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Research Article

Numerical Study of an Electroosmotic Micromixer

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ABSTRACT

Electroosmotic micromixers utilize electroosmotic flow to enhance fluid mixing at the microscale, which is particularly beneficial in biochemical applications requiring rapid mixing of multiple fluid streams. This study examines an asymmetric electroosmotic micromixer to assess the impact of inlet velocity and applied voltage on the mixing index (MI) and pressure drop (Δp). The results show that the applied voltage significantly improves mixing quality while having a minimal effect on Δp. For instance, when the inlet velocity (U_{in}) is 0.2 mm/s, increasing the applied voltage from 0 to 6 V boosts the MI from 64.61% to 67.66%. At U_{in} = 0.8 mm/s, this enhancement is more pronounced, with the MI rising from 65.92% to 85.55%. Additionally, the study reveals that the MI increases with inlet velocity for a given applied voltage.

1. Introduction

Applications for microfluidics are many and span a number of industries, including environmental monitoring, cell biology, pharmaceuticals, and medical diagnostics. Microfluidic devices, often known as "lab-on-a-chip" systems, are perfect for point-of-care testing in medical diagnostics because they allow for quick and accurate diagnostic procedures with small sample quantities. Microfluidics helps the pharmaceutical business by simulating human organ functioning in "organ-on-a-chip" systems, which improves drug testing and minimizes animal testing [1-3]. Furthermore, because microfluidics makes it possible to precisely manipulate and analyze individual cells, it is essential to cell biology. By highly sensitively detecting contaminants in soil, water, and air, it also helps with environmental monitoring [4].

Micromixers are a main component of microfluidic devices. Passive and active are the two main types of micromixers. Geometric features like T-type, Y-type, barriers, and curved channels are used in passive micromixers to increase mixing efficiency by chaotic advection without the need for external energy sources [5-8]. Their simplicity and minimal reagent use make them widely utilized in biological and chemical processes. In contrast, active micromixers greatly increase mixing efficiency by using external forces such as pressure, magnetic [9], electric [10], and acoustic [11, 12] fields to create complex fluid movements.

Gayen et al. [13] considered electrokinetic processes, such as electroosmotic flow, to increase mixing efficiency in a micromixer containing two fluids with varying

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concentrations. The optimum mixing quality was obtained by taking into account the four stiff baffles and microelectrodes that are positioned on the chamber's outside. The paper calculated these impacts using a solution based on finite elements. A low input velocity of 0.05 mm/s yielded the highest mixing quality (99.67%), whereas a greater inlet velocity and a higher AC electric field frequency yielded the lowest quality (15.78%).

A pure electroosmotic flow of a non-Newtonian fluid through a nonuniformly charged micromixer with obstacles organized in staggered and lined orders was studied by Mehta et al. [14] to determine its mixing and hydrodynamic properties. The power-law model was used to characterize the fluids' constitutive behavior. The findings indicated that with more increases in shear-thickening fluid and staggered barrier placement, the presence of heterogeneously charged surfaces improves mixing.

Using the Oldroyd-B constitutive model, Chen et al. [15] examined the mixing of viscoelastic fluids in a micromixer with a conductive cylinder. The Helmholtz-Smoluchowski theory was used to estimate the frictional deformation effect. The effect of electric field strength and polymer concentration on the mixing of polyacrylamide solutions was also assessed in this work. The velocity decreased with increasing polymer content, according to the results, and PAA solutions had a mixing efficiency that was 20–40% greater than that of Newtonian fluid.

The present paper introduces an asymmetric electroosmotic micromixer (Fig. 1) to explore the role of inlet velocity and applied voltage on mixing index and pressure drop.

2. Governing Equations

The governing equations, i.e., continuity and Navier-Stokes equations, in the unsteady state for the mixing of two fluids are as follows:

$$\nabla \cdot \vec{V} = 0 \quad (1)$$

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

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

The convective-diffusion transport equation is expressed as:

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

which c and D are concentration and molecular diffusion coefficient, respectively. Equation 4 is used to determine the electric potential:

$$\nabla^2 V = 0 \quad (4)$$

Here, V is the applied voltage. Besides, the mixing index is calculated as follows:

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

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.

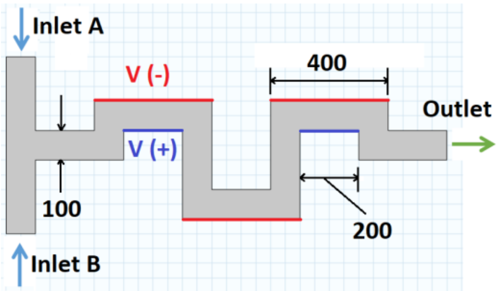

Fig. 1. Schematic of the proposed electroosmotic micromixer. The dimensions are in micrometers.

