Electroosmosis – a Mechanism of Micromixer and Micropump


### Abstract

Electroosmotic flow in microchannels is restricted to low Reynolds number regimes characterized by extremely weak inertia forces and laminar flow. Consequently, the mixing of different species occurs primarily through diffusion, and hence cannot readily be achieved within a short mixing channel. The current study presents a numerical investigation of electrokinetically driven flow mixing in microchannels with various numbers of incorporated patterned rectangular blocks. Furthermore, a novel approach is introduced which patterns heterogeneous surfaces on the upper faces of these rectangular blocks in order to enhance species mixing. The simulation results confirm that the introduction of rectangular blocks within the mixing channel slightly enhances species mixing by constricting the bulk flow, hence creating a stronger diffusion effect. However, it is noted that a large number of blocks and hence a long mixing channel are required if a complete mixing of the species is to be obtained. The results also indicate that patterning heterogeneous upper surfaces on the rectangular blocks is an effective means of enhancing the species mixing. It is shown that increasing the magnitude of the heterogeneous surface zeta potential enables a reduction in the mixing channel length and an improved degree of mixing efficiency.

### Introduction

The past few years have witnessed a rapid increase in the application of microfluidic devices to chemical and biological analyses. These devices offer significant advantages over their traditional counterparts, including a reduced reagent consumption, a more rapid analysis and a significant improvement in
performance. Species mixing is a fundamentally important aspect of these devices since it is this mixing which generates the biochemical reactions necessary for their successful operation. Obtaining a complete species mixing in either pressure- or electrokinetically driven flow microfluidic devices is difficult because the operation of these devices is limited to low Reynolds number regimes characterized by laminar flow. Therefore, species mixing is diffusion dominated and requires both a long mixing channel and an extended retention time to attain a homogeneous solution.

Accordingly, many researchers have developed a number of enhanced microfluidic mixing devices. These can broadly be classified as either passive or active mixers. Passive mixers typically use particular channel geometry configurations to increase the interfacial area between the liquids to be mixed. Liu et al [1] proposed a 3D serpentine channel which achieved mixing through chaotic advection, a mechanism which becomes more effective as the Reynolds number increases to 70. However, practical application of this device is constrained by the challenges associated with the micro-fabrication of the complex 3D structure and the need for a high Reynolds number to stir the fluids sufficiently to generate chaotic advection. Stroock et al [2, 3] presented a passive method for mixing streams of steady pressure-driven flow in microchannels with patterned grooves. This method created spiral circulations around the flow axis at low Reynolds numbers, and stretched and folded the streams in order to achieve a complete mixing within a short channel length.

The present study adopts a numerical simulation approach investigate the mixing characteristics of 2D steady troosmotic flows in microchannels. The species mixing efficiency is enhanced by means of rectangular blocks located within the microchannel. Furthermore this study develops a novel approach in which heterogeneous surfaces are patterned on the upper faces of the rectangular blocks in order to further improve species mixing. The influence of various heterogeneous surface zeta potentials on the species mixing efficiency is thoroughly investigated and some brief conclusions are then presented.

Simulation
Adopting a continuum assumption, electroosmotic flow can be modeled by the Navier–Stokes equations modified to include the body force term generated by the interaction between the excess ions of the electrical double layer and the external electric field. The governing equations of the electroosmotic flow are the continuity and momentum equations, which are given respectively, by

\[ \nabla \cdot \vec{V} = 0 \]  
\[ \rho_f \left[ \frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} \right] = -\nabla p + \mu \nabla^2 \vec{V} + \rho_e \vec{E} \]

\[ \vec{E} = -\nabla \Psi \]

\[ \nabla^2 \Psi = -\frac{\rho_e}{\varepsilon \varepsilon_0} \]
Inflow:

\[
\begin{align*}
\frac{\partial \psi^*}{\partial x^*} &= 0, & \phi^* &= \phi_{in}^*, & \frac{\partial u^*}{\partial x^*} &= 0, \\
\frac{\partial v^*}{\partial x^*} &= 0, & p^* &= 0, & C^* &= C_{in}^*
\end{align*}
\]

Outflow:

\[
\begin{align*}
\frac{\partial \psi^*}{\partial x^*} &= 0, & \phi^* &= \phi_{out}^*, & \frac{\partial u^*}{\partial x^*} &= 0, \\
\frac{\partial v^*}{\partial x^*} &= 0, & \frac{\partial p^*}{\partial x^*} &= 0, & \frac{\partial C^*}{\partial x^*} &= 0
\end{align*}
\]

