Available online at http://ijim.srbiau.ac.ir/
Int. J. Industrial Mathematics (ISSN 2008-5621)
Vol. 13, No. 3, 2021 Article ID IJIM-1417, 8 pages
DOR: http://dorl.net/dor/20.1001.1.20085621.2021.13.4.14.3
Research Article

Science and Research Branch (IAU)

Effect of Cross-Section on the Mixing of Liquid Species in Helix Micromixers, A Numerical Approach

T. Dehgani [*], R. Pirkhoshghiafe [†], P. Balazadeh [‡], F. Sadegh Moghanlou [§¶]

Received Date: 2020-02-18 Revised Date: 2020-06-26 Accepted Date: 2021-08-31

Abstract

Micromixers are an important part of microfluidics systems. In the present work, mixing was enhanced through the three helix types of micromixers. As a result of Dean vortices, a mixing index of 99% obtained at a very short length of the micromixers for the Reynolds number of 10. It is also obtained that the micromixer with rectangular cross-section showed better enhancement compared to the circular and triangular cross-section.

Keywords : Micromixer; Secondary flow; Laminar flow; Numerical method; Mixing Index.

---

1 Introduction

In recent years, the microfluidic branch attracted much more attention and revolutionized various fields of technology due to its wide applications in biological analysis, chemical synthesis, and heat transfer [1, 2, 3, 4]. Decreased size of flow channels causes the increased surface to volume ratio of the flow passage and subsequently increased rate of heat and mass transfer [5, 6, 7, 8, 9]. Miniaturization also has the benefit of controlling the reaction rate using a controlled mass flow rate. Microfluidics caused a new important concept of Lab-On a Chip (LOC), which gathers several chemical operations in a small chip [10, 11]. Many of the processes that occur in LOC require the mixing of two or more species, so the proper mixing in micro dimensions is a basic requirement. Mixing is mainly based on two mechanisms of molecular diffusion and chaotic advection[12, 13]. The small size of microchannels results in low ranges of Reynolds numbers, therefore the flow is generally laminar. Compared to turbulent flow, the fluctuations in laminar flow are absent and as a result, diffusion is the dominant mechanism of mixing which is a time-consuming process [14]. It is needed to enhance the mixing through the microchannels to obtain a completely mixed sample in a short time and decreased the length of the channel. Enhancement in mass and heat transfer are divided into passive and active methods [15, 16, 17]. Active micromixers employ external energy to make

---

[*] Department of Mechanical Engineering; University of Mohaghegh Ardabili, Ardabil, Iran.

[†] Department of Mechanical Engineering; Tabriz University, Tabriz, Iran.

[‡] Department of Mechanical Engineering; University of Mohaghegh Ardabili, Ardabil, Iran.

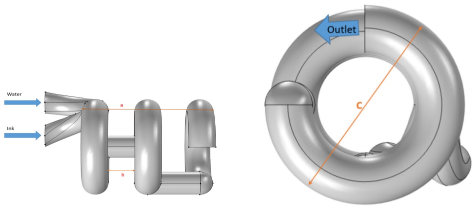
[§] Corresponding author. f˙moghanlou@uma.ac.ir, Tel:+98(914)7502678.

[¶] Department of Mechanical Engineering; University of Mohaghegh Ardabili, Ardabil, Iran.