3. Grid Independence Test and Validation

Four grids with 12682, 49637, 108492, and 174365 elements are considered to conduct the grid independence test. It is found that the grid with 108492 elements is appropriate for the simulations because the difference between the results obtained from two finer grids is negligible. The schematic representation of the grid used for the simulations is depicted in Fig. 2.

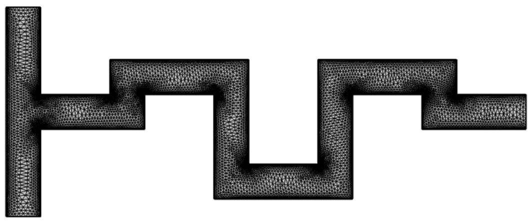

Fig. 2. The computational grid used for the simulations.

The numerical results of Bahrami et al. [10] are utilized for the validation of the current results. Table 1 demonstrates that the results obtained from the present numerical simulations are in agreement with those reported by Bahrami et al. [10]. Hence, the present numerical method can be employed for the simulations.

Table 1. Values of mixing index for different amounts of frequency.

Frequency (Hz)	Present work	Bahrami et al. [10]
2	81.32	81.28
4	94.41	94.36
8	93.97	93.86
10	80.09	80.01

4. Results

Figs. 3 to 6 depict the concentration contour along the micromixer at U_{in} = 0.2 mm/s, 0.4 mm/s, 0.6 mm/s, and 0.8 mm/s, respectively, for different applied voltages. In the absence of an electric field, the mixing process is performed based on the influence of molecular diffusion. By applying the electric field, some vortices are formed near the electrodes, leading to an improvement in the mixing quality. In other words, one important mechanism for improving fluid mixing at the microscale is the creation of vortices in an electroosmotic micromixer. Usually, an electric field interacts with the produced charges in the diffuse double layer close to electrodes or channel walls in this process.

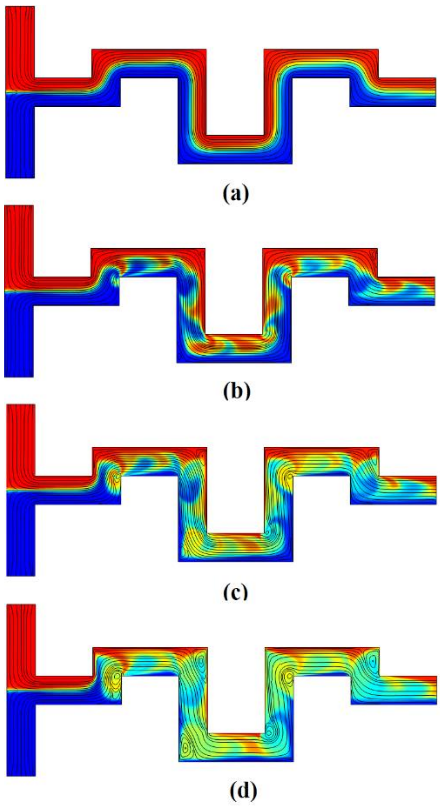

Fig. 3. Concentration contour along the micromixer for U_{in} = 0.2 mm/s when the applied voltage is: (a) 0 V, (b) 1 V, (c) 3 V, and (d) 6 V.

By upsetting laminar flow and producing chaotic flow patterns, the nonuniform electric field in devices like AC electroosmotic micromixers produces micro vortices at electrode gaps, which greatly increase mixing efficiency. Similar to this, variations in electroosmotic flow velocities in T-type microchannels with nonuniform zeta potentials cause electrokinetic vortices to develop, which efficiently agitate the fluid and promote mixing.

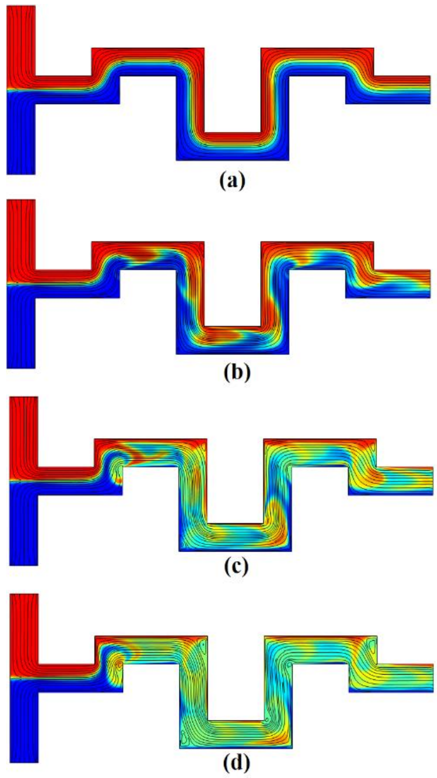

Fig. 4. Concentration contour along the micromixer for U_{in} = 0.4 mm/s when the applied voltage is: (a) 0 V, (b) 1 V, (c) 3 V, and (d) 6 V.

