International Communications in Heat and Mass Transfer 71 (2016) 188–196

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical and experimental analyses of planar micromixer with gaps and baffles based on field synergy principle☆

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ARTICLE INFO

Available online 30 December 2015

Keywords:
Micromixer
Gap
Baffle
Field synergy principle
Mass transfer enhancement
Comprehensive performance evaluation

ABSTRACT

The characteristics of fluid flow and mass transfer in a novel micromixer with gaps and baffles are studied numerically and experimentally. Based on the principles of multiple vortices, abrupt contraction/expansion and twice split/recombine, the effects of gaps and baffles are investigated considering both mixing performance and pressure drop at Reynolds numbers ranging from 0.1 to 60. The mixing efficiency of the novel micromixer is found to be as high as over 94% at extremely low ($Re = 0.1$) or high Reynolds number ($Re \geq 40$). The mechanism of mass transfer enhancement in the novel micromixer is analyzed by the field synergy principle. It is found that the novel micromixer is helpful to mass transfer enhancement which can be attributed to a good synergy between the velocity field and the concentration field. It is shown that the field synergy principle provides an alternative way to evaluate the performance of micromixers. In addition, the influence of the different locations of gaps and baffles on the mixing performance is analyzed. The comprehensive performance of micromixers is investigated by the field synergy principle and the ratio of the mixing index to the pressure drop (MI/PD). The merits of rapid mixing, low energy consumption and short mixing length make the novel micromixer more promising in microfluidic application.

1. Introduction

In recent years, micromixer has been broadly applied in biological analysis and chemical synthesis as an important component in Lab-On a Chip (LOC) and micro-total analysis systems (μTAS) [1,2] where rapid and high-efficiency mixing is required. Mixing process of two or more reagents is a critical issue for microfluidic application [3,4]. The flow regime is usually laminar with low Reynolds number (Re), and the interface tension and viscous effect between two fluids play more important roles compared with inertia effect in small hydraulic diameter channels. The scaling effects of the microchannels, such as entrance effect, surface roughness and slippage phenomena, have a significant influence on the flow stability and the transport of mass, momentum and heat in the microscale [5,6]. When two species of fluids flow in the micromixer, the mixing performance mainly relies on the molecular diffusion and the mixing process is time-consuming [7,8]. According to the rate of diffusive mixing characterized by $DA\nabla C$, there are three ways to increase the mass transfer in micromixers, i.e., to improve the diffusion coefficient D, to increase the species concentration gradient ∇C and to increase the interfacial surface area A between different species of fluids. As the temperature rises up, the diffusion coefficient will increase. However, high temperature may have a strong impact on the physical properties of some reagents, which should be avoided in some practical applications. And due to the actual working conditions, it is limited to increase the gradient of species concentration. Therefore, increasing the interfacial surface area between different fluids in micromixers is considered to be an effective method to enhance the mass transfer.

Various kinds of micromixers have been reported to reduce the mixing time, the microchannel length and the pressure drop. According to whether moving parts or external energy is provided to the micromixer or not, micromixers are generally divided into two categories: active and passive micromixers. Active micromixers utilize external energy including magneto hydrodynamic [9], ultrasonic [10], electroosmosis [11], pulse flow [12] and thermal distribution [13] to enhance the mixing efficiency. But they have disadvantages such as high consumption of energy, and difficulty in fabrication and integration with other microfluidic components. Constructal design is a potential technique for process intensification and is widely applicable to the process of heat and mass transfer [14–31]. Passive micromixer is an application of constructal design in microfluidic which does not need any external energy. The mixing efficiency is improved by optimizing the geometrical structure to increase the contact area and shorten the diffusion length. The passive micromixer includes three-dimensional (3D) mixers [19,20] and planar mixers [21–31]. The planar mixers have been widely applied in microfluidic systems because they are easy to manufacture and integrate without complicated multi-layer structures compared to 3D mixers. The most common mixing principles

☆ Communicated by: Dr. W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.12.029
0735-1933/

in planar micromixers include lamination and chaotic mixing. Split-and-recombine (SAR) mixers [21,22] are representative micromixers utilizing lamination mechanisms. The mixing efficiency can also be greatly increased by chaotic convection. By changing the geometrical structure, the fluid is split, stretched, folded, broken and a transverse motion is created in the micromixers. A lot of ways can achieve chaotic convection, such as through different geometries including curves [23, 24], grooves [25,26] and obstacles [27–31]. Placing obstacles inside the microchannel is a popular method to achieve chaotic advection. The obstacles create vortices and increase the contact area between two fluids. Some micromixers can achieve highly efficient mixing by synthesizing two or more mixing mechanisms. Xia et al. [21] designed a P-SAR micromixer with fan-shaped cavities. The fluids were split into several streams and then recombined by lamination mechanism and vortices were generated by fan-shaped cavities using a chaotic mechanism at the same time. The mixing performance was enhanced by a synergistic effect of unbalanced inertial collision, Dean vortices, and expansion vortices. Then, Xia et al. [22] presented a modified P-SAR micromixer with dislocation sub-channels using similar principles. A rapid and efficient mixing was achieved among a wide range of Reynolds numbers.

