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Micro T-Mixer with Baffles: Effect of Baffle Height and Setting Angle on Mixing

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Abstract

Chaotic mixing in eight different types of micro T-mixer flow has been studied experimentally and numerically. The present experimental study was performed to visualize two-liquid flows in a micro T-mixer with baffles. The Reynolds number, baffle height and setting angle were varied to investigate their effect on the mixing performance. Three micro T-mixer models were produced, which are several centimeters long and have a rectangular cross-section of few millimeters a side. The mixing of two-liquid was measured using the laser induced fluorescence (LIF) technique. Moreover, three-dimensional numerical simulations were conducted with the open-source CFD solver, OpenFOAM, for the same configuration as used in the experiments to investigate the detailed mechanism of the chaotic mixing. As a result, it was found that the mixing of two-liquid is greatly improved in the micro T-mixer with baffle. The baffle height and setting angle show a significant influence on the mixing performance.

Keywords

Micromixer, Baffles, Liquid-Liquid Mixing, LIF, CFD

1. Introduction

Recent advancements in microfabrication technology have led to the development of microdevices composed of microstructures, which are widely used in various fields such as biotechnology, medicine, and chemistry. In analytical chemistry, μTAS (micro total analysis system) and Lab-on-a-Chip are being put to practical use, and in synthetic organic chemistry, microreactors are being studied [1]. The microdevices used in these fields require the mixing of different liquids, therefore, they are equipped with built-in micromixers, and the micromixer is an important component that greatly affects the performance of the microdevice. However, the micromixer consists of microscopic channels, generally the flow is laminar with a low Reynolds number, and a physical mixing by turbulence cannot be expected. The mixing in a laminar flow occurs mainly by molecular diffusion and requires a long time for the mixing to occur. Therefore, a micromixer operating in a laminar flow regime, which can perform a high-efficiency mixing in a short time period is in great demand.

Micromixers are divided into active and passive micromixers based on the mixing method. Active micromixers mainly use external forces such as the electric field [2] and magnetic field [3] to promote mixing, therefore, they require complex driving devices. Passive micromixers use the shape of the flow path to promote mixing, which allows the equipment to be smaller and more space-saving. Investigations of channel geometries that promote mixing have been conducted, and numerous reports have shown that complex channel geometries are advantageous for mixing [4]. On the other hand, there are contradictions in practical applications because complex channel geometries create stresses in design. T-shaped micromixer, which has baffles in the flow channel to facilitate mixing, is a relatively simple structure that reduces stress in design. A baffle is a plate-shaped obstacle installed in the flow path to disturb the flow. Therefore, T-shaped micromixer with baffles was adopted in this study. In a previous study, the effect of baffle and setting angle on the mixing performance was investigated for Reynolds number in a range of $1 \le Re \le 10$, and the setting angle of the baffle was varied in a range of $0^\circ \le \theta \le 45^\circ$. In this study, the results of micro T-mixer without and with baffles were compared and reported that the baffle angle of $\theta = 15^\circ$ showed a high mixing index and a small pressure loss within the flow regime ($Re \le 10$) [5].

In the present study, to enhance the mixing in the laminar flow, a T-shaped micromixer with baffles was adopted. The optimum installation conditions of the baffle were investigated by an experimental work and a computational fluid dynamics (CFD) analysis.

2. Methods

2.1. Experimental Method

Figure 1 shows a schematic diagram of the experimental setup. First, the experimental model was placed in a viewing block to facilitate observation of the flow, and the surrounding area was filled with water. Next, a syringe pump was used to inject working fluids (water and colored water with 0.04% fluorescent paint dissolved in water) at a constant flow rate. The working fluids enter through two inlets, mix in the channel area of the micro T-mixer, and finally, the mixed fluid exists through one outlet. The flow rate Q [mL/min] was calculated for each Reynolds number Re from the cross-sectional area of the mixing area.

Figure 2 shows the micro-channel model used in the experiment. The dimensions of each part of the experimental model are given in Table 1. In this study, in order to investigate the effect of different baffle angles θ [˚] on the mixing performance, experiments were conducted on full-scale models with $\theta = 0˚$ and $\theta = 45˚$ to compare the baffle angles based on the results of a previous work [5]. The geometric configuration of the baffle section is shown in Figure 3. Moreover, to investigate the effect of the baffle height in proportion to the channel height, h_b [%], on the mixing performance, numerical analysis and full-scale experiments were conducted for the case of $\theta = 0˚$. Figure 4 shows the configuration of the baffle section for each baffle height, h_b. In addition, for the comparison of baffle heights, models with h_b = 100% and 75% were used based on the results of the numerical analysis.

