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Short communication

Vortex micro T-mixer with non-aligned inputs

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We describe a novel design for a micromixer that generates vortical flow in a rectangular microchannel with tangentially aligned inlet channels. The mixing performance of the proposed vortex T-mixer with non-aligned inputs is compared to a simple T-mixer as a function of Reynolds number. The mixer generates the formation of mixing-inducing flows even at low Reynolds numbers as compared to a simple T-mixer. The vortex initially formed at the inlet of a rectangular microchannel increases the interfacial area of the fluid streams by stretching. The proposed vortex mixer is easy to fabricate and offers a tunable control for the generation of vortical flow based on Reynolds number.

1. Introduction

Mixing of fluids at the microscale is one of the most important operations in the development of microfluidic systems for applications in chemical, biochemical, and biomedical systems [1,2]. Attaining rapid mixing is a challenge because the flow is laminar; mixing mainly relies on molecular diffusion across the interface of the fluid streams in microchannels. Diffusive mixing is very slow and requires channels that are longer than the size of the microfluidic devices [3]. Innovative shape modifications of channels and a comprehensive understanding of the transport of fluids have been the key approaches in the development of micromixers capable of efficiently mixing small volumes of fluids. Modulation of the interface of the fluid streams is currently the main focus of researchers since the mixing of fluids takes place across the interface [4,5].

One of the promising micromixer designs is directed toward harnessing vortical flow. The advantage of vortical flow is its ability to efficiently increase the interfacial area of fluid streams by stretching. The shape of such micromixers encompasses designs ranging from simple channels with continuous bends (to create transverse flows) to strategically designed grooved wall channels. Transverse flows in the form of Dean vortices in channels with bends and curves have been developed based on centrifugal forces that occur when a fluid stream undergoes changes in direction, and have been effectively studied for mixing applications [6–10]. Micromixers using vortical flow for mixing applications employ different design modification. Creating a single vortex using diagonal grooves and a pair of vortices using staggered herringbone grooves on walls have been widely used to rapidly increasing mixing within a short distance [3]. The micromixer has shown very high mixing performance by increasing the interfacial area of the fluid streams at an exponential rate. Micromixer designs with tangentially aligned inlet channels have been applied to create vortical flow in microchannels [11–14]. Vortical flows in planar circular mixing chambers with tangential inlet and outlet channels have been reported for mixing applications [11,12]. Lin et al. [13] used multiple fluid streams from inlet channels to create a vortex in cylindrical microchambers. Long et al. [14] used vortical flow for mixing by employing a single tangentially aligned inlet channel with combined fluid streams similar to Lin et al. [13]. Since a micromixer is one of the important components in a microfluidic system, it must be strategically designed in terms of practical applications, ease of fabrication, integration, and mixing performance. The micromixer reported by Chung et al. [11] is planar and hence can be easily fabricated, but the design is effective for mixing only at Reynolds numbers above 50 [11]. However, a three-dimensional (3D) structure with long drop-down distances of the mixing chambers (the distance between the planes of the inlet and outlet channels) can effectively work at Reynolds numbers of $Re \geq 2.5$ [13] and $Re \geq 10$ [14], but will be difficult to integrate with the main microfluidic systems. Since microchannels are commonly rectangular in shape, applying design modifications to create vortical flow in such shapes will find great practical applications.

The shape of a general T-mixer is the simplest, and this design can form an integrated unit (in the form of T or Y-joints) for most

