CHEMICAL ENGINEERING RESEARCH AND DESIGN 93 (2015) 1–11

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

An effective passive micromixer with shifted trapezoidal blades using wide Reynolds number range

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ARTICLE INFO

Article history:
Received 12 August 2014
Received in revised form 30 November 2014
Accepted 1 December 2014
Published on line 6 December 2014

Keywords:
Asymmetrical micromixer
Low Reynolds number
Shifted trapezoidal blades
High mixing efficiency

ABSTRACT

In this paper, a novel micromixer design, called the shifted trapezoidal blades (STB) micromixer, has been designed and fabricated to provide high mixing efficiency even at low Reynolds number (*Re*) based on the combination of several mixing principles, including vortices, transversal flows and chaotic advection. Although the STB micromixer has 3D geometrical structure, it can be easily fabricated by one-step photolithography technique, using only one mask and two inclined exposures and an aluminum base with 15° inclines. We conducted intensive numerical study to evaluate the performance of the proposed STB micromixer using COMSOL Multiphysics package with a wide range of Reynolds number from 0.5 to 100. We have fabricated STB micromixers for testing and verification. Both experiment and simulation results demonstrated that the STB micromixer had stable mixing efficiency of 80% or above for Reynolds number values in the range from 0.5 to 100. The most effective mixing performance was achieved at $Re = 40$ in which the STB micromixer had the highest mixing efficiency value (95%) and a moderate pressure drop $\Delta P = 30.27$ kPa. The proposed STB micromixer provided better mixing performance and smaller footprint compared to the previous micromixers presented in literatures. With a high mixing efficiency and the advantage of being easy to fabricate, the STB micromixer can be utilized in various microfluidic, point-of-care, point-of-need, central automatic diagnosis, and pre-treatment systems including sensor control systems.

1. Introduction

In the diagnosis based on RNA synthesis, sensitive biochemical detection, national screening of cancer, monitoring of water contamination, monitoring of molecular changes in the environment, PCR amplification, tissue engineering, enzyme reaction, and protein folding, the rapid well-mixed reagents are vitally important in order to achieve fast and accurate analysis under precise control of smallest reagents consumption. Micromixers thus play an important role in transforming the complex liquids such as heterogeneous fluids into homogenous liquids that can be easily used for further sample preparation, sample concentration/separation, extraction of active bio components and complex analyses (Giordano and

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http://dx.doi.org/10.1016/j.cherd.2014.12.003

Cheng, 2001). Moreover, micromixers may play an even more important role when molecular biological methods are used within point-of-care, point-of-need, doctor's offices or bed side technologies. When blood, oil/water, saliva, biopsies, soil/water samples are collected from human or biological sources, it is very important to homogenize and concentrate the samples and all included elements. The category of micromixers according to their applications in chemical, biology and detection/analysis was presented by Jeong et al. (2010). The authors concluded that most applications of micromixer technologies require *Re* between 0.1 and 100 and mixing time from 0.01 s to 1 s.

