Numerical Study on the Mixing Performance of Ring-Type Electroosmotic Micromixer with Configurations of Obstacle in the Mixing Chamber

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ABSTRACT

In order to achieve fast mixing in the micromixer, a new type of electrokinetic mixer with a ring-type channel is introduced. The proposed mixer takes two fluids from different inlets and combines them into a ring-type mixing chamber. The fluids enter a two different inlets (25 μm, respectively) and outer radii (inner radius: 25 μm and outer radius: 50 μm, respectively). The total channel length is 500 μm, and four microelectrodes are positioned on the outer wall of the mixing chamber. The electric potentials on the four microelectrodes are sinusoidal in time with various maximum voltage, zeta potential and frequency values. Also, in order to compared with mixing performances as configurations of obstacle in the chamber, we performed several obstacle modeling and numerical analysis using commercial code, COMSOL. The concentration, flow and electric fields in the channel were calculated and the results were graphically depicted for various flow and electric conditions.

Keywords: Micromixer, Mixing performance, Zeta potential, Concentration.

1 INTRODUCTION

Due to the vast application field of micromixers and micro structured mixers, such as homogenisation, chemical reaction, dispersion and emulsification, the efficiency of mixing in these devices is very important for the overall process performance. Indeed, mixing will affect various process parameters including heat and mass transfer rates, process operating time, cost and safety, as well as procudt quality. For this reason, it is important to understand the mixing process ocuurring in micromixer.

Rapid and efficient mixing is important for many microfluidic applications but challenging process in many microfluidic systems that perform complex chemical synthesis and analysis. Most existing microfluidic mixing systems are limited to low Reynolds number regimes. According to scaling law, decreasing the mixing path can shorten the mixing time and enhance mixing quality. For this reason, it is important to understand the mixing process in micromixers. To do this, one must to be able to characterize and evaluate the mixing performance and the outcomes of the mixing process [1].

Micromixers can be classified into two types: passive and active [2-5]. The operation principles of the passive-type mixers are mainly based on fluid stretch, folding, breakup, and molecular diffusion. Some passive micromixers reduce the diffusion path between fluid streams by splitting and then recombining them.

Because of methods that can easily integrate electrodes into microfluidic and nanofluidic devices, electro-kinetically-driven mixing devices are under extensive investigation for use as active micro-mixers [6]. Electro-osmosis to generate electrical potential gradients has been proposed as a propulsion mechanism for bio-fluids. It would eliminate the need for a moving apparatus [7]. This technology has led to the need for an efficient fluid control mechanism for micro-fabricated systems that perform complex chemical synthesis operations. For example, localized flow circulations within the bulk flow near regions of the microchannel wall with oppositely-charged surface heterogeneities were investigated and these circulations were successfully applied to enhance species mixing in T-shaped micro-mixer [8]. The results indicated that these heterogeneous regions reduce the required length of the mixing channel by 70%.

The mixing phenomena is modeled by simulation methods (e.g. computational fluid dynamics, lattice-Boltzmann method) to obtain local three-dimensional flow information, which may be difficult or even impossible to access with experimental techniques. As a result, there are a large number of computational studies on the mixing in single phase flow micro devices, and on the increasing number of applications of such mixing and devices to gas-liquid and liquid-liquid dispersions [9].

In this study, the mixing performance of a righ-type electro-osmotic micromixer was numerically investigated. Also, in order to confirm the mixing performance with the change of obstacle configurations in the mixing chamber, we performed to numerical analysis using the commercial code, COMSOL. Especially, the concentrations of the fluids were considered for each condition for various values of voltage and frequency at the electrode and zeta potential.

2 NUMERICAL DETAILS

We used numerical methods to obtain a better understanding of the complex flow-phenomena in the electro-osmotic mixer. Three-dimensional Navier-Stokes equations governing the fluid behaviors were employed in this study to simulate two aqueous fluids mixing in the designed micromixer. The simulation is conducted at unsteady-state conditions. Most solid surfaces acquire a surface charge when brought into contact with an electrolyte. In response to the spontaneously formed surface charge, a charged solution forms close to the liquid-solid interface. The electric field generating the electro-osmotic flow displaces the charged liquid in the electric double layer. In this study, we used the Helmholtz-Smoluchowski relation between the electro-osmotic velocity and applied electric field instead of the thin electric double layer. The equation systems used in the above simulations are shown as follows:

