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Investigation on the splitting-merging passive micromixer based on Baker's transformation

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ABSTRACT

Passive micromixers have a wide applications due to no need of external energy and moving parts. Stratification of chaotic advection is an important mechanism to enhance mixing efficiency in micromixers. A novel Baker-based micromixer with ceaseless stratification was designed on the basis of chaotic theory. In order to illustrate the perfect mixing efficiency and mixing mechanism in such a micromixer, numerical simulations were carried out, and comparisons with other splitting-merging micromixers named Helical-mixer and Smale-mixer are conducted. The numerical results show us that, the Baker-mixer has more excellent mixing efficiency at low Reynolds number because of more-folds of interfacial areas between two streams caused by stratification effect. However, the mixing efficiency of Baker-mixer is not a patch on that of Smale-mixer at high Reynolds number. The reason should be that, bending channels in Smale-mixer can induce secondary flow to enhance convection mixing. LIF experiments were conducted and the mechanism of chaotic mixing in Baker-mixer and validity of numerical method are verified by the good agreement between numerical results and experimental results. A powerful auspice for the design of the high-performance chaotic passive micromixer is provided.

1. Introduction

The integrated microfluidic devices called as lab-on-a-chip can offer many advantages, e.g., extremely low volume consumption, inexpensive and small, very short sample-to-result time, over the traditional analytical devices. Efficient mixing in microdevices is required for DNA analysis, mass spectrometry, biosensors, surface patterning, and other applications [1–4]. It is known to all, a relative long time should be taken for the mixing of species in microdevices because molecular diffusion is dominant, while the convective mixing caused by turbulence is not practically attainable at low Reynolds number. The micromixers can be categorized into active and passive mixers. Active mixers utilize external energy, such us electrical energy, magnetic energy, acoustic energy, mechanical energy and so on, to induce transverse flows [5–9].

Passive micromixer has been widely used in many microdevices because of the simplicity in fabrication and manipulation. The passive mixing in a single micro-channel is attractive for two reasons. Firstly, a passive mixing scheme, which relies solely on a constant flow source, is generally more robust and easier to implement than an active mixing scheme which exerts the control over the flow field by using the moving parts or changing the pressure gradients. Secondly, a single channel can maintain a relatively constant cross section, which results in the lower strain rates than that if the flow is split into multiple smaller streams [10,11]. Therefore, in order to enhance the diffusion and mixing of species in the micro-channel, Kamholz et al. [12] and Nguyen, N.T.[13] proposed a new concept named "chaotic advection", i.e. the passive fluid particles are advected by a periodic, laminar velocity field and exhibit chaotic trajectories.

Chaotic advection can enhance the stretching and folding of species interfaces. This deformation of the fluid-fluid boundaries increases the interfacial areas across which diffusion occurs, and enhances the mixing efficiency [14]. Lee et al. [15] summarized all kinds of chaotic mixer for micro-channels. Liang et al. [16] studied the mixing characteristics of the contraction-expansion helical mixer in the laminar regime. It is found to be superior in comparison to the regular helical mixer at higher Reynolds number. Adam T. et al. [17] designed and fabricated a micromixer with short turning angles for self-generated turbulent structures, the mixing efficiency of 98% was obtained at Reynolds number less than 2. Z.H. Lu et al. [18] investigated a micromixer with 2 T-type premixers and 4 butterfly-shape cross-channels, the corresponding residence time is 0.44 ms for 90% and 0.49 ms for 95%. C.Y. Lin et al. [19], demonstrated a self-vortical micromixer without obstructions, the perfect mixing can be achieved even in lower Reynolds number. They studied a mixer with J-shaped baffles also [20], and better mixing performance was exhibited, the percentage of mixing was about 1.2 to 2.2 times higher when compared to those without baffles in the range of Reynolds number 5 to 350. We designed and simulated a passive chaotic micromixer with helical channel on the basis of chaotic theory 2006 [10], the mechanism of chaotic advec-

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tion is based on a Smale-transformation. Much more better mixing efficiency can be achieved especially at lower Reynolds number because of better stratification in such a mixer.

In spite of the well-documented theoretical evidence for the passive mixer, the mixing efficiency is not approving when Reynolds number is lower than 1 because the chaotic convection in such case is not strong enough. Only when the interfacial areas between species are very large, the mixing efficiency will be absolutely approving. It is obvious that increasing the interfacial areas is important for obtaining higher mixing efficiency when Reynolds number is lower than 1. Therefore, the main objective of present work is to clarify the mechanism of chaotic advection for lower Reynolds number.

2. Theory and model

2.1. Theoretical basis

The motion of fluid particles is described mathematically with a map or mapping. Let denote the region occupied by the fluid. We refer to points in as fluid particles. The flow of fluid particles is mathematically described by a smooth, invertible transformation, or map, of into, denoted for one advection cycle. Similarly, advection cycles are obtained by repeated applications of, denoted. Mixing is a critical concept. Within the domain, let denote a region of species named sample and let denote another species named detection. Mathematically, we denote the amount of sample that is contained in after applications of the mixing process by, that is the volume of that ends up in after advection cycles. Then the fraction of sample contained in is given by [21].