disturbances in fluid and increase the advection part of mixing [18] while passive micromixers do not require external energy and enhancement is accomplished mainly by variation in geometry of the channel [19]. The choice of mixer type depends on the end-user needs for either ease of fabrication, rapid mixing, high throughput, or accurate dosing. The mixing enhancement investigation in micromixers is carried out by both numerical and experimental methods[20]. The fabrication of the samples in these scales is generally complicated and sometimes impossible, however, the numerical methods can provide detailed information at any desired point. Numerical simulations are proven to be a reliable method in a wide range of engineering fields like biomechanics [21], manufacturing [22, 23, 24], heat, and mass transfer[25, 26] and multiphysics systems [27, 28]. Chen et al. [29] used serpentine micromixers to enhance the mixing. They found that the mixing index decreased when the Reynolds number was in the range of 0.1 to 1. However, the mixing index increased at the Reynolds numbers more than 1. Chen and Li [30] enhanced the mixing of species in a zigzag microchannel utilizing a topology optimization (TPZ) method. The experiments performed at Reynolds numbers of Re 0.5 or Re 5 and they achieved a mixing index of 93%. Wang et al. [31] used triangle obstacles to investigate the mixing in Reynolds number ranging from 0.1 to 500. They concluded that the apical angle as well as more group of triangle obstacles had an important role in mixing enhancement. They also achieved a maximum enhancement of 91.2% at their optimum design. Tsai et al. [32] introduced a new design of micromixers to generate multidirectional cortices. Generated Dean vortices resulted in a 72% mixing efficiency at Re=81 at a length of 4.25 mm. Chen et al. [33] investigated two-dimensional Y-type and T-type micromixers based on fractal theory and generalized Murrays law. They reported that the bifurcation angle was a very important parameter on mixing and found the best angle. They also compared some variations on T-type micromixers such as T symmetry and semicircle-T asymmetry. Liu et al. [34] investigated the mixing enhancement in a 3D serpentine square wave and also straight microchannels. They reported that the serpentine micromixer showed better performance than two other shapes. Kleinstreuer et al. [35] used microfluidics set up to investigate the mixing phenomenon on drug delivery. They reported that a design with baffles and injection units resulted in improved mixing compared to the simple T-Shape model. Chen and Shen [36] performed a series of numerical simulations to investigate the mixing in stacking E-shape micromixer (SESM) and folding E-shape micromixer (FESM). They reported a considerable mixing enhancement as a result of splittingrecombination and chaotic advection mechanisms. The present work aims to improve the mixing of miscible liquids using secondary flow. In this regard, helix type micromixers with different cross sections are designed and the mixing enhancement is studied numerically by the finite element method. The effect of channel cross section on the formation of secondary flows is investigated. Three shapes of circular, triangular, and rectangular cross sections were considered and the effect of generated dean vortices on mixing index at the Reynolds numbers of 0.2 to 10 was investigated.

2 Governing equations and geometry design

The designed geometries of the present work are shown in Figure 1. The channel has a swirling passage with different cross-section shapes. Detailed information of geometries is given in Table 1.



(a) (b)

Figure 1: Channel geometry and design parameters (a) side view of micromixer and (b) top view of helical micromixer

Both entering fluids are considered to have the same properties. The fluids are Newtonian, incompressible and there is no chemical reaction.

Table 1: Micromixers design parameters [all units are in μm]

Shape	a	b	c
Circle	2500	500	1050
Rectangle	2560	439	975
Triangle	3500	1000	1192.5

The density and viscosity of both fluids are 998.2 $\frac{kg}{m^3}$ and 0.00097 Pa.s respectively. By neglecting the gravitational force, the governing equations at steady state condition are as follows [37, 38]: The continuity equation:

$$\nabla.V = 0 \tag{2.1}$$

Naiver-stokes equation:

$$\rho V\nabla.V = -\nabla P + \mu\nabla^2 V \tag{2.2}$$

Species convection-diffusion equation:

$$V\nabla c = D\nabla^2 \tag{2.3}$$

Where $\rho(\frac{kg}{m^3})$ and $\mu(\frac{kg}{m.s})$ are density and dynamic viscosity of the fluids respectively, $V(\frac{m}{s})$is the fluid velocity, $P(Pa)$ is pressure, $c(\frac{mol}{m^3})$ is the mole concentration of species, and $D(\frac{m^2}{s})$ is the diffusion coefficient of the species.

The Reynolds number is introduced as follow:

$$R_e = \frac{\rho V d_h}{\mu} \tag{2.4}$$

where $d_h(m)$is the hydraulic diameter of the microchannel cross-section. Mixing Index (MI) [39] which is used to measure and compare the obtained results defined as:

$$MI = 1 - \sqrt{\frac{\int(c-\bar{c})^2 \mathrm{d}A}{A.\bar{c}(1-\bar{c})}} \tag{2.5}$$

where, c, is the concentration distribution at any desired cross section plane, $(\bar{c})$ is the averaged value of the concentration on the selected plane and A is the cross-section area at the selected place through the channel length. MI is 0 for a complete segregated system and reaches a value of 1 for the homogeneously mixed case. The velocities at both inlets are considered to be uniform and have the same values. Reynolds number which is calculated based on inlet hydraulic diameter, changes in the range of 0.2 to 10. The outlet pressure is kept at the gauge pressure of 0 Pa. The walls have no-slip boundary conditions. The concentration value, c, is 1 and 0 $(\frac{mol}{m^3})$ at the entries.

