Chemical Engineering Journal 249 (2014) 246–251

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Rapid vortex microfluidic mixer utilizing double-heart chamber

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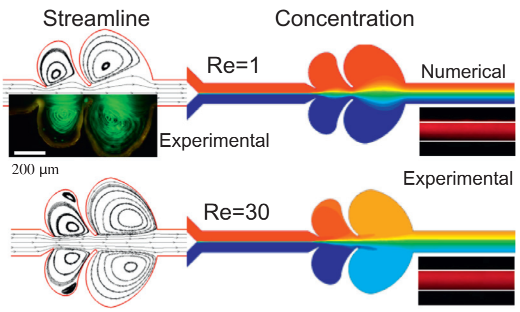
HIGHLIGHTS

- A novel vortex micromixer is proposed comprising an injection channel, a nozzle structure and a double-heart mixing chamber.
- The double-heart chamber can induce symmetrical rotating vortex structures.
- The mixing ratio reaches 92% even at Reynolds numbers as low as Re = 1 given a nozzle ratio of 0.25.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 December 2013
Received in revised form 9 March 2014
Accepted 11 March 2014
Available online 20 March 2014

Keywords:
Micromixer
Microfluidic
Double-heart chamber
Vortex

ABSTRACT

A novel vortex micromixer is proposed comprising an injection channel (Y-shaped or Interlaced-shaped), a nozzle structure and a double-heart mixing chamber. In the proposed device, the species are loaded into the injection channel and undergo an initial mixing effect as a result of natural diffusion. The partially-mixed species are then passed through the nozzle structure into the double-heart chamber, where they are further mixed by symmetrical rotating vortex structures before flowing into the exit channel. The flow phenomena and species concentration distributions within the nozzle structure and double-heart mixing chamber are evaluated by means of numerical simulations. The numerical results are confirmed by performing flow visualization experiments. It is shown that the mixing ratio in the Interlaced-shaped micromixer reaches 92% even at Reynolds numbers as low as Re = 1 given a nozzle ratio of 0.25. Overall, the results presented in this study show that the proposed vortex micromixer provides a simple yet effective solution for mixing problems in the micro-total-analysis systems (µ-TAS) field.

1. Introduction

In the same way that microelectronics revolutionized the modern world at the end of the twentieth century, so the recent trend toward system miniaturization, coupled with the development of microfluidic devices, has brought about profound change in the biomedical and chemical analysis fields [1–15]. Microfluidic systems [16–27] have many benefits compared to their large-scale counterparts, including a lower sample and reagent consumption, an increased analysis speed, an improved sensitivity, the capability for parallel processing, an improved performance and reliability, and better potential for integration with other microchips and detection systems.

The performance of many microfluidic systems is fundamentally dependent on a thorough mixing of the species. Existing

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http://dx.doi.org/10.1016/j.cej.2014.03.037
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microfluidic mixing schemes can be broadly categorized as either active or passive [28–41]. Active microfluidic mixers achieve mixing by stirring or agitating the fluid flow using some form of external energy supply. By contrast, passive microfluidic mixers mix the species by means of molecular diffusion or chaotic advection effects induced by specifically-designed microchannel features (e.g., grooves, ridges, obstacles, and so on).

Active microfluidic mixers utilize many different mixing mechanisms, including electrokinetic instabilities, electrokinetic/pressure perturbations, dielectrophoretic forces, acoustic/ultrasonic disturbances, electro-hydrodynamic impellers, and magnetic or thermal disturbances [42–46]. Wen et al. [42,47] presented a numerical and experimental investigation into the mixing efficiency of a microfluidic mixer actuated by a DC or AC electromagnet. It was shown that for a sample comprising water-based ferrofluid and de-ionized (DI) water, a mixing ratio of 95% could be obtained within 2.0 s given a peak DC magnetic field intensity of 60 Oe. Liu et al. [48] investigated the mixing characteristics and scaling-up performance of an asymmetrical T-shaped micromixer with replaceable channel plates. The results showed that the mixing performance was determined primarily by the geometries of the convergence region and mixing channel region of the device, respectively. Moreover, it was shown that by widening the continuous fluid channel of the micromixer to several millimeters, a high mixing efficiency could be obtained at Reynolds numbers as high as Re = 6000. Yu et al. [49] developed an active micromixer comprising a main microchannel and a micro/nano junction. In the proposed device, an electric voltage was applied across the microchannel; thereby inducing a bulk electroosmotic flow (EOF) within the channel and vertical flows near the nano-junction. The experimental results showed that the micromixer achieved a mixing performance of up to 90%.

