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Numerical and experimental investigations of chaotic mixing behavior in an oscillating feedback micromixer

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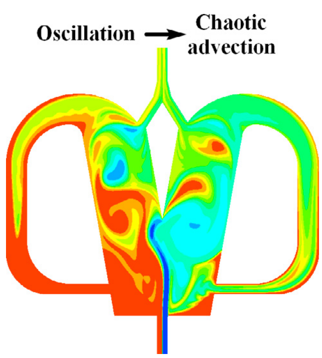
HIGHLIGHTS

- A 2-D high-efficiency micromixer was designed using the Coanda effect.
- Transverse flow perturbation was generated through the feedback channel.
- Time-periodic chaotic mixing behavior was investigated.
- Lagrangian particle tracking was employed to characterize chaotic advection.

GRAPHICAL ABSTRACT



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ABSTRACT

An oscillating feedback micromixer comprising an inlet channel, two Coanda steps, a divergent chamber, a splitter, two feedback channels, and an outlet channel was designed considering the Coanda effect. Two-dimensional unsteady simulations were employed to study the impact of the Reynolds number on the oscillation frequency, pressure drop, and chaotic mixing. The switching mechanism of the fluidic oscillation based on the Coanda effect was examined in detail. Three Lagrangian particle tracking indicators, the Poincaré maps, particle dispersion distribution, and stretching of fluid filaments, were employed to observe and quantify the mixing induced by chaotic advection. The Lagrangian simulation results showed that the average stretching index increased from 4.91 to 5.57 with Reynolds number (*Re*) increased from 33.3 to 100. In addition, the mixing efficiency was quantified using a mixing index based on the standard deviation of the scalar species distribution. The results indicated that the mixing efficiency increased with the increase of Reynolds number, and the mixing efficiency of 75.3% could be achieved at $Re = 100$. The mixing of colorless and blue deionized water was tested experimentally to verify the simulated concentration fields, and the experimental results were in good agreement with the simulation results.

1. Introduction

In recent years, micromixing technology has developed rapidly. Micromixing devices have had a considerable impact on the fields of biomedical diagnostics and drug development and are widely used in the food and chemical industries (Lee et al., 2016). Because of micromixers' small dimensions, flows in micromixers are lami-

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nar, and species transport relies mainly on molecular diffusion; thus, rapid mixing is difficult to achieve in microfluidics (Kumaran and Bandaru, 2016). To address this problem, a variety of micromixers have been designed, and they can be classified into two main types depending on the mixing strategy: active micromixers and passive micromixers (Hessel et al., 2005). In active micromixers (Deshmukh et al., 2001; Huang et al., 2006; Liu et al., 2003), mixing is realized by supplying external energy. Such devices can provide effective mixing, but they generally require complicated control systems; thus, they are difficult to fabricate and integrate. In contrast, passive micromixers can be used to achieve good mixing by applying a special microchannel structure design. Therefore, passive micromixers are easier to manufacture and operate, so they are widely used in microfluidics.

Passive micromixers can be classified as lamination micromixers (Roudgar et al., 2012; Hsieh et al., 2013; Bessoth and Manz, 1999; Löb et al., 2004) and chaotic advection micromixers (J.J. Chen et al., 2011; Haller et al., 2015; Tofteberg et al., 2010; Li et al., 2013; Stroock et al., 2002; Nimafar et al., 2012; Hossain et al., 2010). However, in most lamination micromixers, a long mixing channel and sufficient mixing time are needed to achieve complete mixing owing to the low diffusion rate caused by the thermal motion of molecules. Unlike lamination micromixers, chaotic advection micromixers can constantly fold and stretch the fluid (Ottino, 1989), and the striation thickness is sharply decreased, so the mass transfer is greatly increased.

