Journal of Thermal Engineering, Vol. 7, No. 2, Special Issue 13, pp. 47-57, February, 2021
Yildiz Technical University Press, Istanbul, Turkey

MIXING ENHANCEMENT IN ELECTROOSMOTIC MICROMIXERS

Narges Jafari Ghahfarokhi[1], Morteza Bayareh[1,*], Afshin Ahmadi Nadooshan[1], Sara Azadi[1]

ABSTRACT

Micromixers have important applications in various pharmaceutical and medical fields. In the present study, the enhancement of mixing index in electroosmotic micromixer with different geometries is investigated. The commercial software COMSOL Multiphysics 5.4 is employed to solve the mathematical models. The SIMPLEC algorithm is employed for coupling the velocity and pressure fields. A second-order upwind scheme is used to reduce the artificial diffusivity. The results show a remarkable effect of the electric field on the mixing efficiency. The optimum geometry is the one with no obstacle in the mixing chamber. For the optimum geometry, it is demonstrated that the mixing efficiency increases with the voltage, however there are optimum values for frequency and inlet velocity in which the micromixer exhibits its best performance. The optimum values of frequency and inlet velocity are 8 Hz and 0.1 mm/s, respectively. It is revealed that the micromixer with no obstacle can reach the mixing efficiency of about 97%.

Keywords: *Electroosmotic Micromixer, Numerical Simulation, Mixing Efficiency, Obstacle*

INTRODUCTION

Micromixers are widely used in chemical reactions, medical industries, and biomechanics [1]. In the biological industries, rapid mixing of large molecules such as proteins, nucleic acids and various biofluids has attracted many attentions [2]. Micromixers are divided into two categories: active and passive micromixers. In active micromixers, mixing is performed using external forces such as electric [3, 4], magnetic [5], acoustic [6], thermal [7], etc. Passive micromixers do not require external forces and work based on their geometries [8]. Among these external forces, the electrokinetic force is divided into four types: electroosmotic, electrophoretic, streaming potential and sedimentation potential [9]. An applied voltage can drive a liquid flow in a capillary tube. If slip boundary condition is imposed on the tube walls, the electrochemical double layer results in a streaming profile. This is a principle of the electroosmosis. Electroosmosis is one of the main mechanisms of electrokinetic that works based on the induced charge in the fluid phase due to contact with the dielectric surface [10, 11]. Since the Reynolds number in micromixers is of order of 10, the flow regime is laminar and mixing is mainly due to the molecular diffusion. Thus, external energy sources can be used to perturb the flow field and improve the mixing performance.

Many researchers have investigated the mixing performance of electroosmotic devices [12-16]. Bhattacharyya and Bera [12] investigated the mixing index in a long microchannel considering pressure-driven electroosmotic flow. They placed a rectangular block on a wall of channel and demonstrated that the vortical flow generated at the rear of the block depends on the Debye length. It was revealed that as the vortex becomes stronger, the mixing efficiency enhances. Peng and Li [13] showed that the uniformity of flow velocity and electric field in a microchannel depends on the value of ionic concentration of the electrolyte solution. They demonstrated that mixing efficiency is low for two solutions when one of them has very high ionic concentration and another has low concentration. Zhang et al. [14] used planar floating electrodes to enhance the mixing index and reached the mixing efficiency of 94.7% for flow rate of 1500 μm/s. they showed that the mixing index increases with the voltage and decreases with the inlet velocity and fluid viscosity. It was concluded that there is an optimal value for the mixing index when frequency is changed. Wu and Chen [15] used fractal structure to study the influence of electrodes on the mixing performance. They employed an alternating voltage of 5 V and reached the mixing index of 95.2% compared to the electrodeless micromixer with the efficiency of 50% at the same volume flow rate. Usefian and Bayareh [16] proposed a novel electroosmotic micromixer with a convergent chamber connected to a straight microchannel. They

This paper was recommended for publication in revised form by Regional Editor Erman Aslan
[1] Department of Mechanical Engineering, Shahrekord University, Shahrekord, Iran
**E-mail address: m.bayareh@sku.ac.ir*
Orcid id: 0000-0003-3719-0373, 0000-0002-1821-3771, 0000-0003-4345-9527, 0000-0002-1306-3794
Manuscript Received 29 March 2020, Accepted 31 May 2020

employed AC and DC electric fields and revealed that the strength of the vortices created by DC electric field is higher than that of AC one. It was shown that the mixing efficiency enhances with the voltage and decreases with the inlet velocity.

According to the previous researches, micromixer geometry and arrangement of electrodes have significant influences on the mixing performance of electroosmotic micromixers. In the present study, the effect of four obstacles placed in a hexagonal chamber on mixing performance of a micromixer is compared with a no-obstacle one to evaluate the formation of vortices within the channel. The optimal geometry is realized and then the influence of voltage, inlet velocity and frequency on its mixing quality is investigated.

