

Fabrication and numerical optimization of microfluidic-based spiral micromixer

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Received 05/01/2023, Revised 21/06/2023, Accepted 14/10/2023.

Abstract

In this paper, recommended spiral passive micromixer was designed and simulated. spiral design has the potential to create and strengthen the centrifugal force and the secondary flow. A series of simulations were carried out to evaluate the effects of channel width, channel depth, the gap between loops, and flowrate on the micromixer performance. These features impact the contact area of the two fluids and ultimately lead to an increment in the quality of the mixture. In this study, for the flow rate of 25 $\mu\text{l}/\text{min}$ and molecular diffusion coefficient of $1 \times 10^{-10} \text{ m}^2/\text{s}$, mixing efficiency of more than 90% is achieved after 30 (approximately one-third of the total channel length). Finally, the optimized design fabricated using proposed 3D printing method.

Keywords

Microfluidics, Micromixer, Drug Delivery System, Polymeric Micelles, Numerical Optimization.

1. Introduction

Microfluidics is an emerging field in diagnostic and therapeutic [1]. Numerous microfluidic devices have ventured into the study for biological and chemical purposes in the areas of drug delivery systems (DDS) in the last decades [2]. Microfluidic devices receiving increasing attention due to considerable advantages, including: small dimensions, capable of containing extremely low volume of fluid, low fabrication costs, low analysis time, and etc. [3, 4]. There are many types of Microfluidic devices, such as microvalves [5], microreactors, micropumps, etc. One of the most basic components which has significant impact on the performance and sensitivity of microfluidic systems is micromixer. In these devices due to small dimensions, larger surface-to-volume ratios can be obtained [6]. In addition, the fluids flowrate is generally low and the regime in the microchannels is basically laminar. Generally, the mass transfer mechanism in the micro-scale relies on molecular diffusion which is inherently a slow phenomenon [7]. Therefore, in microfluidics devices, due to the small Reynolds number, fluids mixing is challenging. Achieving a complete and rapid mixing of multiple samples is the goal of using micromixers.

Different Types and designs for micromixer have presented by researchers. Micromixers are totally divided into active and passive micromixers [8, 9]. Passive micromixers, simply require energy to drive the fluids and often use complex channel designs to improve the diffusion phenomena. Active micromixers usually require external energy sources, such as magnetic, and electrical [10], etc. Passive micromixers are much easier

to integrate, but based on their structure, they might require complex fabrication processes [11]. Conversely, Active micromixers often include simple designs, but due to the requirement of external energy sources, it is difficult and costly to integrate them into a single microfluidic chip [12]. external energy sources are essential for fluids distribution, contact area increment, or chaotic advection induction [6].

Passive micromixers can be sub-classified as three-dimensional (3D) and two-dimensional (2D) based on the structure. 3D structures reliant on complex spatial designs which can enhance mixing effect, require complicated fabrication methods. Whereas, 2D passive micromixers, with simple planar designs have fewer mixing efficiency, but fabrication process is simple [6, 11]. Effectively improving contact area between fluids and as a result, enhancement in the molecular diffusion, are challenges in such structures [13]. Parallel lamination [8], spiral-channel [14, 15], convergence-divergence based [16], unsymmetrical [17] and obstacle (or baffle) based [18, 19] are among several available approaches in literature to develop micromixers. In 2003, The spiral-channel micromixer was presented by Vanka et al. [20]. Mixing in 2D spiral-channel micromixers basically depends on the advection caused by the secondary flow or Dean vortices created by the inertia force [21]. To achieve high mixing efficiency (ME) several loops are required. Hence, to increase the mixing effects of spiral mixers, creative structures using few numbers of loops have been proposed [11]. In 2006, Sudarsan et al. [22], proposed double spiral-channel micromixer in which ME reached more than 90% at the end of the second spiral-

channel. In 2012, Li et al. [23], modified labyrinth-like multiple spiral based micromixers with a chamber in the middle. In 2013, Yang et al. [24], used 3D double layers of spiral channel that ME increases with the height of channel and using cylindrical geometry. In 2018, Mehrdel et al. [14], presented a planar design using expansion and contraction sections and could reach the ME of 85% and 98.5%, for one and three loops, respectively.