The literature contains many proposals for passive micromixing schemes, including parallel lamination, injection, serial lamination, embeddedbarriers, droplet formation, intersecting channels, chaotic advection, three-dimensional serpentine structures, twisted channels, surface-chemistry treatment, and so on [50–57]. Cho et al. [58] performed a numerical investigation into the mixing performance of electrokinetically-driven non-Newtonian fluids through microchannels containing rectangular or wavy blocks patterned with a heterogeneous zeta potential on their upper surfaces. The results showed that the rectangular blocks yielded a more effective improvement in the mixing efficiency than the wavy blocks. However, for both types of block, the mixing efficiency was improved by increasing the patterned surface area or increasing the number of blocks. Fu et al. [59] presented a chaotic vortex micromixer comprising an open mixing chamber, a sealed mixing chamber and an inter-connecting serpentine microchannel. In the proposed device, an external gas pressure driving force was applied to the samples within the open chamber, prompting the formation of a vortex structure and pushing the samples through the microchannel into the sealed chamber. As the species entered the sealed chamber, a compression force was produced, which caused the formation of a second vortex structure and forced the species back through the serpentine channel into the open chamber. The numerical and experimental results showed that the reciprocating perturbation of the fluid flow resulted in a reaction ratio of almost 100% within 6 s given a gas pressure driving force of 1.5 kg/cm^2. Ren and Leung [60] performed a numerical and experimental investigation into the mixing effect within a rotating zigzag microchannel. It was shown that the intensity of the perturbing cross flow in the cross-sectional plane was enhanced as a result of the centrifugal acceleration forces developed by the rotation of the channel and the curved bends of the microchannel, respectively, and the Coriol is force.

This paper proposes a rapid passive micromixer incorporating a Y-shaped or Interlaced-shaped injection channel, a nozzle structure and a double-heart mixing chamber. The idea comes from the wisdom of the ancient fishermen who use double heart-shaped, tide trap fishes in Penghu's Chimei Island, Taiwan. The mixing performance of the proposed device is evaluated as a function of the nozzle ratio and Reynolds number by means of computational fluid dynamics (CFD) simulations. The simulation results are verified via a series of flow visualization experiments.

2. Fabrication and experimental details

Fig. 1 presents a schematic illustration of the proposed microfluidic mixer. Fig. 2 presents a simplified overview of the fabrication process used to realize the proposed device. (Note that a detailed description of the fabrication procedure can be found in Ref. [61].) Briefly, a thin layer of AZ 4620 photoresist was applied to a glass substrate and patterned with the required microchannel configuration by means of a standard photolithography technique (Fig. 2(a) and (b)). The patterned PR layer was hard baked and was then used as a mask in etching the glass substrate in commercially-available buffered HF (BOE, J.T. Baker, USA). The substrate was etched for 45 min to obtain a microchannel depth of 40 μm (Fig. 2(c)). The etched glass substrate was then immersed in diluted KOH solution (KOH (45%):DI = 1:9, 80 °C) in order to remove the residual PR layer (Fig. 2(d)). Fluid via holes were drilled in a bare glass slide using a diamond drill-bit (ϕ1.5 mm) (Fig. 2(e)). The two glass substrates were cleaned in a boiling Piranha solution, carefully aligned, and then bonded in a sintering oven at a temperature of 580 °C for 10 min (Fig. 2(f)). The entire fabrication process was completed within 10 h.

Fig. 3 presents a schematic illustration of the experimental setup used to characterize the performance of the proposed microfluidic mixer. As shown, the main items of experimental equipment included two syringe pumps (KDS-200, KD Scientific, USA), a fluorescence microscope (E-400, Nikon, Japan) with a mercury lamp module, a CCD module (DXC-190, Sony, Japan) with a high-speed image acquisition interface (DVD PKB, V-gear, Taiwan), and a PC. The mixing tests were performed using 1 mM sodium borate buffer (pH = 9.2) and sodium borate buffer with RO water and 10^{-4} MRhodamine B fluorescence dye.

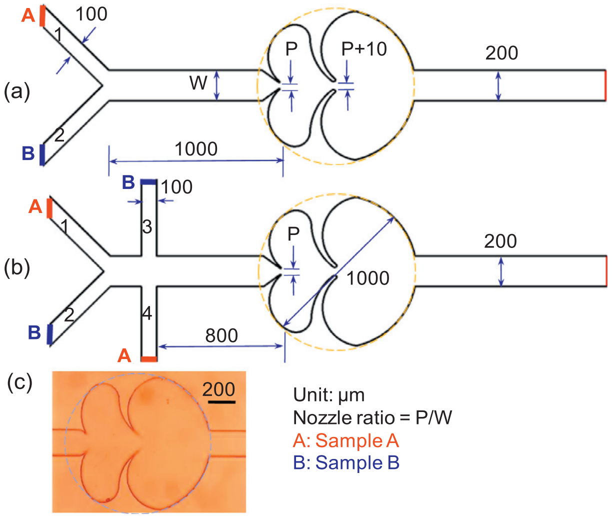

Fig. 1. Schematic illustration of proposed micromixer: (a) Y-shaped injection channel, (b) Interlaced-shaped injection channel, and (c) OM image of double-heart chamber.