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Research Article

T-Shaped Active Micromixer Analysis: AC Electric Field Effect

Ahmad Najafpour [a,*], Nastaran Faraji [b], Fatemeh Iji [c]

[a] *Department of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran*
[b] *Department of Mechanical Engineering, University of Isfahan, Isfahan, Iran*
[c] *Department of Physics, Shahid Beheshti University, Tehran, Iran*

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ABSTRACT

In order to improve the performance of the micromixer and increase the mixing index, this research has simulated and investigated the effect of using an electric field using COMSOL Multiphysics software. The proposed case in this work is a 2D T-shaped micromixer with two inlet openings of dimensions 100 µm, and the length of the mixing channel is 1400 µm. The results indicate that increasing the voltage from 0 V to 20 V enhances the mixing index in the micromixer, resulting in improved mixing. Increasing the inlet velocity from 0.2 mm/s to 0.8 mm/s leads to a pressure drop of 124.27%, 249.13%, and 373.41%, respectively. With an increase in the voltage applied by the electrodes, mixing index values fluctuate more over time compared to lower voltages.

1. Introduction

Active micromixers are microfluidic devices that improve mixing by disrupting fluid flow in microchannels, where diffusion limits natural mixing [1]. They do this by employing external energy sources [2]. In order to accelerate the mixing process, these mixers use a variety of external fields, including pressure, acoustic, magnetic, electric, and thermal forces, to create perturbations that increase the area of contact between fluids or cause chaotic advection [3-6]. Active micromixers require external power input to stir or agitate fluids, enabling faster and more efficient mixing compared to passive micromixers, which rely solely on channel geometry and diffusion. Although they are often more complicated and expensive to construct and integrate, this makes them especially useful in applications requiring quick and thorough mixing, such as chemical synthesis, biological analysis, and microfluidic lab-on-a-chip devices [7].

Electroosmotic micromixers operate by applying an electric field to induce electroosmotic flow in microchannels [8]. The fluid motion is fueled by the electric field's interaction with the electrical double layer at the channel walls. Usually, this flow creates recirculating vortices close to the electrodes, which actively agitate the fluids by repeatedly stretching and folding fluid components and utilizing diffusion on a small scale to improve mixing efficiency [9]. Asymmetric and chaotic microvortices that disturb fluid surfaces and encourage quick mixing can be produced by modulating the electric field in time or space, for example, by employing alternating current or switching electric potentials. To maximize vortex generation and mixing performance, design solutions often incorporate patterned electrodes,

*** Corresponding author.**
E-mail address: amdnajafpour@gmail.com

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fractal channel shapes, or induced charge electroosmosis. Electrode spacing, voltage magnitude, and channel shape are important factors that affect mixing; in general, greater voltages and smaller electrode gaps improve mixing by accelerating fluid deformation and convection [10]. In microfluidic applications that require effective, regulated mixing at low Reynolds numbers, these micromixers are useful.

Sasaki et al. [11] demonstrated a fast micromixer of fluids in a microchannel. An AC voltage was applied to two coplanar meandering electrodes arranged in parallel to the channel to provide the AC electroosmotic flow used in the mixer. Dilution tests utilizing a dye solution in a 120 μm-wide channel were carried out to illustrate the mixer's functionality. Up to 12 mm/s, rapid mixing was noted for the flow velocity. Compared to diffusional mixing without an extra mixing mechanism, the mixing time of 0.18 s was 20 times quicker. The mixer operated with a shorter mixing length when compared to the performance of previously reported micromixers, especially for low Peclet numbers.

Xiong et al. [12] designed a new kind of micromixer based on the Koch fractal concept. Irregular alternating eddy currents were created in the microchannel to enhance fluid mixing in order to increase the micromixer's mixing performance under the influence of fractal and electric fields. A micromixer with a superior mixing effect was produced by adjusting the fractal structure, direct current voltage size, electrode spacing, electrode layout, and numerical computations. The mixing efficiency approached 99% when the electroosmotic micromixer contained three sets of electrode pairs arranged alternately and Re = 0.01.