GOVERNING EQUATIONS

The governing equations for mixing of Newtonian incompressible fluids are continuity and momentum equations [15]:

$$\nabla.\vec{u} = 0 \tag{1}$$

$$\rho\left(\frac{\partial\vec{u}}{\partial t} + \vec{u}.\nabla\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \rho_e\vec{E} \tag{2}$$

where $\vec{u}$ is the velocity vector, p the pressure, ρ the density and μ the dynamic viscosity. Since electroosmotic slip velocity is employed for micromixer walls, $\rho_e\vec{E}$ is ignored in the momentum equation. By applying this boundary condition, electroosmotic flow is generated, leading to that the liquid moves in the direction of the electric field with the following velocity [16]:

$$\vec{v} = -\frac{\varepsilon_o\varepsilon\zeta_w}{\mu}\vec{E} \tag{3}$$

where $\zeta_w = -0.1$ V indicates zeta potential, $\vec{E}$ is the applied electric field, $\varepsilon = 80.2$ is dielectric constant, and $\varepsilon_o = 8.854 \times 10^{-12}$ C/Vm is the permittivity of vacuum.

The electric potential V_e applied in the liquid is calculated by the Laplace equation:

$$\nabla^2 V_e = 0 \tag{4}$$

where $\vec{E} = -\nabla V_e$. Boundary condition is imposed on the electrodes are presented in Eq. 5 for AC electric field [16]:

$$V = V_o\,Sin(2\pi f t + E_o) \tag{5}$$

where V_o is the maximum AC potential and f is the frequency.

Mixing index is calculated as follows [16]:

$$MI = 1 - \sqrt{\frac{1}{N}\sum_{i-1}^{N}(\frac{C_i - \bar{C}}{\bar{C}})^2} \tag{6}$$

where $\bar{C}$ is the average concentration, C_i is the concentration at each point and N is the number of nodes in the considered area.

VERIFICATION

In order to verify the present results, the results of Keshavarzian et al. [17] who considered the effect of electrical potential on a micromixer, are used. Figure 1 shows a schematic of their micromixer and Table 1 presents its parameters. They mounted 8 electrodes on mixing chamber wall and inner circular obstacle symmetrically. Figure 3 shows the concentration as a function of channel width obtained from the present work and those reported by Keshavarzian et al. [17]. This figure illustrates that there is good agreement between the present results and those of Keshavarzian et al. [17] with the maximum error of 1.28%.

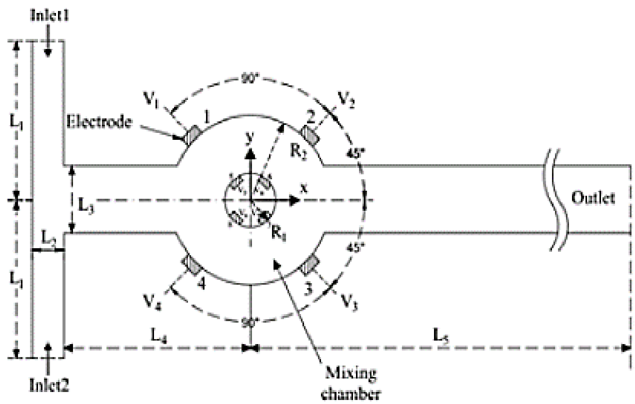


Figure 1. Schematic of the micromixer
[From Keshavarzian et al. [17] with permission from Physics Society of Iran and Isfahan University of Technology]

Table. 1. Properties of the micromixer
[From Keshavarzian et al. [17] with permission from Physics Society of Iran and Isfahan University of Technology]

Property	
Inlet velocity	U=0.001 m/s
Conductivity of ionic solution	$\sigma = 0.11845$ s/m
The permittivity of vacuum	$\varepsilon = 80.2$
Zeta potential	$\xi_0 = -0.1\ V$
Electric potential	V_0=3 V
Molecular diffusion coefficient	$D = 1\times10^{-11}$
Density	$\rho = 10^3 kg/m^3$
Dynamic viscosity	$\mu = 10^{-3}$ kg/m ^{3}
Frequency	F=8 Hz

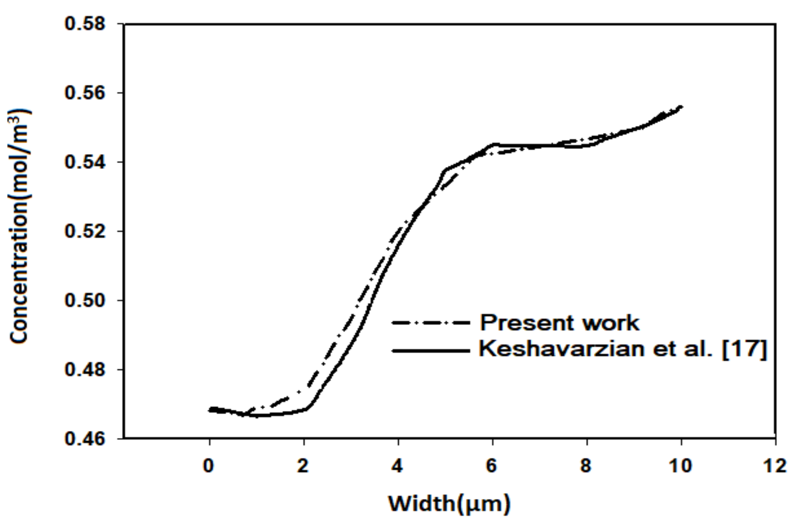


Figure 2. Concentration as a function of channel width

RESULTS AND DISCUSSION

Figure 3 shows different micromixers proposed in the present work. Four electrodes are placed on walls of mixing chamber symmetrically. The position of electrodes is the same for different micromixers. Case *a* has no obstacle and four other cases have different shapes of obstacle, including circular, rectangular, diamond, and octagonal.