3 Numerical procedure

The computational domain for all types of cross sections is meshed by unstructured tetrahedral meshes. The meshed geometry for the circular cross section is shown in Figure 2. A grid independence result is depicted in Figure 3. which shows the variation of velocity of one point in the middle of the channel versus the number of meshes. For the three geometries, the computations are carried out by 150000 grids. Considering the fluid flow as incompressible and laminar the governing equations are solved in steady state condition. The convection-diffusion equation can easily become unstable, so these equations are discretized by the Galerkin Least Square method (GLS) to improve the stability of the solution.

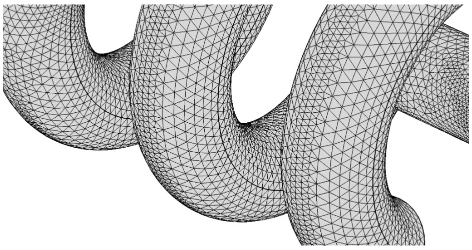


Figure 2: Meshed geometry of circular cross section micromixer

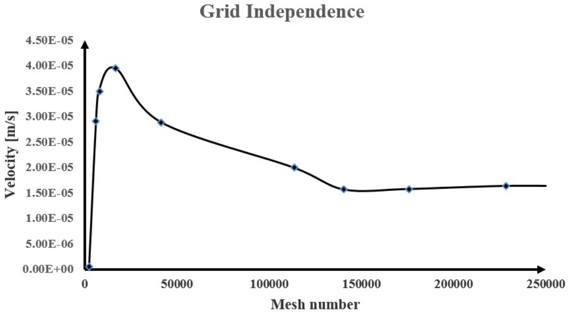


Figure 3: Grid dependency for the circular cross section

In a simple micromixer which is a straight channel, the flow is inherently laminar which mixing is essentially based on molecular diffusion. This mechanism is very slow and needs more lengths of the channel, however, increasing the convection mechanism of mixing would augment the mixing process. Generated secondary flows, according to Figure 4. is an effective way of increasing the convection part of mixing. Figure 4 shows the velocity vectors at a defined cross section in Reynolds number of 7, which shows the transverse flows across the channel. The curvature of the channels leads to the formation of centrifugal force and subsequent secondary flows. The concentration distribution through the micromixer for three different cross section in five Reynolds numbers at diffusivity of 1×10^{-11} is shown in Figure 5. By increasing the Reynolds number, mixing quality raises in all types of micromixers. In $R_e = 0.2$ the low velocity of the fluid flows causes a weak mixing in all three types of cross sections.Increasing Reynolds number leads to the generation of secondary flows through the channel cross section. The secondary flows result in fluid motion in a transverse direction and subsequently augmenting the mixing. As the Reynolds number increases, secondary flows become stronger, and as a result convection part of mixing increases which enhances the mixing of species.In Figure 6 the three locations (sec1, sec2, and outlet) through the channel are chosen to investigate the mixing distribution at diffusivity of 1×10^{-11} at the Reynolds numbers 1 and 10. These results are shown in Figure 7 and Figure 8, respectively for all three cross sections. In all these cross sections, increasing the Reynolds number enhances mixing efficiency. Referring to Figure 7 and Figure 8, it is clear that at Reynolds number of 1 the mixing efficiency is less than Reynolds 10. Increasing the Reynolds number results in the formation of stronger vortices, and increases the mixing. To investigate the mixing quantitatively, the mixing index (MI) for Diffusivity of 1×10^{-11} is calculated and is given

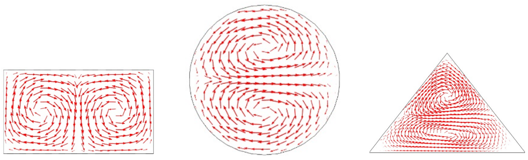

(c)