A novel 3D electroosmotic micromixer with a variable module was presented by Feng et al. [13]. According to simulation data, the number, size, and location of vortices created by the fluid in the microchannel changed depending on the electric field. When the Reynolds number was less than 10, the micromixer had a good mixing effect, but when Re was greater than 10, it rapidly declined. Smaller pressure drop, more flexibility, and consistent high mixing efficiency were features of the new electroosmosis micromixer.

Schiffbauer et al. [14] introduced a novel ion-selective microsphere-containing micromixer with a spherical chamber. An external pressure gradient was used to introduce the stratified liquid into the chamber. An external electric field was then directed to produce electroosmotic flow in opposition to pressure-driven flow, which causes mixing. For strong mixing, the ideal applied electric field values were found.

Using electroosmotic principles, Kumar et al. [15] examined the effects of microfluidic mixing in a circular mixing chamber micromixer. They investigated how fluid mixing dynamics are affected by microchamber diameter, inlet velocity, alternating current voltage amplitude, and AC frequency. The results indicated that decreasing the diameter of the circular microchamber increases the electroosmosis force and mixing efficiency by decreasing the linear distance between microelectrodes. This increased efficiency was mostly due to the nonlinear relationship between microchamber shape and electroosmotic flow.

Shamloo et al. [16] proposed the use of AC electric current in a 2D micromixer. They investigated the effects of geometric changes, input velocity, electric voltage, and frequency. The results of their work showed that the mixing index values in the optimal state in geometries one-ring type, diamond type, and two-ring type are 99.4, 98, and 99.8, respectively.

This research investigates the effect of the electric field on mixing in a two-dimensional T-shaped micromixer. The proposed geometry has 4 square mixing units, each of which contains two positive and negative electrodes on both sides.

2. Numerical methodology

2.1. Geometry and boundary conditions

The present work investigates a two-dimensional micromixer with 4 units. Each mixing unit consists of two electrodes with electrical voltages of positive and negative. The fluid with the properties specified in Table 1 enters the mixing channel at a constant velocity from inlets A and B, and the condition of zero static pressure is considered at the outlet of the channel. The geometric dimensions and boundary conditions of the present problem are shown in Fig. 1.

Table 1. Fluid properties [16].

Material	Water
Density(kg/m3)	10^3
Dynamic viscosity (Pa.s)	10^{-3}
Diffusion coefficient (D_i) (m^2/s)	0.6×10^{-11}
Electrical conductivity (S/m)	0.11845
Relative permittivity (ε_r)	68

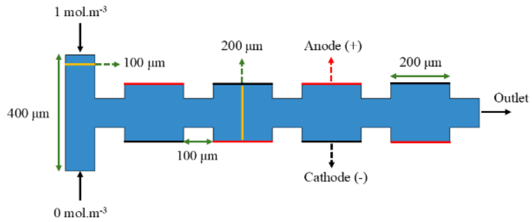

Fig. 1. (a) Geometric dimensions and boundary conditions.

2.2. Governing equations

The Navier-Stokes and continuity equations that govern the mixing of two fluids in an unsteady condition are as follows:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla\vec{V}\right) = -\nabla P + \mu\nabla^2\vec{V} \tag{2}$$

where $\vec{V}$, P, ρ, and μ represent the velocity vector, pressure, density, and dynamic viscosity, respectively.

The convective-diffusion transport equation is:

$$\frac{\partial c}{\partial t} + \vec{V} \cdot \nabla c = -D\nabla c \tag{3}$$

Here, c and D are concentration and molecular diffusion coefficient, respectively. Besides, the following relation is utilized to estimate the electric potential:

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

Here, V is the applied voltage.

The mixing index is determined as [17]:

$$MI = \left(1 - \left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{c_i - \bar{c}}{\bar{c}}\right)^2}\right)\right) \times 100 \tag{5}$$

where c_i is the local concentration of each component and $\bar{c}$ is the average concentration. N also represents the number of grid points in the desired cross-section.

2.3. Data Analysis

The value of ΔP can be concluded as follows [18-20]:

$$\Delta P = P_{in} - P_{out} \tag{6}$$

3. Grid Study

Mesh quality in numerical problems has a significant impact on solution results [21-24]. In the present work, in order to achieve a suitable mesh, the fluid flow velocity profile at the channel outlet has been investigated at a velocity of 0.6 mm/s, voltage = 6 V, and t = 0.5 s. The obtained results show that the fine mesh (12208 elements) is a suitable choice for solving the present problem (Fig. 2).

