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Research paper

Computational simulation and fabrication of smooth edged passive micromixers with alternately varying diameter for efficient mixing

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ABSTRACT

To improve the efficiency of passive micromixers, microchannels of varying geometry have been widely studied. A highly efficient passive micromixer was developed by alternatively varying the cross-sectional diameter along the flow. Microfluidic channels of various geometries were designed and the fluid flow patterns were studied using COMSOL Multiphysics. The extent of mixing in the microchannels for the various designs were analyzed and the most efficient micromixer was further optimized for best mixing performance. The optimized design was fabricated using direct laser write lithography. The spin speed, exposure energy, baking temperature, baking and development time were observed to play an important role in fabrication. Experimental evaluation of the simulation results was carried out by injecting coloured solutions through the PDMS microchannels and by electrochemical studies.

1. Introduction

Microfluidics has attained increased popularity because of its applications in a wide variety of fields such as drug delivery [1], polymerization [2], heat transfer [3], analytical assays [4], clinical diagnostics [5] and molecular separations [6]. Microfluidic systems are highly efficient in the microscale but this reduction in size introduces new complexities that are not relevant in the macrofluidic scale. One of the major challenges encountered is the homogeneous mixing of fluids as the Reynolds number is very low (<10) within the microfluidic channels. As a result, the flow is laminar with reduced contact time between the two fluid streams. Viscous effects due to molecular diffusion dominate mixing at the micro scale [7]. Micromixers are specially designed structures with geometries that decrease the total length of fluid path while increasing the contact time between different fluid streams in a laminar flow [8]. The development of microfluidic systems with efficient mixing is obligatory to realize the full potential of Micro Total Analysis Systems (μTAS) and Lab-On-A-Chip (LOC) devices.

In a microfluidic system, mixing can either be active or passive. In active mixing, external energy source is employed for enhancing agitation. Active mixers include dielectrophoresis [9,10], electrokinetic disturbance [11,12], pressure perturbation [13–15], magneto-hydrodynamic disturbance [16] and ultrasonic vibrations [17,18] to enhance mixing. But the difficulties associated with the integration and fabrication of active mixers [19,20] makes passive micromixers an attractive alternative. In passive mixing, no external energy source is required for moving the fluid through the microchannel. The pressure gradient between the inlet and the outlet cause the fluid to move the fluid through the channel at a constant rate. In this case, the extent of mixing is influenced by channel geometry and laminar perturbations. Numerous studies have been carried out using passive micromixers involving T-shaped and Y-shaped inlets, zigzag flow path, serpentine structures, baffle arrangement, all of which improve mixing efficiency by altering the channel geometry. In T-shaped and Y-shaped channels, the fluid flows parallel to each other and hence it takes a longer time for diffusion to occur [21–23]. The efficiency of such channels can be improved by splitting the inlet stream into a number of sub-streams and rejoining them, which helps reduce the diffusion path and increases the contact time [24–27]. Numerical and experimental studies on the effect of 3D serpentine, square wave, and straight microchannels were studied by Liu et al. [28]. From their flow-visualization experiments, it was observed that the three-dimensional serpentine channel had better mixing rate compared to square-wave and straight channels.

Mixing efficiency can be remarkably improved by introducing chaotic advections in the laminar flow by altering the geometry of the microchannels [29,30]. Literature reviews shows that obstacles in the fluid path introduce whirl flow resulting in traversal mass flow [31–35]. Jeon et al. carried out such studies by incorporating various

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obstructions and utilizing channels with different flow patterns such as contraction-enlargement and zig-zag paths [36]. It was seen from their studies that zig-zag microchannels showed superior mixing compared to the other geometries. Simulation studies by Hossaian et al. showed that square wave microchannel resulted in a better homogeneous fluid compared to zig-zag and curved microchannel [7].

In this study, a passive micromixer that incorporates meander structures with alternately varying diameters has been designed, simulated and fabricated to achieve high mixing efficiency. CADian and CleWin softwares were used for designing the microfluidic channels, while fluid flow patterns were analyzed using computational fluid dynamics (CFD) tool COMSOL Multiphysics. Optimization of length, diameter and geometry of the microchannel to enhance mixing at shorter time were carried out through numerical studies. The effects of mixing in sharp vs. smooth channels were studied and the design was finalized based on optimum mixing at shortest diffusion length. The optimized design was fabricated using direct laser write lithography following standard procedures and the simulation results were experimentally verified.

2. Micromixer design and numerical studies

2.1. Design

To investigate the effect of geometry on fluid mixing within microchannels, straight and meander channels were modeled and simulated (Fig. 1). The length (L) depth (D) and height (H) of the microchannel was designed as 54.5 mm, 150 μm and 6.3 mm respectively. The design has a primary inlet 'A' which splits into three substreams a1, a2 and a3 which are connected to the secondary inlets 'B', 'C' and 'D' respectively. Mixing starts from the point of contact between the two streams. 'X', 'Y' and 'Z' represent the three outlets. The analytes to be detected are introduced through the primary stream A while the respective reagents pass through B, C and D respectively.