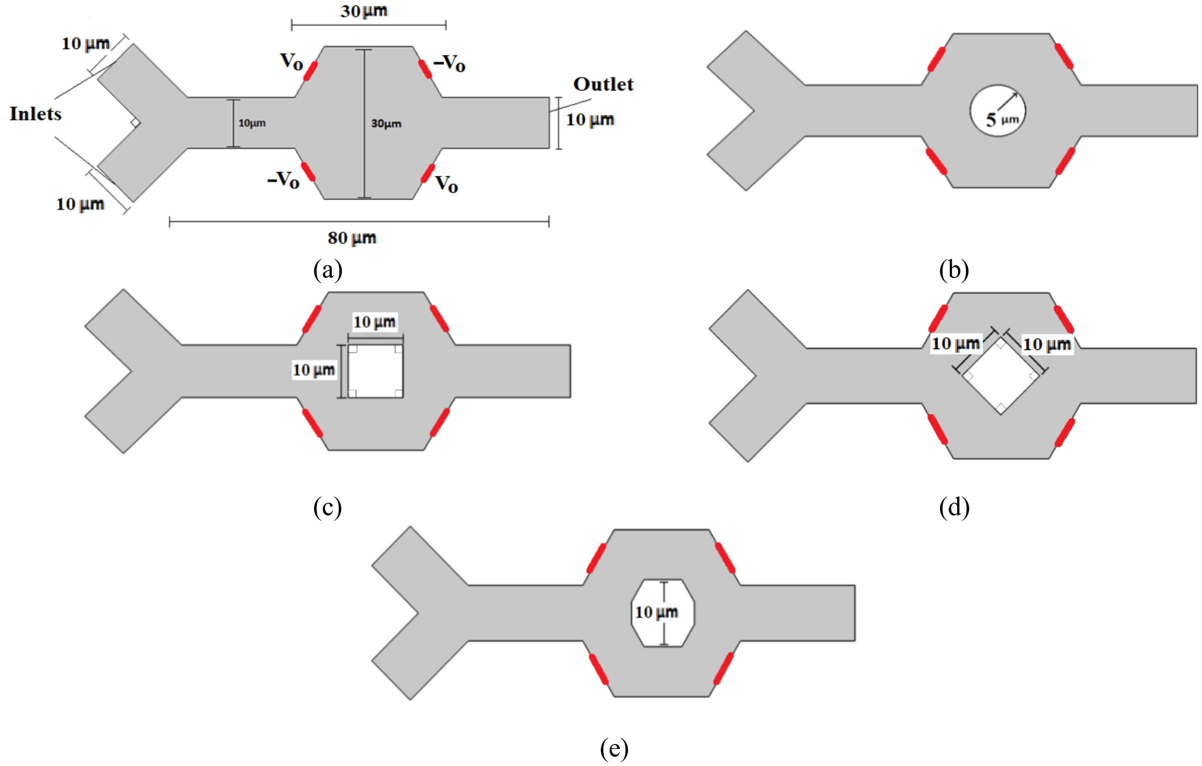


Figure 3. Different micromixers proposed in the present work: (a) without obstacle, (b) circular obstacle, (c) rectangular obstacle, (d) diamond obstacle, and (d) octagonal obstacle

Grid Study

In this study, tetrahedral grids are used for the computational domain [18]. Nine grid resolutions (from extremely coarse to extremely fine) are employed to determine the appropriate grid for the case *a* of Figure 3. Figure 4 demonstrates that further increase in the grid points of finer case does not lead to significant change in the results. Thus, finer grid resolution with 682390 elements is used for further simulations. It should be pointed out that this grid is appropriate for all cases considered in Figure 3.

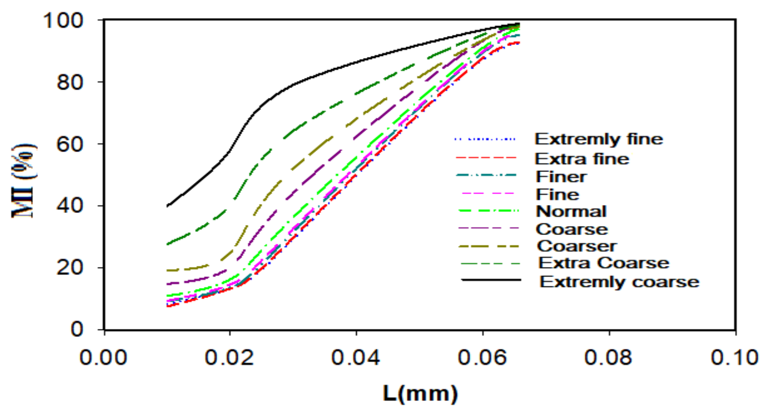


Figure 4. Mixing quality as a function of channel length for different grid resolutions

Determination of Optimal Geometry

To determine the optimal geometry, mixing quality is calculated for five cases considered in Figure 3. AC electric field with the frequency of 8 Hz and electric potential of 3 V is applied to the fluid flow within the micromixers. The inlet velocity is 0.1 mm/s and number of nodes is $N = 20$ for each cross section. Figure 5 shows the concentration contours for different geometries. It can be observed that the case *a* has the best mixing performance qualitatively. To quantify the mixing index, Equation 6 is used and the corresponding results are shown in Figure 6. This figure confirms that the geometry with no obstacle has the maximum mixing efficiency than other cases. The mixing quality of geometries *a*, *b*, *c*, *d*, and *e* at their outlets is 91.67, 73.92, 71.42, 59.44, and 64.99 respectively. Figure 7 illustrates the streamlines throughout different micromixers for different micromixers at $U_o = 0.1$ mm/s, v= o.1 V, f = 8 Hz. This figure shows the considerable effect of electric field on the streamlines for all cases. The vortices are created around the obstacles and close to the electrodes. These vortices lead to the circulation of the streams, resulting in an enhancement of mixing quality. It is worth noting that the vortices in the mixing chamber of the micromixer without obstacle circulate more regions of the two flows, while the vortices of other micromixers circulate each stream separately in the regions between the wall and the obstacles. Thus, the mixing rate in the micromixer with no obstacle is higher than those with obstacles.

