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A micromixer with two-layer serpentine crossing channels having excellent mixing performance at low Reynolds numbers

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HIGHLIGHTS

- Experimental and numerical analyses of a novel micromixer with two-layer crossing channels were performed.
- The micromixer showed at least 96% mixing throughout a Reynolds number range (0.2–120).
- At low Reynolds numbers (0.2–10), the micromixer showed about 99% mixing at the exit.
- The proposed micromixer showed lower pressure drop than TLCCM for Re larger than 10.

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ABSTRACT

A novel design is presented for a chaotic micromixer using two-layer serpentine crossing microchannels. The performance of the micromixer was analyzed both numerically and experimentally. The numerical analysis was performed using three-dimensional Navier-Stokes equations with a convection–diffusion model for the species concentration in a Reynolds number range of 0.2–120. An experimental model of the micromixer was fabricated by soft lithography with polydimethylsiloxane (PDMS). Two working fluids, water and dye-water mixture were used for numerical analysis except for the experimental validation of numerical results. Both the numerical and experimental analyses confirm that the micromixer achieves a high level of mixing over a wide range of Reynolds numbers through splitting, enlarging, recombination, and folding mechanisms. The micromixer showed over 95% mixing throughout the tested range of Reynolds number. Especially, about 99% mixing was achieved at Reynolds numbers less than ten. Thus, the proposed micromixer can be used in microfluidic systems which require fast mixing at low Reynolds numbers.

1. Introduction

Microfluidics technology enables the miniaturization of laboratory instruments into lab-on-a-chip (LOC) devices for various chemical and biological applications [1–4]. This technology is gaining attention from researchers due to the faster analysis speeds, higher efficiency, and small sample volumes. Efficient mixing of liquid samples plays an important role in LOC [5] and micro-scale total analysis systems [6]. Generally, fluid flow at the micro-scale is laminar, so mixing is governed by molecular diffusion, which requires a greater channel length to achieve a homogeneously mixed solution than turbulent diffusion.

Various types of micromixers have been developed to achieve rapid and homogenous mixing. Micromixers are generally categorized according to the mixing principles as active or passive mixers. Active micromixers require an external energy source, unlike passive micromixers [7,8]. Passive micromixers are more favorable than active micromixers due to their simple fabrication, simple integration with microfluidic systems, and greater robustness and stability [9,10].

The performance of the passive micromixers mostly depends on the channel geometry. Thus, clear understanding of the flow phenomena within the microchannel is required to develop micromixers. Computational fluid dynamics (CFD) based on three-dimensional (3D) Navier-Stokes equations is a promising technique for developing efficient micromixers [9,10]. Mixing in passive micromixers relies on chaotic advection as well as molecular diffusion [10]. Molecular diffusion can be enhanced by enlarging the contact surface between fluid samples and reducing the diffusion