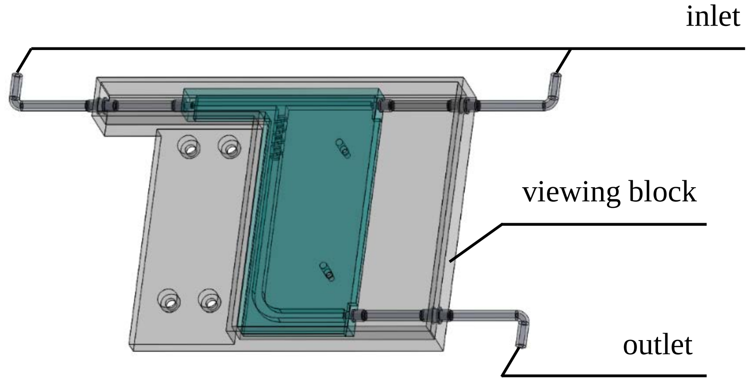


Figure 1. Experimental setup.

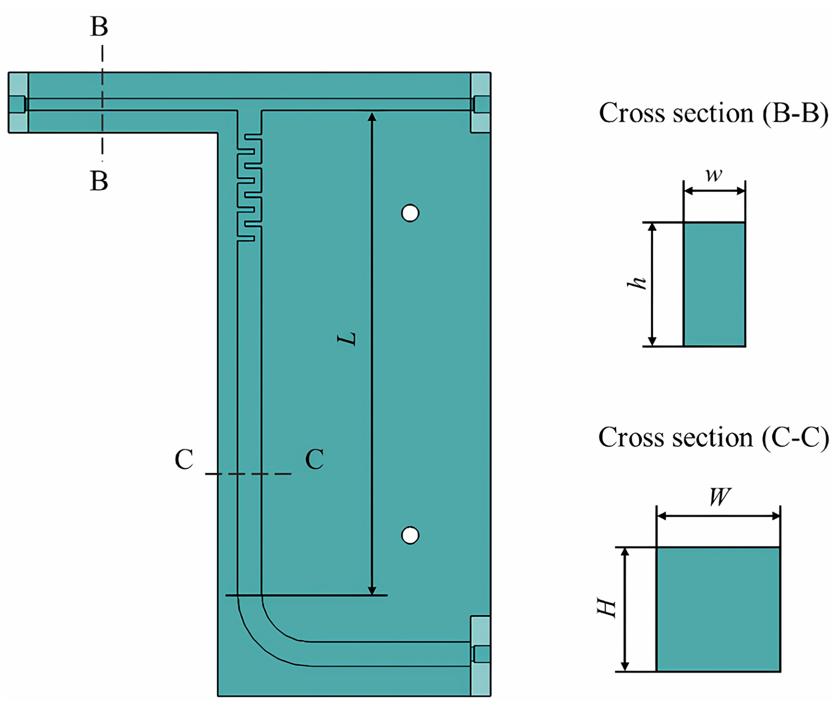


Figure 2. Experimental model.

Table 1. Dimensions of experimental model.

L [mm]	*w* [mm]	*h* [mm]	*W* [mm]	*H* [mm]
120	3	6	6	6

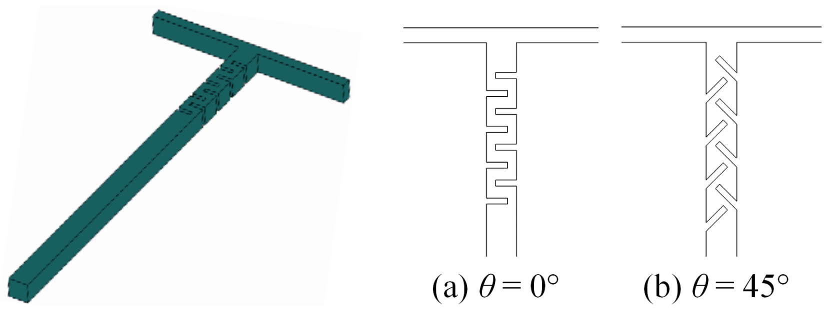


Figure 3. Baffle setting angle.

