Chemical Engineering Journal 162 (2010) 760–767

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Mixing performance of unbalanced split and recombine micomixers with circular and rhombic sub-channels

Mubashshir Ahmad Ansari, Kwang-Yong Kim *

Department of Mechanical Engineering, Inha University, 253 Younghyun-dong, Nam-gu, Incheon 402-751, Republic of Korea

ARTICLE INFO

Article history:
Received 1 March 2010
Received in revised form 27 May 2010
Accepted 28 May 2010

Keywords:
Micromixer
Mixing index
Unbalanced split and recombine
Navier–Stokes equations
Pressure drop

ABSTRACT

Mixing performance has been evaluated for planar split and recombine micromixers with asymmetric sub-channels. The three-dimensional Navier–Stokes equations have been used to analyze fluid flow and mixing in a Reynolds number range from 1 to 80. The widths of the split channels are kept unequal to create unbalanced collisions of the fluid streams. Two shapes of the split channel have been considered; circular and rhombic. In the case of rhombic sub-channels, higher mixing is realized when width of the major sub-channel is either three or four times as wide as the minor sub-channel unlike the case of circular sub-channels. The results show the lowest mixing performance for the case of balanced collisions of fluid streams. The pressure-drop characteristic has been also analyzed at various Reynolds numbers.

1. Introduction

Mixing of fluids in channels of sub-millimeter dimensions is a fundamental operation required on microfluidic devices. The flow in such devices is laminar which makes it difficult to mix the fluids in a simple smooth microchannel. A wide variety of micromixers, operating on different mixing principles have been extensively reported by different researchers [1,2]. Micromixers can be broadly classified as active and passive micromixers. The active micromixers employ some external sources of energy to agitate the flow such as electric fields, magnetic fields, and acoustic waves [3–6]. Although active micromixers are effective in rapid mixing of the fluids, it is more difficult to fabricate, integrate and operate as compared to passive micromixers. The complex fabrication and integration of active micromixers with all operating devices is expensive and renders mass production difficult.

Passive micromixers are based on shape modification of the microchannels to produce a specific flow pattern which enhances mixing. The very basic design strategy is to make a series of bends to microchannels in different shapes, e.g., serpentine [7], zigzag [8], and curve [9], to create transverse flows to attain rapid mixing. Patterning on the wall floor with grooves to create chaotic flow has also been demonstrated to be utilized in mixing enhancement [10,11].

One of the important design categories of the passive micromixer belongs to split and recombine of microchannels [12–27] where the main channel is split into two or more streams and then the sub-channels recombine after certain distance in a repetitive fashion. The split sub-channels can be three-dimensional or planar. In three-dimensional split and recombine micromixers, the fluid streams are directed to create multiple interfaces. In such design, thus, the interface area increases gradually by directing the fluid streams in a specific pattern through the split channels and the length of diffusion for the molecules decreases which are favorable for effectively enhancing mixing [13–22]. However, the three-dimensional structure is difficult to fabricate and demands multiple steps in the microfabrication process as compared to planar split and recombine micromixers.

Planar split and recombine micromixers have been studied from simplest design with multiple streams [23–28]. Bessoth et al. [23] reported a design of planar split and recombine micromixer with a total of 32 streams, which showed efficient mixing. The major reason in attaining rapid mixing was the large number of streams. Jeon et al. [24] reported a micromixer with three sub-channels that explored the idea on recycle flow from two side channels joining the main central channel.

The simple split and recombine micromixers have been studied with some design modification to attain improved mixing. The design of the split and recombine micromixers with two channels has been modified by some researchers in order to attain rapid mixing [25–27]. Hong et al. [25] applied an innovative idea using modified Tesla structure for mixing in a wide range of flow rates. The design shows diffusive mixing at low flow rates and convective mixing at high flow rates. The main principle in mixing is Coanda effect which increases the transverse dispersion. The mixing efficiency was increased by providing constriction to the flow in the zone of split and recombine with the sub-channels of rhom-

* Corresponding author. Tel.: +82 32 872 3096; fax: +82 32 868 1716.
E-mail address: kykim@inha.ac.kr (K.-Y. Kim).

1385-8947/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2010.05.068

bic shape [26,27]. The design of the split channels was modified to butterfly shaped with sharp folded channels for providing stirring action to mix the fluids with equal width of the two split channels [28]. These were few reported techniques to enhance mixing performance of the planar split and recombine micromixers.

In case of the split and recombine microchannel with two symmetric split sub-channels, it is difficult to mix the fluids at lower Reynolds numbers, where the mixing is mainly governed by molecular diffusion. In that case, the fluid streams will split and recombine without creating any perturbation to the interface of the fluid streams. The flow structure at a junction of split and recombine resembles to the flow in simple T-mixers where the two streams from the inlet channels come into contact at the T-junction. The design is effective in mixing of fluids only at higher Reynolds numbers [29,30]. At higher Reynolds numbers, collision of the fluid streams due to the effect of split and recombine improves mixing performance.

