Mixing Performance Analysis of Serpentine Microchannels with Straight and Curved Bends

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1 Introduction

Microfluidics is a term which deals with transport phenomena at the microscopic scales and techniques and components employed for controlling and actuating the fluids. The microfluidic systems are the fast-growing technology, and the microfluidics study is significant for implementing lab-on-a-chip (LOC). The LOC systems are moreover recognized as micro total analysis systems (µTAS) that can execute maximum stages of chemical and biological processes [1, 2]. Microfluidics has many applications in many different fields including cosmetics, pharmaceuticals, biotechnology, medicine, and also in physical sciences for control systems and heat management. A microchannel is one of the vital components of microfluidic systems. The microchannel is a channel that has a height and width in the order of micrometers (µm). A microchannel which mixes fluid is called a micromixer. The geometries are built into the circuits which are known as microfluidic chips. This technology has been the reason for a good deal of research, as it offers a means for carrying out the key chemical evaluation processes in the biomedical field [1–3].

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Micromixers can be classified into two main categories as active and passive. Each of these micromixers has different capacity, mixing speed, and operating requirements. For example, an active micromixer requires power input to make mixing possible in the device.

In contrast, a passive micromixer achieves mixing with the applied pressure for fluid motion. As such, some micromixers are more suitable for a particular application than the others. Active micromixer generally provides correct mixing, but their fabrication is cost-intensive, and integration with different devices is difficult. For this reason, passive micromixers are favored in several situations [4–6].

Many researchers report the mixing performance of passive microchannels. The various geometries like wavy structure, curved shape, static micromixers, 3D serpentine, square wave, straight microchannels, spiral-shaped microchannel, serpentine microchannel with cyclic L-shaped units, serpentine microchannel with non-aligned inputs, etc., have been used by different researchers for analyzing the effect of geometry/shape on the mixing performance analysis [7–15]. Many researchers have also studied the microchannel-based on the split and recombine (SAR) process. In SAR, the two fluids to be mixed are split and recombined to optimize the diffusion process. The different passive micromixer configurations developed by various researchers are planar SAR micromixer, micromixer using two-dimensional (2D) modified Tesla structures, two-layer crossing channels (TLCCM), ellipse-like micropillars, P-SAR micromixer with cavities (fan-shaped), modified P-SAR micromixer with dislocation sub-channels, etc. The mixing performance has been observed enhanced due to the SAR process and the subsequent chaotic advection [16–18]. Different researchers report some numerical investigations on mixing behavior of microchannels using different types of obstacles and grooves along the mixing path. [19–24] and reported that recirculation zones are created downstream of these obstructions, which resulted in mixing performance enhancement. Few of the researchers have fabricated the microchannels using different methods like laser machining, photochemical machining, micro-milling, etc. [25–35].

Based on the above reported various studies, it is noted that the microchannel is governed by the two main parameters as pressure drop and mixing index (or mixing length). Still, there is scope for comparative analysis of serpentine microchannels with straight bends and curved bends. Also, the effect of width and height (aspect ratio) on the mixing analysis is impressive. This paper presents the mixing performance analysis with straight and curved bends. COMSOL Multiphysics 5 was used for performing the simulations. The aspect ratio (ratio of channel width to height) was varied as 0.75, 1, and 1.25. The pressure variation (drop) and mixing within straight and curved serpentine microchannel is analyzed.

2 Methodology—Numerical Simulations

2.1 Microchannel Geometry

In the present study, two microchannel configurations with Y-shaped inlet have been considered—a serpentine microchannel with straight bends and a serpentine microchannel with bends. The computational models for the same are developed in COMSOL Multiphysics 5.0 and are presented in Fig. 1a, b for the serpentine microchannel with straight and curved bends, respectively. The dimensions (width and height) of the microchannel considered are 400 μm for both the configurations for aspect ratio 1. The width of the channel is kept constant, and the height is varied for aspect ratio of 0.75 and 1.25. Two different fluids have been fed through two different inlets, namely Inlet 1 and Inlet 2. The fluid velocity (*u* mm/s) for both the inlets has been assumed to be the same.

