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Parametric study on mixing process in an in-plane spiral micromixer utilizing chaotic advection

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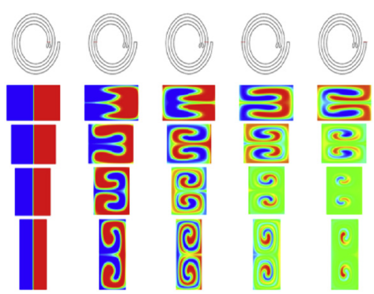
HIGHLIGHTS

- A high-throughput micromixer is proposed and numerically characterized.
- The investigated micromixer has a simple, in-plane structure.
- The studied micromixer is energetically efficient; it causes a rather small pressure drop.
- Different parameters such as Reynolds number of flow, the curvature and cross-section of the microchannel are investigated.
- The dominant mixing mechanism of the spiral micromixer is chaotic advection which makes it high throughput and rapid.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent advances in the field of microfabrication have made the application of high-throughput microfluidics feasible. Mixing which is an essential part of any miniaturized standalone system remains the key challenge. This paper proposes a geometrically simple micromixer for efficient mixing for high-throughput microfluidic devices. The proposed micromixer utilizes a curved microchannel (spiral microchannel) to induce chaotic advection and enhance the mixing process. It is shown that the spiral microchannel is more efficient in comparison to a straight microchannel, mixing wise. The pressure drop in the spiral microchannel is only slightly higher than that in the straight microchannel. It is found that the mixing process in the spiral microchannel enhances with increasing the inlet velocity, unlike what happens in the straight microchannel. It is also realized that the initial radius of the spiral microchannel plays a prominent role in enhancing the mixing process. Studying different cross sections, it is gathered that the square cross section yields a higher mixing quality.

1. Introduction

Over the past two decades, microfluidics has experienced an exponential growth due to their widespread applications, in particular, the biomedical and biochemical sciences. Microfluidics are widely used in laboratory research such as single cell manipulation [1], DNA analysis [2], dynamic cell sorting [3–5], and etc. The ultimate goal of microfluidic research is designing standalone devices which could be able to operate without needing a

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specialist; these devices are called micro-Total Analysis Systems (μTAS), and also Lab-on-Chips (LOC). Efficient micro-mixing, which is an imperative process for any miniaturized standalone analysis system, remains a key challenge due to the unfavorable laminar flow regime. At a macro-scale level, mixing is simply achieved by a turbulent flow; fluctuations and vortices in a turbulent flow increase the surface contact and decrease the mixing path which causes effective mixing [6]. However, at a micro-scale level, the flow is mostly laminar which prevents direct implementation of the conventional methods. A wide variety of micromixing approaches are reported in the literature, most of which can broadly fall into two categories: active and passive mixers.

Active micromixers are those utilizing an external energy source as well as fluid pumping energy to induce time-dependent perturbations to stir and perturb the fluid for accelerating the mixing process. Active mixers can be further categorized by the type of external disturbance effects they make use of, such as pressure field [7,8], electrohydrodynamic [9], dielectrophoretic [10], electrokinetic [11,12], and acoustic [13–15] disturbance mixers. Although active micromixers generally yield higher mixing quality in comparison to their passive counterparts, they are less utilized in practical standalone miniaturized analysis systems due to their shortcomings [16]. Active micromixers require additional integrated parts (e.g. energy sources and perturbation actuators) that make their fabrication process more complex and less cost effective. Furthermore, some external energy sources like ultrasonic waves can produce high-temperature gradients that can harm biological fluids. Therefore, active mixers are less popular when applying microfluidics to biomedical and biochemical applications [17].

On the other hand, passive micromixers do not require an external energy source other than the fluid pumping energy. These micromixers rely solely on the geometrical properties of the microchannel to stir the fluid. The mixing process is accelerated by minimizing the diffusion length and maximizing the interfacial area between the two fluids. Their fabrication process is often more convenient, and therefore, less expensive than those of active micromixers. Due to their simplicity, they are easily integrated into complex LOCs. All in all, these advantages make them more widely used in practical μTASs. According to the literature, efficient passive mixing is commonly achieved by either lamination-based mixers or chaotic advection-based ones [18].

