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The effect of curvature angle on mixing efficiency in curvilinear microchannels

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The aim of this study is to investigate the effect of curvature angle on mixing efficiency in curvilinear microchannels. For this, three microchannels geometries with curvature angles of 180°, 230°, and 280° were fabricated, and the performance of each microchannel in mixing two fluids was studied by performing extensive experiments over a wide range of Reynolds numbers from 38 to 205. The involving mechanisms in mixing process was carefully examined for all of the microchannels. For each geometry, the optimum Reynolds number, the one, at which the minimum mixing length was obtained, was reported. Moreover, the microchannel with the highest mixing efficiency was determined.

1. Introduction

Micromixing is one of the major application areas of microfluidic chips, which find applications in analytical processes and chemical and biological engineering [1], including but not limited to chemical reactors [2], DNA amplification [3], drug delivery [4], and polymer synthesis [5]. It is classified into two major types: passive and active mixing. In the former one, there exists no external force, and mixing occurs due to the forces created by channel geometry; while in the latter one an external force is utilized to enhance the mixing process, such as electrical or magnetic forces. Passive micromixers benefit from lower levels of complexity and fabrication costs [6].
In present work, the effect of curvature angle on mixing efficiency of curvilinear microchannels is studied. The three microchannels have different curvature angles of 180°, 230°, and 280°. Mixing experiments are performed on each of them over a wide range of Reynolds numbers.

2. Materials and Methods

Considering the curvilinearity of the microchannels in this study, the most dominant mixing principle is due to the secondary flow, also known as Dean vortices. In contrast to straight microchannels, curved channels introduce two counter-rotating vortices because of the velocity difference between the inner and outer walls. Consequently, in a curved microchannel, the fluid near the outer wall undergoes an inward motion, while the fluid near the inner wall moves outward. These vortices are characterized by the dimensionless Dean number, De, defined as [7]:

$$De = \sqrt{\frac{D_h}{2R}}Re \quad (1)$$

where D_h is the hydrodynamic diameter of the microchannel, R is the radius of curvature of the curved channel, and Re is the Reynolds number of the flow.
The geometries of the curvilinear microchannels are depicted in Fig. 1. All of the microchannels have a uniform width and height of 350 μm and 90 μm, respectively. Figure 1(a-c) illustrates three geometries having curvature angles of 180°, 230°, and 280°, respectively.
All of the chips were fabricated out of PDMS via standard soft lithography processes; the details of the fabrication steps can be

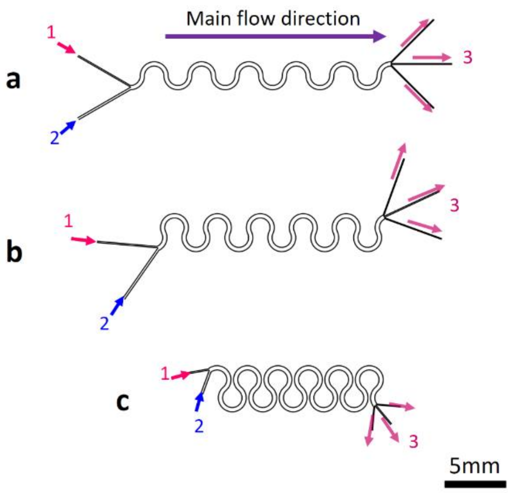

Figure 1. *Curvilinear microchannels with curvature angles of (**a**) 180°, (**b**) 230°, and (**c**) 280°. 1: Rhodamine B inlet, 2: water inlet, 3: outlet of the mixed fluid.*

found in [6].
Each microchannel has two inlets for DI water and 0.1 mM fluorescent solution of Rhodamine B, and three inlets. Two 60 mL syringes were filled with the two fluids and put on a dual infusion syringe pump (kd Scientific LEGATO® 200) to be propelled to the microchannels with varying total flow rates from 500 μL/min to 2500 μL/min in 100 μL/min increments (corresponding to Reynolds numbers of 38 to 205). The syringes were connected to the microchannels through TYGON tubing (IDEX Corp., IL), 300 mm in length and having internal diameter of 250 μm, and metallic fittings (IDEX Corp., IL).
To visualize the flow behavior, each chip was mounted on an inverted fluorescent microscope (ZEISS life cell imager) to take images from the entire channel geometry. The images, then, were processed with the ZEN Blue software to extract the fluorescence intensity values of pixels.
To quantify the mixing performance of the microchannels, the mixing efficiency, M, defined as [7]:

$$M = 1 - \frac{1}{\bar{I}}\sqrt{\frac{1}{N}\sum(I_i - \bar{I})^2} \quad (2)$$

is calculated at the outlet of each microchannel. In this formula, I_i is the intensity of each pixel, $\bar{I}$ is the average intensity at the outlet, and N is the total number of the pixels. Accordingly, a zero value of M corresponds to unmixed fluids, while unity indicates complete mixing.