$$\rho\left[\frac{\partial V}{\partial t}+(V\cdot\nabla)V\right]=-\nabla p+\mu\nabla^{2}V+\rho_{e}E \tag{1}$$

where ρ is the fluid density, V is the fluid velocity, p is the static pressure, μ is the molecular viscosity, ρ_e is charge density and E is the intensity of electric field. Also, the Helmholtz-Smoluchowski equation can be written as:

$$U_{slip}=-\frac{\varepsilon\zeta E_{x}}{\mu} \tag{2}$$

where is ε the permittivity and ζ is the zeta potential. In order to determine the mixing performance, we analyzed the concentration fields of the flow using the following equation:

$$\frac{\partial c}{\partial t}+\nabla\cdot(-D\nabla c)=A-u\cdot\nabla c \tag{3}$$

where c is the concentration, u is the velocity, D is the diffusion coefficient, and A is the reaction ratio. However, $A=0$ in this study because there was no chemical reaction.

Assuming that there are no concentration gradients in the ions that carry the current, we can express the current balance in the channel through Ohm's law and the balance equation for current density. In addition, we used a convection-diffusion equation to describe the concentrations of the dissolved substances in the fluid.

Figure 1 shows the geometry of an electro-osmotic mixer. The mixer takes two fluids from different inlets and combines them into a single channel that is 50 μm wide and each inlet size is 25 μm, respectively. The fluids then enter the central loop, where four microelectrodes are positioned along the outer wall of the loop. These microelectrodes impose a spatially-varying electric field and the fluids are manipulated via the electro-osmotic slip boundary condition before they enter the outlet channel. The electric potentials on the microelectrodes are time-dependent, and this adds chaotic mixing in the mixing chamber. In this study, we performed a two dimensional numerical analysis using the commercial code, COMSOL.

Table 1: Boundary Conditions applied to this study

Model	Inlet velocity [μm/s]	Voltage(V_0) [V]	Zeta potential(ζ) [V]	Frequecy [Hz]
Circle	200	1, 2	-0.1	4, 8
Square		1, 2	-0.1	4, 8

The electric potentials on the four microelectrodes produced a sinusoidal curve with respect to time for the maximum voltage of 2 V and frequency of 8 Hz. Details of boundary condition applied to this study are shown as Table 1. The potentials of electrodes 1 and 3 were denoted as $V_0\sin(2\pi ft)$ and the potentials of electrodes 2 and 4 were $-V_0\sin(2\pi ft)$. The working fluid was an electrolyte that possessed the same properties as water, i.e., it had a relative permittivity of $\varepsilon=78.3$, a conductivity of an ionic solution of $\sigma=0.11845$ S/m and a diffusion coefficient of $D=10^{-11}$ m^2/s. We assumed a zeta-potential of -0.1 V. The inlet velocity produced parabolic graph with a mean value of 200 μm/s ($Pe=7\times10^{-2}$, $Re=1\times10^{-2}$), and the inlet$_{upper}$ and inlet$_{lower}$ concentration values were 1 and 0 mol, respectively. We neglected the slip velocity along the wall of the inlet and outlet, where no-slip boundary conditions were applied, because the electric field density, which decomposes exponentially from the microelectrodes, is proportional to the slip velocity. The time scale of the transient effect in the micromixer was set to 0.125/60 s and total calculation time was 3 s.

In order to analyze the flow characteristics inside the micromixer with change of obstacle configurations in the mixing channel, two-dimensional unstructured grids containing approximately 17,800 elements were generated using COMSOL preprocessor, as shown in Fig. 2. A fine grid system was used due to the simultaneous effects of electro-osmotic flow and convection-diffusion within the mixing chamber.