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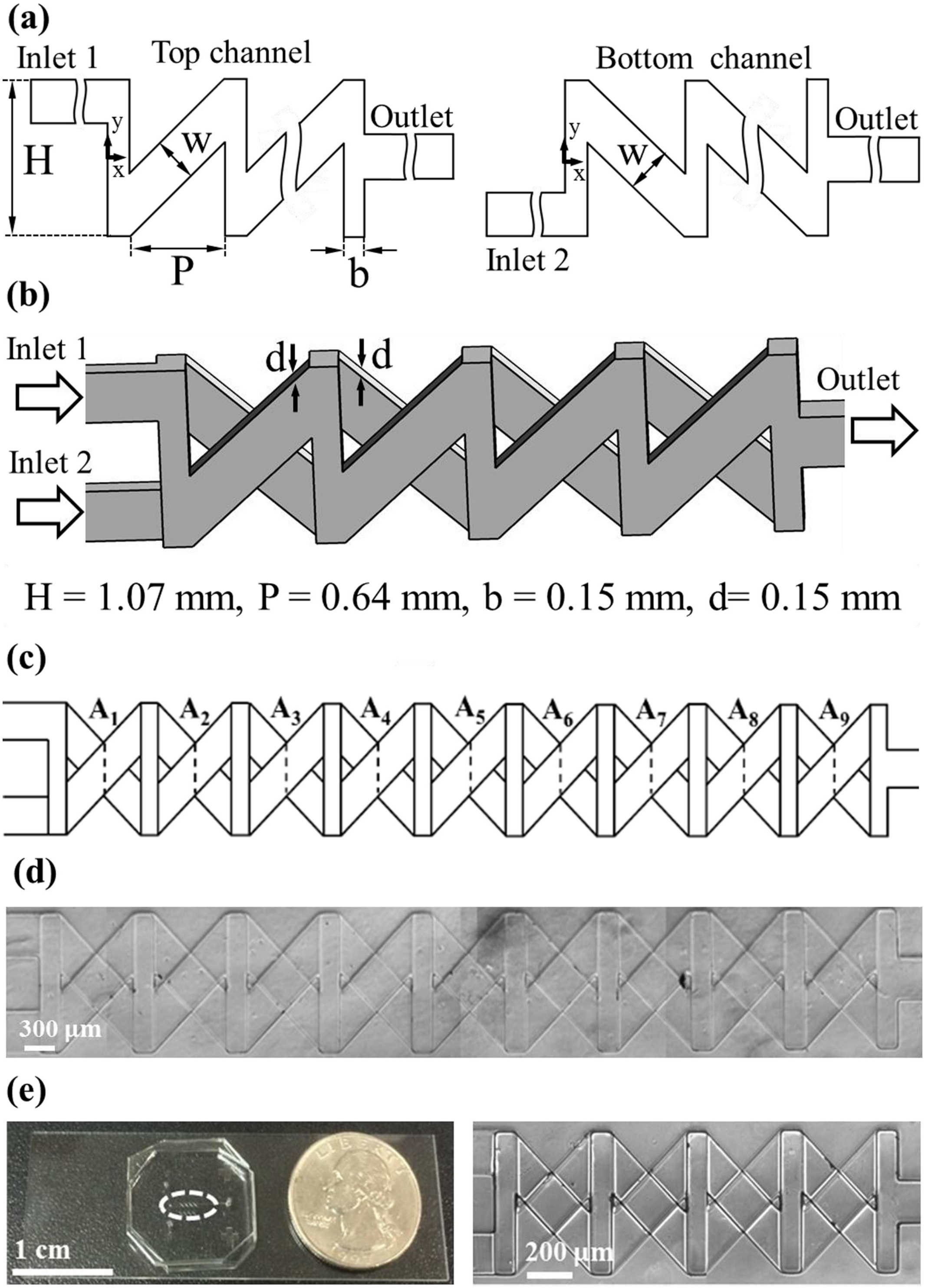

Fig. 1. Micromixer geometry with two-layer serpentine crossing microchannels and geometric parameters. (a) Schematic diagram of the top and bottom channel layers with inverse-N and N-shaped segments, respectively. (b) 3D view of the micromixer, where both the layers are interconnected at the middle of the “X” shape and the vertical sections. (c) Locations of cross-sectional planes A_1–A_9 at the nodes of the crossing structures. (d) Optical image of the micromixer with nine mixing units. (e) Optical image of a micromixer composed of four mixing units used only for the parametric study (the dotted ellipse in the left figure is enlarged in the right figure).

length, and chaotic advection enlarges the contact surface by manipulating the bulk flow inside the microchannels [11].

Several studies reveal that micromixers based on chaotic advection show efficient mixing in an extensive range of Reynolds number [10,12]. Chaotic advection caused by the periodic perturbation of the two-dimensional flow can remarkably enhance the mixing efficiency in the laminar flow regime. A chaotic flow structure can be generated by modifying the channel shape so that the laminar flow continually stretches, folds, splits, and recombines within the channel. This flow phenomenon is reported for various microchannel shapes [13,14], including a staggered herringbone structure [15], split and recombine structure [16], Tesla structure