For passive micromixers, it is very important to employ high-efficiency microstructure designs to promote chaotic advection. Secondary flow is the key to production of chaotic advection. An oscillator can effectively produce secondary flow, so the oscillating micromixer, among existing passive mixers, may be a good choice for strengthening the chaotic mixing in microfluidics. In the oscillating micromixer, transverse flow perturbation can be generated, which can destroy regular parallel flows and facilitate the production of chaotic advection. To date, a number of oscillating micromixers have been reported, and can be classified into two goups: the impinging-jet-based oscillating micromixer and the oscillating feedback micromixer (Sun and Sun, 2011; Yang et al., 2007; Jeon et al., 2004). Sun and Sun (2011) presented an experimental study of the mixing process in an impinging-jet-based micromixer, in which a concave surface was used to generate an impinging jet. Their results indicated that the mixing properties in the impinging-jet-based oscillating micromixer were sharply improved by the sustainable flapping motion. Oscillating feedback micromixers (as showed in Fig. 1) were also investigated by several groups. For instance, Yang et al. (2007) proved that the self-flapping motion in an asymmetric microfluidic feedback oscillator accelerated the biochemical reaction between two fluorescent proteins, B-phycoerythrin and an allophycocyanin alpha subunit. Jeon et al. (2004) studied an oscillating feedback micromixer and investigated the influence of the Reynolds number and geometric structure on the mixing performance using a simulation. The characterization of mixing in the micromixer was verified by using an aqueous NaOH solution and a phenolphthalein solution composed of equal volumes of ethanol and water. The experimental results indicated that complete mixing could be achieved at a flow rate of 0.1 ml min^{-1} and a short residence time of 0.11 s. Xu and Chu (2015) also reported an oscillating feedback micromixer with three different geometric structures. The results indicated that there were three mixing mechanisms in oscillating feedback micromixers with increasing Reynolds numbers: vortex mixing, internal recirculation mixing, and oscillation mixing. And the three mixing mechanisms enabled the transverse movement of liquid lumps inside laminar parallel flows. Consequently, efficient chaotic advection mixing could be achieved. Further, the results also proved that the mixing performance of oscillating feedback micromixers was suitable for mixing different liquids at a high Reynolds number, and a mixing efficiency of 100% could be achieved for two miscible liquids. Owing to their excellent mixing performance, oscillating feedback micromixers have even been used in microextraction (Wang and Xu, 2014; Xu and Chu, 2014; Xu and Dai, 2015; Xu et al., 2016).

Briefly, compared with other chaotic advection micromixers, the oscillating feedback micromixer can be more easily fabricated and achieve efficient mixing at high Reynolds numbers by chaotic advection. Unlike other micromixers, oscillating feedback micromixers exhibit increased fluid mixing efficiency with decreasing residence time owing to the increasing flux, i.e., Reynolds number. Thus, there is great potential to achieve more efficient fluid mixing in microfluidics with a much shorter residence time. Therefore, understanding the mixing mechanism and characterizing the chaotic advection strength in oscillating micromixers

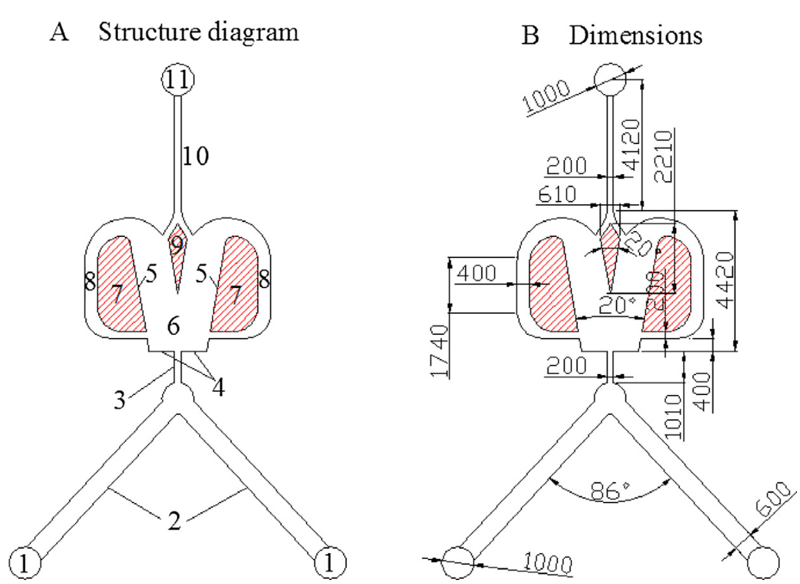

Fig. 1. Diagram of the oscillating feedback micromixer: (A) configuration and (B) dimensions of the micromixer. 1: Inlet port; 2: Y-type feed channel; 3: inlet channel; 4: Coanda step; 5: attachment wall; 6: divergent chamber; 7: barrier; 8: feedback channel; 9: splitter; 10: outlet channel; 11: outlet port.