In this work, we proposed planar designs for spiral micromixer. Moreover, Effect of different parameters, such as flowrate, channel width, channel depth, and gap between loops were discussed. The novelty of recommended design is achieving high ME in wide range of flowrates. Moreover, the design has the potential to be scaled down by eliminating the outer loops.

The rest of this paper is organized as follow: section 2 presents the structural design and material properties for simulations. In section 3 the mathematics and equations were discussed. In section 4 the proposed fabrication process presented. Finally, the result of this paper and the comparison with those existing in the literature to better understand merits and demerits of each discussed in section 5 and 6, respectively.

2. Design and Materials

2.1. Structural design

Fig. 1 illustrates isometric view of the proposed passive spiral micromixer design. The design consists of two inlets, spiral channel and an outlet. The two fluids were injected separately through inlet channels of 220 μm width (W_c) and 260 μm height (H_c). The gap between the spiral sections loops (W_s) is 240 μm . These channels were connected to a 2 mm straight channel over two 60° Y-shaped junctions.

The micromixer has the overall size of 25×16 mm and spiral section diameter is about 7.3 mm. The total channel length is about 92 mm. When fluid flows through the spiral channel, secondary flows or Dean flow are developed in the cross-sectional plane (CS refers to cross-section plane number which is discussed in section 5). Dean vortices were formed by centrifugal forces [6].

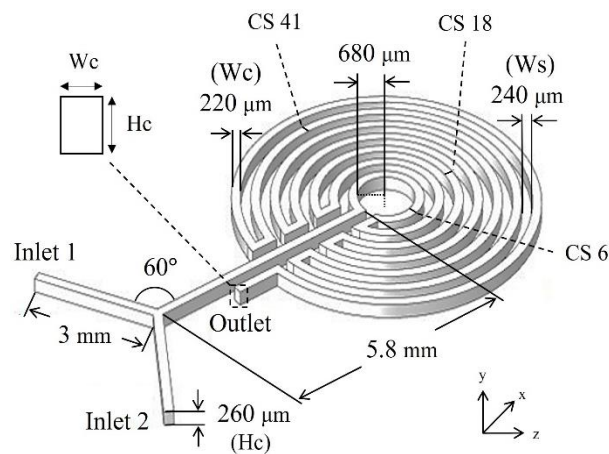


Fig. 1. Structure and schematic designs of micromixer.

2.2. Material properties

The materials properties used in this study are presented in Table I. [25]

Table I. Materials properties of fluids

Material properties	Main Fluid	Second fluid
Concentration (mol/m ³)	0.78	3.32
Density (Kg/m ³)	901.5	951.1
Viscosity (Pa.s)	5.1×10 ⁻⁴	8.7×10 ⁻⁴

3. Mathematics and equations

Generally, the flow in micro scale could be assumed for most microfluidic analysis as steady, laminar, Newtonian and incompressible. Conservation equation of continuity (1), momentum (2), and energy (3) are the governing equations for the simulation of fluid dynamics. These equations are [26]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{V} = 0 \quad (1)$$

$$\frac{\partial \rho \mathbf{V}}{\partial t} = -\nabla \cdot (\rho \mathbf{V} \mathbf{V}) + \rho \mathbf{f} + \nabla \cdot \boldsymbol{\tau} \quad (2)$$

$$\frac{\partial \rho e}{\partial t} = \nabla \cdot (\rho e \mathbf{V} - \boldsymbol{\tau} \mathbf{V} + \mathbf{q}) \quad (3)$$

Where $\mathbf{V}$ is velocity vector, ρ refers to the density, $\mathbf{f}$ is the body forces, $\boldsymbol{\tau}$ indicates to the shear stress tensor, e is the energy, and $\mathbf{q}$ is the heat-flux vector.

Defining numerical diffusion in the simulation of mixing process is one of the key issues [11]. Equation of convection-diffusion transport (4) is used to define the concentration distribution [27]:

$$\frac{\partial c}{\partial t} + \mathbf{V} \cdot \nabla c = D \nabla^2 c \quad (4)$$

where c is species concentration and D defines diffusion coefficient.

Dimensionless parameters which are used to express the mixing effects include Reynolds number (5), Peclet number (6), and Dean number (7). These parameters are defined as follows, respectively [8, 27]:

$$\text{Re} = \frac{\rho U D_h}{\mu} \quad (5)$$

$$\text{Pe} = \frac{U D_h}{D} \quad (6)$$

$$\text{De} = \text{Re} \sqrt{\frac{D_h}{R}} \quad (7)$$

Where U is average velocity, D_h defines hydraulic diameter, μ express viscosity, and R illustrates the mean radius of the channel curvature.

