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Numerical and experimental investigation on micromixers with serpentine microchannels

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ABSTRACT

This paper aims at study and analysis on species mixing performance of micromixers with serpentine microchannels by numerical simulation and experiment in depth. Mixing experiments with blue ink and yellow ink were implemented for six micromixers, and three better structures (square-wave, multi-wave and zigzag) were picked for further simulation research. Lots of productive numerical analysis were carried out for studying the mixing performance for Reynolds number (*Re*) values in the range from 0.1 to 100. The mixing efficiency decreases while *Re* varies from 0.1 to 1, and increases while *Re* varies from 1 to 100. At the *Re* of 0.1 and 100, the mixing performance of three structures is similar. Vortices, transversal flows and chaotic advection were produced with the increase of *Re*. Compared with the multi-wave micromixer and the zigzag micromixer, the square-wave micromixer is more efficient on mixing duo to its more sharp turns and longer path of the flow with *Re* being between 0.1 and 100. The results also show that the square-wave micromixer has higher pressure drops than the other two because of more sharp turns. Each square-wave unit enhances mixing obviously with the increase of *Re* and at a certain *Re* the former unit has a stronger effect on mixing than the latter. When *Re* is more than 100, the mixing efficiency can reach above 95% with a moderate pressure drop less than 50 kPa. Both experiment and simulation results demonstrated that the square-wave serpentine micromixer is flexible, effective, easily fabricated and integrated to a microfluidic system.

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1. Introduction

An advanced technology named microfluidic has drawn more and more attention, which allows miniaturization and integration of micro-devices into a system for a wide range of applications. Micromixers as important components of microfluidic systems are diverse and widespread. A well-designed micromixer can reduce the analysis time and the footprint of a lab-on-a-chip system [1]. Due to the small feature size and low flow velocity in the microchannel, Reynolds is generally low and the macroscopic turbulent fluctuations in the homogenize fluid sample are absent at the microscopic scale. So, researchers have to design effectively the structures of microchannels and microchambers. Numerical studies play a key role in optimum design of micromixers, and many fruitful research results have been obtained. Three-dimensional flow inside a cylindrical tube was researched through a numerical study of chaotic advection and mixing in a spatial period [2]. Numerical simulation which is based on computational fluid dynamics has been proved to be reliable for both qualitative and quantitative analysis of flow structures, species concentration and mixing performance [3–11]. What's more, the 3D serpentine micromixer and the square-wave micromixer with cubic grooves have been designed and simulated, and the mixing quality and pressure drop of them were evaluate [12]. Afzal et al. proposed an efficient mixing system for a microfluidic platform that uses periodic sinusoidal characteristics in space and time. A convergent–divergent channel with sinusoidal walls represented the most effective coupling with pulsatile flow among the five tested geometries [13]. A numerical investigation on mixing and flow structure in a serpentine microchannel with non-aligned input channels was performed [14]. Cieslicki and Piechna elaborated the mechanism of mixing process in a manifold which mimics the geometrical properties of vascular systems [15]. Ansari and Kim evaluated mixing performance for planar split and recombine micromixers with asymmetric sub-channels [16]. Mixing index was evaluated to measure the degree of mixing in the micromixer. Pressure drops were also calculated with fixed axial length in two cases. A trapezoidal-zigzag micromixer composed of trapezoidal channels in a zigzag and split-recombine arrangement was presented. The micromixer enables multiple mixing mechanisms, including splitting–recombining, twisting, transversal flows,

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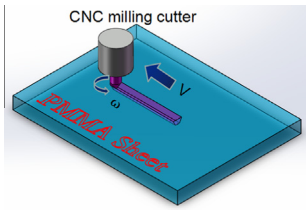

Fig. 1. The schematic of processing microchannels on PMMA by CNC milling machine.

vortices, and chaotic advection [17]. The effects of different types of wall protrusions on microfluidic mixing were studied using computational fluid dynamics (CFD) simulations [18]. The effects of geometric parameters on the mixing performance of a staggered herringbone mixer with patterned grooves were numerically investigated. Analyses of the mixing phenomena, geometric parameter, pressure loss and flow rate through grooves were conducted [19]. Because the basic T-mixer completely rely on molecular diffusion, a long channel usually is necessary. To effectively mix in a short mixing length, a chaotic flow is expected. The geometry and operating conditions of a micromixer with convergent-divergent sinusoidal walls under pulsatile flow were optimized to maximize the mixing performance. The results indicated that the Kriging model predicts the best optimum design with a mixing index of 92.35% at the outlet of the micromixer [20]. Jain et al. analyzed the effect of groove shape on micromixing performance and search for the optimal groove shape for a pressure-driven flow across the microchannel. Various parametric studies are carried out to compare the optimal groove structure with other common groove type micromixers for a range of Peclet number [21]. Miyake et al. presented an injection micromixer with 400 nozzles arranged in a square array and simulation conforms the micromixer is very effective [22,23].

