Study on Flow Characteristics of Microfluid in Electroosmotic Flow Mixer

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Abstract. As one of the important components of modern microfluidic devices, micromixers have attracted more and more attention. Among many microfluidic mixers, electro-osmotic flow mixers have been widely studied and applied due to their advantages such as simple structure, convenient control and remarkable mixing effect. In this paper, a two-dimensional numerical model of an electro-osmotic flow micromixer with an annular mixing chamber is established by means of the simulation software COMSOL Multiphysics. The mixing process of fluid in the electro-osmotic flow micromixer is simulated, and the flow characteristics of fluid in the micromixer are analyzed. The analysis shows that the electroosmotic flow micromixer generates electroosmotic flow under the action of alternating electric field, and disturbs the fluid to form vortex, thus greatly improving the mixing efficiency. The results show that the micromixing efficiency increases with the increase of zeta potential and applied alternating electric field potential, and in a certain range, the micromixing efficiency increases first and then decreases with the increase of alternating electric field frequency.

1. Introduction

In recent years, microfluidic devices have been widely used in the fields of biological detection, biotechnology, chemical reactors, medicine, and environmental monitoring. To facilitate chemical and biological reactions, it is often necessary to mix and pump various reagents and chemicals. Due to the small feature size of the microdevice and the low Reynolds number of the fluid, it is usually impossible to enhance the turbulence of the mixture [1]. The main ways of liquid mixing in microfluidic devices are molecular diffusion and convection diffusion. The mixing efficiency is very low and it is difficult to reach the level required for actual testing and production.

Electro-osmotic flow micro-mixers driven by electric fields can generate osmotic flow in micro-channels, drive fluids into chaotic flow states, distort the flow lines of laminar flow fields, and generate vortex flow fields in micro-channels. Thus, the contact area between fluids is increased to the greatest extent, and the mixing efficiency is improved. Because of its simple structure, convenient operation, and high mixing efficiency, it has become the most widely studied and applied technology in microfluidics and chip analysis systems [2-3].
Scholars at home and abroad have done a lot of research in the fields of electroosmosis and microfluidic mixers. Zhang et al. controlled the solution flow rate in the microchannel by inducing electroosmosis in the microchannel to generate a vortex flow field in the fluid, and designed an active micromixer that can significantly improve the micromixing efficiency [4]. E. Zholkovskij et al. analyzed the phenomenon of electroosmotic flow of power-law fluid in a slit microchannel [5]. Morteza Nazari et al. investigated the effect of the flexibility of conductive plates on the efficiency of an inductive charge electric micromixer under an isochronous time-varying electric field[6].Mahdi Sheikhzad Saravani and Mohammad Kalteh investigated the effects of surface heterogeneous potential and slip boundary conditions by studying the heat transfer of nanofluids flowing in microchannels[7].

2. Problem formulation

2.1. Micromixer model

Suppose that two fluids enter a 10 μm wide channel from different inlets, and then the liquid enters an annular mixing chamber. Four microelectrodes were placed on the outer wall of the mixing chamber at 45 °, 135 °, -45 °, and -135 ° angles, respectively. Assuming the aspect ratio (channel depth and width) is large enough, the mixer can be modeled using 2D section geometry. Figure 1 is a schematic diagram of a micromixer.

In the upper half of the inlet, the concentration of the solute is a given c₀; the lower half is zero. Therefore, suppose that in the middle of the inlet boundary, the concentration suddenly changes from 0 to c₀, and the mixed solution flows out of the outlet through convection. There is no chemical reaction between the two fluids in the mixer.

The zeta potential (ζ) is evenly distributed on the upper and lower walls of the microchannel. The four electrodes are symmetrically distributed on the annular mixing chamber. Their potentials are sinusoidal in time, have the same amplitude (V₀), and the same frequency (f), but they are alternating in polarity.