For a rectangular microchannel, the hydraulic diameter is defined as [28, 29]:

$$D_h = \frac{2W_c H_c}{W_c + H_c} \quad (8)$$

Where W_c and H_c are the channel width and depth, respectively. The flow patterns are determined by the Reynolds number (the ratio of inertia to viscous forces). Generally, in microchannels due to small dimensions of channels and low fluid flow velocity, the flow regime is laminar. Depends on micromixers geometry, types of fluids and boundary conditions, they may reach high mixing efficiency at low, high or optimal Reynolds number [12]. Peclet number (the ratio of mass transport due to convection to that of diffusion) is considered when there is a competition between mass transfer mechanism,

convection and diffusion [12]. The Peclet number expresses the flowrate through the microchannel for the mixing process with a constant diffusion coefficient. For laminar flow regime, the Peclet number is proportional to the mixing length [27]. Finally, the Dean number is employed for the micromixers with spiral channels. The main parameter for a mixer is the mixing efficiency (ME). In this study, the micromixer performance is evaluated by following equation [30]:

$$ME = \left[1 - \frac{\int |c - c_{\infty}| dA}{\int |c_0 - c_{\infty}| dA} \right] \times 100 \quad (25)$$

Where c is the cross-sectional concentration profile. c_{∞} and c_0 are the concentration profiles associated with a completely mixed and completely unmixed states, respectively. In addition, due to the laminar nature of microfluidic systems, incompressible laminar formulation is used for fluid domain. The initial and boundary conditions for simulation of micromixer are including: 1) Initial condition for all variables were zero; 2) For all walls, no-slip boundary condition was considered; 3) The boundary condition for fluid inlets is considered fully-developed; 4) The fluid was driven by flowrate at inlets which was swept from 1 to 100 $\mu\text{l}/\text{min}$.

4. Proposed fabrication method

In this study we have focused on numerical analysis so far to show the feasibility of our design in practice, here is the proposed fabrication process (Fig. 2). The use of Polydimethylsiloxane (PDMS) is proposed as a substrate. First, the design of micromixer is drawn in CAD software (Fig. 2a). The design is then sent to a 3D printer (Digident Quick, 5 μm resolution, Mobtakeran Mechatronics Ark engineering company, Iran) to make a mold out of ABS material (Fig. 2b). After the printing process, the mold needs to be treated, so that it doesn't have as many contaminants. For this aim, the mold is cleaned with soap and DI-water. Then, it is rinsed in pure ethanol 3 times and is dried with nitrogen gas immediately before placing in the 60 $^{\circ}\text{C}$ oven for 20 minutes (Fig. 2c).

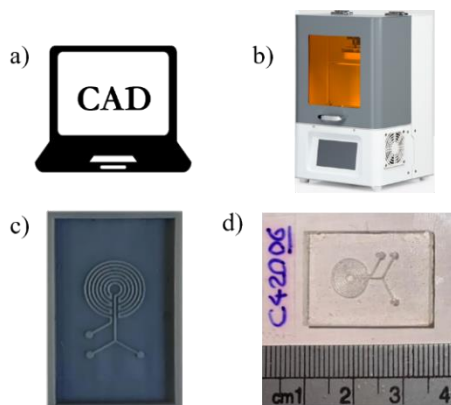


Fig. 2. Fabrication process.

Subsequently, PDMS (SYLGARDTM 184, Dow, USA) is mixed with the curing agent at a ratio of 10:1 and is degassed for 10 minutes. PDMS is poured on the mold and placed in the oven for 8 hours at 85 $^{\circ}\text{C}$. The last step is the bonding of the prepared PDMS with a sheet (as a substrate). In this step, the PDMS is removed

from the mold and attached to the substrate with a plasma jet for 3 minutes at a power of 40 W (Fig. 2d). Fig. 3 and Fig. 4 illustrate the 3D printed mold and fabricated micromixer using 3D printing method, respectively.



Fig. 3. 3D Printed mold.