However, in the above mentioned planar split and recombine micromixers, the mixing is mainly due to constrictions to the flow [26,27]. The rhombic micromixer has constriction in the recombine zone and at the end of the micromixer. The idea of providing constriction to the flow is not novel as it can be applied to any design of microchannel in order to harness the reduced length of the diffusion for the fluid molecules for increasing mixing. Also, providing constriction to the flow will require higher pumping power due to higher pressure drop. However, in a planar micromixer with two splits without any constriction, the mixing will not be effective as it will create straight interface similar to T-mixers. The zone of recombination of the fluid streams can be the point of focus to convert simple recombination into collisions of the fluid streams to increase mixing. A basic concept of unbalanced collisions of fluid streams for enhancing mixing in planar split and recombine micromixers was proposed in a previous work [31] with numerical and experimental results for circular sub-channels. In this work, the remarkable effectiveness of the unbalanced collisions was verified by evaluating the mixing performance in comparison with the balanced collisions with symmetric sub-channels.

In the present work, the mixing performances of planar split and recombine micromixers with rhombic and circular sub-channels are evaluated numerically when the design of unbalanced collisions [31] is introduced. The analyses of the flow and mixing have been performed by solving three-dimensional Navier–Stokes equations in a range of Reynolds number from 1 to 80. The main channel of the micromixers is split into two subchannels (rhombic or circular shape) of unequal widths in a repeating manner. The micromixer has been analyzed by fixing the flow area in the sub-channels for different levels of unbalance in the collisions controlled by varying the width ratio of the split subchannels.

2. Micromixer model and numerical analysis

Fig. 1 shows the schematic models of the micromixer with the main channel splitting into two sub-channels of unequal widths for circular (Fig. 1(a)) and rhombic (Fig. 1(b)) shapes. The micromixers have total four units of split and recombination. The sub-channels with wider width has been named as major sub-channels while the other as minor sub-channels. The main idea of asymmetric sub-channels is to create unbalance collisions due to the difference in the inertia of the fluid streams from two sub-channels to enhance mixing.

The various dimensions of the micromixer are $w = 300\,\mu\text{m}$, Lo = 500 μm, Le = 2.95 m, and d_o = 900 μm. The pitch, Pi (=1.2 mm), is fixed and the same in both cases (circular and rhombic sub-channels). The widths of the sub-channels are varied with fixed total width which equals to the width of the main channel ($w_1 + w_2 = w = 300\,\mu\text{m}$) in order to maintain constant area of flow. The widths of the main channel, major and minor sub-channels are denoted by w, w_1 and w_2, respectively. In varying the widths of the sub-channels, the outer wall is shifted keeping the inner wall fixed for both circular and rhombic shapes. The height of the micromixer model has been kept constant at 200 μm for both circular and rhombic shapes.

The steady, incompressible flows in the micromixers are analyzed by solving three-dimensional continuity and Navier–Stokes equations:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho(\vec{V} \cdot \nabla)\vec{V} = \nabla p + \mu \nabla^2 \vec{V} \tag{2}$$

Computational domain has been discretized by structured grids. The mesh density was kept high near the zone of split and collision of the fluid streams. The details of the numerical methods including numerical schemes and discretization methods can be found in the previous paper [32]. Ethanol and water have been selected as the working fluids for mixing analysis. The two inlets have been assigned with 100% water and 100% ethanol, respectively, which come into contact at the T-junction and the pass through a series of the split and recombine mixing segments. The inlets and outlet have been assigned uniform velocity profile and zero static pressure as boundary conditions. The Walls have been assigned no slip boundary condition. The properties of the water and ethanol are measured at 20 °C. The diffusivity of water and ethanol is commonly taken as $1.2 \times 10^{-9}\,\text{m}^2\,\text{s}^{-1}$. The densities of water and ethanol are 9.97×10^2 and $7.89 \times 10^2\,\text{kg/m}^3$, respectively.

Along with investigating the mixing and flow field in the micromixer, it is critical to quantify mixing in order to compare the mixing performance of different designs. The mixing performance of the micromixer has been measured by calculating the mixing index from the variance of the mass fraction on planes perpendicular to x-axis defined as follows:

$$\sigma^2 = \frac{1}{N}\sum (c_i - \bar{c}_m)^2 \tag{3}$$

$$M = 1 - \sqrt{\frac{\sigma^2}{\sigma^2_{\max}}} \tag{4}$$

where σ^2 is the variance, $\sigma^2_{\max}$ is maximum variance of the fluid mixture, c_i is the mass fraction at ith sampling point on the plane. $\bar{c}_m$ is the optimal mixing mass fraction and M is the mixing index. N represents the number of the sampling points for the concentration on the plane. M_o denotes the value of the mixing index at 5.5 mm downstream of the end of the last sub-channels.

3. Results and discussion

The mixing performance and fluid flow in the design of the micromixers based on unbalanced spits and collisions of the fluid streams [31] has been analyzed numerically. Fig. 2 shows the samples of structured grid systems for circular and rhombic sub-channels, respectively. The mesh density is adjusted so that it becomes higher near the regions where the split and cross-collision of fluid streams take place. Fig. 3 shows the results of the grid independency test with five different grid systems wherein the number of nodes ranges from 320×10^3 to 2250×10^3 for circular sub-channels with $w_1/w_2 = 2.0$. From the results of this test, the grid system with 1560×10^3 nodes has been selected as the optimum grid system on which further analyses are performed.

Fig. 4 shows the contour-plot of the velocity field on the xy-plane for circular sub-channels with $w_1/w_2 = 2.0$ at Re = 60. Throughout the micromixer that is comprised of four segments, the velocity in