![Figure 1. Schematic of the micromixer](image)

In the study of electroosmotic micromixing, there are many influencing factors and the actual situation is complicated [8]. In order to simplify the calculation, the following basic assumptions are set based on the Poisson-Boltzmann model in this study:

1. The dielectric constant of the solution is not affected by external conditions, and it is set to a constant.
2. NaCl solution is selected as the electrolyte solution. Its positive and negative ions are balanced and equal, and there is no concentration gradient.
3. The fluid in the microchannel is a viscous incompressible Newtonian fluid, and the liquid density and dynamic viscosity are constant.
4. The fluid flow in the microchannel is a fully developed steady state flow, and the effects of temperature and gravity fields in electroosmotic flow are not considered.
5. The wall surface of the microchannel is insulated and symmetrical, and there is no wall slip.
2.2. Parameter setting
Set the physical properties of the mixed fluid to be the same as water, with a temperature of 20 °C and a pressure of 1 atm; the density of the fluid is 1000 kg/m³, the dynamic viscosity is 10^{-3} Pa·s, and the conductivity is 0.11845 S/m, The relative dielectric constant is 80.2. The diffusion coefficient is 10^{-11} m²/s. See Table 1 for specific setting parameters.

Table 1. Numerical Simulation of parameter values.

| Parameter                              | Symbol | Value | Unit |
|----------------------------------------|--------|-------|------|
| Import average speed                   | $U_0$  | 0.1   | mm/s |
| Import concentration                   | $c_0$  | 1     | mol/m³ |
| Fluid temperature                      | $T$    | 293.15| K    |
| Fluid pressure                         | $P$    | 1     | atm  |
| Zeta potential                         | $\zeta$| -0.1  | V    |
| Alternating electric field amplitude   | $V_0$  | 0.1   | V    |
| Alternating electric field frequency   | $f$    | 8     | Hz   |

2.3. Governing equations

2.3.1. Governing equation of flow field. Because the electrolyte solution is set as a viscous incompressible fluid, and the flow is laminar, the Navier-Stokes equation can be used to describe the flow in the microchannel [9]:

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F}
\]

(1)

\[
\nabla \mathbf{u} = 0
\]

(2)

In the formula, $\rho$ is the density of the electrolyte solution; $\mathbf{u}$ is the fluid velocity vector; $t$ is the time; $p$ is the fluid pressure; $\mu$ is the hydrodynamic viscosity coefficient; $\mu \nabla^2 \mathbf{u}$ is the viscous force to which the fluid is subjected; $\mathbf{F}$ is the applied bulk force. In the electroosmotic microfluidic flow, gravity, buoyancy, etc. have little effect on the microfluidic flow and can be ignored. In the electroosmotic flow model, only the external electric field force is considered, so $\mathbf{F}$ is expressed in unit volume. The electric field force experienced.

In the electroosmotic flow, an external electric field interacts with the electric double layer to generate an electric volume force. This electric field force drives the ions in the diffusion layer to migrate and move, and under the action of the viscous force of the microfluid, it drives its surroundings. Directional motion of the fluids. The volumetric force per unit charge is:

\[
F_e = \rho_e E
\]

(3)

2.3.2. Governing equation of electric field. The potential distribution in the electric double layer is controlled by the Poisson equation [10], which is expressed as:

\[
\nabla^2 \Psi = -\frac{\rho_e}{\varepsilon}
\]

(4)

In the formula, $\Psi$ represents the electric double layer potential; $\rho_e$ represents the net charge density; $\varepsilon$ represents the dielectric constant of the electrolyte solution, and its value is the product of the vacuum dielectric constant $\varepsilon_0$ and the relative dielectric constant $\varepsilon_r$ of the solution.
Since the influence of the temperature field is not considered and $\sigma$ is regarded as a constant, the applied electric field can be described by the Laplace equation:

$$\nabla^2 \varphi = 0$$  \hspace{1cm} (5)