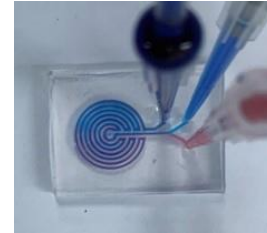


Fig. 4. Fabricated spiral micromixer.

5. Results and discussion

5.1. Effects of geometry parameters

In this section, the results of FEM analysis will be discussed. Finally, the comparison of mixing performance of recommended design and the ones in the references [23] and [24] will be presented. Performance of micromixers is analysed by applying the fluids of flowrate 25 $\mu\text{l}/\text{min}$. One of the concerns in simulation of micromixer is the molecular diffusion between multiple fluids. Therefore, to analysis the mixing process, the diffusion coefficient is considered as $1 \times 10^{-10} \text{ m}^2/\text{s}$ [31, 32]. ME varies as the fluid flows through the microchannel. Defining the ME value in each loop can be effective in understanding the micromixer performance. Effect of channel width, channel depth and gap between loops are studied in Fig. 5, Fig. 6 and Fig. 7, respectively. Figure 8 illustrates the effect of flowrate on ME. In our design, to evaluate the changes in ME, 7 cross-sections along each loop are considered which includes total number of 51 cross-sections shown in Fig. 1.

5.1.1. Effect of channel width

The effect of channel width (W_c) on ME is discussed in this subsection. Fig. 5 shows the ME of the recommended designs with different w_c in defined cross-sections. In the figure, channel widths were 200, 220, 240, 260 μm . This result illustrates the channel width of 200 μm can reach the ME of 88% (in entrance of 5th loop). When the channel width is 260 μm , micromixers can reach the ME of 82%. It is tangible that the increase of the channel width causes the increase of fluid volume in the channel with the same surface area. At the flowrate of 25 $\mu\text{l}/\text{min}$, the mixing process is based on the diffusion mechanism and longer channel length and more time is needed to achieve high ME. Therefore, by increasing the channel width, the ME will drop. Moreover, by increasing the

channel width, the Dean number decreases from 1.65 to 1.1

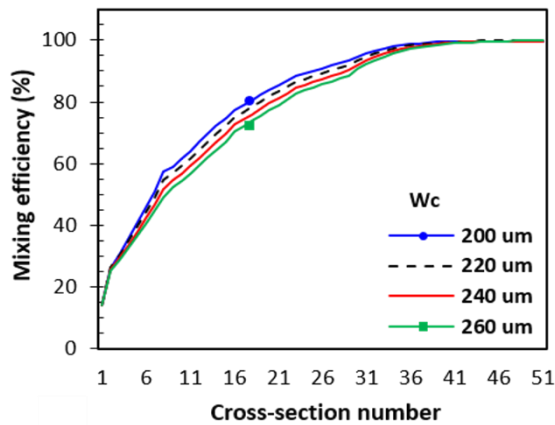


Fig. 5. ME versus cross-section number for various channel width.

5.1.2. Effect of channel depth

In this section, to evaluate the effect of channel depth (H_c) on ME, several simulations for the H_c of 110 μm ($\frac{H_c}{W_c} = \frac{1}{2}$), 220 μm ($\frac{H_c}{W_c} = 1$), 260 μm ($\frac{H_c}{W_c} = 1.2$), 440 μm ($\frac{H_c}{W_c} = 2$) are ran. According to Fig. 6, increase of H_c increase mixing efficiency. For example, the channel with 110 μm depth can get the ME of 78% (in entrance of 5th loop). This value for the channel depth of 440 μm , increase to 82%. Increasing the H_c enrich the secondary flow or Dean vortices which are developed in the channel cross-sectional plane. Thus, the contact area of fluids increases and the ME improves. In recommended design, due to spiral structure of the channels, greater Dean vortices are developed in central loops. Thus, ME increase sharply.

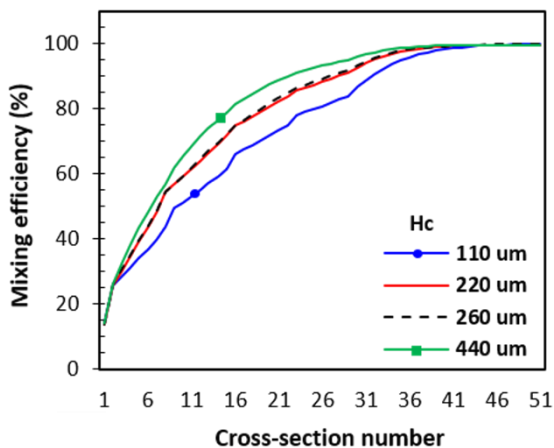


Fig. 6. Effect of channel depth on ME in various cross-section number for different channel depth.

