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Mixing performance of a planar micromixer with circular obstructions in a curved microchannel

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ABSTRACT

A numerical investigation of the mixing and fluid flow in a new design of passive micromixer employing several cylindrical obstructions within a curved microchannel is presented in this work. Mixing in the channels is analyzed using Navier–Stokes equations and the diffusion equation between two working fluids (water and ethanol) for Reynolds numbers from 0.1 to 60. The proposed micromixer shows far better mixing performance than a T-micromixer with circular obstructions and a simple curved micromixer. The effects of cross-sectional shape, height, and placement of the obstructions on mixing performance and the pressure drop of the proposed micromixer are evaluated.

Keywords: Micromixer; Circular obstructions; Curved microchannel; Mixing index; Navier–Stokes equations; Reynolds number

1. Introduction

A wide range of applications for microfluidic systems is being realized in fields such as miniaturized analytical systems for chemistry and biology (e.g., genomic and proteomic analysis), clinical diagnostics, and micro-total analysis systems (μTAS) (Sanders and Manz, 2000; Verpoorte, 2002; Reyes et al., 2002; Auroux et al., 2002; Chow, 2002). Many microsystems need to mix two or more fluid streams to fulfill the task. Therefore, the micromixer unit is one of the critical elements of μTAS. To obtain fast diagnosis results, efficient and fast mixing of the reagents is needed.

Due to low Reynolds numbers, the flows in microchannels are laminar flows, and thus the mixing is dominated by molecular diffusion. If mixing relies only on the diffusion process, considerable time and a long channel length are necessary, thereby resulting in high-pressure drop and high cost. To overcome these difficulties, researchers have tried to obtain efficient and fast mixing even at low Reynolds numbers.

To enhance mixing, an active or passive method can be employed. Active mixing is achieved by perturbing the flow field using external sources of energy including electro-kinetic force (Jacobson et al., 1999; Oddy et al., 2001), ultrasonic actuation (Zhu and Kim, 1998; Yang et al., 2001), thermal power (Mao et al., 2002; Tsai and Lin, 2002), and periodic pressure perturbation (Fujii et al., 2003; Glasgow and Aubry, 2003; Niu and Lee, 2003). Active micromixers have obvious advantages over passive micromixers, but their complexity with respect to integration with microfluidic systems leads researchers to consider alternatives. On the other hand, passive micromixers do not require an external source of energy other than the basic pressure head used to drive the fluid flow. Passive micromixers can be classified into two types of mixing mechanisms: chaotic advection and lamination. Chaotic micromixers enhance mixing with three-dimensional (3-D) channel structures (Liu et al., 2000; Jen et al., 2003; Kim et al., 2004) or geometrical planar shapes (Hong et al., 2001; Wong et al., 2003; Bhagat et al., 2007). The planar designs are easier to fabricate and to integrate with micro-systems, but they need to operate at $Re > 100$. This results in a higher pressure drop (Wong et al., 2003) or the need for long channels; e.g., longer than 10 mm when working at $Re < 1$ to achieve higher performance (Bhagat et al., 2007). Mixing in lamination micromixers depends on the molecular diffusion mechanism (Wu and Nguyen, 2005; Ducree et al., 2006). Although these devices can achieve higher mixing at low Reynolds numbers, their fabrications are usually complicated.

Micromixers with obstructions use chaotic advection, and have been proposed by many researchers for a straight channel. In many cases, the splits and recombinations are realized

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Nomenclature

C_i	mass fraction at sampling point i
C_m	optimal mixing mass fraction
d_1, d_2	diameters of the small and large circular obstructions, respectively
H	height of the channel
h	height of the obstruction
L_m	length of the main channel
L_e	length of the exit channel
M	mixing index
P	pressure
Re	Reynolds number
R_1, R_2	radii of the inner and outer circular walls
R_m	radius of the centerline in the curved channel
V_j	average velocity in x_j direction
V_{ij}	velocity of fluid component i in x_j direction
W	width of the main channel
x, y, z	streamwise, spanwise, and cross-streamwise coordinates, respectively
Greek letters	
θ	inclination of the obstruction
γ	variance
μ	absolute viscosity
ρ	fluid density
ρ_i	density of fluid component i
Γ_i	molecular diffusion coefficient of fluid component i

by introducing obstructions into the path of the main flow. Lin et al. (2007) studied numerically and experimentally a T-micromixer with J-shaped baffles. Bhagat et al. (2007) proposed a planar passive microfluidic mixer with different shapes of obstructions in a T-channel that is capable of mixing at low Reynolds numbers. Wang et al. (2007) proposed a Y-micromixer with a cylindrical obstruction in order to disrupt the flow. The disruption to the flow field alters the flow direction from one fluid to another. In this way, convection can occur to enhance the mixing. Hossain and Kim (2010) numerically investigated the effects of geometric parameters on the mixing performance of a straight groove micromixer. They found that the number of grooves per cycle increases the mixing index and decreases the pressure drop. In a recent study, Ansari et al. (2010) improved the mixing performance of a simple split and recombination micromixer using unbalanced splits and collisions of fluid streams over Reynolds number range, $10 \leq Re \leq 80$.