In lamination-based mixers, fluids are guided alongside each other in a microchannel, and the mixing process occurs at the interfacial area between fluids due to molecular diffusion. Utilizing T- or Y- shaped microchannel is probably the most investigated passive mixing principle and is among the easiest lamination techniques [19–21]. The T- and Y- shaped mixers' efficiency can easily be enhanced by splitting the main inlet to into several substreams and then rejoining them to form a laminated stream [6]. These multi-lamination mixers improve the mixing quality by reducing the mixing length and increasing the interfacial area between fluids [22,23]. Buchegger et al. [24] presented a multi-lamination micromixer with four wedge-shaped inlet channels. Employing the wedge-shaped inlets, they achieved a highly uniform mixing in a low millisecond range. Tofteberg et al. [25] reported a novel passive micromixer integrating a controlled 90° rotation of a flow cross-section followed by a split into several channels. The main advantage of Tofteberg et al.'s micromixer was the simple in-plane design of channels, whereas other lamination based mixers reported in the literature need out of plane channels to split and recombine the fluids. Since the mixing process in lamination based mixers solely depends on the interfacial molecular diffusion, these mixers are rather slow, and therefore, they are most sensible to be used for mixing small Reynolds flows.

Another class of passive micromixers employ chaotic advection to enhance mixing process between fluids. Advection is the transport mechanism of a substance in a moving fluid due to the fluid's bulk motion. This phenomenon also occurs at lamination-based mixers; but because it happens in the direction of fluid flow, it has no tangible effect on increasing the mixing quality. These transversal secondary flows cause an exponential growth of the interfacial area between the fluids, which significantly enhances the mixing quality. These transverse components of flow can be generated by either embedding obstacles in the way of flow [26,27], or by using 3D convoluted channels [28–30] and 2D curvilinear channels [31–33].

Inserting obstacles into the mixing channel is almost the simplest way to get chaotic advection. Barriers can be embedded into the walls of the microchannel [34] or in the channel itself [26,35,36]. Bhagat et al. [35] designed, simulated, and fabricated a micromixer with diamond-shaped obstacles that achieved high mixing quality over a wide range of flow conditions. Tseng et al. [37] numerically studied the base-line micromixer by Bhagat et al., and enhanced the mixing quality by inserting boundary protrusions into the walls. Shih and Chung [38] designed, simulated, and fabricated an obstacle planar micromixer with a high mixing quality over a wide range of Reynolds numbers.

Three dimensional microfluidic structures are also utilized to achieve chaotic advection. Generally, these mixers consist of a repeating mixing unit that stretches and folds the fluids to achieve the desired mixing quality. Liu et al. [28] fabricated a 3D serpentine structure with C-shaped repeating unit. They reported a high mixing quality at moderately high Reynolds numbers ($Re > 25$). At a Reynolds number of 70, the 3D structured mixer yielded 16 times higher mixing quality than T-shaped mixer and 1.6 times more than square-waved channels. However chaotic-advection based micromixers yield high mixing quality under relatively high Reynolds numbers, Chen and Meiners [30] fabricated a double L-shaped 3D structure by which they achieved effective mixing at purely laminar flow ($Re = 0.1–2$). The main drawback of these mixers is the three-dimensional structure which makes the fabrication process complicated. Chaotic advection can also be induced in mixers with in-plane structures. Hong et al. [39] designed, simulated, and fabricated a novel in-plane micromixer using modified Tesla structure. Utilizing Coanda effect [40], they achieved effective mixing in a wide range of flow conditions. Mengeaud et al. [31] numerically characterized micromixers with zigzag shaped channels. They studied a broad range of Reynolds numbers and conducted that below a critical Re number of ~80 mixing entirely occurs by molecular diffusion. Hossain et al. [41] performed a thorough parametric examination on a micromixer with a modified Tesla structure. They numerically optimized the micromixer considering the mixing quality and the pressure head loss as the objective functions and geometrical properties as the effective parameters. Afzal and Kim [42] numerically optimized a passive pulsating micromixer with convergent-divergent walls. Due to the unsteady nature of the modeled mixer, they assessed the mixing performance of the mixer by a time-averaged mixing quality. They considered the mixing quality as the single objective function and the geometrical and flow variables as the effective parameters.Yang et al. [43] designed and fabricated a three-dimensional double layer spiral micromixer. They investigated the efficiency of the micromixer in a broad Reynolds range (8–40). They reported that the erect channel, which connected the two layers of spiral channels, plays a prominent role in the mixing of the working fluids. Garofalo et al. [44] proposed utilizing several units of S-shaped microchannels to be used in mixing applications. They numerically investigated the effect of dimensionless numbers such as Peclet, Dean and Schmidt in their research. Li et al. [45] designed and