2.2 Boundary Conditions

The simulations for the developed microchannels have been carried out using COMSOL Multiphysics 5. The physics used for simulations in COMSOL is laminar flow and transport of diluted species. Using suitable boundary conditions, the governing equations, i.e., Eqs. 1–3, have been solved in the software. The boundary

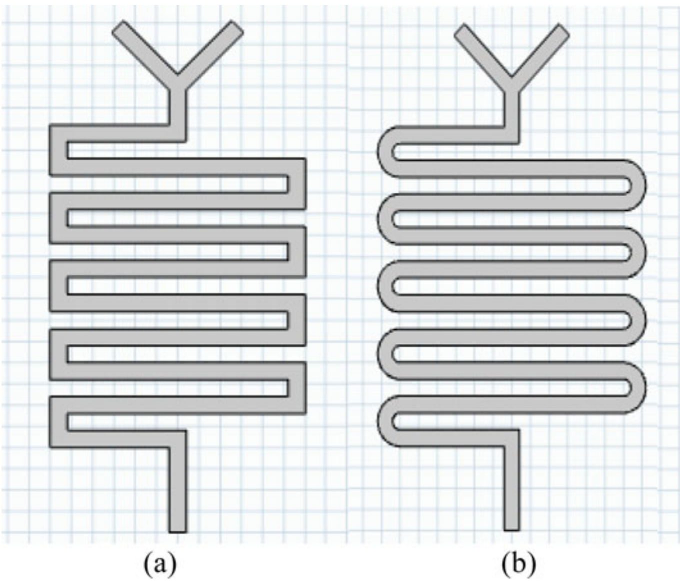


Fig. 1 Serpentine microchannel **a** with straight bends **b** with curved bends

conditions used are the equal velocities at the two inlets, atmospheric pressure at the outlet, symmetry at the interface between the fluids, and no-slip conditions at the microchannel walls. The fluids at the two inlets have been considered as water and ethanol at 25 °C. At the inlet boundaries, the concentrations of fluids have been taken as 10 mol/m^3 and that for fluid 2 as 0 mol/m^3. The diffusion coefficient of ethanol in water has been taken as 1.0×10^{-9} m^2/s. The inlet velocity is varied from 0.5 to 1 mm/s.

For the developed computational models, the steady-state condition for the fluid flow and convection and diffusion of the species have been assumed. The mass and momentum balance for the incompressible and isothermal Newtonian fluids in microchannels are expressed by Navier–Stokes and continuity equations, and the equations are as follows:

$$\nabla . u = 0 \tag{1}$$

$$\nabla (u.\nabla)u = \nabla.\left[-pI + \nabla\left(\nabla u + (\nabla u)^T\right) - 2/3\nabla(\nabla.u)I\right] + F \tag{2}$$

where $u = (u, v, w)$ is the flow velocity field, ρ is the density of the fluid, p is fluid pressure, μ is the dynamic viscosity of the fluid, I is the unit diagonal matrix, and $F = (f_x, f_y, f_z)$ is a volume force affecting the fluid.

Due to the convection and diffusion, the mixing in the flow takes place. The following equation has governed mass transport:

$$\nabla.(-D.\nabla c) + u.\nabla c = R \tag{3}$$

2.3 Meshing

For the computational analysis of the microchannel models, the unstructured mesh has been used. For avoiding the effect of increased meshing elements on the quality of the simulation results, the simulations have been carried out with different mesh size (domain elements). For both the configurations of the microchannel, the results for pressure drop are compared at various domain elements. The meshed serpentine microchannel with straight and curved bends is depicted in Fig. 2a, b, respectively.

3 Results and Discussion

Using COMSOL Multiphysics 5.0 software, the 3D models of the serpentine microchannel with straight and curved bends have been developed, and then, simulations have been carried out. Equations 1–3 have been solved by using

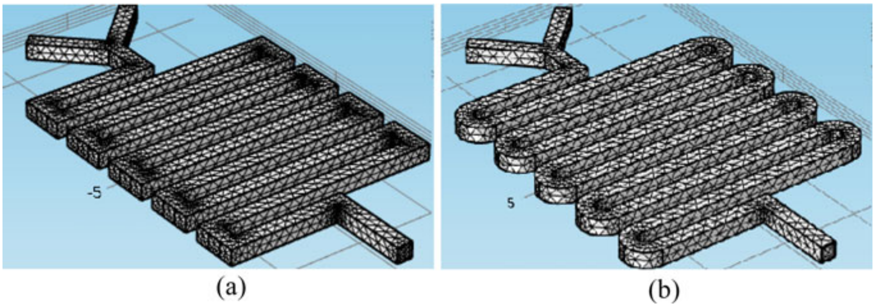


Fig. 2 Meshing for serpentine microchannel **a** with straight bends **b** with curved bends

considered boundary conditions. Water is used as the primary fluid, while ethanol has been used as the secondary fluid (both at 25 °C).

3.1 Effect on the Pressure Drop (Pa)

The influence of the aspect ratio on the pressure drop is analyzed. The aspect ratio considered for the analysis was 0.75, 1, and 1.25. The velocity of inlet fluids was varied with a velocity of 0.5 mm/s, 0.75, and 1 mm/s. The sample images for the pressure drop measurement for serpentine microchannel with straight bends and curved bends are shown in Fig. 3a, b, respectively.