Figure 4: Velocity vector of different cross sections at $R_e = 7$

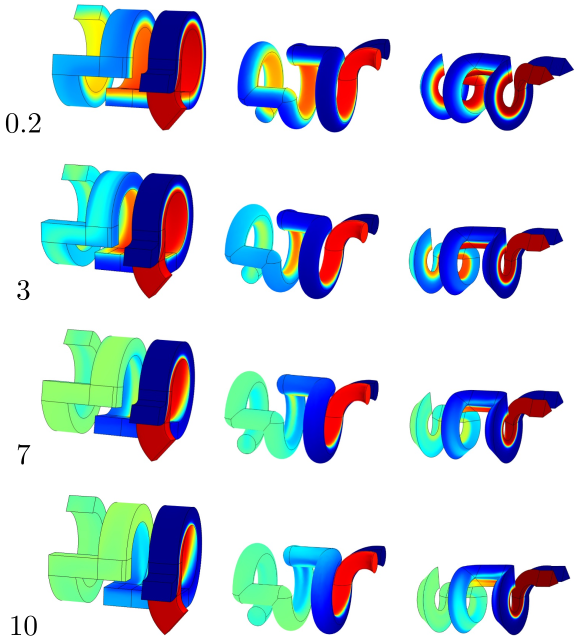


Figure 5: Concentration distribution in rang of Reynolds from 0.2 to 10

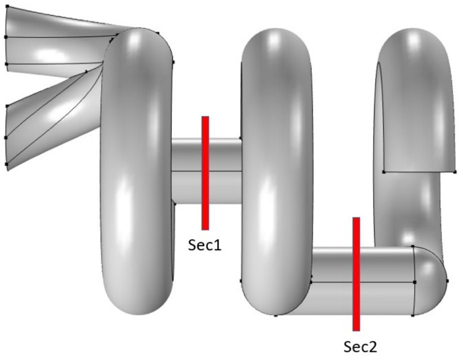


Figure 6: Section placement at Geometry

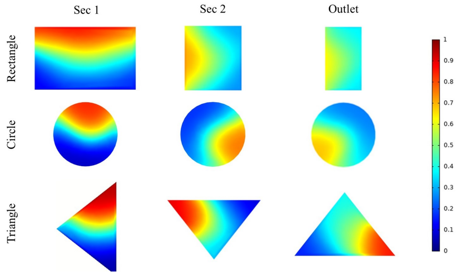


Figure 7: Concentration through the microchannel at Reynolds 1

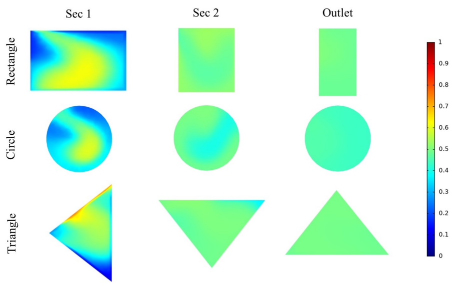


Figure 8: Concentration through the microchannel at Reynolds 10

in Figure 9. A value of 0 for MI equals a segregated medium whereas a value of 1 corresponds to a homogeneous mixture. It is clear that, by increasing the Reynolds number in each cross section, the mixing index increases. In low Reynolds number transverse flow is negligible and the mixing process occurs mostly based on molecular diffusion. By increasing Reynolds number, the secondary flow becomes stronger and advection mixing through the micromixers plays a dominant role, therefore mixing efficiency enhances. Figure 9 shows that mixing efficiency in the rectangular cross section is better than other mentioned cross sections.

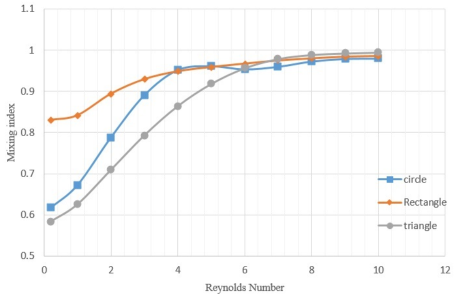


Figure 9: Meshed geometry of circular cross section micromixer

4 Conclusion

Micromixers play an important role in medical applications, chemical reactions, and the mixing process. Micromixers are the significant part of microfluidics systems which their correct design causes reduced space and time of mixing and consequently more compact microfluidics systems. In the present work, the effect of cross section shape on mixing is investigated in helix type micromixers. The Reynolds number is considered to be in the range of 0.2 to 10. It is demonstrated that as Reynold number increases, the mixing index is enhanced for all three sections (rectangular, triangular, circle). The results show that among the introduced geometries, the rectangular cross section works better than the others. All three types of cross sections reach to a maximum value of 99% at Reynolds number of 10.

