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Mixing enhancement of low-Reynolds electro-osmotic flows in microchannels with temperature-patterned walls

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ABSTRACT

Mixing becomes challenging in microchannels because of the low Reynolds number. This study aims to present a mixing enhancement method for electro-osmotic flows in microchannels using vortices caused by temperature-patterned walls. Since the fluid is non-isothermal, the conventional form of Nernst–Planck equation is modified by adding a new migration term which is dependent on both temperature and internal electric potential gradient. This term results in the so-called thermo-electrochemical migration phenomenon. The coupled Navier–Stokes, Poisson, modified Nernst–Planck, energy and advection–diffusion equations are iteratively solved by multiple lattice Boltzmann methods to obtain the velocity, internal electric potential, ion distribution, temperature and species concentration fields, respectively. To enhance the mixing, three schemes of temperature-patterned walls have been considered with symmetrical or asymmetrical arrangements of blocks with surface charge and temperature. Modeling results show that the asymmetric arrangement scheme is the most efficient scheme and enhances the mixing of species by 39% when the Reynolds number is on the order of 10^{-3}. Current results may help improve the design of micro-mixers at low Reynolds number.

1. Introduction

In the recent decades, the rapid advancement of MEMS has made it possible to integrate the multi-functional micro devices on a chip (Lab-On-a-Chip) for biological and biochemical uses. One of the most common elements used as a main part of MEMS devices is micro-mixer. Appropriate and controllable mixing of species in these devices is of great importance for scientific research and applications. At small scale, the flows mostly remain in laminar regime through micro-channels, which makes diffusion as the main mechanism of mixing. As a result, one may have to design long enough microchannels for appropriate mixing of species. Therefore, control of mixing and mixing enhancement in microchannels has been of great interest in recent years [1].

Various designs and studies are conducted to increase convection in mixing enhancement. Passive micro-mixers are designed with specific geometry features in order to increase the chaotic flow regime. Previous studies and schemes include three dimensional serpentine mixers [2–4], zigzag or waveform mixers [5], staggered herringbone mixers [6], micro-mixers with patterned blocks [7], parallel lamination of micro-mixers with the basic of T-mixer or Y-mixer [8]. However, difficulty in manufacturing microchannels with designed specific geometric features poses limitation on the use of passive schemes. On the other hand, micro-mixers based on active mixing enhancement methods are designed in such a way that the external mechanical or electrical forces cause the chaotic flow pattern. In fact, these forces generate transverse flows through the microchannel. The external mechanical forces could be implemented, for instance, by pressure disturbance methods such as serial segmentation [9], pressure disturbance along the microchannel [10] and integrated micro-stirrer in the mixing channel [11]. For the electrical forces, they could be implemented by electro-hydrodynamic disturbance, dielectrophoretic disturbance and electrokinetic disturbance methods [12]. Several studies have been conducted to reveal the mechanism of these forces in the micro-mixers. These studies have shown that by specifying the operating conditions, the active mixing strategies yield an efficient species mixing as a result of the repeated stretching and folding of the sample streams at the interface between them [1,13].

In recent years, the electrokinetically driven flow techniques in MEMS devices enable us to manipulate the flow regimes and as a result, enhance the mixing of species sample. Wang et al. [14] showed that in an electrokinetically driven flow such as electro-osmotic flow, the mixing enhancement effect for the interlaced

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arrangement of zeta potential-patterned walls is higher than that for symmetrical arrangement. Tang et al. [15] and Coleman and Sinton [16] showed that through applying a periodically varying electric field to the side channels of a T-/cross-shaped micro-mixer, the species could be injected alternately into the main microchannel. The time-dependent external electric field and the effects of this scheme on the mixing enhancement have been the research subject of some literatures [17,18]. They have demonstrated that, for instance, with sinusoidally alternating external electric fields, the flow field could emerge as a wavy-flow pattern.

Electrokinetic flows have significant parameters such as temperature gradient which could be used as a key resource for active control of mixing in these type flows. Alizadeh et al. [19] showed that by applying a temperature difference between inlet flow and walls of a microchannel, one can control vortex scales formed in the flow field. It was shown that the temperature gradient changed the ion distribution. Consequently, the net electric charge density and as a result the electrical body force are redistributed in such a way according to the ion distribution [20].

As mentioned above, mixing enhancement of species in micro-mixers has emerged as one of the challenging subjects in MEMS. In the present study, the temperature field is used as an external-like source to change the ion distribution and electrical body force [19]. Compared with our previous work [19], this work will present a modified Nernst–Planck equation which could properly model the ions species electrodynamic transport in non-isothermal fluids. This modification allows us to investigate the impacts of temperature gradient in both transverse and longitudinal direction of micro-channel. The problem is formulated by solving the Poisson equation for internal electric potential field, modified Nernst–Planck equation for ion distribution, Navier–Stokes equation for flow field, advection–diffusion equation for species concentration and energy equation for temperature distribution. Since the governing equations are coupled together, they are solved by an iterative process. In this work, the coupled lattice Boltzmann methods are used to solve the governing equations numerically. The Navier–Stokes, Poisson–Nernst–Planck equations for ions species distribution and the advection–diffusion equation for species concentration are solved using the multiple lattice Boltzmann methods [21] and the energy equation is solved using a model for thermal evolution equation with generalized heat source term [22].