The pressure drop was recorded, and the effect of aspect ratio on pressure drop for serpentine microchannel with straight bends and curved bends is shown in Fig. 4a, b, respectively. It is observed from Fig. 4 that the pressure drops increase with increase in the aspect ratio from 0.75 to 1.25. Also, the pressure drops increase with increase in velocity from 0.5 to 1 mm/s. The reason behind this is as the aspect

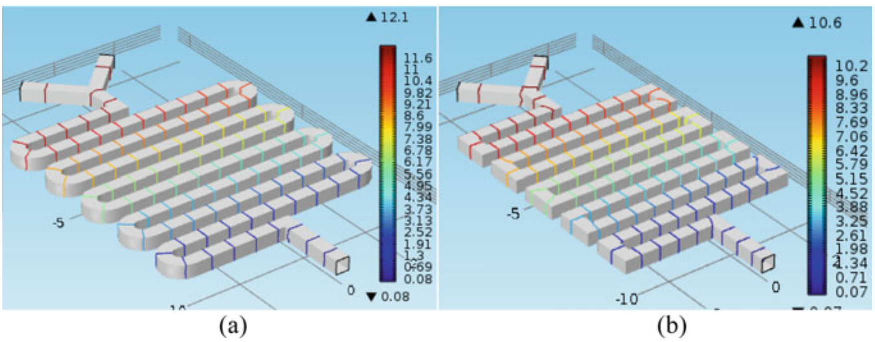


Fig. 3 Pressure drop for serpentine microchannel at 0.5 mm/s velocity for **a** with straight bends **b** with curved bends

ratio increases the cross-sectional area of the microchannel increases. The same fluid will experience more pressure in a lesser area and less pressure in the increased area. Therefore, the pressure drop increases with an increase in aspect ratio. From Figs. 4 and 5, it can also be noted that the pressure drop is more for the serpentine microchannel with curved bends as compared to serpentine microchannel with straight bends. The fluids experience more pressure in curved bend configuration due to its shape, and this leads to increased pressure drop for serpentine microchannel with curved bends as compared to serpentine microchannel with straight bends.

3.2 *Effect on the Mixing Length*

The term mixing length refers to the distance along the channel where the mixing index is achieved as 1, i.e., the mixing of the two fluids is 100%. The mixing length is recorded in COMSOL Multiphysics 5 software. The sample images for the

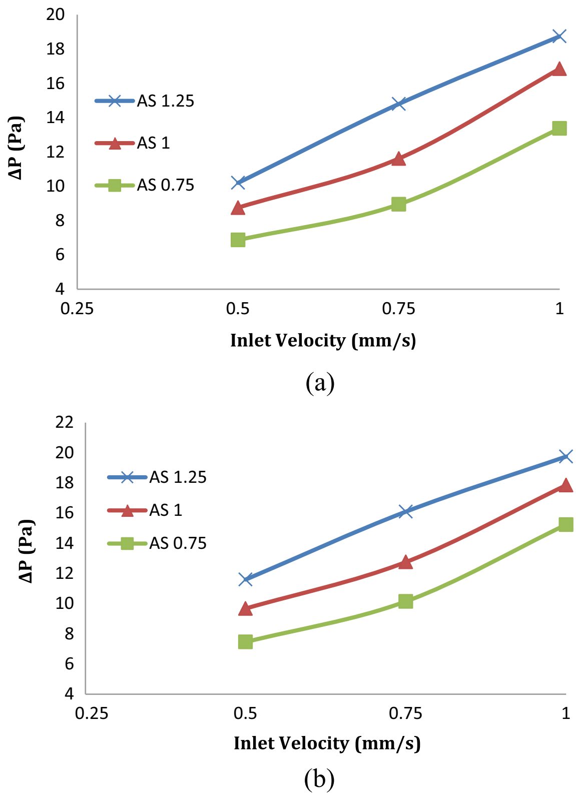


Fig. 4 Effect of aspect ratio on pressure drop for serpentine with **a** straight bends **b** curved bends

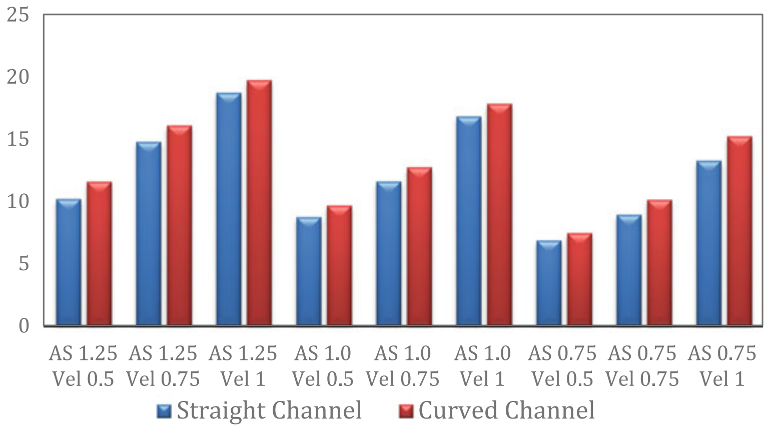


Fig. 5 Comparative pressure drop analysis for serpentine with **a** straight bends **b** curved bends