3. Results

Figures 2 to 4 show the flow behavior in the microchannels with 180°, 230°, and 280° curvature angle, respectively, under different flow conditions, indicated by Reynolds number. Accordingly, as the

Reynolds number increases, the Dean vortices become higher in magnitude, resulting in the mixing effect. Moreover, the mixing index at the outer of the microchannels are plotted against Reynolds number in Figure 5. The microchannel with 280° curvature angle exhibits a higher mixing efficiency.

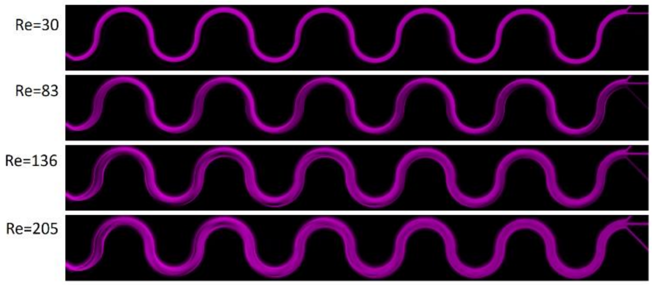

Figure 2. *Fluids flow in the microchannel with 180° curvature angle at different Reynolds numbers.*

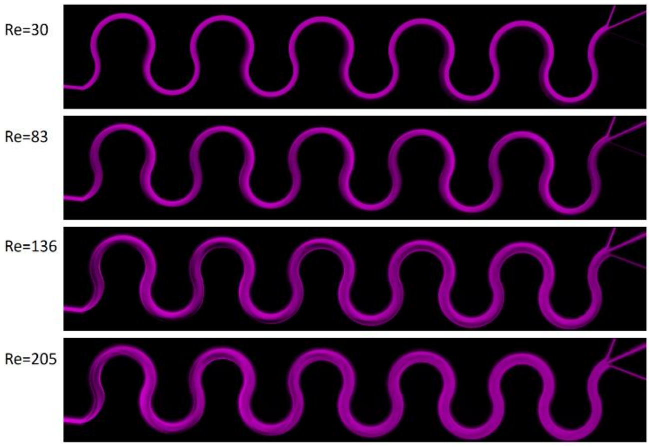

Figure 3. *Fluids flow in the microchannel with 230° curvature angle at different Reynolds numbers.*

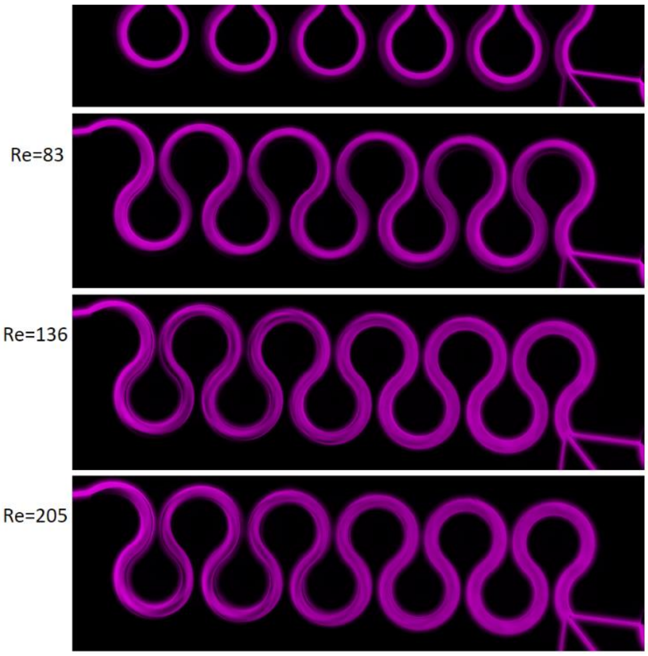

Figure 4. *Fluids flow in the microchannel with 280° curvature angle at different Reynolds numbers.*

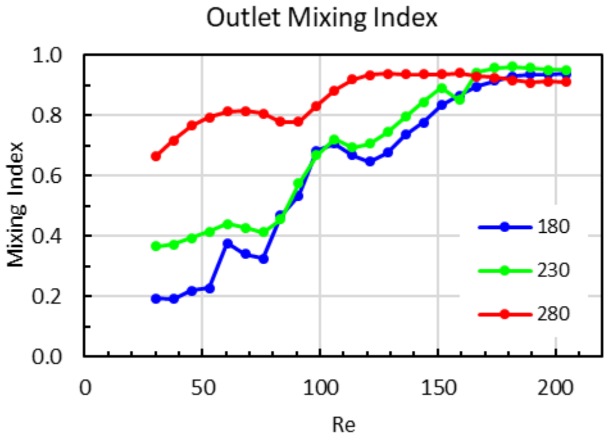

Figure 5. *Fluids flow in the microchannel with 180° curvature angle at different Reynolds numbers.*

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