The governing equations of the current problem were discretized using the finite element method in COMSOL Multiphysics. Equations are solved while incorporating the remaining relevant values into the calculations.

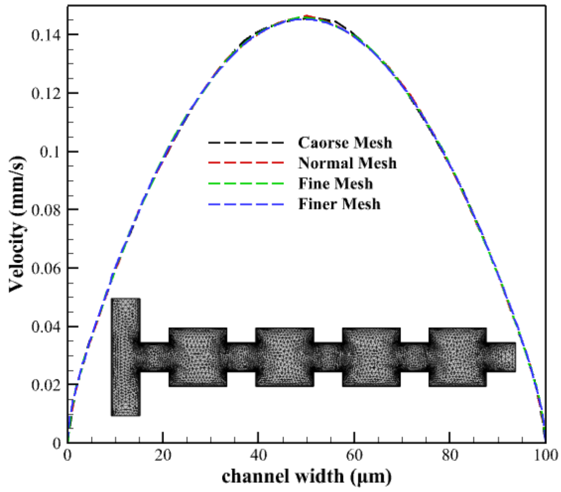

Fig. 2. Grid study.

3.1. Validation

In order to ensure the accuracy of the results of the present work, the numerical method used in the present work has been compared with the results reported in the study by Shamloo et al. [16], the details of which are shown in Fig. 3.

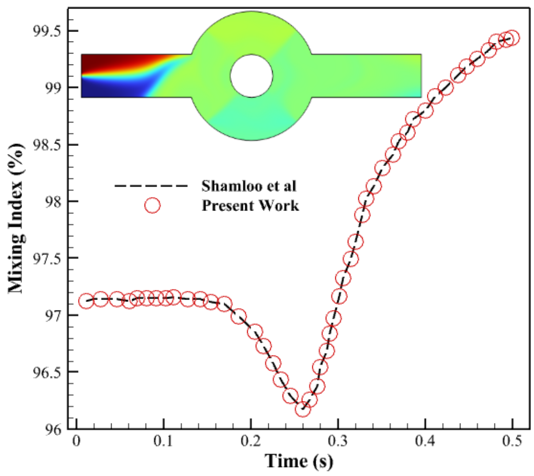

Fig. 3. Comparison of the results obtained with the numerical method compared to the work of Shamloo et al. [16].

4. Results and discussion

4.1. Effect of AC Voltage Variations

The effect of AC electrical voltage variations at a frequency of 8 Hz on the concentration distribution is shown in Fig. 4. The results obtained show that, with the input velocity remaining constant, increasing the voltage increases the penetration of two different species (red and blue regions) into each other, ultimately enhancing mixing in the micromixer.