Curved micromixers have been studied by several researchers (Hossain et al., 2009; Jiang et al., 2004; Sudarsan and Ugaz, 2006). They indicate that curved micromixers without obstructions are effective only at high Reynolds numbers. Obstructions in straight channels only cause split and recombinations, but obstructions in curved microchannels cause secondary flows at high Reynolds numbers as well as splits and recombinations. Therefore, curved micromixers with obstructions are effective for mixing at both high and low Reynolds numbers.

In the present study, a curved micromixer with obstructions is proposed for efficient mixing for a wide range of Reynolds numbers (Re = 0.1–60). Three obstruction shapes were tested by solving 3-D Navier–Stokes equations to determine the effect of the cross-sectional shape of the obstructions on mixing performance. The effects of height and the placement of obstructions on mixing were also evaluated. The mixing performance of the proposed micromixer was compared to the performance of a T-micromixer with obstructions and a simple curved channel.

2. Micromixer model

Fig. 1 shows schematic diagrams of the curved and straight micromixers with cylindrical obstructions. In both micromixers, the width (W) and height (H) of the main channel are commonly 100 μm. Two different fluids enter into the micromixers from different inlets. The dimensions of the micromixers are as follows: inlet channel length, $L_0 = 0.2$ mm; channel length with obstructions, $L_m = 3.5$ mm; and exit channel length, $L_e = 1.8$ mm. For the curved channel shown in Fig. 1(a), the radius of the inner circular wall is $R_1 = 0.2$ mm and the radius of the outer circular wall is $R_2 = 0.3$ mm. The angular distance between adjacent large and small obstructions is $\theta = 15^\circ$ and is uniform throughout the channel. Therefore, there are six large and twelve small cylindrical obstructions in a half-cycle whose diameters (d_1 and d_2) are 0.04 mm and 0.03 mm, respectively. The height of the obstructions (h) varies from 20 to 100 μm. Fig. 1(b) shows a schematic diagram of the T-micromixer with cylindrical obstructions. The dimensions of the obstructions are the same as in the curved channel. The axial distance between the adjacent obstructions is equal to $R_m\theta$. Water and ethanol were selected as the two working fluids for mixing. The properties of water and ethanol were taken at a temperature of 20 °C. The densities of water and ethanol are 998 and 789 kg m^{-3}, respectively. The viscosities of water and ethanol are 0.9×10^{-3} and 1.2×10^{-3} kg m^{-1} s^{-1}, respectively. The analysis was performed for a Reynolds number range from 0.1 to 60.

In this work, a parametric study on the geometry of a curved micromixer with obstructions (Fig. 1(a)) was performed to improve the mixing performance with various shapes, heights, and placements of the obstructions.

3. Numerical analysis

A commercial CFD code, ANSYS CFX-11.0 (2007), was used to analyze the mixing and fluid flow in the micromixer. The code solves the continuity, Navier–Stokes, and species convection–diffusion equations for steady and incompressible flows using the finite volume method. Each fluid component has its own equation for the conservation of mass as follows:

$$\frac{\partial(\rho_i V_j)}{\partial x_j} = -\frac{\partial}{\partial x_j}(\rho_i(V_{ij} - V_j)) \tag{1}$$

$$V_j = \sum \frac{(\rho_i V_{ij})}{\rho} \tag{2}$$

$$\rho_i(V_{ij} - V_j) = -\frac{\Gamma_i}{\bar{\rho}}\frac{\partial \rho_i}{\partial x_j} \tag{3}$$

where ρ_i is the density of fluid component i in the mixture (i.e., the mass of fluid component i per unit volume); V_j is the average velocity field; $\rho_i(V_{ij} - V_j)$ is the relative mass flux; and V_{ij} is the velocity of fluid component i. The differential motion of the individual components in the mixture is accounted for by the relative mass flux term. This term may be modeled in