Nomenclature	
c	Concentration, $\frac{mol}{m^3}$
D	Diffusion coefficient, $\frac{m^2}{s}$
ρ	Density of fluid, $\frac{kg}{m^3}$
μ	Viscosity of fluid, $\frac{kg}{m.s}$
V	Velocity of fluid, $\frac{m}{s}$
P	Pressure, Pa
R_e	Reynolds number
MI	Mixing Index
d_h	Hydraulic diameter, μm
A	Area, m^2

References

[1] F. Sadegh Moghanlou, S. Noorzadeh, M. Ataei, M. Vajdi, M. Shahedi Asl, E. Esmaeilzadeh, Experimental investigation of heat transfer and pressure drop in a minichannel heat sink using Al2O3 and TiO2water nanoluids, *J. Brazilian Soc. Mech. Sci. Eng.* 42 (2020) 315. http://dx.doi.org/10.1007/s40430-020-02403-5/.

[2] M. Fattahi, K. Vaferi, M. Vajdi, F. Sadegh Moghanlou, A. Sabahi Namini, M. Shahedi Asl, Aluminum nitride as an alternative ceramic for fabrication of microchannel heat exchangers, *A numerical study, Ceram. Int.* 46 (2020). http://dx.doi.org/10.1016/j.ceramint.2020.01.195/.

[3] C. Y. Lee, W. T. Wang, C. C. Liu, L. M. Fu, Passive mixers in microfluidic systems, *A review, Chem. Eng. J.* 288 (2016) 146-160. http://dx.doi.org/10.1016/j.cej.2015.10.122/.

[4] T. Adibi, S. E. Razavi, O. Adibi, M. Vajdi, F. Sadegh Moghanlou, The response of nano-ceramic doped fluids in heat convection models, *A characteristics-based numerical approach, Sci. Iran.* In press (2021).

[5] M. Ataei, F. Sadegh Moghanlou, S. Noorzadeh, M. Vajdi, M. Shahedi Asl, Heat transfer and Pressure drop in a minichannel heat sink, *Using hybrid Al2O3/TiO2water nanofluid, Heat Mass Transf.* (2020).

[6] F. S. Moghanlou, A. S. Khorrami, E. Esmaeilzadeh, H. Aminfar, Experimental study on electrohydrodynamically induced heat transfer enhancement in a minichannel, *Exp. Therm. Fluid Sci.* 59 (2014) 24-31. http://dx.doi.org/10.1016/j.expthermflusci.2014.07.019/.

[7] S. Nekahi, M. Vajdi, F. Sadegh Moghanlou, K. Vaferi, A. Motallebzadeh, M. zen, U. Aydemir, J. Sha, M. Shahedi Asl, TiB2 SiC-based ceramics as alternative efficient micro heat exchangers, *Ceram. Int.* (2019). http://dx.doi.org/10.1016/j.ceramint.2019.06.150/.

[8] M. Vajdi, F. Sadegh Moghanlou, E. Ranjbarpour Niari, M. Shahedi Asl, M. Shokouhimehr, Heat transfer and pressure drop in a ZrB2 microchannel heat sink, *A numerical approach, Ceram. Int.* (2019). http://dx.doi.org/10.1016/j.ceramint.2019.09.146/.

[9] F. Sadegh Moghanlou, A. Shams Khorrami, E. Esmaeilzadeh, M. Vajdi, Effect of strong electric field on heat transfer enhancement in a mini channel containing Al2O3/oil nanofluid, *J. Brazilian Soc. Mech. Sci. Eng.* 43 (2021) 149. http://dx.doi.org/10.1007/s40430-021-02869-x/.

[10] G. Cai, L. Xue, H. Zhang, J. Lin, A Review on Micromixers, *Micromachines* 8 (2017) 274. http://dx.doi.org/10.3390/mi8090274/.

[11] H. M. Xia, S. Y. M. Wan, C. Shu, Y. T. Chew, Chaotic micromixers using two-layer crossing channels to exhibit fast mixing at low Reynolds numbers, *Lab Chip.* 5 (2005) 748. http://dx.doi.org/10.1039/b502031j/

[12] S. P. Sullivan, B. S. Akpa, S. M. Matthews, A. C. Fisher, L. F. Gladden, M. L. Johns, Simulation of miscible diffusive mixing in microchannels, *Sensors Actuators B Chem.* 123 (2007) 1142-1152. http://dx.doi.org/10.1016/j.snb.2006.10.025/.