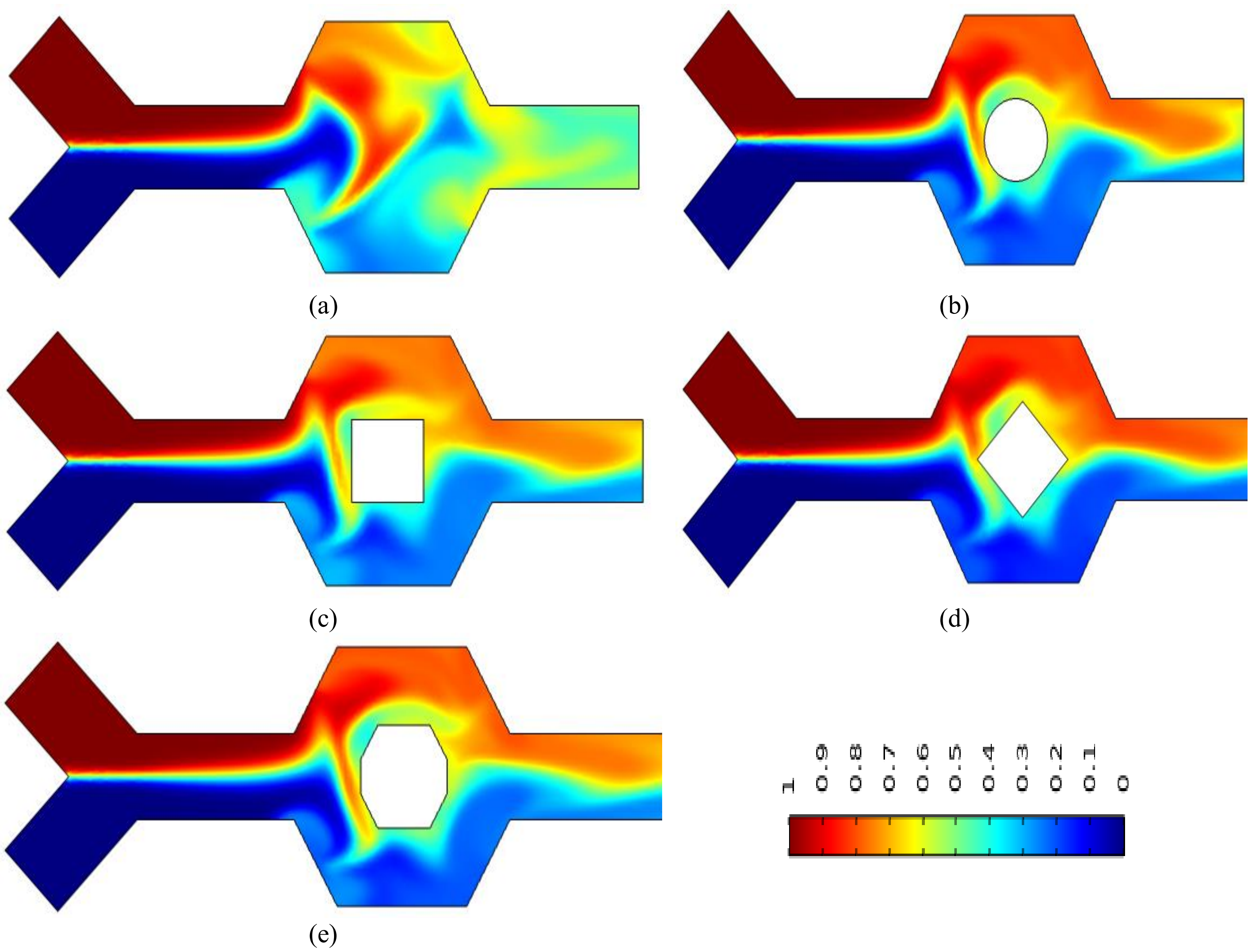


Figure 5. Concentration contours for different micromixers for $U_o = 0.1$ mm/s, v= o.1 V, and f = 8 Hz