Experimental research which can promote numerical simulation each other is also carried out and many important progress have been achieved. The 3D serpentine micromixer and the square-wave micromixer with cubic grooves were studied due to their simple fabrication and efficient mixing performance. The flow and mixing characteristics were numerically investigated for a wide range of Reynolds numbers: 8–160 [12]. Chip production and experiments are significant, many scholars in the field of microfluidics carried out a large number of experiments and confirmed the accuracy of the numerical simulation. Bessoth et al. reported a parallel lamination mixer with 32 streams that can achieve full mixing in 15 ms [24]. He et al. reported the concept of the serial lamination micromixer that can be applied to electrokinetic flows. Utilizing electro-osmosis flows between the multiple intersecting microchannels, mixing is enhanced clearly [25]. Fu et al. proposed a novel vortex micromixer comprising an injection channel (Y-shaped or Interlaced-shaped), a nozzle structure and a double-heart mixing chamber, and the numerical results were confirmed by performing flow visualization experiments [26]. Chen et al. presented a new micromixing strategy that mimics

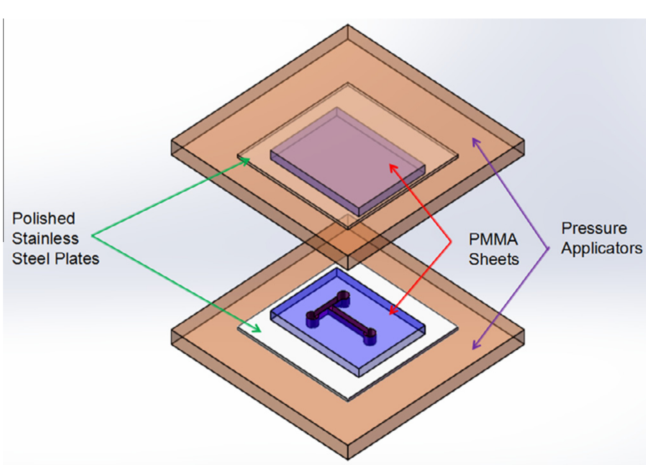

Fig. 2. The schematic of the hot embossing and bonding process on PMMA.

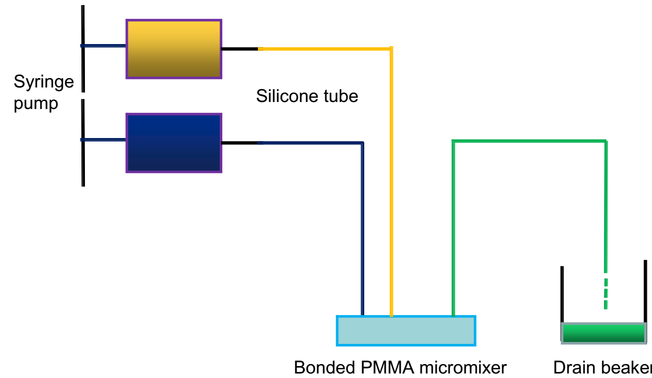

Fig. 3. Experimental setup of mixing test.

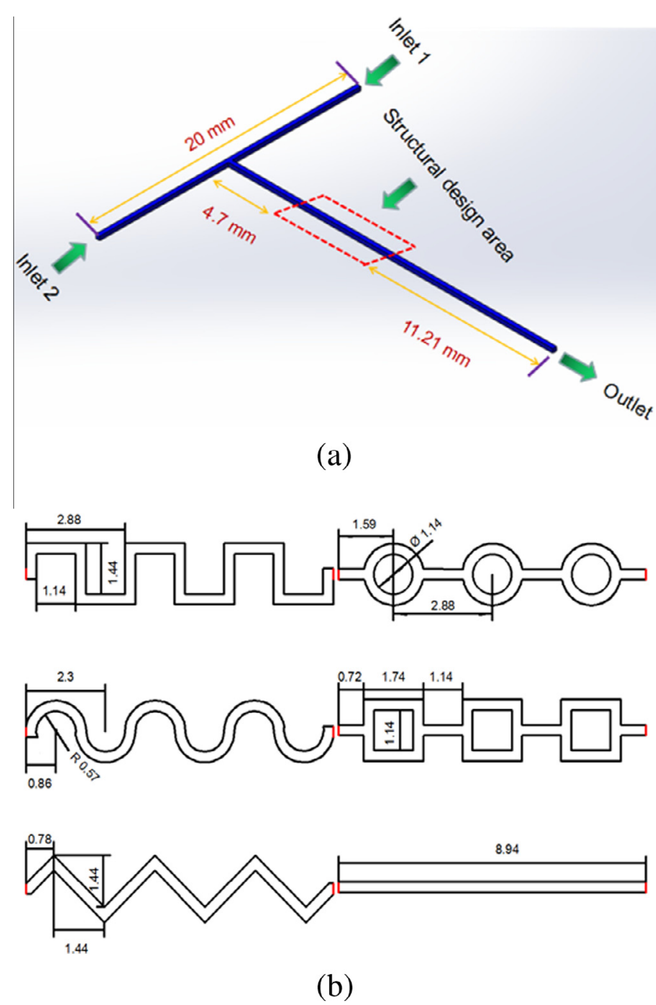

Fig. 4. Schematic diagrams of the micromixers: (a) 3D model, (b) 2D size maps of structural design area.

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