Chaos is a phenomenon discovered by an American scientist named Lorenz in 1963 in an experiment for simulating atmospheric turbulence [22]. It was said that there was up to now no universally accepted definition for chaos yet [23]. Nevertheless, in practice, a map may be called chaotic if the orbits have some positive Lyapunov exponents. Lyapunov exponent is a number associated with an orbit, describing its stability in the linear approximation. It is known that the Bernoulli property embodies a deterministic chaotic system to behave [24].

Smale, an American mathematician, established a geometrical model named Smale horseshoe in the 1960s [25]. Smale horseshoe model is one of chaotic model which reveals the essence of chaotic mixing, i.e., stretching and folding to disrupt the periodicity of advection cycle. Fig. 1(right) is the schematic diagram of Smale transformation. However, the Smale transformation is isomorphic to Bernoulli transformation with an invariant set of zero volume theoretically. Baker transformation is however isomorphic to Bernoulli transformation in arbitrary region of R [26]. Hence, Baker transformation is the best transformation for chaotic mixing in theory, because the fluids can be compressed, stretched, cut and stacked to realize more layers of stratification. Fig. 1(left) is the schematic diagram of Baker transformation.

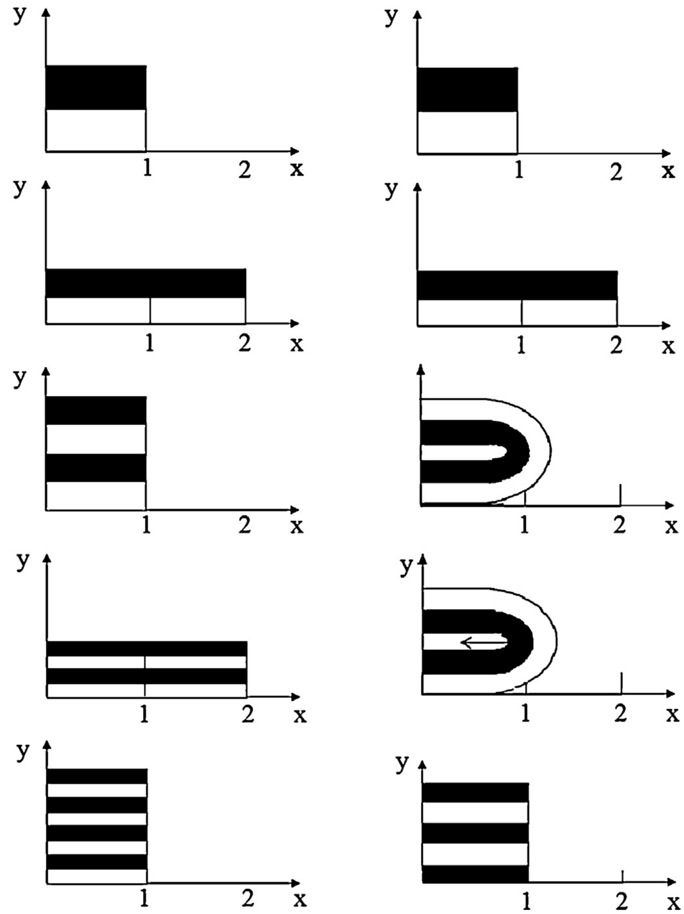

Fig. 1. Schematic diagram of Baker transformation (left) and Smale transformation (right).

2.2. Description of micromixer models

On the basis of chaotic mixing theory, Baker-mixer and Smale-mixer were constructed on account of Baker transformation, in order to insight into the mechanism of chaotic mixing (see in Fig. 2). To clarify the weight of convective effect, stratification effect in Smale-mixer, a Helical-mixer with identical convective effect to Smale-mixer was constructed. All three mixers have two inlets for sample and detection respectively, the size of inlet and outlet are both 100 μm × 100 μm, along with the channel size being the same as that in Ref. [10] for comparison. Mixing unit is defined as fundamental element for mixing with periodic splitting and merging structures. To Smale-mixer and Helical-mixer, the length of mixing unit with 2 splitting and merging structures is 800 μm, while the length of mixing unit with only one splitting and merging structure is 400 μm to Bakermixer. It is worth noting that, the channel in mixing unit of Baker-mixer is somewhere contracted to half size (50 μm) of original channel (100 μm). All of other dimensions of the microchannels in three mixers are 100 μm.

3. Numerical model

3.1. Control equations

Assumed incompressible fluids with smaller velocity in a microchannel, equation of continuity can be written as:

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

where $\vec{V}$ is velocity vector.

Consider incompressibility and constant viscosity, momentum conservation equation neglecting gravity can be written as:

$$\rho \left[\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} \right] = -\nabla p + \mu \nabla^2 \vec{V} \qquad (2)$$

where p, ρ and μ are pressure, density and dynamic viscosity, respectively.