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Simulation and fabrication of a three-dimensional microfluidic mixer in a monolithic glass substrate

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Abstract

We present a three-dimensional (3 D) microfluidic mixer made in a monolithic glass substrate, which comprises a microchannel structure with multiple bends either in plane or out of plane of the substrate and with varying cross-section. The microfabrication of the mixer is achieved using a photosensitive elastomer as mask and powder blasting as the erosion technique for the glass. Numerical simulation by Comsol Multiphysics is used to simulate the fluid flow in the mixer. It is found that the mixing operation is governed by chaotic advection and multiple vortices, as induced by the multiple channel bends and the strongly varying microfluidic cross-section. We demonstrate very efficient and rapid mixing of parallel laminar flow streams that enter the mixer.

Keywords: powder blasting, nozzle-diffuser, mixer, microfluidic, glass, elastomer

1. Introduction

Effective mixing is an indispensable process in many microfluidic devices used in chemistry, biology and clinical diagnostics. Numerous different microchannel designs for mixing liquid streams have been developed in the past few years [1-5]. Passive micromixers are of particular interest, as they do not require any external actuation principle, apart from the supply of the flow streams. Usually passive mixers are designed with specific geometry in order to continuously increase the interfacial area between the liquid streams to be mixed. This can be obtained either by a flow splitting-and-recombining process or by chaotic advection generated by the presence of a lateral transport over the channel cross-section. The increase of the contact area between different streams associated with

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diffusion generally enables a rapid mixing operation. In this work, we present an affordable and very efficient 3D microfluidic mixer comprising multiple microchannel bends, either in plane or out of plane of the substrate, and with a channel cross-section that varies at different locations along the channel.

2. Experimental

In Figure 1, we show schematic diagrams of the 3D microfluidic mixer with an enlarged view of a single nozzle-diffuser element. The mixer is composed of several of such nozzle-diffuser elements that are interconnected by in-plane arc-shaped microchannels that have a width of 160 μm and a depth of 100 μm. The dimensions of the nozzle-diffuser element are as shown in Figure 1. The nozzle holes are eroded using the powder blasting technique at an oblique angle, while the diffuser holes are eroded at the opposite oblique angle. The two oblique impact angles are selected in a way that a connection between two adjacent holes is obtained in the bulk of the glass substrate.

The complete structure is fabricated in glass using the powder blasting technique [4]. Three processing steps are required to fabricate the complete mixer: erosion at normal incidence of the powder particle stream to define the planar arc-shaped channel parts (Figure 2a), followed by two erosion steps at an oblique angle. At each oblique angle, an array of inclined holes is obtained, as indicated in Figures 2b and 2c. Figure 2d presents the completed 3D micromixer obtained after the three processing steps. Due to the conical-shape profile of the eroded holes, the embedded ‘microtunnels’ inside the glass substrate behave as nozzle–diffuser elements.

3. Simulation

The 3D microfluidic mixer is studied by computational fluid dynamics using Comsol multiphysics. The laminar flow Navier-Stokes equation is used to calculate the flow velocity field within the microchannel. The velocity field is used in the convective-diffusion equation to determine the concentration distribution of the species by mixing operation. The complete structure is meshed in a customized way with locally fine structural meshes to obtain accurate results with low numerical diffusion and to lower the overall cell count. We have set a normal velocity at inlet, ambient pressure at outlet and no slip along the walls. For all simulations, the fluid considered is water.

4. Results and discussion

Figures 3a and 3b present the concentration distribution obtained via numerical simulation in the first 3 nozzle-
diffuser elements of the mixer at Re=3 and 21, respectively. At the low Reynolds number Re= 3, the two streams remain mostly in parallel and the mixing is incomplete. Figure 3c shows the velocity streamlines within the mixer at Re=3; the flow velocity is not sufficient to significantly disturb the laminar flow and mixing is governed only by diffusion. At this low Reynolds number, a long channel with at least more than 10 nozzle-diffuser elements is needed to achieve good mixing. As the flow rate is increased to give Re=21, Figure 3b shows that the two fluids are well mixed already after the second nozzle-diffuser element. At Re=21, the fluid flow reaches a high velocity, as when it enters the nozzle hole tangentially, a swirling flow is created as shown in Figure 3d. The rotation direction of the swirling flow depends on the position of the inlet with respect to the nozzle hole. This swirling flow acts as a stirring mechanism, which increases the extent of mixing. Moreover, in the curved channels, transverse secondary flows are generated. Their magnitude is continuously increased with increasing Reynolds number, resulting in more elongation and deformation of the interfacial area between the two different streams, which is of benefit to more diffusion and efficient mixing. Figure 4 shows the lateral displacement towards the outer wall induced by the secondary flow, as indicated by the arrows profile. Two different cross-sections are selected to show the shape and the strength of the secondary flow, depending on the position and the curvature ratio of the curved segment of the mixing channel. In the in-plane curved segment, two symmetric vortices appear in the cross-section, as shown in Figure 4a. When the fluid enters the out-of-plane bended nozzle-diffuser element, a pair of strong and weak vortices is produced at the throat cross-section, as shown in Figure 4b.

Figure 3. (a,b) Concentration distribution for the first three nozzle-diffuser elements at Reynolds numbers Re=3 (a), Re=21 (b). (c,d)Velocity streamlines for the three first nozzle-diffuser elements at Reynolds numbers Re=3 (c), Re=21 (d).

Figure 4. Cross-section of the transverse velocity field (arrows) and the concentration distribution (colors) in (a) an in-plane curved segment of the microchannel and (b) the throat of a nozzle-diffuser element. Re=21.
To evaluate experimentally the mixing performance, parallel streams of blue and yellow solutions were injected into the mixer, for flow rates in the range of 2 to 200 µl/min. The contact interface between the two solution turns into green colour. To calculate the mixing index, the captured image is first converted to gray-scale using Image-J software. The mixing index is defined as the standard deviation of the intensity of the individual pixels, for the different locations of the channel:

\[
\text{Mixing index} = (1 - \sqrt{\frac{1}{N} \sum_{j=1}^{N} \left( \frac{I_j - I_{ref}}{I_{ref}} \right)^2}) \cdot 100\%
\]

The term \(I_j\) is the intensity value at a pixel \(j\), and \(I_{ref}\) is the average intensity over the window area of interest.

Figure 5a shows a typical example of a mixing operation at Re=21. The rectangles represent the windows for the mixing index evaluation and the arrows indicate the flow direction. The windows have the same area of 20 \(\times\) 160 \(\mu\)m\(^2\) and are selected at different locations along the microchannel mixer. In Figure 5b, we can see that the mixing index is continuously increased after each nozzle-diffuser element. The 3D geometry of the mixer forces the flowing fluids to develop complex flow patterns at each nozzle-diffuser element, which are beneficial for the improvement of mixing in the laminar regime.

5. **Conclusion**

Powder blasting at an oblique impact angle has been successfully used to fabricate a complex 3D mixer in a monolithic glass substrate. The mixer topology consists of a curved microchannel that incorporates a series of nozzle-diffuser elements buried inside the glass substrate. Comsol simulation shows the advantage of such particular 3D structure presenting flow patterns with complex spatial distribution. The mixing is improved by the combination of stretching, folding and chaotic advection mechanisms. The device exhibits a good mixing efficiency at a flow rate in the range of 2 to 200 µl/min.

**References**


