A comparative numerical design of the static and electrostatic micromixers

Abdolreza Habibi¹ · Shahrokh Shojaei^{1,5} · Pedram Tehrani² · Mojtaba Hassani³ · Alireza Karimi⁴

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Abstract

Lab-on-a-chip (LOC) is a microfluidic system aiming to improve the diagnosis and treatment of various forms of diseases with several applications in biological science and chemical engineering. LOC encompasses different functions in a small chip, such as the mixing, reaction, separation, and analysis. Micromixer as the most important part of the LOC is responsible of mixing two or more samples for analysis. The design of the micromixers has a key asset in their mixture ability. This study aimed to compare various designs of the static and electrostatic micromixers using computational fluid dynamics. The results revealed the advantage of electrostatic micromixers compared to the static ones in mixing. The results were interpreted as the velocity and concentration profiles, and were compared. This study could well compare different designs of the micromixers and show how design can be an effective parameter in mixture of the fluids in a LOC. The results of the concurrent study have practical implications in designing of the micromixers with higher mixture ability.

Keywords Lab-on-a-chip · Micromixer · Design · CFD · Velocity · Concentration

1 Introduction

The application of the microfluidic chip is in a rapid rise due to its widespread use in various clinical trials. Lab-on-a-chip (LOC) is a microfluidic system improving the diagnosis and treatment in various fields, such as biological science and chemical engineering [1–4]. LOC by itself encompasses several functions into a very small chip, i.e., mixing, reaction, separation, and analysis [5]. Among these, micromixer has a key role as it mixes two or more samples for analysis.

Generally, two types of micromixers have been introduced so far, i.e., active and passive. Active micromixers are more intricate and therefore can be difficult to fabricate, control, and integrate into LOC. However, in the passive micromixer, mixing performance can be improved

by adjusting the geometry shape. Therefore, the research on geometry of micromixers becomes more applicable [6–8]. A suitable mixture is always a big deal in micromixers and several studies have been conducted in designing or optimizing the structure of the micromixers [9–11]. For instance, in biomedicine, a micromixer for blood analysis needs the sample to be homogeneously mixed with anti-coagulants and with reagents that help detect bacteria, viruses, or DNA [12]. For high homogeneity of the sample, several studies have proposed various micromixers with different structures of microchannels. However, there is still a lack of knowledge on designing of the micromixers being able to provide a suitable mixture after fluids interactions.

This study aimed to numerically compare the structure of six different static and electrostatic micromixers with

✉ Shahrokh Shojaei, shahrokh.shojaei@gmail.com; Abdolreza Habibi, habibiabdolreza@yahoo.com; Pedram Tehrani, p.tehrani@iauctb.ac.ir; Mojtaba Hassani, mojtabahasani11@gmail.com; Alireza Karimi, karimi@kyudai.jp | ¹Department of Biomedical Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran. ²Department of Mechanical Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran. ³Department of Biomedical Engineering, Faculty of Engineering, University of Isfahan, Isfahan, Iran. ⁴Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan. ⁵Stem cells Research Center, Tissue Engineering and Regenerative Medicine Institute, Central Tehran Branch, Islamic Azad University, Tehran 13185/768, Iran.

various microchannels structures using computational fluid dynamics (CFD). The velocity and concentration contours in various microchannel structures were computed and compared.

2 Materials and methods

Incompressible Navier–Stokes equations were used to address the dynamic properties of velocity and pressure of the fluidic flows [13]:

$$\rho(u \cdot \nabla)u + \nabla p - \nabla \cdot \eta(\nabla u + (\nabla u)^T) = f \quad (1)$$

$$-\nabla \cdot u = 0 \quad (2)$$

where u is the fluidic velocity, p is the fluidic pressure, ρ is the fluidic density, η is the fluidic viscosity, and f is the body force loaded on the fluid.

In topology optimization of the Navier–Stokes flow, the body force can be expressed as [14].

$$f = -\alpha u \quad (3)$$

where α is the impermeability of a porous medium. Its value depends on the optimization design variable γ [14].

$$\alpha(\gamma) = \alpha_{\min} + (\alpha_{\max} - \alpha_{\min}) \frac{q(1 - \gamma)}{q + \gamma} \quad (4)$$

where $\alpha_{\min}$ and $\alpha_{\max}$ are the minimal and maximal values of α , respectively, and q is a real and positive parameter used to adjust the convexity of the interpolation function in Eq. (4). The value of γ can vary between zero and one, where $\gamma=0$ corresponds to an artificial solid domain and $\gamma=1$ to a fluidic domain, respectively. Usually, $\alpha_{\min}$ is chosen as 0, and $\alpha_{\max}$ is chosen as a finite but high number to ensure the numerical stability of the optimization and to approximate a solid with negligible permeability [15].

The geometric model is divided into three parts: the inlet, the design area, and the outlet. Among them, the body force f of the inlet and the outlet (non-design area) in the Navier–Stokes equations is 0, so f can be defined as follows:

$$f = \begin{cases} -\alpha u, & \text{in } \Omega_D \\ 0, & \text{in } \Omega_N \end{cases} \quad (5)$$

where Ω_D is the design area and Ω_N is the non-design area.