2. Problem definition

Fig. 1 shows three schematic designs of micro-mixers with patterned temperature and zeta potential walls. In Fig. 1, red, blue and red–blue blocks represent parts of the microchannel walls with different amounts of T and ψ. Micro-mixer schemes A and B consist of two types of blocks ($red\,block \equiv T = T_{wall}, \psi = \zeta_{wall}$; $blue\,block \equiv T = T_{in}, \psi = 0$) while micro-mixer scheme C, in addition to red and blue blocks, has a third type block, red–blue block ($red - blue\,block \equiv T = T_{in}, \psi = \zeta_{wall}$). Meanwhile, in micro-mixer schemes B and C, the red blocks are placed in a symmetric arrangement while in scheme A they are placed in an asymmetric arrangement. In order to study the distribution of ions species and electrical body force along the width of the micro-mixers, we defined two planes named plane A and B which are placed in $x/H = 2.0$ and $x/H = 2.2$, respectively (Fig. 1). The EOF studied in this paper is an electrolyte flow through a two dimensional microchannel with length L and width H. The inlet electrolyte is kept at constant temperature T_{in} while $T_{in} < T_{wall}$. The fluid motion is caused by both external electric field with strength E_x applied by use of an Anode and a Cathode placed at the two ends of the microchannel and pressure gradient. The ratio of length to width of this microchannel (L/H) is equal to 5 and the electrolyte considered here is symmetric and has a 1:1 ionic ratio ($|Z_+| = |Z_-| = Z = 1$). In this study, it is assumed that the microchannel is made of PDMS, and the electrolyte is a dilute solution of NaCl.

In order to characterize the relative size of the thickness of electric double layer (EDL), the dimensionless parameter κ is defined as $\kappa = KH = H/\lambda$ with H representing the channel width and λ the Debye length calculated by:

$$\lambda = K^{-1} = \sqrt{\frac{\varepsilon_0 \varepsilon_r K_B T_{wall}}{2Z^2 e^2 n_{i\infty}}} \tag{1}$$

where T_{wall}, as mentioned in Fig. 1, is the red block temperature used as the reference temperature. Here, by selecting the value of κ and H, the value of ion concentration, $n_{i\infty}$, is determined. Sometimes, instead of $n_{i\infty}$ the amount of molar concentration, c, is also determined. In such cases, the molar concentration in K mol/m^3 is calculated as $c = n_{i\infty}/(1000N_A)$, where N_A is the Avogadro constant. Other physical parameters such as μ, ε_r and k are only functions of temperature and assumed constant for a given temperature. The values of these quantities for $T = 19.85$ °C (=293 K) are presented in Table 1.

To study the effects of temperature gradients on the flow field and as a result mixing enhancement of species, we used two set amount of temperatures on the blocks as $T_{wall} = 87.5$ °C, $T_{in} = 12.5$ °C and $T_{wall} = 31.25$ °C, $T_{in} = 25$ °C. Moreover, the amount of zeta potential on the red and blue blocks was kept constant as $\zeta = -50$ mv and $\zeta = 0$ mv, respectively. Considering species concentration, it is assumed that at the inlet of micro-mixers we implemented species boundary condition as $y/H \geqslant 0.5 \rightarrow C_s = 1$ and $y/H < 0.5 \rightarrow C_s = 0$.

3. Mathematical models

3.1. Navier–Stokes equations

For a Newtonian fluid at microscale without any mass source and in laminar flow regime, the conventional continuity and Navier–Stokes equations are still valid as [23]:

$$\begin{aligned} &(a) \quad \tfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \\ &(b) \quad \tfrac{\partial (\rho \boldsymbol{u})}{\partial t} + \boldsymbol{u} \cdot \nabla (\rho \boldsymbol{u}) = -\nabla p + \nabla \cdot [\nu \nabla (\rho \boldsymbol{u})] + \boldsymbol{F} \end{aligned} \tag{2}$$

where ρ (kg/m^3) is the density of the electrolyte, $\boldsymbol{u}$ (m/s) is the flow velocity vector, t (s) time, p (Pa) fluid pressure, ν (m^2/s) the kinetic viscosity and $\boldsymbol{F}$ (N/m^3) is the body force density which may include all the implemented body forces such as electrical body force or pressure gradient. In cases that the fluid is incompressible, the pressure gradient could be included in $\boldsymbol{F}$. As a result, while in this study the pressure gradient is considered in some case of micro-mixer types, so one can define the body force as:

$$\boldsymbol{F} = \boldsymbol{F_e} + \boldsymbol{F_p} = -\rho_e(\nabla \varphi + \nabla \psi) + \nabla P \tag{3}$$

where $\nabla \varphi$ is the external electric potential field and in this study we have $-(\nabla \varphi)_x = E_x, (\nabla \varphi)_y = 0$, $\nabla \psi$ is the internal electric potential field which we ignored the impact of $(\nabla \psi)_y$ due to the low ion concentration dissolved in electrolyte [19].

Boundary conditions governing Navier–Stokes equations for three micro-mixer schemes are as follows:

$$\begin{aligned} &\textit{for red, blue and red} - \textit{blue blocks}: \\ &y = 0 \;\rightarrow\; u = v = 0, y = H \;\rightarrow\; u = v = 0 \\ &\textit{for inlet and outlet}: \\ &x = 0 \;\rightarrow\; \frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = 0, p = P_{atm} \\ &x = l \;\rightarrow\; \frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = 0, p = P_{atm} \end{aligned} \tag{4}$$