microchannel has been evaluated and reported. A numerical investigation of mixture performance based on flow structure, thermal mixing of two liquids (hot and cold), mixing index, pressure drop, quantitative mass fraction, heat transfer, and many other indicators have been studied for different behavioral indicators with two φ ratios of nanoparticles and different numbers of Reynolds.
It was found that the adding of the elliptic barriers considerably augments the mixing performance. The use of nanoparticles provides the best mixing performance, specially at low to moderate Reynolds numbers, beside at higher Reynolds numbers, the basic fluid gives better results where mixing is dominated by mass convective. The results showed that the introduction of nanoparticles is recommended for enhancing heat transfer and mixing in low Reynolds. The secondary flow creates an improved convective mass transfer. That is why the mixing increases with the cost of a higher pressure drop for the T-mixer with elliptic barriers for the range of Re from100 to 500.

The future scope
Further work will focus on understanding the twisting, splitting and recombination mechanism of flow interfaces. More work is needed for different experimental tests for different miscible fluids, it will be more interesting to analyze the RTD (residence time distribution) with this design and can be extended to other possible micromixer designs.

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