[13] Z. Chen, M. R. Bown, B. OSullivan, J. M. MacInnes, R. W. K. Allen, M. Mulder, M. Blom, R. vant Oever, Performance analysis of a folding flow micromixer, Microfluid, *Nanofluidics* 6 (2009) 763-774. http://dx.doi.org/10.1007/s10404-008-0351-z/

[14] N. T. Nguyen, Micromixers, fundamentals, design and fabrication, *William Andrew,* 2011.

[15] R. L. Webb, N. H. Kim, Principles enhanced heat transfer, *CRC Press*, 2005.

[16] M. Sakkaki, F. Sadegh Moghanlou, S. Parvizi, H. Baghbanijavid, A. Babapoor, M. Shahedi Asl, Phase change materials as quenching media for heat treatment of 42CrMo4 steels, *J. Cent. South Univ*, (2020).

[17] V. Hessel, H. Lwe, F. Schnfeld, Micromixersa review on passive and active mixing principles, *Chem. Eng. Sci.* 60 (2005) 2479-2501. http://dx.doi.org/10.1016/j.ces.2004.11.033/

[18] G. Kunti, A. Bhattacharya, S. Chakraborty, Rapid mixing with high-throughput in a semi-active semi-passive micromixer, *Electrophoresis*, 38 (2017) 1310-1317. http://dx.doi.org/10.1002/elps.201600393/

[19] R. R. Gidde, P. M. Pawar, B. P. Ronge, P. V. Jadhav, CFD Based Analysis of Simple T-Junction and Y-Junction Micro Mixers with Different Obstacles, in: Techno-Societal 2018, *Springer International Publishing, Cham,* 2020: pp. 357-365. http://dx.doi.org/10.1007/978-3-030-16962-6_37/

[20] T. Dehghani, F. Sadegh Moghanlou, M. Vajdi, M. Shahedi Asl, M. Shokouhimehr, M. Mohammadi, Mixing enhancement through

a micromixer using topology optimization, *Chem. Eng. Res. Des.* 161 (2020) 187-196. http://dx.doi.org/10.1016/j.cherd.2020.07.008/

[21] Z. Hajati, F. Sadegh Moghanlou, M. Vajdi, E. Razavi, S. Matin, Fluid Structure Interaction of blood flow around a vein valve, *BioImpacts,* (2020).

[22] M. Sakkaki, F. Sadegh Moghanlou, M. Vajdi, F. Pishgar, M. Shokouhimehr, M. Shahedi Asl, The effect of thermal contact resistance on the temperature distribution in a WC made cutting tool, *Ceram. Int.* 45 (2019). http://dx.doi.org/10.1016/j.ceramint.2019.07.241/

[23] F. Sadegh Moghanlou, M. Vajdi, J. Sha, A. Motallebzadeh, M. Shokouhimehr, M. Shahedi Asl, A numerical approach to the heat transfer in monolithic and SiC reinforced HfB ceramic cutting tools, *Ceram. Int.* (2019). http://dx.doi.org/10.1016/j.ceramint.2019.05.095/

[24] F. Sadegh Moghanlou, M. Vajdi, J. Sha, A. Motallebzadeh, M. Shokouhimehr, M. Shahedi Asl, A numerical approach to the heat transfer in monolithic and SiC reinforced HfB2, ZrB2 and TiB2 ceramic cutting tools, *Ceram. Int.* 45 (2019) 15892-15897. http://dx.doi.org/10.1016/j.ceramint.2019.05.095/

[25] S. Nekahi, K. Vaferi, M. Vajdi, F. Sadegh Moghanlou, M. Shahedi Asl, M. Shokouhimehr, A numerical approach to the heat transfer and thermal stress in a gas turbine stator blade made of HfB2, *Ceram. Int.* (2019). http://dx.doi.org/10.1016/j.ceramint.2019.08.112/

[26] K. Vaferi, S. Nekahi, M. Vajdi, F. Sadegh Moghanlou, M. Shokouhimehr, A. Motallebzadeh, J. Sha, M. Shahedi Asl, Heat transfer, thermal stress and failure analyses in a TiB2 gas turbine stator blade, *Ceram. Int.* 45 (2019). http://dx.doi.org/10.1016/j.ceramint.2019.06.184/