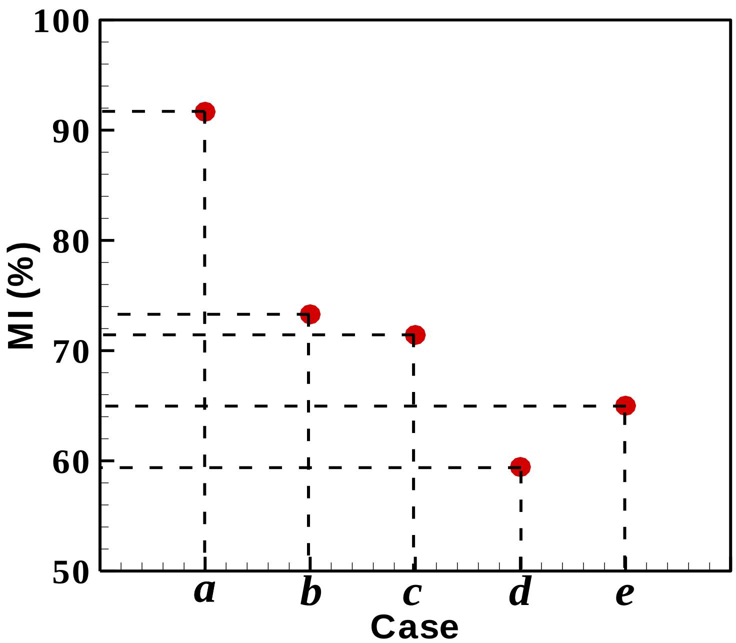


Figure 6. Mixing quality as a function of channel length for different micromixers for U_o = 0.1 mm/s, v= o.1 V, and f= 8 Hz

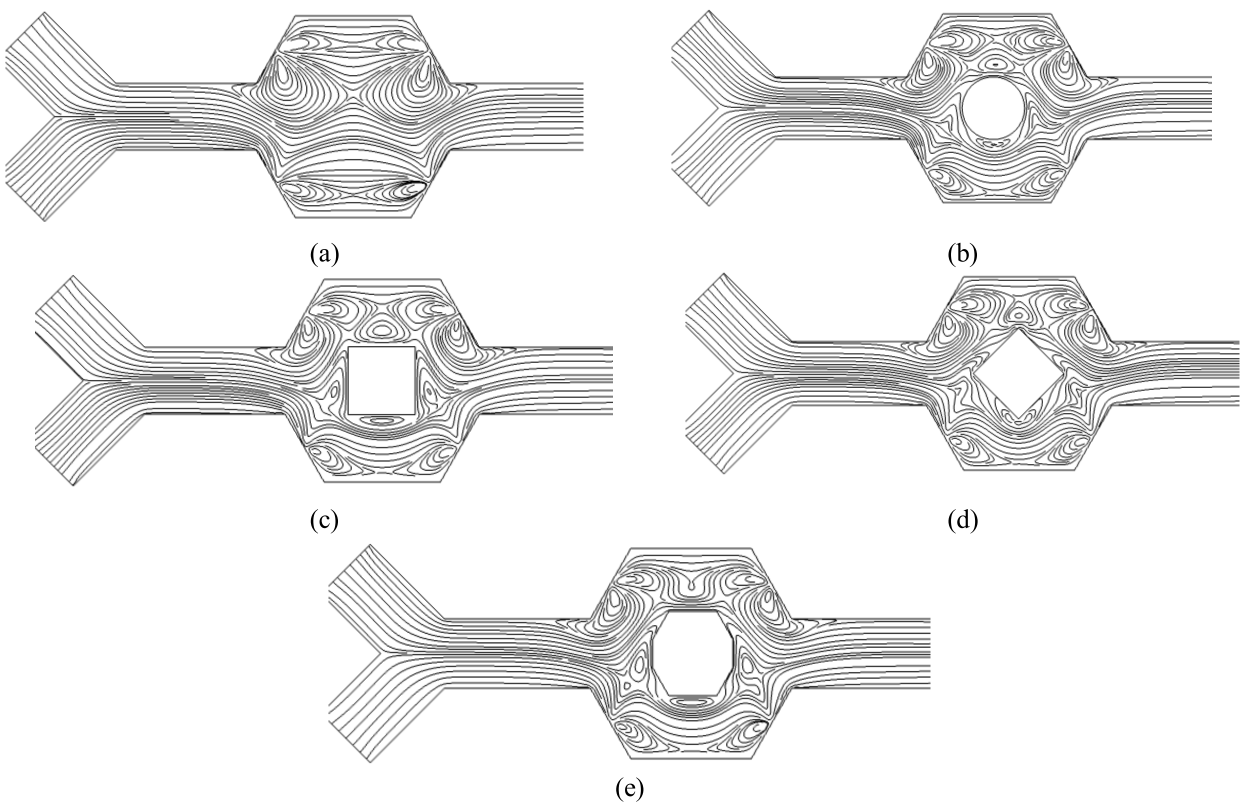


Figure 7. Effect of electric field on streamlines throughout different micromixers for U_o = 0.1 mm/s, v= o.1 V, and f = 8 Hz

Voltage Effect

In this section, the effect of voltage on the performance of micromixer is studied. It was known that as the voltage increases, the mixing quality enhances due to higher influence of electroosmotic force than inertial one [16]. The strength of vortices depends on the electroosmotic force. Figure 8 illustrates the variations of mixing quality for different values of the voltage. It can be observed that as the voltage increases, the mixing index is enhanced. It varies from 64.77% for the voltage of 0.05 V to 96.99% for the voltage of 0.7 V. Streamlines are plotted in Figure 9 for these two voltages. This figure demonstrates that the vortices occupy greater area in the chamber as the voltage enhances, leading to higher rate of mixing. As the voltage increases, the two main vortices circulate more parts of the fluid flow at the interface due to stronger electroosmotic force.

