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Design and test of a passive planar labyrinth micromixer for rapid fluid mixing

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ABSTRACT

In this paper, we explore the possibility of improving the efficiency of Dean vortex-based mixers by only employing smooth-walled simple two-dimensional (2D) geometries. Numerical simulation results reveal that the symmetries of Dean flows in the prevalent "S-shaped" mixers can be broken up by adding a simple 180° turn between two consecutive curved channels. A planar labyrinth micromixer that is composed of multiple such mixing units is designed for improved mixing. The mixer is fabricated in a single lithography step and the labyrinth has a footprint of 7.32 mm × 7.32 mm. Experiments using fluorescein isothiocyanate solutions and deionized water demonstrate that our design achieves fast and uniform mixing within 9.8 s to 32 ms for Reynolds numbers (Re) between 2.5 and 30. For the first time, multiple fluid bands are observed at $Re = 5$ in a simple 2D microchannel design without using obstructions or split-and-recombine features. An inverse relationship between mixing length and mass transfer Péclet number (Pe) is observed. Due to the simple planar structure, the micromixer can be easily integrated into lab-on-a-chip devices where passive mixing is needed.

1. Introduction

Rapid and efficient mixing is essential to a plethora of microfluidic systems targeted for applications in biological analysis, chemical synthesis, drug discovery, and DNA sequencing [1]. In microchannels where the flow is strictly laminar, the transverse components of the flow that stir the fluids to achieve proper mixing are absent, so the mixing of species between streams depends exclusively on molecular diffusion. Transverse flows can be generated in micro scale by time-periodic modulation of the flow field via external electric, magnetic, thermal or acoustic energy [1,2]. These approaches, termed as active mixing, have proven efficient but they are often difficult to fabricate, operate, maintain and integrate into microfluidic systems.

Passive micromixers, on the other hand, do not require external energy except for pumping and they are generally more robust and less expensive. The mechanisms employed for passive micromixing can be broadly classified into *lamination* and *chaotic advection*. In lamination micromixers, such as the split-and-recombine micromixer [3] and the topologic micromixer [4], the fluid streams are repeatedly split into multiple fluid lamellae and subsequently recombined to mimic a series of Baker's transformation [5]. The multi-lamella structure formed in this process leads to an exponential reduction in the striation thickness so that molecular diffusion alone results in rapid mixing. In contrast to lamination, micromixers based on chaotic advection rely on transverse flows that stretch, fold and break up volumes of fluid to achieve sufficient mixing. Chaotic advection can be passively achieved in three-dimensional (3D) flow through the perturbations that are imposed by space-periodic geometries, such as the staggered herringbone grooves [6] and the 3D serpentine microchannel with repeating "C-shaped" units [7]. While both lamination and chaotic advection micromixers have demonstrated excellent mixing capabilities, the 3D flow networks associated with most of these designs require sophisticated multilayer lithography and therefore are difficult to integrate with other in-plane microfluidic components. Ultimately, it would be desirable to achieve rapid and efficient mixing with simple planar 2D geometries that can be fabricated in a single lithography step.

Efficient mixing has been successfully achieved with complex planar 2D geometries, such as the 2D meandering microchannel with perforated walls [8] and the planar straight channel incorporated with diamond-shaped [9] or pillar obstructions [10]. These patterns can effectively enhance the mixing process by either imposing a constant perturbation on the internal flowlines of the fluid or partially break-up and recombine the flow. The drawback is that using these complex geometries significantly increases the surface area of the system, which consequently increases the likelihood of fouling. The feasibility of producing chaotic advection in simple planar smooth-walled 2D microchannels has been investigated with zigzag [11], rhombic [12], and curved [13–18] mixing units. The zigzag and rhombic micromixers require atypically intermediate Reynolds numbers ($Re > 80$) to induce laminar

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recirculations that aid mixing [11,12]. In planar curved microchannels, transverse Dean flows arising from centrifugal effects offer an attractive possibility of providing chaotic mixing [13]. For $Re \sim O(10)$, the generated Dean flows on the cross-sectional plane are characterized by a pair of counter-rotating vortices that is symmetric with respect to the horizontal midplane of the microchannel [14]. The reflectional symmetry is undesirable for chaotic mixing as the elliptic stream lines of Dean vortices form two “islands” that do not mix well with the surrounding fluid [5,17]. This effect becomes more pronounced for comparatively weak Dean vortices. Thus, it comes as no surprise that the mixing efficiency of micromixers based on Dean flows has not been significantly enhanced at intermediately low Reynolds numbers ($1 < Re < 10$) [13–17]. For instance, Dean flows at $Re \sim O(10)$ in the “S-shaped” microchannels only oscillate the interface between two streams without achieving sufficient mixing [14,17]. Although employing spiral microchannels can sustain the vortices over a longer distance, the generated secondary flow is not strong enough to significantly increase the extent of mixing until high flow rates ($Re > 10$) are reached [13,15]. Multiple fluid strips, which indicate a significant increase of interfacial area for mixing, have not been observed until $Re = 30$ with such design [13]. To achieve more chaotic mixing, methods such as generating two additional counter-rotating Dean vortices [14], air bubble injection [17] and adding a series of split-and-recombine units [18] have been used with micromixers based on Dean flows. However, the Dean numbers ($De > 150$) [14] required to create additional vortices are normally out of the operation range for most real-world microfluidic systems. Introducing air bubbles or split-and-recombine features into the mixers increases either the complexity or the flow resistance of the system.