5.1.3. Effect of gap between loops

Fig. 7 shows the effect of gap between loops (W_s) on ME with respect to channel cross-sectional plane. For the gap of 200 μm ME reaches to 86% at the entrance of 5th loop. ME could reach 86.7% when W_s is 260 μm . Despite increase of the gap between loops causing the higher length of the channel, it makes intangible change in the

Dean number for the recommended design in this study. For example, the Dean number for the W_s of 200 μm is 1.1 and when W_s increases to 260 μm , Dean number is 1.6. Therefore, there is no noticeable difference on the ME of micromixers by increasing the gap between loops.

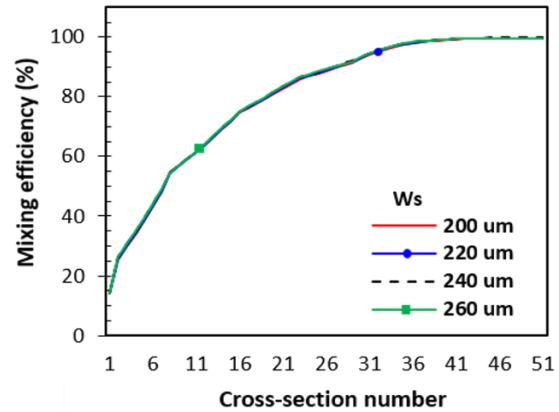


Fig. 7. ME versus cross-section number for various gap between the loops.

5.2. Effects of flowrate

The effect of flowrate on ME was presented in the Fig. 8. As mentioned before, molecular diffusion is dominant in micro scale, and secondary Dean vortices are effective in spiral channels. By varying the inlet flowrate, the proposed micromixer behaves diversely. The critical flowrates for the design are 5 and 50 $\mu\text{l/min}$. For flowrates lower than 5 $\mu\text{l/min}$, molecular diffusion (Equation 4) plays a key role in mixing process. Fluids passing through the microchannels slowly and have enough time for molecular diffusion to take place. Thus, ME increase by lowering the flowrate from 5 $\mu\text{l/min}$. In addition, for the flowrates of higher than 50 $\mu\text{l/min}$, Dean vortices enhance and fluids contact area increases remarkably in the cross-sectional plane of channel. Therefore, mixing efficiency increases.

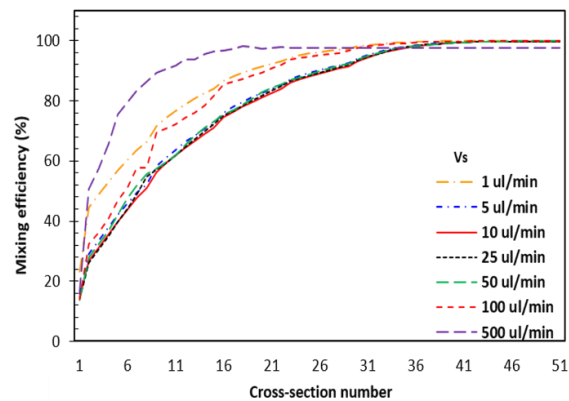


Fig. 8. Effect of flowrate on ME in various cross-section number.

Fig. 9 illustrates the ME with respect to flowrate. In our design, there are critical points (CP) for flowrate which affect the mixing efficiency as well. According to Fig. 10, it's obvious that for flowrates until CP_1 , due to low flowrates and creeping flow regime, diffusion is dominant and ME is high. By increasing flowrate to CP_2 , while the velocity increases, time duration in which fluids settle together decreases. In other word, not only flowrate is not high enough to develop secondary flow

but also its high enough that fluids could reach to the end of the channel without having adequate time for diffusion to take place. Considering this issue, ME decreases remarkably. flowrate to CP_2 , while the velocity increases, time duration in which fluids settle together decreases. In other word, not only flowrate is not high enough to develop secondary flow but also its high enough that fluids could reach to the end of the channel without having adequate time for diffusion to take place. Considering this issue, ME decreases remarkably. For flowrates higher than CP_2 , secondary flows gradually start to develop in the cross-section of the channels. Thus, fluids contact area increases remarkably and ME reaches to higher values. In this case, diffusion and convection mass transfer mechanisms act for mixing phenomenon. CP_3 is a point in which the secondary flows reach greatest amount and convection becomes the dominant phenomenon in mixing process.