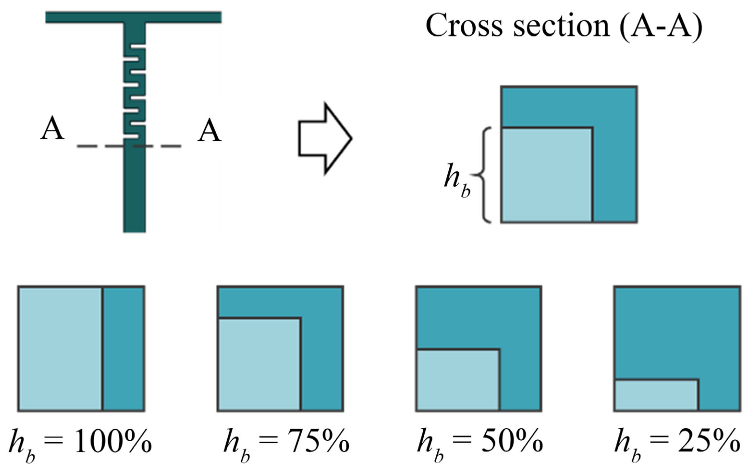


Figure 4. Baffle height.

2.1.1. LIF

The mixing of two liquids was measured using laser induced fluorescence (LIF). The mixing index was calculated from the LIF images taken at different cross-sections in the channel. The fluorescent dye used is the Central Techno Sunlumisis ink with excitation wavelengths of 365 nm to 375 nm and fluorescence wavelength of 510 nm, and a UV laser (CET190904-7375, Central Techno) with a wavelength of 375 nm was used as the light source for visualization. A high-speed camera (LaVision HSS-4G) was used to capture images, and the fluorescence intensity distribution was calculated from the acquired images using LaVision DaVis10.

2.1.2. PIV

To calculate the flow field, particle image velocimetry (PIV) measurements were performed by photographing the main flow near the baffle. A working fluid mixed with tracer particles (EBM FLUOSTAR) with excitation and fluorescence wavelengths of 550 nm and 580 nm, respectively, was introduced into the flow channel. The flow field was calculated from the obtained images using LaVision DaVis10.

2.2. Computational Analysis

2.2.1. Computational Method

In this study, the computational work was performed to replicate the experimental work, and in this work, simulating the mixing of two incompressible fluids, the Navier-Stokes equations formulated by continuity equation, alpha diffusion equation and momentum conservation equations were used as the governing equations. The twoLiquidMixingFoam solver [6], which is a solver for mixing two incompressible fluids in OpenFOAM, was used for simulating the problem.

2.2.2. Computational Conditions

Water (liquid 1) and colored water (liquid 2) flow into the micromixer from two inlets (inlet 1 and inlet 2, respectively) as shown in **Figure 5**. The two liquids are mixed in the channel, and finally, the mixed flow is discharged from the outlet.

The computational domain was meshed with 3D structured mesh elements by using the snappyHexMesh utility [6] in OpenFoam. The velocities at each inlet were set steady and parabolic, consistent with the realistic channel flow. The no-slip boundary conditions were applied to the solid walls. At the channel outlet, a zero-gradient or outflow condition was imposed. Since the simulation is incompressible, only the pressure gradient is relevant, and therefore, the outlet pressure was set to a reference value of zero.

3. Results and Discussion

Mixing index M indicating the degree of mixing in the channel was evaluated by the following equations [7].

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

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(C_i - \overline{C_m}\right)^2} \tag{2}$$

where C_i is the concentration at each point, C_m is the average concentration, and N is the number of sampling points at a given cross-section. σ is the standard

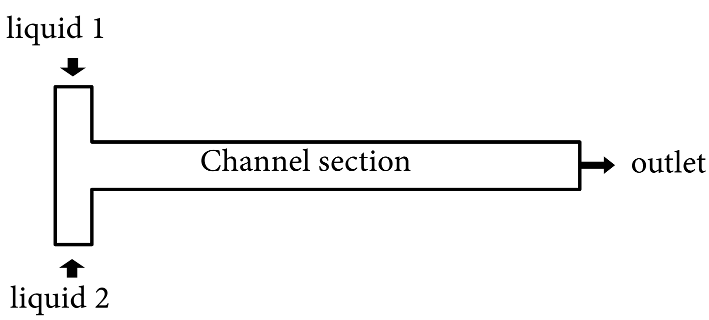


Figure 5. Schematic diagram of micro T-mixer.

deviation of mass fraction at a given cross-section, and σ_{max} is the maximum standard deviation of mass fraction. From the equation, M approaches 1 as the mixing performance reaches the maximum.