Since the intention of this work was to develop microfluidic channels for multiple analyte detection in LOCs, each of the geometry that was analyzed consisted of a single sample inlet, three reagent inlets and three analysis wells as a model design. Fig. 1.A depicts the straight channel having no obstructions. Here, the two streams flow parallel to

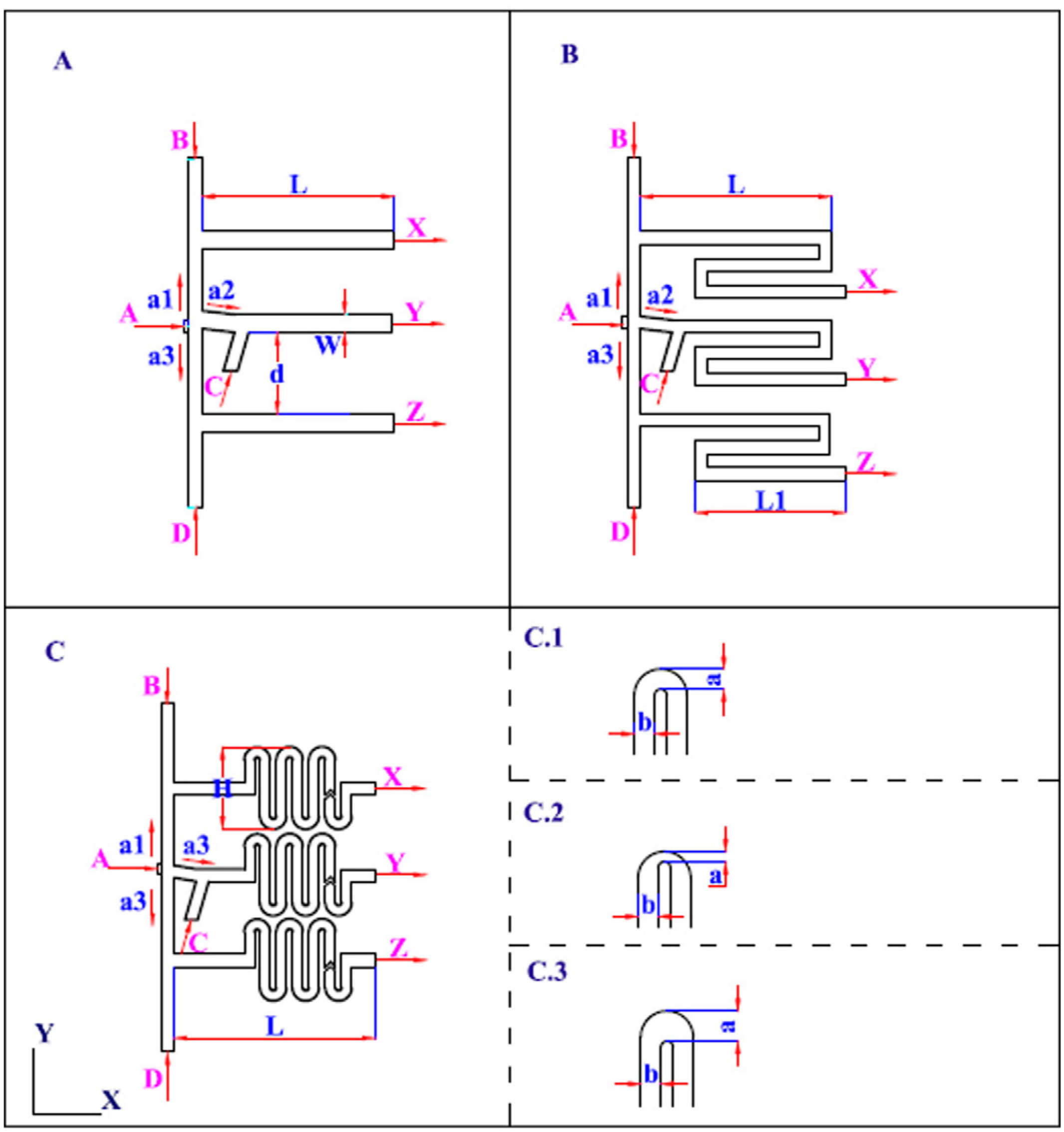

Fig. 1. Different geometries of the microfluidic channels (A) straight microchannels with no meander structures, (B) straight microchannels modified for increasing time of diffusion, (C) microchannels with meander structures. (Inset: Meander structures with alternatively varying diameters in the ratio 1:1 (C.1), 2:1 (C.2), 1:2 (C.3).