The expression of the intensity vector of the applied electric field is:

$$\mathbf{E} = -\nabla \varphi$$  \hspace{1cm} (6)

2.3.3. Governing equation of concentration field. Inside the micromixer, the convection-diffusion equation can be used to describe the concentration of dissolved substances in the fluid, and its concentration transport equation is:

$$\frac{\partial c}{\partial t} + \mathbf{\nabla} \cdot (\mathbf{D} \nabla c) = \mathbf{R} - \mathbf{u} \cdot \nabla c$$  \hspace{1cm} (7)

In the formula, $c$ represents the concentration of dissolved substances; $\mathbf{D}$ represents the diffusion coefficient; $\mathbf{R}$ represents the reaction rate. Since no reaction occurs, $\mathbf{R} = 0$ in this model; $\mathbf{u}$ represents the flow field velocity.

2.3.4. Fluid constitutive equation. When a fluid is subjected to an external force, normal and shear stresses are applied to the fluid microelements, resulting in normal and shear strains in the corresponding directions. For the incompressible Newtonian fluid studied in this model, the relationship between the shear stress $\tau$ between the fluids and the shear strain rate $\gamma$ and the velocity gradient of the flow field in the direction perpendicular to the shear force is:

$$\tau = \mu \frac{\partial u}{\partial x} = \mu \gamma$$  \hspace{1cm} (8)

In the formula, the shear stress $\tau$ is proportional to the shear strain rate $\gamma$, $\mu$ is a proportionality factor, and $\mu$ is the dynamic viscosity coefficient of the fluid.

2.4. Boundary conditions

2.4.1. Laminar flow field boundary condition. At the inlet, it is assumed that the inlet channel starts from a position where the solution already has a fully developed laminar flow. The solution at the entrance boundary had a fully developed flow and the average speed was 0.1 m / s. At the outlet, the mixed fluid flows freely at the right end boundary, the pressure at the outlet boundary is 0, and the backflow is set to be suppressed.

For other walls, the slip velocity of electroosmotic flow can be obtained through Helmholtz-Smoluchowski relationship:

$$u_{\text{EOF}} = \frac{\varepsilon_r \varepsilon_0 \zeta E}{\mu}$$  \hspace{1cm} (9)

In the formula, $u_{\text{EOF}}$ represents the slip velocity of the electroosmotic flow; $\varepsilon_r$ represents the relative dielectric constant of the solution; $\varepsilon_0$ represents the vacuum dielectric constant; $\zeta$ represents the zeta potential; $E$ represents the applied electric field strength; $\mu$ represents the viscosity of the fluid.

2.4.2. Electric field boundary condition. In the model, except for the electrodes, other boundaries are electrically insulated, and the boundary conditions of the electrical insulation determine that the component of the electric field in the normal direction is zero:
\[ -\sigma \nabla E \cdot \mathbf{n} = 0 \]  \hspace{1cm} (10)

At the same time, an alternating electric field was applied at the electrodes, and they were symmetrically distributed with the same potential and frequency but the opposite polarity. The potentials of electrodes 1 and 3 are \( V_0 \sin (2\pi ft) \); the potentials of electrodes 2 and 4 are \( -V_0 \sin (2\pi ft) \).

2.4.3. Concentration field boundary condition. For dilute mass transfer, the transfer mechanism is convection diffusion, and electric field migration is not considered; all boundaries are adiabatic.

A sample solution with a concentration of 1mol/L flows into the upper part of the inlet, and a dilution solution with a concentration of 0 flows into the lower part of the inlet. The diffusion coefficient is \( 10^{-11} \text{m}^2/\text{s} \), and the fluid enters at a speed of 0.1m/s. The boundary condition is that the concentration of reagent in the upper part of the sample at the inlet channel is 1 mol/L, and the concentration of the lower half is zero; the mixed liquid flows out at the outlet.