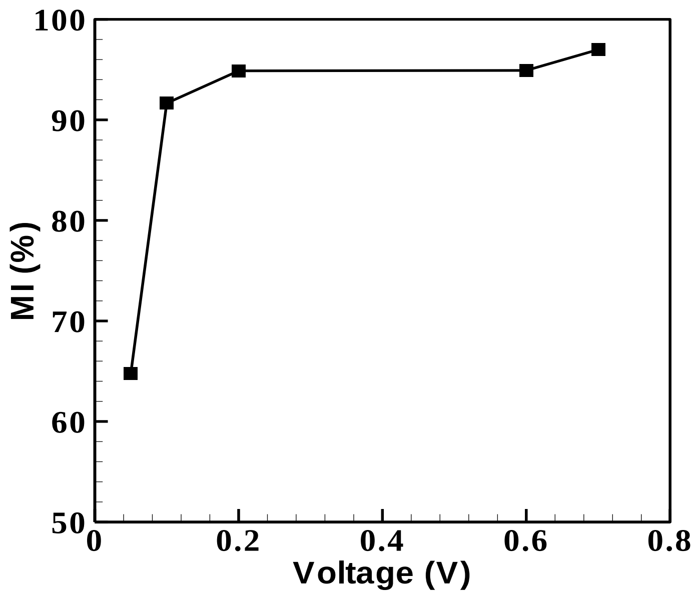
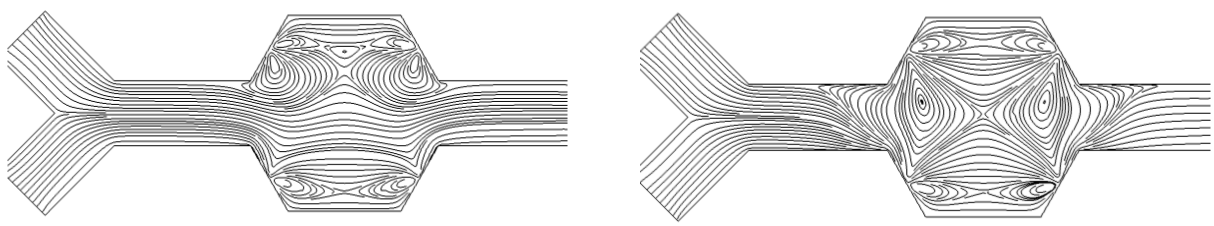


Figure 8. Mixing index for U_o = 0.1 mm/s, f = 8 Hz and different voltages



(a) (b)

Figure 9. Streamlines through the micromixer without obstacle for U_o = 0.1 mm/s, f = 8 Hz
(a) v = 0.05 V, and (b) v = 0.7 V

Inlet Velocity Effect

Figure 10 shows the values of mixing index for different inlet velocities of 0.05, 0.08, 0.1, 0.15, 0.2 and 0.5 mm/s. This figure demonstrates that inlet velocity of 0.1 mm/s leads to maximum mixing efficiency. In other words, there is an optimal value for inlet flow velocity. As mentioned before, there is a competition between inertial and electroosmotic forces in electroosmotic micromixers. Hence, three cases can be occurred: i) mixing efficiency increases with the inlet velocity, ii) mixing efficiency decreases with the inlet velocity, and iii) mixing efficiency has an optimal value. These conditions depend on the voltage, frequency, phase amplitude and geometrical parameters. In the present study, case (iii) happens, i.e. an optimal value is achieved for different inlet velocities. The value of mixing index is calculated at the channel outlet for different inflow velocities. It is 84.70, 87.62, 91.69, 60.62, 40.63, and 23.58% for the inlet velocities of 0.05, 0.08, 0.1, 0.15, 0.2 and 0.5 mm/s, respectively. As the inlet velocity increases, the inertial force becomes stronger. Electroosmotic force overcomes the inertial force for inlet velocity of 0.1, resulting in the formation of stronger vortices (Figure 11). As shown in Figure 11, for the case of U_o = 0.5 mm/s, inertial force prevents the creation of strong vortices and mixing quality decreases considerably.

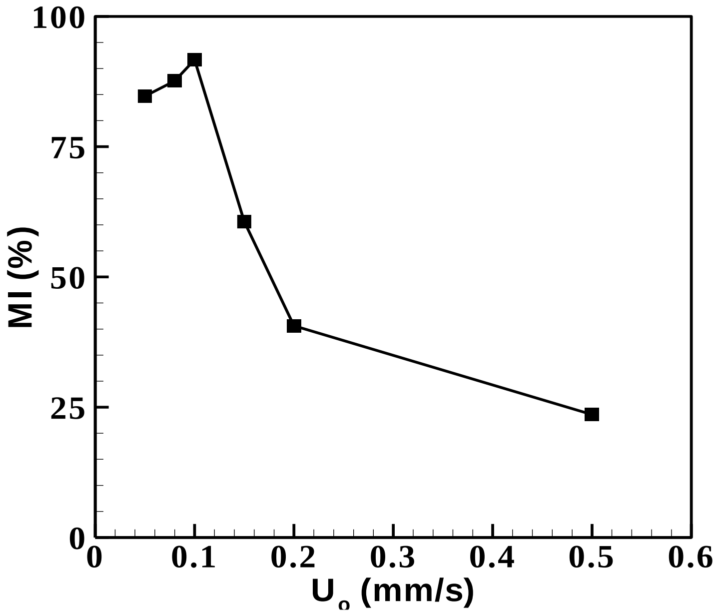
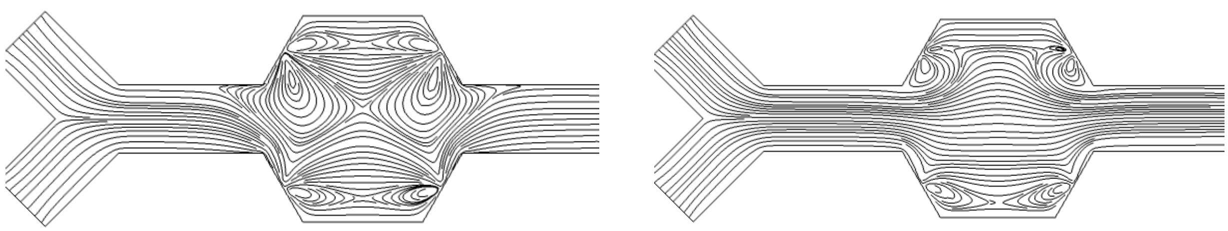