3.1. Effect of Baffle Setting Angle on Mixing

3.1.1. LIF

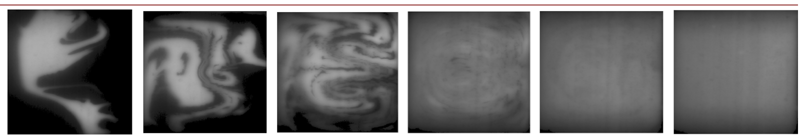
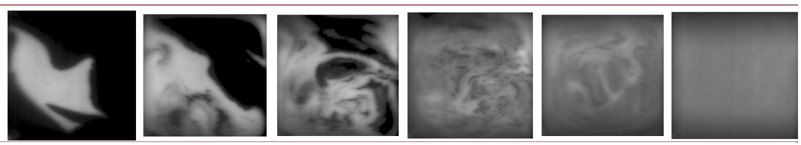
Table 2 shows the images obtained from the LIF measurement. Figure 6 shows the results of the mixing index M calculated from the LIF images in Table 2 using Equations (1) and (2).

Table 2 and Figure 6 show that for $Re \geq 100$, both setting angles of the baffle of $\theta = 0^\circ$ and 45° have a good mixing condition, and the mixing index approaches to $M = 0.8$, while in a range of $10 \leq Re \leq 75$, the mixing index for the setting angle of $\theta = 0^\circ$ is higher than that for $\theta = 45^\circ$.

3.1.2. PIV

Table 3 shows the flow field around the baffle obtained from the PIV measurements. Note that for $Re = 10$, the vector scale is increased by a factor of 5 over the others.

Table 2. Effect of baffle setting angle on mixing process by LIF.

	$Re = 10$	$Re = 50$	$Re = 75$	$Re = 100$	$Re = 150$	$Re = 200$
$\theta = 0^\circ$						
$\theta = 45^\circ$						

0 50 100

Concentration [%]

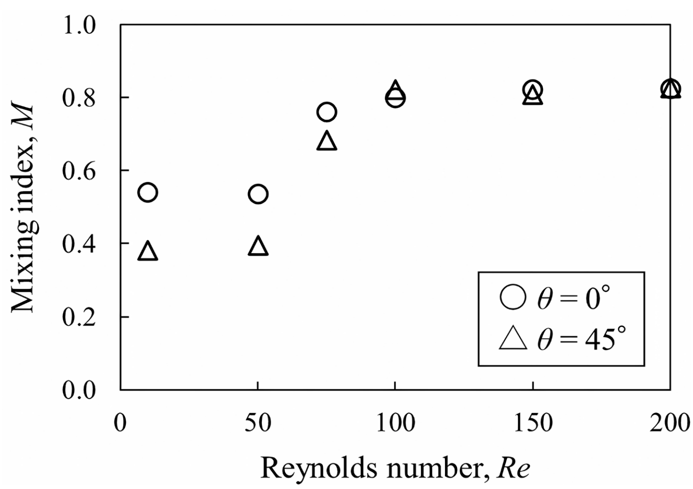
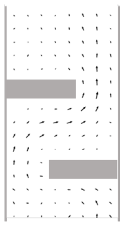
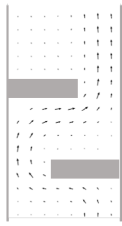
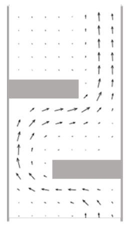
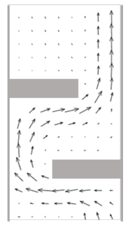
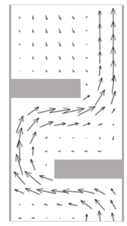
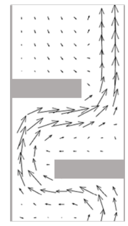
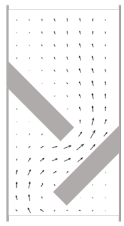
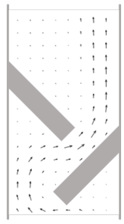
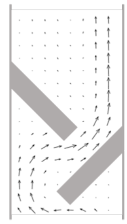
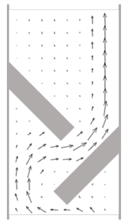
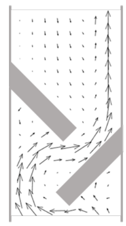
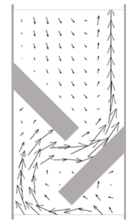


Figure 6. Effect of baffle setting angle on mixing index in micro T-mixer.