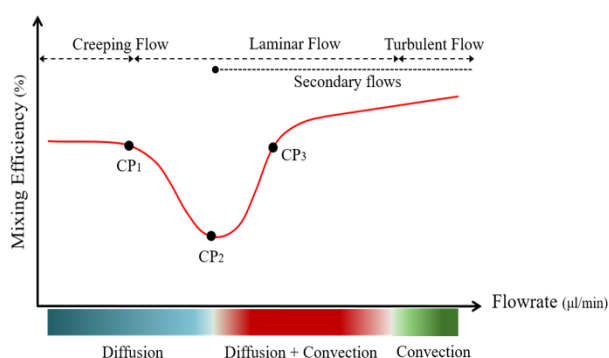


Fig. 9. Mechanism of secondary flow.

Fig. 10 and Fig. 11 show the graphic diagram of mixing process for the flowrate of 25 and 100 $\mu\text{l}/\text{min}$, respectively. According to the graph, it is obvious that increase of flowrate from 25 to 100 $\mu\text{l}/\text{min}$ enhances the Dean vortices in the channel cross-sectional plane; fluids contact area increases roughly. Therefore, mixing could reach the maximal value of ME. At the entrance of the second loop, ME are 71% and 89% for the flowrates of 25 (Fig. 10b) and 100 $\mu\text{l}/\text{min}$ (Fig. 11b), respectively.

5.3. Comparison

In this section, we compared the advantageous and disadvantageous of the proposed design with other reported micromixers after regenerating and simulating their designs with information given in the relevant article (Table II). Ref [24] presented a double-layer 3D spiral structure which has a complex structure. Although it could reach higher mixing efficiency in short channel length, it needs a complicated fabrication process. Moreover, ref [23] expressed a planar spiral micromixer. The channel width and depth were 220 and 240 μm respectively. Complete mixing process (ME of more than 90%) takes place after about 38 mm. For the flowrate of 25 $\mu\text{l}/\text{min}$ and the diffusion coefficient of $1 \times 10^{-10} \text{ m}^2/\text{s}$, this value is 30.9 mm (about one third of the total channel length) for our recommended design. To work with fluids with lower viscosity, according to the design, last 3 loops can be eliminated from the structure to decrease the overall size of the designs.

Table II. Comparison between different desings.

Design	Ref [24]	Ref [23]	Our Design
Length (μm)			
Length for ME > 90%	51,00	38,000	30,400
Total Length	18,400	94,900	92,700

6. Conclusion

In this study, inspired by Li [23], we proposed a microfluidic-based passive micromixer design which has the potential to be used in drug delivery application. Then, we evaluated the effect of channel width, channel depth and gap between loops on the mixing efficiency of micromixers. Finally, we checked out the effect of flowrate on ME. Our design could reach the ME more than 90% in one third of the total channel lenght and has the potential to be reduced in size if needed.

7. Acknowledgements

The authors gratefully acknowledge funding by the Ministry of Science, Research and Technology of Iran, and Science and Technology Park of East Azerbaijan with Javaneh grant award under contract number of Parsa-05-99-01-000323.