[27] F. Sadegh Moghanlou, M. Vajdi, M. Sakkaki, S. Azizi, Effect of graphite die geometry on energy consumption during spark plasma sintering of zirconium diboride, *Synth. Sinter.* 1 (2021) 54-61. http://dx.doi.org/10.53063/synsint.2021.117/

[28] M. Vajdi, S. Mohammad Bagheri, F. Sadegh Moghanlou, A. Shams Khorrami, Numerical investigation of solar collectors as a potential source for sintering of ZrB2, *Synth. Sinter.* 1 (2021) 76-84. http://dx.doi.org/10.53063/synsint.2021.128/

[29] X. Chen, T. Li, H. Zeng, Z. Hu, B. Fu, Numerical and experimental investigation on micromixers with serpentine microchannels, *Int. J. Heat Mass Transf.* 98 (2016) 131-140. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.041/

[30] X. Chen, T. Li, A novel passive micromixer designed by applying an optimization algorithm to the zigzag microchannel, *Chem. Eng. J.* 313 (2017) 1406-1414. http://dx.doi.org/10.1016/j.cej.2016.11.052/

[31] L. Wang, S. Ma, X. Wang, H. Bi, X. Han, Mixing enhancement of a passive microfluidic mixer containing triangle baffles, *Asia-Pacific J. Chem. Eng.* 9 (2014) 877-885. http://dx.doi.org/10.1002/apj.1837/

[32] R. T. Tsai, C. Y. Wu, An efficient micromixer based on multidirectional vortices due to baffles and channel curvature, *Biomicrofluidics* 5 (2011) 014103. http://dx.doi.org/10.1063/1.3552992/

[33] X. Chen, Z. Zhang, D. Yi, Z. Hu, Numerical studies on different two-dimensional micromixers basing on a fractal-like tree network, Microsyst, *Technol.* 23 (2017) 755-763. http://dx.doi.org/10.1007/s00542-015-2742-x/

[34] R. H. Liu, M. A. Stremler, K. V. Sharp, M. G. Olsen, J. G. Santiago, R. J. Adrian, H. Aref, D. J. Beebe, Passive mixing in a three-dimensional serpentine microchannel, *J. Microelectromechanical Syst.* 9 (2000) 190-197. http://dx.doi.org/10.1109/84.846699/

[35] C. Kleinstreuer, J. Li, J. Koo, Microfluidics of nano-drug delivery, *Int. J. Heat Mass Transf.* 51 (2008) 5590-5597. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.04.043/

[36] X. Chen, J. Shen, Numerical analysis of mixing behaviors of two types of E-shape micromixers, *Int. J. Heat Mass Transf.* 106 (2017) 593-600. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.034/

[37] S. Wong, M. Ward, C. Wharton, Micro T-mixer as a rapid mixing micromixer, *Sensors Actuators B Chem.* 100 (2004) 359-379. http://dx.doi.org/10.1016/j.snb.2004.02.008/

[38] J. Judy, D. Maynes, B. W. Webb, Characterization of frictional pressure drop for liquid flows through microchannels, *Int. J. Heat Mass Transf.* 45 (2002) 3477-3489. http://dx.doi.org/10.1016/S0017-9310(02)00076-5/

[39] P. V. Danckwerts, The definition and measurement of some characteristics of mixtures,*Appl. Sci. Res.* 3 (1952) 279-296. http://dx.doi.org/10.1007/BF03184936/

Tohid Dehghani received his M.Sc in Mechanical Engineering from the University of Mohaghegh Ardabili, Iran. His research is focused on mixing enhancement in microchannels using passive methods.

Reza Pirkhoshghiafe received M.Sc degree in mechanical engineering from the University of Tabriz, the B.Sc degree in mechanical engineering from the University of Mohaghegh Ardabili. His research interests include microfluidics and FSI simulation and their applications.

Parisa Balazadeh is M.Sc student in Mechanical Engineering from the University of Mohaghegh Ardabili, Iran. Her research interest is in Microfluidics and Droplet Generation.

Farhad Sadegh Moghanlou is the assistant professor at the University of Mohaghegh Ardabili, Iran. His research interest is in microfluidics and heat and mass transfer. Dr. Moghanlou is the head of the Microfluidics lab at the University of Mohaghegh Ardabili.