Figure 10. Mixing index for v = 0.1 V, f = 8 Hz and different inlet velocities



(a) (b)

Figure 11. Streamlines through the micromixer without obstacle for v = 0.7 V, f = 8 Hz
(a) U_o = 0.1 mm/s, and (b) U_o = 0.5 mm/s

Frequency Effect

In this section, the influence of frequency is examined on the mixing performance of the micromixer *a*. The frequency has the values of 4, 6, 8, 10, 12, 16 Hz. Figure 12 shows the mixing efficiency for v = 0.1 V, U_o = 0.1 mm/s and different frequencies. The figure reveals that there is an optimum value for the frequency (f = 8 Hz), in which the mixing quality has maximum value of 91.69% at channel outlet. The variation of mixing efficiency with respect to the frequency is similar to that of inlet velocity. In other words, the effective parameters such as frequency, voltage, inlet velocity and micromixer geometry determine the existence of optimal value for mixing index. For example, Usefian and Bayareh [16] showed that the mixing efficiency enhances with the frequency monotonically for their proposed micromixer. Figure 13 illustrates the streamlines through the micromixer for the optimal frequency and the one in which the mixing index is minimum. It can be observed that the strength of two main vortices is affected by the amount of the frequency. Electroosmotic force is larger for f = 8 Hz compared to f = 16 Hz. In other words, the deviation of interface is smaller when the frequency increases from 8 Hz to 16 Hz.

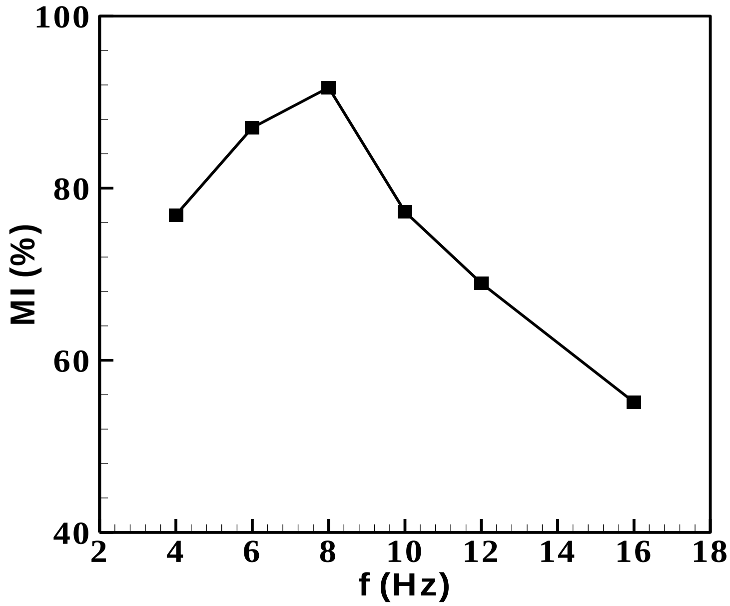


Figure 12. Mixing efficiency for v = 0.1 V, U_o = 0.1 mm/s and different frequencies

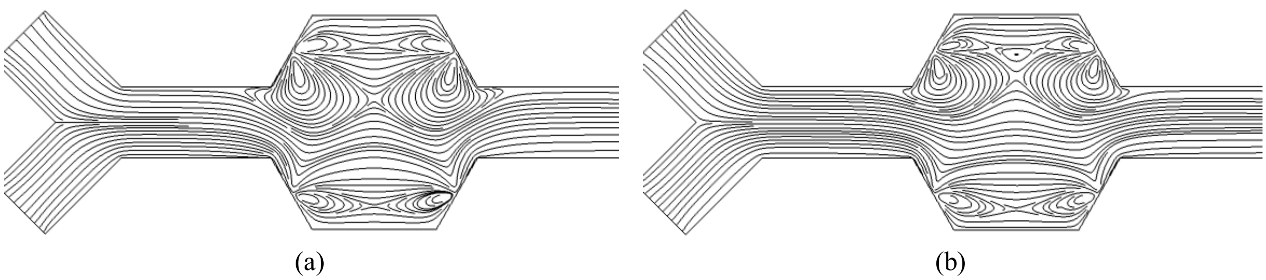


Figure 13. Streamlines through the micromixer without obstacle for v = 0.7 V, U_o = 0.1 mm/s
(a) f = 8 Hz, and (b) f = 16 Hz