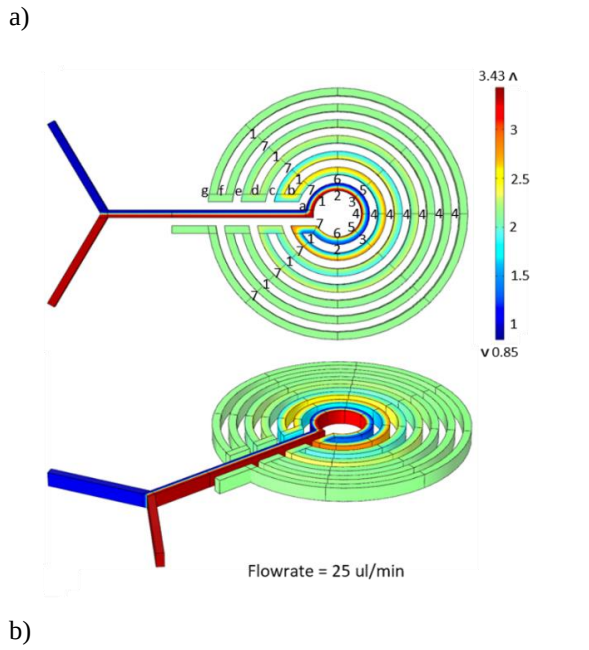


Fig. 10. (a) Graph of ME in the channel cross-sectional plane, (b) Isometric graph of diffusion phenomena for the inlet flowrate of 25 $\mu\text{l}/\text{min}$.

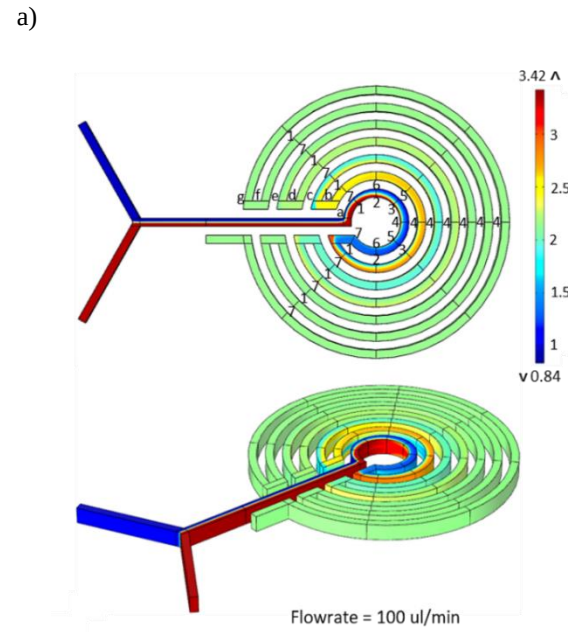


Fig. 11. (a) Graph of ME in the channel cross-sectional plane, (b) Isometric graph of diffusion phenomena for the inlet flowrate of 100 $\mu\text{l}/\text{m}$