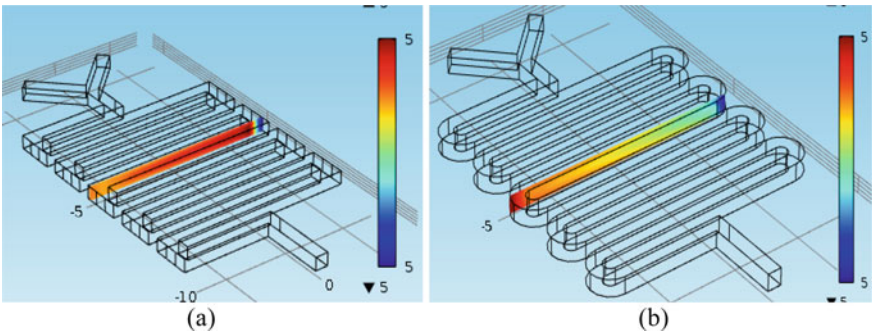


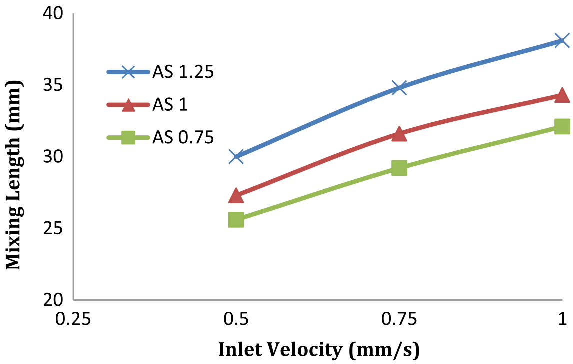
Fig. 6 Sample images for mixing at the cross section of the channel for serpentine with **a** straight bends **b** curved bends

mixture across the cross section for serpentine microchannel with straight bends and curved bends are presented in Fig. 6a, b, respectively.

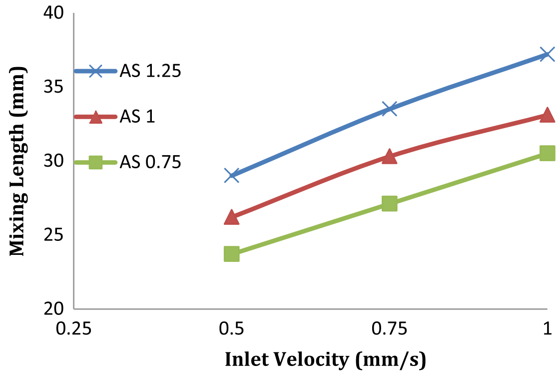
The effect of aspect ratio on mixing length is presented in Fig. 7a, b for serpentine microchannels with straight bends and curved bends.

From Fig. 7, it can be seen that the mixing length is noted lesser for the microchannels smaller aspect ratio. It increases with increase in aspect ratio from 0.75 to 1.25 for both the considered microchannel configurations. This increase is because the flow is laminar at lesser fluid velocities, and the mixing in the microchannels is because of diffusion. Aspect ratio 0.75 indicates the broader cross section, and the aspect ratio 1.25 showed the smaller the cross section. The more area is available for diffusion in case of the larger cross-sectional area; hence, the lesser mixing length is observed at lower aspect ratio, and the increased mixing lengths are noted for the larger aspect ratio 1.25. Also, the mixing lengths are found

Fig. 7 Effect of aspect ratio on mixing length for serpentine microchannel with **a** straight bends **b** curved bends



(a)



(b)

lesser for serpentine microchannel with curved bends as compared to that for the serpentine microchannel with straight bends. This smaller mixing length is due to the effect of Dean vortices forming at the curved bends, which enhances the mixing and leads to reduced mixing lengths as compared to that for straight bends.

4 Conclusions

The mixing performance analysis of a serpentine microchannel with straight bends and curved bends has been studied using computational analysis with COMSOL Multiphysics 5.0 software. The aspect ratio considered in the analysis is 0.75, 1, and 1.25. The influence of aspect ratio on the pressure drop and mixing length is investigated. Based on the numerical analysis, the following conclusions are drawn:

- The pressure drop increases proportionally with an increase in the aspect ratio from 0.75 to 1.25.

- The mixing length also increases with an increase in aspect ratio from 0.75 to 1.25.
- The higher-pressure drops are noted for the serpentine microchannel with curved bends as compared to serpentine.
- The mixing lengths are observed lesser for the serpentine microchannel with curved bends as compared to straight bends.

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