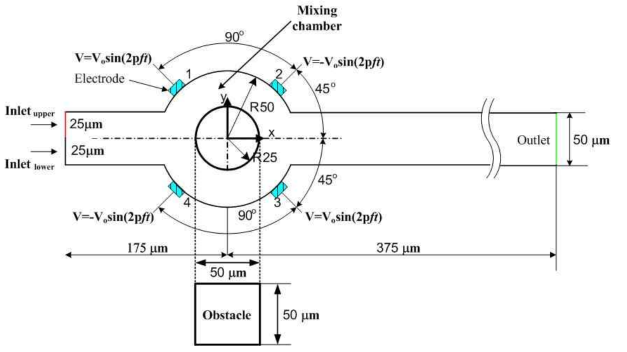
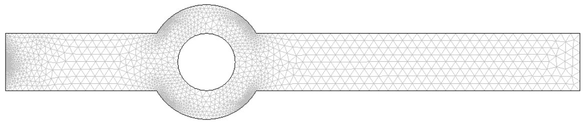
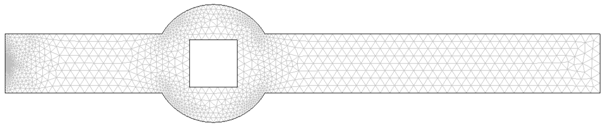


Figure 1: Schematic of the modeled electro-osmotic micromixer in this study.



(a) Circle model

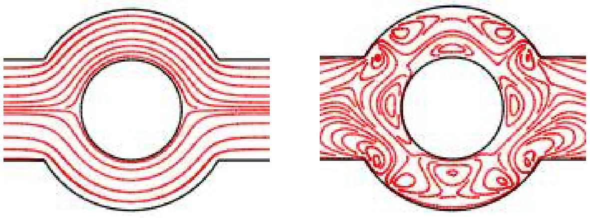


(b) Square model

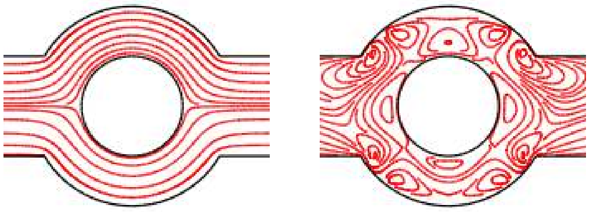
Figure 2: Grid systems.

3 RESULTS AND DISCUSSION

Effective mixing implied repeated stretching and folding of fluids in combination with diffusion at a small scale. As shown in Figs. 3~4, it is shown that the distribution of streamlines with configuration of obstacle in the mixing chamber for for V_0= 0.1 V, *f*= 4 Hz, ζ= -0.1 V and the transient behaviors are plotted for one cycle of sine curve. In both cases are shown up similar flow patterns, and note that fluids are moved into the mixing chamber by the electric fields produced by each electrode. Also, these fluids are performed to vorticity around the electrode. The fluid particles stayed in the central loop to show stretching and folding for a long time before they entered the outlet channel. This fact indicates a chaotic advection, which expedites the final part of mixing through molecular diffusion.

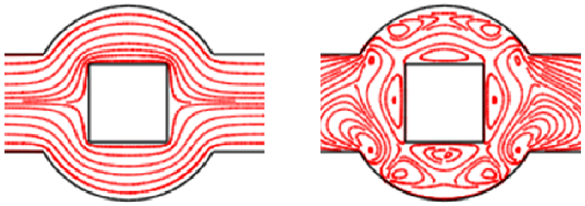


(a) 0 s (b) 0.0625 s

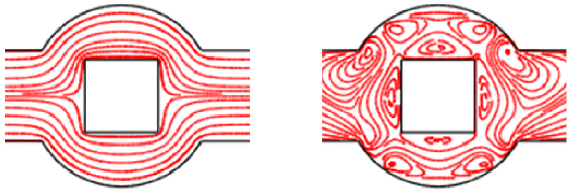


(c) 0.125 s (d) 0.1875 s

Figure 3: Streamlines at circle configuration obstacle in the mixing chamber with one cycle of sine curve for V_0=0.1 V, *f*=4 Hz and ζ=-0.1 V.