In this paper, we explore the possibility of improving the efficiency of Dean vortex-based mixers by only employing smooth-walled simple 2D geometries without split-and-recombine features. The successful development of such micromixers will be very attractive because using simple 2D geometries would significantly reduce fabrication complexity, undesirable fouling, and flow resistance. The fluid mixing in two proposed mixing geometries were investigated and compared with an “S-shaped” design by numerical simulation. The most efficient geometry was then used as the basic mixing unit to construct a compact planar micromixer. Finally, the performance of the micromixer was experimentally studied and compared against a planar serpentine micromixer (PSM) over Reynolds numbers between 2.5 and 30.

2. Design and simulation

2.1. Design of basic mixing units

In Dean vortex-based mixers, mixing is achieved by transverse Dean flows that arise in the vertical plane of curved channels due to centrifugal effects [13]. Curved channels are the basic mixing elements for Dean vortex-based mixers. Dean vortex-based mixers employing recurring right-handed (R) and left-handed (L) curved channels have failed to create sufficient mixing at $Re \sim O(10)$ [14,17]. This is because the arrangement of mixing elements in the R-L-R-L-R sequence only undulates the interface between two fluids. Also, having multiple such repeating elements will not eliminate unmixed regions (e.g. islands) [19,20]. If geometries capable of breaking this sequence are added between consecutive mixing elements, it is expected that improved mixing can be achieved from a systematic destruction of flow symmetries [19,20].

Two basic mixing units were designed to explore the possibility of breaking up the R-L-R-L-R sequence in the “S-shaped” mixers. Also, an “S-shaped” mixing unit (SMU) consisting of a Y-junction, two opposite semicircles, two short straight channels, and one long connecting channel was designed to provide a baseline for comparison. In the first design, the long connecting channel was used to form two 90° turns between the two semicircles. In the second design, the long connecting channel was used to create a 180° turn between the two semicircles. The angle of the Y-junction (θ), the radius of the curved channel (R), the length of the short channel (L_1), the length of the connecting channel (L_2), the width of the channel cross-section (W), and the channel height (H) are all kept constant for three designs. The dimensions are as follows: $\theta = 30^\circ$, $R = 1.6$ mm, $L_1 = 0.22$ mm, $L_2 = 1.0$ mm, $W = 0.22$ mm, and $H = 0.267$ mm. Due to the geometric hindrance of the design, $L_2 > 2W$. Increasing L_2 will increase the footprint of the design but will not have significant effects on the mixing efficiency, because molecular diffusion is the only mechanism that enhances mixing in straight channels under the Reynolds number range studied in the paper. The abrupt turns formed between the connecting channels and the semicircles are functional mixing units here. Fig. 1 shows the schematic diagrams of the SMU, “S-shaped” mixing unit with two 90° turns (SMU90^2), and “S-shaped” mixing unit with a 180° turn (SMU180).

2.2. Numerical simulation of mixing

To analyze the flow and mixing in the three different mixing units, the same mathematical model as used by Mengeaud et al. [11] was employed. The numerical simulation was performed by using the commercial code, FLUENT 6.3.26. Based on the finite volume method, the FLUENT 6.3.26 solved the continuity equation and the Navier–Stokes equations in the case of an incompressible flow and a steady-state condition. The concentration distribution of species was obtained by solving the diffusion–convection equation. Gambit 2.2.30 was used to create 3D hexahedral meshes for the full model. The space was discretized with the second-order upwind scheme. The velocity and pressure fields were solved by using the SIMPLEC (Semi-Implicit Method for Pressure Linked Equations Consistent) algorithm. Constant normal velocity at the two inlets and zero static pressure at the outlet were assigned as the boundary conditions. The solutions were considered as converged when the adjacent relative error was less than 10^{-5}. The physical properties of water were chosen as those of the working fluid. The diffusion coefficient of a solute in water was set to $6.4 \times 10^{-10}\ \mathrm{m^2/s}$ to match the diffusion coefficient of fluorescein isothiocyanate (FITC). The grid independency was tested through verifying the results with various control volume sizes. The test indicated that the critical control volume has a transverse width of 10 μm, a lateral width of 5.5 μm, and a height of 4.5 μm, which corresponds to 2,496,000 cells for the full model.

As shown in Fig. 2a, after two mixing elements in the SMU, the interface is approximately brought back to its original position (from frame a-1 to a-7). Because of the reflection symmetry of Dean vortices, the inversion of the channel curvature in the second mixing element only inverts the rotation direction of the vortices (as indicated by the arrows in frames a-2 and a-6). Numerical analysis of the concentration contour shows that only 9.4% mixing is achieved (see Supplementary information S1). The rotational forces that are imposed on the streams in the top half vertical plane of the SMU have a sequence of counterclockwise (CCW) and then clockwise (CW). This simulation result is in accordance with other reported experimental and numerical data in the literature [14,17]. In the SMU90^2, as the two streams are traveling along the first curved channel, centrifugal forces pull the solute stream (indicated by red color) that is on the left side of the image to the right (frame b-2 to b-3). As the fluid experiences the first 90° turning, the stream at the inner corner accelerates and the stream at the outer corner decelerates. This induced momentum imbalance creates rotational forces so that the solute stream is brought back to the left (frame b-4). After the next inversed 90° turn, the rotational