Table 3. Flow patterns of PIV.

	$Re = 10$	$Re = 50$	$Re = 75$	$Re = 100$	$Re = 150$	$Re = 200$
$\theta = 0^\circ$						
$\theta = 45^\circ$						
						↗: 57.9 mm/s

The flow field at baffle setting angle $\theta = 45^\circ$ shows that for $10 \leq Re \leq 75$, a dead water zone occurs at the base of the baffle. This suggests that the dead water area did not promote an increase in the interface and reduced the mixing rate.

3.2. Effect of Baffle Height on Mixing

3.2.1. Numerical Simulations

The effect of baffle height on mixing in the flow channel was investigated, and the relationship between the height of the baffles in the channel and mixing index is shown in **Figure 7**. Here, the results for the baffle heights of h_b = 25%, 50%, 75%, and 100% of the channel height (H) are presented in the figure, and it was found that the mixing performance is high in the range of $Re > 10$. Moreover, a high mixing index can be obtained when the baffle heights are h_b =75% and 100% of channel height.

3.2.2. Experiment

Table 4 shows the LIF images with h_b = 75% and h_b = 100% obtained from the actual experiment, and **Figure 8** shows the results of calculating the mixing index from the images in **Table 4**.

Comparing h_b = 75% and h_b = 100%, similar mixing conditions were obtained, indicating a similar trend to the results of the numerical analysis. However, the mixing index of the experimental results is generally lower than that of the numerical analysis. There are two main reasons for this. One cause in the numerical analysis is thought to be an error due to the shape of the mesh. This error can be reduced by changing the mesh shape from tetrahedral to hexahedral or by increasing the number of meshes. A possible cause of the error in the actual experiment could be the error in the LIF measurement. When the laser sheet was irradiated into the channel, the laser was attenuated at the edges of the channel, which weakened the fluorescence intensity and reduced the mixing index.

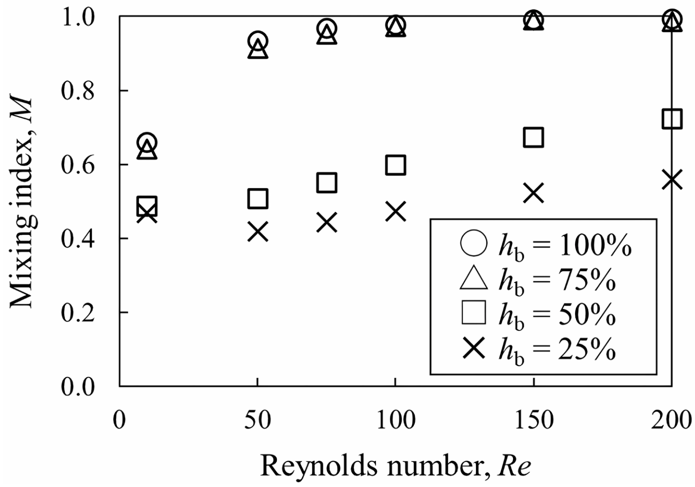


Figure 7. Effect of baffle height on mixing index at setting angle $\theta = 0^\circ$ by CFD.