(a) 0 s (b) 0.0625 s

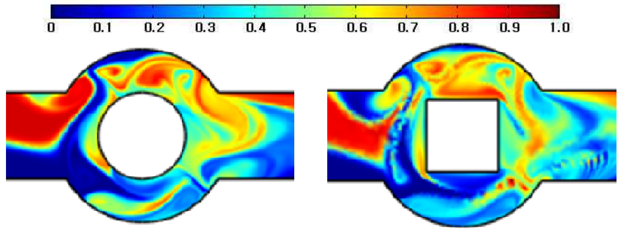


(c) 0.125 s (d) 0.1875 s

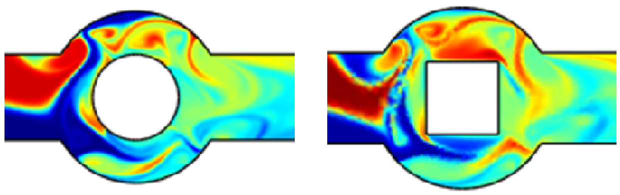
Figure 4: Streamlines at square configuration obstacle in the mixing chamber with one cycle of sine curve for V_0=0.1 V, *f*=4 Hz and ζ=-0.1 V.

Figure 5 shows to compare with the pattern of the concentration of the interfluent stream in the mixing chamber in both cases and channel for various calculation times. In process of calculation time, it is confirmed that the perturbed concentration is going along continuous in the mixing chamber. Also, the mixing performance in the mixing chamber increases by the side of inlet region because of the stretching and folding behaviors by electric field in the mixing chamber. But, from the viewpoint of fluid flow, the circle configuration of obstacle in the mixing chamber is shown more smooth stream than the square's it. This is judged because the case of fluid flow for square obstacle in the mixing chamber is affected by flow resistance with the wall of square.

In order to evaluate the mixing performance of the modeled micromixer with the change of obstacle configuration in the mixing chamber, we extracted



(a) 0.5 s at circle (b) 0.5 s at square



(c) 2.5 s at circle (d) 2.5 s at square

Figure 5: Distributions of concentration in the modeled micromixer with obstacle confirgurations for V_0=0.1 V, *f*=4 Hz and ζ=-0.1 V.

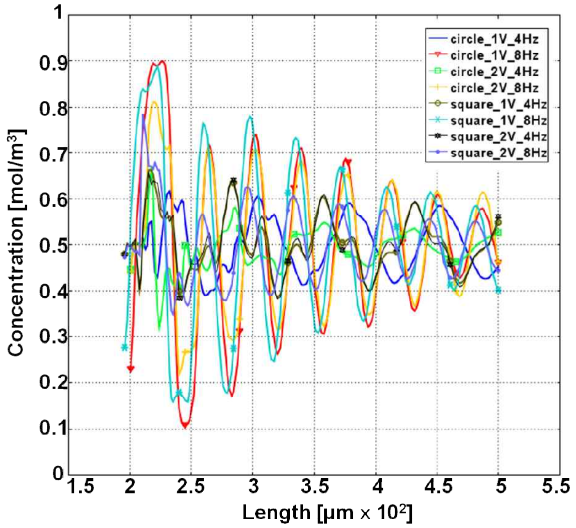


Figure 6: Concentration distributions with obstacle configurations for various values of voltages and frequencies at t=2.5 s

concentration data from the centerline of the modeled micromixer and these results are shown in Fig. 6.

After the mixing chamber, the concentration efficiency reaches over 90% in all cases, which means each fluid was sufficiently mixed and was moved toward the exit of the micromixer. In particular, the oscillation is shown to increase with the increase of frequency, which means it interrupts with stabilization of the mixing. At the same value of zeta potential, the concentration distribution is the most stable in the case of 4 Hz, which means that the fluids were well mixed at proper frequency rather than at high frequency values. Also, the concentration value in the case of applied voltage of 2V was stable more than that of the case of 1V as the flow moved toward the exit. But in case of compared with the change of obstacle configurations in the mixing chamber, there is little difference mixing efficiency.

4 CONCLUSIONS

The electroosmotic actuated active mixer was designed and investigated numerically with obstacle configurations in the mixing chamber. Of particular concern was the concentrations of fluids calculated in each condition for various voltages, frequencies at the electrodes and zeta-potentials. The following conclusions were obtained:

(1) Chaotic behavior was confirmed by the observation of the stretching and folding of material lines owing to the applied electric fields in the mixing chamber.

(2) In evaluation of the concentration value according to the various values of frequencies, the mixing behaviors were actively generated in case of 4Hz.

(3) From the viewpoint of fluid flow, the circle obstacle configuration is shown more smooth pattern than square's it, but there is little difference mixing efficiency with the change of obstacle configurations in the mixing chamber.

5 ACKNOWLEDGEMENT

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