2.5. Numerical methods

The multiphysics coupling function in COMSOL software is suitable for handling many microscale effects in microfluidic devices. For the study of electroosmotic flow, the microfluidic module also provides a special boundary condition of electroosmotic flow velocity. As a fluid wall condition, it can greatly facilitate researchers. At the same time, a special physical interface for simulating the transfer of dilute substances is also provided in the microfluidic template, which can simulate the mass transfer process of the mixture through diffusion, convection and electric field migration. It is suitable for simulating the performance of the micromixer. Demonstrate fluid flow characteristics in a micromixer. Discrete meshing of the ring-shaped micromixer model, using triangular meshes, and in order to improve the accuracy, the fluid dynamics template was used to perform ultra-fine meshing, with a maximum cell size of 0.39 \( \mu \text{m} \); The mesh refinement was achieved with a maximum cell size of 0.2 \( \mu \text{m} \). Finally, 22924 domain units were obtained, including 624 edge units and 22 vertex units.

3. Results and discussion

3.1. Verification of the numerical model

After completing the modeling process, we can use the calculation software that comes with COMSOL Multiphysics software to complete the simulation. By using the solver to calculate the concentration, pressure, velocity field, and potential in the model using ordinary differential equations, the simulation results of fluid flow in the micromixer under steady state and transient conditions can be obtained.

At \( t = 0 \), the applied electric field potential is zero, that is, no electric field is applied. At this time, the fluid in the micromixer is a fully developed laminar flow, and the diffusion mode is only molecular diffusion. Because the fluid is laminar, and the diffusion coefficient is small, the two fluids are not well mixed at the outlet, and the mixing efficiency is very low. Figure 2 shows the steady-state concentration when no electric field is applied.
Figure 2. Steady-state concentration when no electric field is applied.

In order to ensure the accuracy of our numerical model, the numerical results of the unapplied electric field are compared with the existing literature studies, which basically agree \([15-20]\). This validates our numerical model, which will be used to describe the flow characteristics of microfluids in an electroosmotic flow mixer.

3.2. Flow characteristics in hybrid devices

Figure 3 shows the potential lines of an electroosmotic flow micromixer, where the contour lines represent the potential distribution when the device uses the maximum potential \((\pm V_0)\). Because the polarities of the adjacent electrodes are opposite, the fluid can have a stronger disturbance effect and form a vortex flow field.

Figure 3. Potential lines of an electroosmotic micromixer

Figure 4 shows the fluid flow lines in the electroosmotic flow micromixer at \(t = 0.0375s\). The figure shows a typical transient flow line mode. It can be found that after an alternating electric field is applied, the fluid forms a swirling vortex near the four electrodes in the micromixer. The basic process of effective mixing includes repeated stretching and folding of fluid elements and small-scale diffusion.
Due to the application of an AC electric field in the system, the resulting electroosmotic flow disturbed the laminar flow that was originally driven by pressure, causing the fluid starting from the mixer to move up and down, causing extensive folding and stretching of the streamlines, which greatly improved Micromixer mixing efficiency.

Figure 4. Fluid flow lines in an electroosmotic flow micromixer at $t = 0.0375s$

Figure 5 shows the calculation results of the flow field and the concentration field when the electric field and the electroosmotic velocity in the micromixer are at their maximum. Compared with figure 4 when no alternating electric field is applied, it can be clearly found that the mixing efficiency is significantly improved due to the disturbance of the alternating vortex in the flow after the alternating electric field is applied.