Micromixers can be broadly categorized as active micromixers and passive micromixers. The detailed structural designs and mixing mechanisms of previous passive and active micromixers are summarized by Hessel et al. (2005), Nguyen and Wu (2005). Active micromixers with external energy sources provide an effective mixing quality and fast mixing process. Various active micromixers using external energy sources such as ultrasonic vibration (Yang et al., 2001), electrokinetic (Yu et al., 2012), and gas pressure driving force (Fu et al., 2013) were presented. However, these active micromixers consist of many parts, complicating the fabrication process and the integration with other microfluidic systems. In contrast, passive micromixers do not use external energy sources. They primarily rely on the physical microchannels for fluid mixing. Therefore, they have the advantages of stable operation, easy integration, and low-cost manufacture. Most of the passive micromixers are only exploited a single mixing mechanism such as molecular diffusion, splitting-recombining, recirculation, vortices, transversal flow, or chaotic advection. Hydrodynamic focusing micromixer (Knight et al., 1998), and T-shape micromixer (Wong et al., 2004) are typical designs based on molecular diffusion. These micromixers improve the mixing quality by increasing the contacting surfaces of fluids or reducing the diffusion length for faster diffusion effect. However, they have a mixing channel length in the range of centimeters, making the integration with most LOC systems impractical. Hossain et al. (2010) proposed an optimal Tesla micromixer based on the creation of transversal components of velocity, reducing the mixing time and the mixing length. However, this micromixer has a large footprint. Another passive micromixer design based on the concept of splitting and recombining laminar fluid streams was proposed by Chung et al. (2008). The authors presented a planar passive micromixer with rhombic microchannels connected to a nozzle at the outlet. The micromixer exploits the equal spitting-recombining of laminar flows and recirculation zones to enhance mixing efficiency. However, there is no distortion at the interfaces of collision between fluid streams; thus there is no intermixing of the fluid streams in two sub-channels. Therefore, this micromixer has low mixing efficiency at low Reynolds number. In order to create the intermixing in the sub-channels, Ansari et al. (2010), Ansari and Kim (2010) proposed micromixer designs based on the concept of unbalanced splits and cross-collisions of fluid stream. Nevertheless, the mixing efficiency of the proposed micromixers are low, which is under 70% even at $Re = 80$ with a mixing channel length of 8 mm. For increasing the mixing efficiency, Afzal and Kim (2012) suggested an optimal design of micromixer based convergent–divergent channel walls with sinusoidal variations. In their design, the effective vortices created at the throat of the convergent–divergent channel improve the mixing performance. Such a micromixer achieves higher mixing efficiency compared to the previously reported micromixers (Ansari et al., 2010; Ansari and Kim, 2010). However, the mixing efficiency of this micromixer is still lower than 85% for Reynolds number values in the range from 10 to 70. Moreover, these micromixers have a large footprint. The mixing efficiency can be significantly enhanced due to chaotic advection in micromixers. Various micromixer structures have been proposed to obtain chaotic advection such as 3D serpentine (Liu et al., 2000), 3D SAR (Xie et al., 2011), and HVW micromixer (Yoo et al., 2012). Those 3D passive micromixers have effective mixing performance. However, the fabrication is complex, which requires multi-step photolithography and alignments.

In an attempt to overcome drawbacks mentioned above, we propose a novel design of passive micromixer, called shifted trapezoidal blades (STB) micromixer. Our proposed STB micromixer provide a very high mixing efficiency for a wide range of Reynolds number from 0.5 to 100, based on the combination of various mixing principles. In addition, the STB micromixer has 3D dimensional structure with small footprint, and can be easily fabricated in the one-step photolithography technique. The proposed STB micromixer was studied by numerical simulation and experimental analysis. Both simulation and experiment results showed that the STB micromixer can achieve high mixing efficiency even at low Reynolds number thanks to various mixing mechanisms, which are converging and diverging, unequal splitting and recombining, recirculation, and twisting of fluid streams.

2. Structure of a shifted trapezoidal blades (STB) micromixer

The proposed STB micromixer is the combination of a cross-shaped inlet and a mixing channel with seven mixing units as shown in Fig. 1. The fluid A goes into the middle inlet, while the fluid B goes into the side inlets. Those fluids enter the cross-shaped structure and start mixing together by the hydrodynamic focusing before going to the main mixing channel.

In the mixing unit shown in Fig. 2, the channel becomes narrow at the recombining channel because of the two injected trapezoidal blades from both sides. The channel is then unequally split into two shifted subordinate trapezoidal channels. An advantage of the shifted trapezoidal channels is to make an asymmetrical geometry in the mixing channel. Consequently, fluid stream is split into two sub-streams in an unbalanced manner. One stream is bent with 90° and brought through a triangular cross-section A_1, while another stream is first constricted before bending and passing through a smaller triangular cross-section A_2. The sub-stream which is not constricted during splitting is constricted before recombined and vice versa. The difference in cross-section area at turning position leads to the variation in fluid velocity. Smaller cross-section area provides a higher velocity and vice versa. Therefore, the unequal collision of fluid streams occurs at the recombining channel, providing a higher mixing efficiency.

3. Numerical study of the proposed STB micromixer

For fluid flow simulation, the physical model of laminar flow in COMSOL Multiphysics package was used to simulate the three-dimensional model by numerically solving the