From the above analysis, the model of topological optimization problem can be put forward as follows:

$$\min \phi(u, \gamma) \quad (6)$$

$$\text{s.t. } \rho(u \cdot \nabla)u = -\nabla p + \nabla \cdot \eta(\nabla u + (\nabla u)^T) - \alpha(\gamma)u, \text{ in } \Omega$$

$$-\nabla \cdot u = 0, \text{ in } \Omega$$

$$u = u_0, \text{ at } \Gamma_{\text{inlet}}$$

$$u = 0, \text{ at } \Gamma_{\text{wall}}$$

$$p = 0,$$

$$\eta(\nabla u + \nabla u^T)n = 0, \text{ at } \Gamma_{\text{outlet}}$$

$$0 \leq \gamma \leq 1$$

where u_0 is the inlet velocity [16].

Da denotes the penetration ability of a porous medium, and Re represents the ratio of inertia force and viscous force. They are defined as:

$$Da = \frac{\eta}{\alpha_{\max} \times L^2} \quad (7)$$

$$Re = \frac{uL\rho}{\eta} \quad (8)$$

where L indicates the characteristic length of the fluid flow. For non-circular pipes, L indicates hydraulic diameter. η indicates coefficient of kinematic viscosity.

Mixing efficiency of the species can be calculated by the formula as follows [17]:

$$M = 1 - \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{c_i - \bar{c}}{\bar{c}} \right)^2} \quad (9)$$

where M is the mixing efficiency, N is the total number of sampling points, c_i and $\bar{c}$ are normalized concentration and expected normalized concentration, respectively. Mixing efficiency ranges from 0 (0%, not mixing) to 1 (100%, full mixed) [16].

Six different structure of the static and electrostatic micromixers, including three static (Fig. 1) and three electrostatic (Fig. 2), were designed and the flow under the same velocity of 1 cm/s for all the cases were flown into the models from the left side. The flows at the inlet were considered to be laminar, incompressible, and Newtonian. No-slip boundary condition was also considered between the solid and fluid domains.

3 Results and discussions

The profiles of velocity in the static micromixers are illustrated in Fig. 3. The microchannels were structured as square, circle, and ellipse as displayed in this figure. The contours of concentration for these three structures are shown in Fig. 4. The results revealed a higher concentration

Fig. 1 Three different designs of the static micromixers, including a–c

Fig. 2 Three different designs of the electrostatic micromixers, including a–c

at the inlet, while a lower one at the outlet. In addition, the mixing ability of the micromixer with the ellipse looks better as the profile of velocity and concentration showed to be higher at this structure, implying a better result when mixing two or more fluids in a micromixer.

The same analyses have been done for the electrostatic micromixers, and the profiles of the velocity at different simulation times are displayed in Figs. 5, 6, and 7, for various structures. The concentration contour of these structures is also shown in Fig. 8. The results showed that

Fig. 3 Profile of velocity in three different designs of the static micromixers, including **a–c**

Fig. 4 Concentration contours in three different designs of the static micromixers, including **(a–c)**

the location of the electrode has a dramatic influence on the contours of the velocity and concentration. Vortex was observed in all three structures where the electrode was located. The reason is related to the electric pulse process by the electrode which brings about a sudden alteration in the direction of the flow in the micromixers.

In addition, the presence of the electrode led a concentration drop, which relates to an electric shock induced by the electrode.

Although the simple structure and the cost of the static micromixers widen their use in the LOC, it should be noted that the mixing ability of the electrostatic mixers is way

Fig. 5 Profile of velocity in type **a** of electrostatic micromixer at different simulation times, including **a** 0.05, **b** 0.30, **c** 0.50, **d** 0.70, **e** 0.90, and **f** 1 s

better than that of the static ones. These results may have practical implications in micromixers design, and the mixture rate of the fluid dramatically depends on the rate of mixture at the outlet.

4 Conclusions

This study employed CFD method to compare the mixing ability of the static and electrostatic micromixers under various structures of the microchannels. The results were interpreted on a basis of the velocity and concentration

Fig. 6 Profile of velocity in type **b** of electrostatic micromixer at different simulation times, including **a** 0.05, **b** 0.30, **c** 0.50, **d** 0.70, **e** 0.90, and **f** 1 s

and were compared. The electrostatic micromixers showed better mixing ability compared to the static ones. The results have implications not only for understanding of the

velocity and concentration profiles of the micromixers, but also help in choosing of the most suitable structure of the microchannels according to the clinical needs.

Fig. 7 Profile of velocity in type **c** of electrostatic micromixer at different simulation times, including **a** 0.05, **b** 0.30, **c** 0.50, **d** 0.70, **e** 0.90, and **f** 1 s

Fig. 8 Concentration contours in three different designs of the electrostatic micromixers, including **a–c**

Compliance with ethical standards

Conflict of interest The author declares that they have no conflict of interest.

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