Figure 5. Micromixer concentration field

3.2.1. Effect of alternating electric field strength on the mixing efficiency of the micromixer. Based on the numerical model of the electroosmotic flow micromixer that has been established in Section 2 and re-setting the applied potential to 0.15V and 0.3V without changing other parameter values, two sets of simulations were performed. The results are shown in Figures 6 and 7.
Figure 6. Concentration field with electric field potential of 0.15v

Figure 7. Concentration field with an electric field potential of 0.3V

It can be found from Figures 6 and 7 that with the increase of the applied electric field potential, the mixing efficiency of the micro-mixer also improves significantly. The effect of increasing the applied electric field potential on the micromixer is similar to increasing the zeta potential. It can be known from equation (12) that the applied electric field electroosmosis is also an important factor affecting the slip velocity of the electroosmosis. The electric field potential increases. At the same time, in the electric field governing equation, the applied electric field potential is also an important parameter. According to the equation Nernst-Planck equation, it can be found that the applied electric field also controls the electric migration of ions by the electric field force. However, electric field migration is not considered in the transfer mechanism of this model.

3.2.2. Effect of alternating electric field frequency on the mixing efficiency of the micromixer. Based on the numerical model of the electroosmotic flow micromixer already established in Section 2, the external electric field frequency was re-set to 12Hz, 16Hz, 20Hz, and 24Hz without changing other parameter values. Four sets of simulations were performed. The results are shown in Figure 8. It can be found from Figure 8 that with the gradual increase of the frequency of the electric field, the mixing efficiency of the micromixer increases first and then decreases. When the frequency is 16Hz, the mixing efficiency of the micromixer reaches a larger value. When the frequency reaches 24Hz, the mixing efficiency of the micromixer has become very low.
Figure 8. Simulation results at different applied electric field frequencies
By analyzing the governing equation of the micromixer, it can be found that the frequency does not directly control the size of the electroosmotic flow on a large time scale. However, since the frequency of the external alternating electric field can be controlled by the periodic change of the electric field, the fluid will be disturbed, and the streamline will be stretched and folded, so it has the effect of strengthening the mixing. On a small time scale, the frequency of the applied alternating electric field will control the magnitude of the electric field potential in the tangential direction, so that the size of the electroosmotic velocity will change periodically.

When the applied electric field frequency is in a lower range, by increasing the electric field frequency, the frequency of changing the flow direction of the electroosmotic flow can be accelerated, thereby enhancing the disturbance effect of the electroosmotic flow on the fluid, thereby increasing the mixing efficiency of the micromixer.

However, when the frequency of the applied electric field is already at a higher level, increasing the frequency of the electric field will decrease the mixing efficiency. This is because when the frequency of the electric field is too high, since the duration of each cycle is too short, the electroosmotic flow only affects the fluid in the immediate vicinity within a short period of time, and the effect has not spread to further distances. The fluid cannot be disturbed. In this case, the disturbance effect of the electroosmotic flow on the entire fluid is reduced, and the mixing efficiency is reduced.

Further analyzing the relationship between the frequency of the electric field and the mixing efficiency of the micromixer, it was found that the larger the viscous force of the fluid, the smaller the size of the microchannel, and the larger the frequency value at which this mixing efficiency is at its maximum. In this model, when the frequency of the applied electric field is near 16 Hz, the mixing efficiency of the micro-mixer can reach a maximum value.

4. Conclusion

In this paper, a two-dimensional numerical model of an electroosmotic flow micromixer coupled with a flow field, an electric field, and a concentration field is established by using the microfluidic module design of COMSOL Multiphysics software. The conclusions obtained are summarized as follows:

(1) By analyzing the governing equations of the numerical model and the results of simulation, this paper obtains a way to increase the mixing efficiency in an electroosmotic micromixer: by applying an external alternating electric field, a periodically varying electric current is generated in the mixing chamber. Under the action of viscous force, it drives the surrounding fluids to move together, thereby increasing the mixing efficiency of micro-mixing. A larger external electric field potential can significantly improve the mixing efficiency of the electroosmotic micromixer.

(2) By changing the external electric field potential and frequency in the model, the analysis shows that the increase of the external electric field potential will increase the mixing efficiency of the micromixer. As the frequency of the applied electric field increases, the mixing efficiency of the micromixer will first increase and then decrease. Therefore, an appropriate electric field frequency can effectively improve the mixing efficiency of the electroosmotic micromixer.

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