Walls in the x-direction:

\[
\begin{align*}
\psi^* &= \zeta^*, & \frac{\partial \phi^*}{\partial y^*} &= 0, & u^* &= 0, & v^* &= 0, \\
\frac{\partial p^*}{\partial y^*} &= \frac{1}{\text{Re}} \frac{\partial^2 v^*}{\partial y^{*2}} + G_x \cdot \sinh(\psi^*) \left( \frac{\partial \psi^*}{\partial y^*} \right), \\
\frac{\partial C^*}{\partial y^*} &= 0
\end{align*}
\]

Walls in the y-direction:

\[
\begin{align*}
\psi^* &= \zeta^*, & \frac{\partial \phi^*}{\partial x^*} &= 0, & u^* &= 0, & v^* &= 0, \\
\frac{\partial p^*}{\partial x^*} &= \frac{1}{\text{Re}} \frac{\partial^2 u^*}{\partial x^{*2}} + G_x \cdot \sinh(\psi^*) \left( \frac{\partial \psi^*}{\partial x^*} \right), \\
\frac{\partial C^*}{\partial x^*} &= 0
\end{align*}
\]

Results
Figure 3. Numerical results of electroosmotic flow in a T-shaped microchannel: (a) flow streamlines, (b) distribution of species concentration and (c) species concentration profiles in the inlet and outlet regions.
Figure 4. Mixing channel with one rectangular block (30 μm high, 60 μm wide): (a) electric potential distribution of the externally applied electric field, (b) velocity vectors and (c) flow streamlines in the vicinity of the rectangular block.

Figure 5. Electric potential distribution of the externally applied electric field and flow streamlines for the mixing channel with: (a) two and (b) four rectangular blocks.
Figure 6. Species concentration distributions for the mixing channel with: (a) one rectangular block, (b) two rectangular blocks and (c) four rectangular blocks.

Figure 8. Enhancement of species mixing efficiency obtained by increasing the number of rectangular blocks in the mixing channel.
Figure 9. Comparison of species mixing efficiency at each cross section of a straight mixing channel with that of a mixing channel with 20 rectangular blocks. (Note that the mixing length $L_{mix} = 6000 \mu m$ in both cases.)

\[ \tau(x) = \left( 1 - \frac{\int_0^W |C - C_\infty| \, dy}{\int_0^W |C_0 - C_\infty| \, dy} \right) \times 100\% \]
Figure 10. Influence of patterned heterogeneous rectangular block upper surfaces upon flow streamlines in the mixing channel with: (a) one rectangular block, (b) two rectangular blocks and (c) four rectangular blocks. (Note that the heterogeneous surfaces have a zeta potential of $\zeta = +75$ mV in all cases.)
Figure 11. Influence of patterned heterogeneous rectangular block upper surfaces upon species concentration distributions in the mixing channel with: (a) one rectangular block, (b) two rectangular blocks and (c) four rectangular blocks. (Note that the heterogeneous surfaces have a zeta potential of $\zeta = +75 \text{ mV}$ in all cases.)

Figure 12. Species concentration profiles in the outlet region of mixing channels with one, two and four rectangular blocks. (Note that the heterogeneous surfaces have a zeta potential of $\zeta = +75 \text{ mV}$ in all cases.)
Figure 13. Flow streamlines and species concentration distributions of mixing channel with four rectangular blocks with heterogeneous surface zeta potentials of (a) $\zeta = 0$ mV, (b) $\zeta = +25$ mV and (c) $\zeta = +50$ mV.

Figure 14. Influence of the magnitude of heterogeneous surface zeta potential of rectangular blocks on the species concentration profile in the outlet region.

Conclusion
This study has presented a 2D numerical investigation of the mixing characteristics of low Reynolds number electroosmotic flows in microchannels. The effects of various design parameters on the effectiveness of the species mixing have been explored. In the straight mixing channel, species mixing is purely diffusive in nature and hence the mixing efficiency is poor and requires an extended channel length. Although the simulation results have indicated that the introduction of rectangular blocks within the mixing channel enhances the mixing efficiency slightly by forcing the bulk flow to pass through the restricted regions above the upper surfaces of the blocks, it is nevertheless necessary to employ an extended channel length if a significant species mixing enhancement is to be obtained. However, the simulation results have indicated that patterning the upper surfaces of the blocks so that they become heterogeneous surfaces is an effective means of improving the species mixing within a shorter mixing channel length. The results have indicated that the degree of improvement in the species mixing efficiency increases as the magnitude of the heterogeneous surface zeta potential is increased.

It is acknowledged that the fundamental mixing mechanisms of fluid stretching and fluid folding are missing in the 2D analysis presented in the current study. However, further investigation is now under way to study the influence of surface heterogeneity on the electrokinetically driven micro-mixing process through 3D numerical simulation. Subsequently, developing electrokinetically driven micro-mixers with heterogeneous surface zeta potentials will be a challenging yet worthwhile future research topic.