CONCLUSION

In the present paper, the effect of different micromixer geometries on the mixing efficiency was investigated. It was found that the one with no obstacle in the mixing chamber has the maximum mixing quality. Then, the effect of the voltage, inlet velocity and frequency on the mixing performance of the optimum micromixer was examined. There is a competition between inertial and electroosmotic forces in electroosmotic micromixers. Hence, when effective parameters change, mixing efficiency may increase, decrease, or has an optimal value. It was demonstrated that the mixing efficiency increases with the voltage, however there are optimum values for frequency and inlet velocity in which the micromixer exhibits its best performance. The optimum values of frequency and inlet velocity were 8 Hz and 0.1 mm/s, respectively. It was revealed that the micromixer with no obstacle can reach the mixing efficiency of about 97%. There are some suggestions for future works: i) investigation of the effect of electrode arrangement, ii) evaluation of mixing for non-Newtonian fluids in the same geometries, and iii) study of higher magnitudes of Reynolds number.

NOMENCLATURE

$\bar{C}$	Average concentration
C_i	Concentration at each point
$\vec{E}$	Electric field, V/m
f	Frequency, Hz
MI	Mixing efficiency
N	Number of nodes

p	Pressure, Pa
t	Time, sec
$\vec{u}$	Velocity vector, m/s
$\vec{v}$	Electroosmotic velocity, m/s
V_o	Maximum AC potential, V

Greek symbols

ρ_f	Density, $\mathrm{kg/m^3}$
μ	Dynamic viscosity, Pa.s
ζ_w	Zeta potential
ε	Dielectric constant
ε_o	Permittivity of vacuum, C/V

REFERENCES

[1] Bayareh M, Nazemi Ashani M, Usefian A. Active and passive micromixers: a comprehensive review. Chemical Engineering and Processing-Process Intensification, 2020; 147 107771. doi:10.1016/j.cep.2019.107771.

[2] Chen H, Meiners JC. Topologic mixing on a microfluidic chip. Applied Physics Letters, 2004;84(12):2193-2195.

[3] Usefian A, Bayareh M, Shateri A, Taheri N. Numerical study of electro-osmotic micro-mixing of Newtonian and non-Newtonian fluids. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2019; 41(5):238.

[4] Habibi A, Shojaei S, Tehrani P. A comparative numerical design of the static and electrostatic micromixers. SN Appl. Sci. 2019;1:506. doi:10.1007/s42452-019-0491-7.

[5] Usefian A, Bayareh M, Ahmadi Nadooshan A. Rapid mixing of Newtonian and non-Newtonian fluids in a three-dimensional micro-mixer using non-uniform magnetic field. Journal of Heat and Mass Transfer Research, 2019; 6(1):55-61.

[6] Lim E, Lee L, Yeo LY, Hung YM., Tan MK. Acoustically-Driven Micromixing: Effect of Transducer Geometry. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2019; 1:1. doi:10.1109/tuffc.2019.2920683.

[7] Huang C, Tsou C. The implementation of a thermal bubble actuated microfluidic chip with microvalve, micropump and micromixer. Sensors and Actuators A: Physical, 2014;210:147-156. doi:10.1016/j.sna.2014.02.015 .

[8] Usefian A, Bayareh M. Numerical and experimental investigation of an efficient convergent-divergent micromixer. Meccanica, 2020;55:1025-1035.

[9] Pohl HA. Dielectrophoresis: The behavior of neutral matter in nonuniform electric fields (Cambridge Monographs on physics). Cambridge/New York: Cambridge University Press, 1978.

[10] Masliyah JH, Bhattacharjee S . Electrokinetic and colloid transport phenomena. John Wiley & Sons, 2006.

[11] Stone HA, Stroock AD, Ajdari A. Engineering flows in small devices: microfluidics toward a lab-on-a-chip. Annu. Rev. Fluid Mech. 2004;36:381-411.

[12] Bhattacharyya S, Bera S. Combined electroosmosis-pressure driven flow and mixing in a microchannel with surface heterogeneity. Applied Mathematical Modelling, 2015;39(15):4337–4350.

[13] Peng R, Li D (2015) Effects of ionic concentration gradient on electroosmotic flow mixing in a microchannel. Journal of Colloid and Interface Science 440:126–132.

[14] Zhang K, Ren Y, Hou L, Feng X, Chen X, Jiang H, An efficient micromixer actuated by induced-charge electroosmosis using asymmetrical floating electrodes. Microfluidics and Nanofluidics, 2018;22(11). doi:10.1007/s10404-018-2153-2.

[15] Wu Z, Chen X. Numerical simulation of a novel microfluidic electroosmotic micromixer with Cantor fractal structure. Microsystem Technologies, 2019;doi:10.1007/s00542-019-04311-8.

[16] Usefian A, Bayareh M. Numerical and experimental study on mixing performance of a novel electro-osmotic

micro-mixer. Meccanica, 2019; doi:10.1007/s11012-019-01018-y.

[17] Keshavarzian B, Shamshiri M, Charmiyan M, Moaveni A. Optimization of an Active Electrokinetic Micromixer Based on the Number and Arrangement of Microelectrodes. Journal of Applied Fluid Mechanics, 2018;11(6):1531-1541.

[18] Ekiciler, R., Arslan, K. CuO/Water Nanofluid Flow over Microscale Backward-Facing Step and Analysis of Heat Transfer Performance. Heat Transfer Research, 2018;49 (15).