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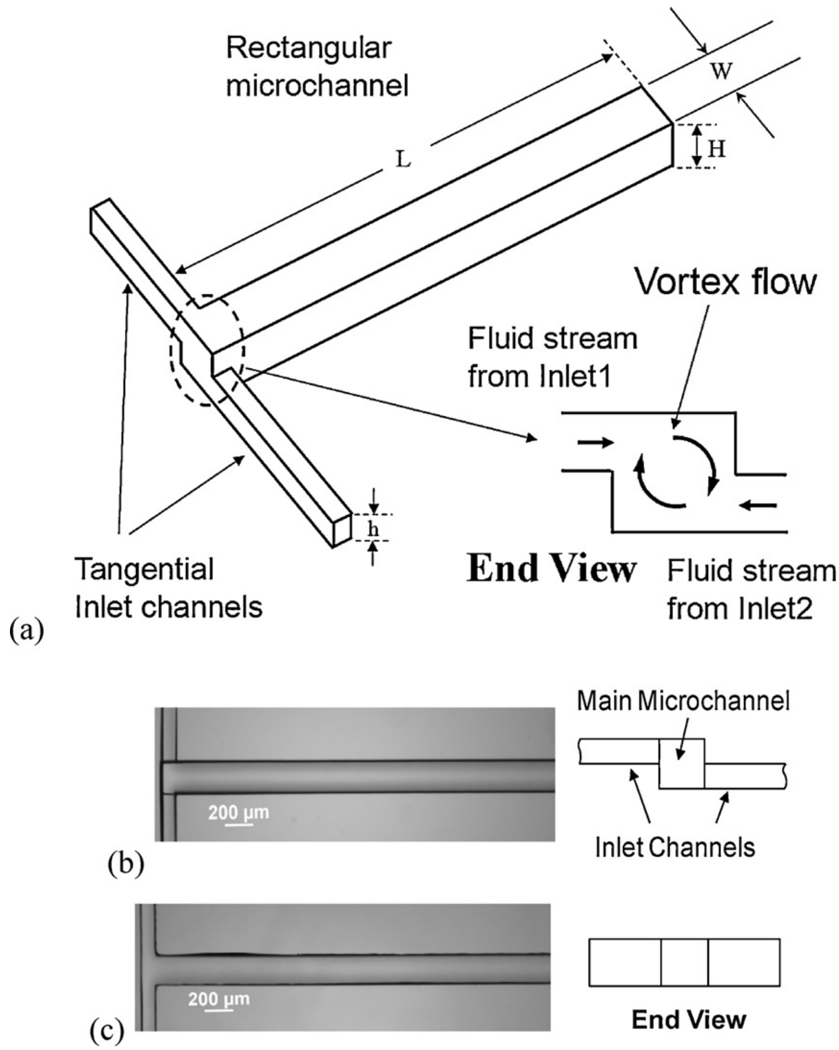

Fig. 1. Schematic of the micromixer. (a) Basic idea of the vortex T-mixer with non-aligned inputs. The inlet channels join the rectangular channel at a tangential position to create vortical flow. The height of the inlet channel is one-half of the rectangular channel ($h = 1/2H$). Optical micrograph of the micromixer. (b) Vortex T-mixer with non-aligned inputs. (c) Simple T-mixer. The vortex T-mixer with non-aligned inputs was fabricated in two layers of equal heights. The micromixer was obtained by bonding the two layers.

micromixers and microfluidic systems [15–23]. In T-mixers, the height of the inlet channels is typically equal to the height of the main channel, where the interplay of the incoming fluid streams starts to create asymmetric flow (engulfment flow) at certain critical Reynolds numbers $Re \geq 136$ [18]. At the same time, this critical Reynolds number for the transition to engulfment flow is not fixed; rather, it lies in a certain range (120–300) [19] depending on the operating conditions and geometry. Below this critical Reynolds number, a vortex pair is observed, but this is not effective in increasing mixing performance. Also, in this regime of Reynolds number, the increase in mixing performance with Re is very slow [18–23]. In the engulfment flow regime, mixing performance increases with the Reynolds number, since the incoming fluid streams are able to intertwine with each other. This implies that the design is ineffective in altering the interfacial area of the fluid streams at lower Reynolds numbers, and hence will not contribute in enhancing mixing performance. In such designs where the inlet channel simply connects to the main channel, efforts have been made to study the effect of interface position on mixing by controlling the flow rate [24]. Detailed study and an understanding of mixing at the microscale will be required for applications in the development of real-time microreactors [26–28].

We describe an experimental study of a novel design for a T-mixer with non-aligned inputs. We demonstrate the formation of a vortex and the use of the proposed mixer in enhancing mixing performance at low Reynolds numbers. The basic idea of the micromixer is shown in Fig. 1(a). The micromixer is comprised of a main rectangular microchannel connected by two perpendicular inlet channels at an offset position. The height of the inlet channel is one-half of the height of the main microchannel. The fluid streams that enter through the tangentially aligned inlet channels create vortical flow into the rectangular microchannel. The mixing performance of the vortex T-mixer with non-aligned inputs is compared with a simple T-mixer.

2. Fabrication, experiment, and mixing analysis

The micromixers were fabricated using soft lithography techniques, Polydimethylsiloxane (PDMS) replica molding, and plasma treatment bonding of the two layers. A master template was obtained by depositing SU-8 negative photo resist (GM 1075, Gersteltec Sarl, Switzerland) on a four inch silicon wafer using the spin coating technique at 1700 rpm to achieve a 90 µm channel height. A properly mixed pre-polymer (Sylgard 184, Dow Corning, USA) and