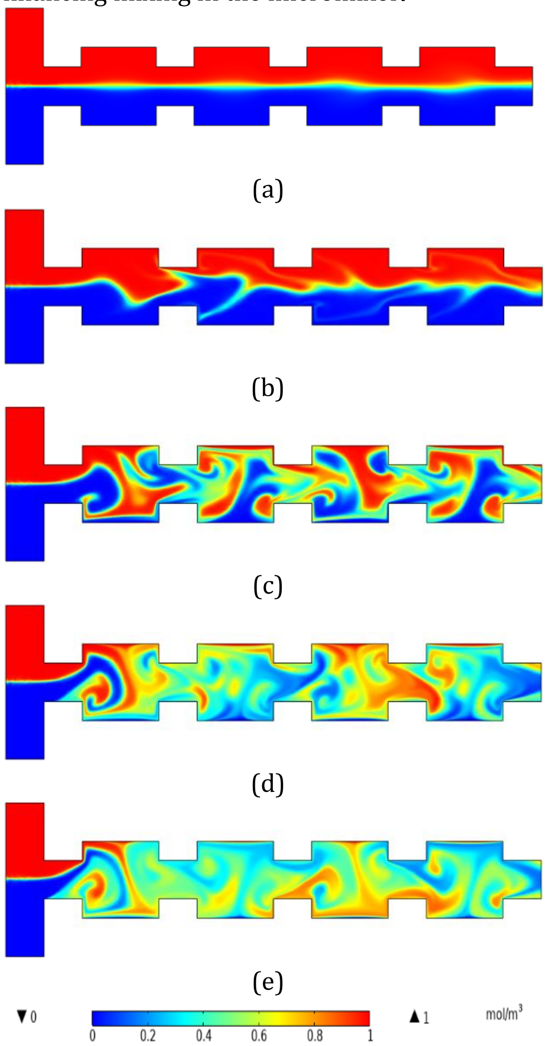

Fig. 4. Concentration for inlet velocity = 0.6 mm/s for different voltages: (a) 0 V, (b) 2 V, (c) 6 V, (d) 12 V, and (e) 20 V at t = 0.5 s.

The graph of the mixing index values with the passage of time from 0 s to 0.5 s is shown in Fig. 5. According to equation (8), the nature of the applied voltage in the AC electric current is sinusoidal and oscillating. According to Fig. 5, in the passive (0 volts), the least oscillation occurred, and with the increase in the applied voltage, the range of changes in the mixing index increased and more oscillation occurred.

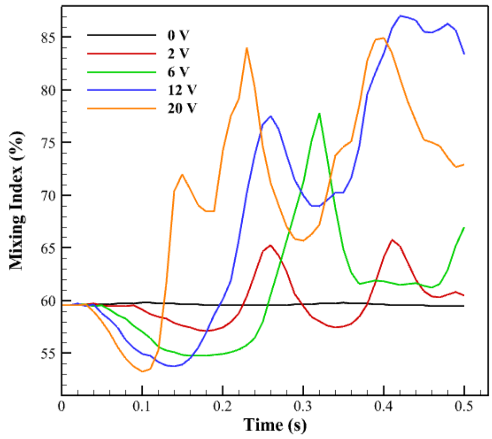

Fig. 5. MI values for the proposed case and inlet velocity = 0.2 mm/s at t = 0 s to t = 0.5 s.

The results show that the pressure drop increases with the fluid inlet velocity and has an upward trend. Fig. 6 shows the pressure drop graph as a function of fluid inlet velocity for velocities 0.2 mm/s, 0.4 mm/s, 0.6 mm/s, and 0.8 mm/s. Increasing the inlet velocity from 0.2 mm/s to 0.8 mm/s leads to a pressure drop of 124.27%, 249.13%, and 373.41%, respectively.

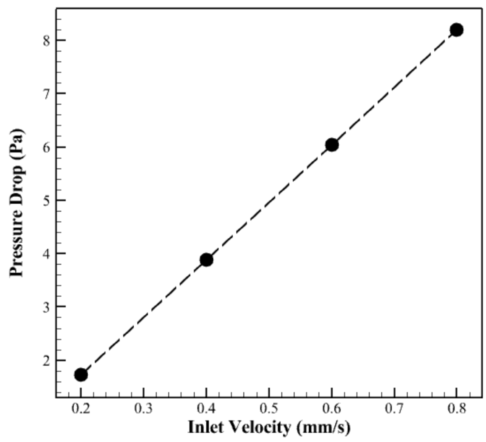

Fig. 6. Pressure Drop values for the proposed case at t = 0.5, V = 0 V, and different inlet velocities.

5. Conclusions

This study investigated the effect of an electric field on concentration distribution and mixing index in a T-shaped micromixer. The results obtained show that creating an electric field improves mixing in the micromixer. The important results of the present study are as follows:

- With the inlet fluid velocity remaining constant, increasing the voltage increases the penetration of layers of two different species into each other, which ultimately increases the mixing index.
- With an increase in the voltage applied by the electrodes, mixing index values fluctuate more over time compared to lower voltages

- The results of the present work show that the pressure drop in the present micromixer increased with increasing inlet velocity from 0.2 mm/s to 0.8 mm/s.

Nomenclature

ΔP	Pressure drop [Pa]
P	Pressure [Pa]
u	Velocity in x direction [m/s]
v	Velocity in y direction [m/s]
w	Velocity in z direction [m/s]
ρ	Density [kg/m^3]
MI	Mixing Index (%)
V	Voltage (V)

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