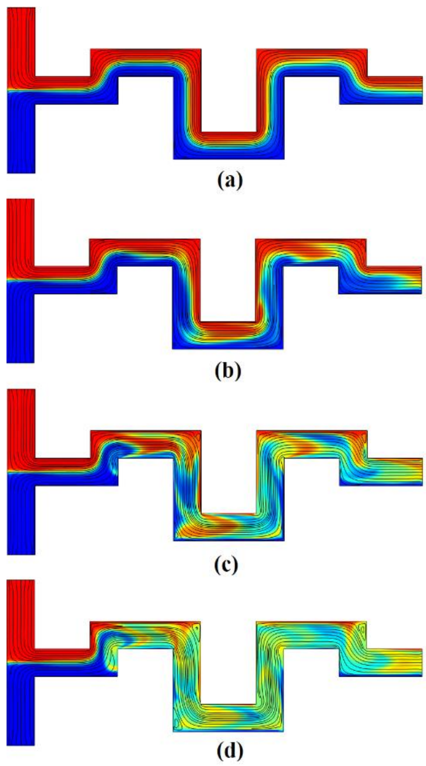

Fig. 5. Concentration contour along the micromixer for U_{in} = 0.6 mm/s when the applied voltage is: (a) 0 V, (b) 1 V, (c) 3 V, and (d) 6 V.

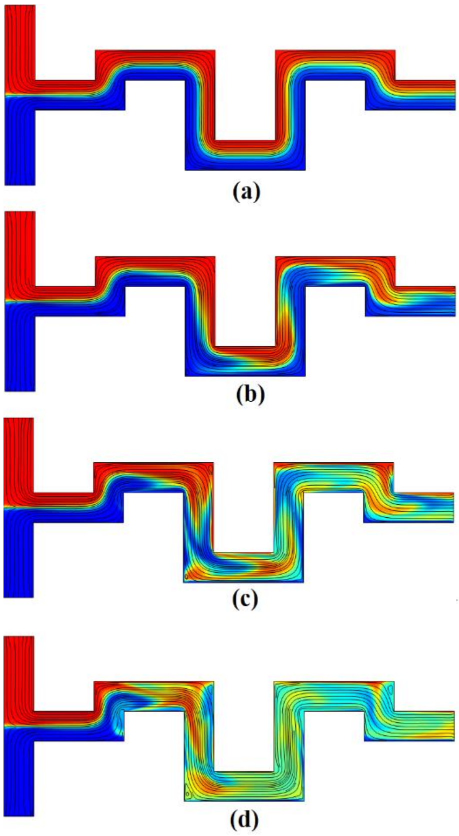

Fig. 6. Concentration contour along the micromixer for U_{in} = 0.8 mm/s when the applied voltage is: (a) 0 V, (b) 1 V, (c) 3 V, and (d) 6 V.

By modifying variables including electrode voltage, zeta potential gradients, and channel design, the intensity and quantity of vortices may be regulated, enabling optimal mixing performance in a range of applications. To further improve mixing efficiency, physicochemically designed surfaces can also create vortices and generate flow reversals.

Table 2 compares the amounts of MI and Δp for various cases studied in the present work. It is observed that the applied voltage has a negligible impact on Δp, while significantly enhancing the mixing quality. For instance, MI is improved from 64.61% to 67.66% by changing the applied voltage from 0 to 6 V when the inlet velocity is 0.2 mm/s. This enhancement for U_{in} = 0.8 mm/s is 65.92% to 85.55%.

Table 2. MI and Δp values for different inlet velocities and applied voltages.

Voltage (V)	U_{in} (mm/s)	Δp (Pa)	MI (%)
	0.2	1.06	64.61
0	0.4	2.12	65.69
	0.6	3.18	65.76
	0.8	4.24	65.92
	0.2	1.06	65.27
1	0.4	2.12	67.41
	0.6	3.18	67.54
	0.8	4.24	66.07
	0.2	1.06	65.08
3	0.4	2.12	80.01
	0.6	3.18	75.05
	0.8	4.24	82.39
	0.2	1.06	67.66
6	0.4	2.12	85.59
	0.6	3.18	83.67
	0.8	4.24	85.55

5. Conclusions

This study examines an asymmetric electroosmotic micromixer to assess the impact of inlet velocity and applied voltage on MI and Δp. The results show that the applied voltage significantly improves mixing quality, with notable examples including an increase in MI from 64.61% to 67.66% when U_{in} is 0.2 mm/s and the voltage is increased from 0 to 6 V. At Uin = 0.8 mm/s, this enhancement is more pronounced, with the MI rising from 65.92% to 85.55%. Additionally, the study reveals that the MI increases with inlet velocity for a given applied voltage. Despite these improvements in mixing quality, the applied voltage has a minimal effect on Δp, making asymmetric electroosmotic micromixers suitable for efficient mixing applications.

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