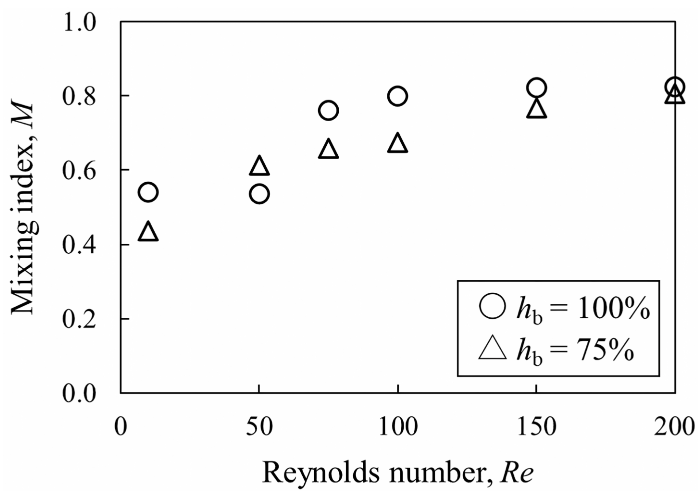
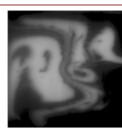
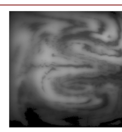
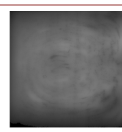
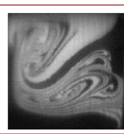
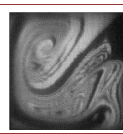
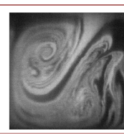
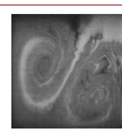
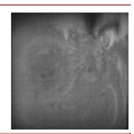
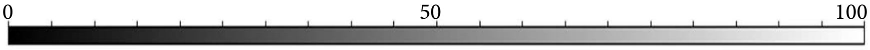


Figure 8. Effect of baffle height on mixing index at setting angle $\theta = 0^\circ$ by LIF.

Table 4. Effect of baffle height on mixing process by LIF.

	$Re = 10$	$Re = 50$	$Re = 75$	$Re = 100$	$Re = 150$	$Re = 200$
h_b = 100%						
h_b = 75%						

0 50 100



Concentration [%]

3.3. Comparison of Pressure Loss

To investigate the effect of changing the baffle height on the pressure loss, the inlet and outlet pressures were calculated numerically to obtain the pressure loss

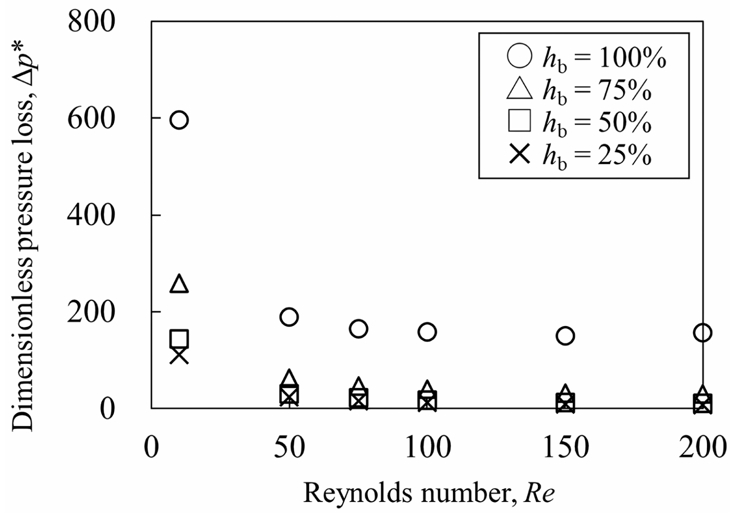


Figure 9. Effect of baffle height on pressure loss at setting angle $\theta = 0^\circ$ by CFD.

Δp. For the baffle height of h_b = 25%, 50%, and 75%, the non-dimensional pressure loss Δp^* was calculated using Equation (3) to evaluate the pressure loss since the model was scaled by one-fifth of h_b = 100%. Where ρ is the fluid density kg/m³ and v is the mean velocity m/s.

$$\Delta p^* = \frac{\Delta p}{\rho v^2} \tag{3}$$

Figure 9 shows the results of the calculated dimensionless pressure loss Δp^*. This figure shows that Δp^* is smaller for h_b = 25%, 50%, and 75% compared to h_b = 100%. Therefore, a change in baffle height has the effect of reducing pressure loss. In particular, h_b = 75% is a suitable baffle shape because it reduces pressure drop without decreasing mixing performance.

4. Conclusions

In this study, the effects of the ratio of baffle height to channel height and the baffle setting angle on the mixing performance were investigated through experiments and numerical analyses. The results revealed the followings.

- While in a range of $10 \le Re \le 75$, the mixing index for the baffle setting angle of $\theta = 0^\circ$ is higher than that for $\theta = 45^\circ$.
- For baffle height of h_b = 75%, the mixing index is similar to h_b = 100%.
- For $10 \le Re \le 200$, a battle of $\theta = 0^\circ$ and h_b = 75% can be considered as a suitable baffle configurations in terms of both mixing index and pressure loss.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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