The mixing efficiency can be improved by the embedded obstacles in micromixers; however, the pressure drop increases at the same time which leads to more power consumption. Shih et al. [28] investigated a planar micromixer with mixing units combining gaps and baffles and optimized the geometric parameters by Taguchi method. Cheri et al. [31] studied micromixers with different chambers and obstacles to obtain an optimum design. The micromixer had a good mixing performance at a short mixing length, but the pressure drop was relatively high. So the optimization and evaluation of micromixers must consider both mixing efficiency and pressure drop. Usually, the mixing efficiency and pressure drop are compared respectively in the literatures. To evaluate the overall performance of the micromixers, the ratio of the mixing index to the pressure drop (MI/PD) is selected as a criterion [31]. For conventional analysis, the high mixing efficiency is generally attributed to chaotic advection. The mixing index, which can be considered as a statistically value, can reflect the uniform degree of species concentration in the micromixer, but cannot completely explain the mechanism of mass transfer enhancement. Thus, an in-depth understanding of the mixing process of the two fluids is needed before one is able to apply the chaotic effect to design a micromixer. In order to analyze the mixing process in the micromixer from the view of mass transfer, the field synergy principle based on the convection–diffusion equation is employed. The field synergy principle is proposed by Guo et al. [32], which indicates that the mass transfer mechanism is related to the interaction between the species concentration field and fluid velocity field [33,34]. The mass transfer can be estimated by the synergetic relation between the velocity vector and species concentration gradient, i.e., synergy angle β_m, while the synergetic relation between the velocity vector and velocity gradient, synergy angle α, illustrates the pressure drop. Being similar to the field synergy principle in heat transfer [35–39], the synergy angle γ ($\gamma = |\alpha - \beta_m|$ [37]) between the velocity gradient and species concentration gradient can assess the comprehensive performance of micromixers. The decrease of the synergy angle β_m is consistent with the increase of the mixing index, while the increase of synergy angle α can reflect the decrease of the pressure drop. Therefore, the synergy angle γ is qualitatively analogous to MI/PD. The field synergy principle in convective mass transfer is an alternative approach to evaluate the performance of the micromixers and gives more information by which the mechanism of the mass transfer enhancement can be analyzed.

In this paper, a new micromixer with gaps and baffles is proposed which uses lamination and chaotic mechanisms comprehensively. The fluid flow and mixing process are investigated by visualization experiments and numerical simulations. As far as the authors' knowledge, analyses of the mass transfer enhancement in the micromixer by adopting the field synergy principle is seldom reported. In the present paper, the effect of gaps and baffles on the mass transfer enhancement is analyzed by the field synergy principle. Moreover, the influence of different locations of gaps and baffles on the comprehensive performance of micromixers is studied based on different evaluation criteria. The optimum geometry is obtained by considering mixing efficiency, pressure drop and field synergy comprehensively and also compared with those from the open literature.

2. Fabrication and experiment apparatus

Fig. 1 plots the schematic diagrams of the micromixer which consists of a cross entrance and a series of gaps and baffles. As shown in Fig. 1(a), fluid 1 flows into the micromixer by inlet 1 and inlet 2, while fluid 2 enters into the micromixer by inlet 3. They initially contact at the cross-section, where a small amount of molecular diffusion is achieved at the interfaces between them. Then, the two fluids are squeezed into the gap G_1. Owing to the abrupt contraction, the fluids are accelerated and a pair of symmetrical expansion vortices is generated behind G_1. The fluids jet on baffle B_1 by the acceleration effect and then split into two streams. The two streams are further separated into three streams by baffles B_2 and B_3. Then, the three streams are recombined in the recirculated regions behind B_2 and B_3. The two streams are recombined again behind baffle B_4 and are concentrated into one stream by gap G_2. At last, the fluids flow into a straight channel. The fluids are split twice and recombined twice in the micromixer.

The geometric parameters of the planar micromixer in the simulation are shown in Fig. 1(b), where a two-dimensional view of x–y is plotted and z is the direction of the microchannel height, which is fixed at 100 μm. The total length of the micromixer is 1.9 mm in the simulation. In order to keep the same flow rate of two fluids, $2w_a = w_c$. The specific geometric dimensions are shown in Table 1.

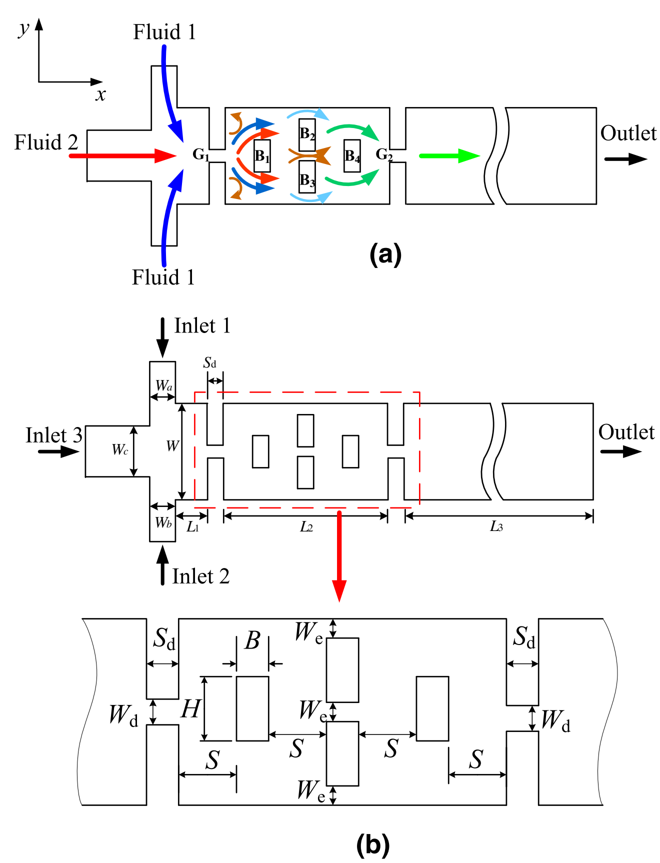

Fig. 1. Schematic diagrams of the new planar micromixer: (a) flow path; (b) geometric parameters.