8. References

- [1]. Zargari, S., et al., *A microfluidic chip for in vitro oocyte maturation*. Sensor Letters, 2016. **14**(4): p. 435-440.
- [2]. Whitesides, G., *The lab finally comes to the chip! Lab on a chip*, 2014. **14**(17): p. 3125-3126.
- [3]. Manz, A., et al., *Planar chips technology for miniaturization and integration of separation techniques into monitoring systems: capillary electrophoresis on a chip*. Journal of Chromatography A, 1992. **593**(1-2): p. 253-258.
- [4]. Gubala, V., et al., *Point of care diagnostics: status and future*. Analytical chemistry, 2012. **84**(2): p. 487-515.
- [5] پورمند، همکاران، پیاده‌سازی و مشخصه‌یابی یک ریزشیر کواک با استفاده از مواد گرمانرم برای کاربردهای آزمایشگاه روی تراشه. مجله مهندسی برق دانشگاه تبریز، ۲۰۱۸، صفحه ۱۰۴۷-۱۰۵۸.
- [6]. Cai, G., et al., *A review on micromixers*. Micromachines, 2017. **8**(9): p. 274.
- [7]. Beebe, D.J., G.A. Mensing, and G.M. Walker, *Physics and applications of microfluidics in biology*. Annual review of biomedical engineering, 2002. **4**(1): p. 261-286.
- [8]. Nguyen, N.-T. and Z. Wu, *Micromixers—a review*. Journal of micromechanics and microengineering, 2004. **15**(2): p. R1.
- [9]. Ward, K. and Z.H. Fan, *Mixing in microfluidic devices and enhancement methods*. Journal of Micromechanics and Microengineering, 2015. **25**(9): p. 094001.
- [۱۰] طالب‌زاده، همکاران، ارائه روشی نوین برای ساخت یک ریزمخلوط‌گر الکترواستاتیکی با الکترودهایی در دو سمت برای کاربردهای زیست-فناوری. مجله مهندسی برق دانشگاه تبریز، ۲۰۱۶، صفحه ۲۵۵-۲۶۵.
- [11]. Ottino, J.M., *The kinematics of mixing: stretching, chaos, and transport*. Vol. 3. 1989: Cambridge university press.
- [12]. Bayareh, M., M.N. Ashani, and A. Usefian, *Active and passive micromixers: A comprehensive review*. Chemical Engineering and Processing-Process Intensification, 2020. **147**: p. 107771.
- [13]. Gravesen, P., J. Branebjerg, and O.S. Jensen, *Microfluidics-a review*. Journal of micromechanics and microengineering, 1993. **3**(4): p. 168.
- [14]. Mehrdel, P., et al., *Novel variable radius spiral-shaped micromixer: from numerical analysis to experimental validation*. Micromachines, 2018. **9**(11): p. 552.
- [15]. Bahrami, D. and M. Bayareh, *Experimental and numerical investigation of a novel spiral micromixer with sinusoidal channel walls*. Chemical Engineering & Technology, 2022. **45**(1): p. 100-109.
- [16]. Raza, W. and K.-Y. Kim, *Unbalanced split and recombine micromixer with three-dimensional steps*. Industrial & Engineering Chemistry Research, 2019. **59**(9): p. 3744-3756.
- [17]. Tran-Minh, N., T. Dong, and F. Karlsen, *An efficient passive planar micromixer with ellipse-like micropillars for continuous mixing of human blood*. Computer methods and programs in biomedicine, 2014. **117**(1): p. 20-29.
- [18]. Wang, H., et al., *Optimizing layout of obstacles for enhanced mixing in microchannels*. Smart materials and structures, 2002. **11**(5): p. 662.
- [19]. Chen, X. and H. Lv, *New insights into the micromixer with Cantor fractal obstacles through genetic algorithm*. Scientific Reports, 2022. **12**(1): p. 4162.
- [20]. Vanka, S., et al. *Novel low Reynolds number mixers for microfluidic applications*. in *Fluids Engineering Division Summer Meeting*. 2003.
- [21]. Raza, W., S. Hossain, and K.-Y. Kim, *A review of passive micromixers with a comparative analysis*. Micromachines, 2020. **11**(5): p. 455.
- [22]. Sudarsan, A.P. and V.M. Ugaz, *Fluid mixing in planar spiral microchannels*. Lab on a Chip, 2006. **6**(1): p. 74-82.
- [23]. Li, P., J. Cogswell, and M. Faghri, *Design and test of a passive planar labyrinth micromixer for rapid fluid mixing*. Sensors and Actuators B: Chemical, 2012. **174**: p. 126-132.
- [24]. Yang, J., et al., *Design and fabrication of a three dimensional spiral micromixer*. Chinese Journal of Chemistry, 2013. **31**(2): p. 209-214.
- [25]. Ghashghaie, F., et al., *Preparation of Poly (dimethylsiloxane) Microparticles via a Co-flow Microfluidic Device and Investigation of Various Parameters Effect on Morphology*. Journal of Applied Research of Chemical-Polymer Engineering, 2020. **4**(3): p. 26-15.
- [26]. Fox, R. and A. McDonald, *Introduction to fluid mechanics*, 1985. 1999, John Wiley, New York.
- [27]. Chen, X. and L. Zhang, *A review on micromixers actuated with magnetic nanomaterials*. Microchimica Acta, 2017. **184**: p. 3639-3649.
- [28]. Hessel, V., H. Löwe, and F. Schönfeld, *Micromixers—a review on passive and active mixing principles*. Chemical engineering science, 2005. **60**(8-9): p. 2479-2501.
- [29]. Cosentino, A., et al., *An efficient planar accordion-shaped micromixer: from biochemical mixing to biological application*. Scientific reports, 2015. **5**(1): p. 1-10.
- [30]. Erickson, D. and D. Li, *Influence of surface heterogeneity on electrokinetically driven microfluidic mixing*. Langmuir, 2002. **18**(5): p. 1883-1892.
- [31]. Taheri, R.A. and V. Goodarzi, *Numerical investigation of mixing improvement in a novel spiral microchannel with baffles*. Engineering Analysis with Boundary Elements, 2022. **144**: p. 518-529.
- [32]. Vatankhah, P. and A. Shamloo, *Parametric study on mixing process in an in-plane spiral micromixer utilizing chaotic advection*. Analytica chimica acta, 2018. **1022**: p. 96-105.