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Combined effects of streaming potential and wall slip on flow and heat transfer in microchannels☆

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ABSTRACT

In this study, the effects of wall slip and streaming potential on liquid flow and heat transfer in planar microchannels with imposed heat flux are numerically investigated. Electrical potential of the electrical double layer, liquid flow and thermal characteristics is determined using the Poisson-Boltzmann, the modified Navier–Stokes and the energy equations, respectively. The analytical solution for pressure-driven electrokinetic flows in microchannels is obtained without introducing the Debye–Huckel approximation. The results reveal that the streaming potential effect retards the liquid flow and leads to an increase in the temperature of electrolyte solution, thereby decreasing the heat transfer rate. On the contrary, the wall slip effect tends to increase the flow velocity and hence enhances the heat transfer. When the above two effects appear in microchannels simultaneously, the wall slip assists the streaming potential to retard the flow. Furthermore, they counteract each other when the zeta potential is large enough.

1. Introduction

Over the last decade, the rapid developments in microfabrication technologies have enabled many different types of microdevices, such as microfluidic chips, micropumps, microvalves, micromixer and microchannel heat sinks, which are widely used in many engineering fields [1]. Fundamental investigations of the fluid flow and heat transfer in microchannels have been conducted by many researchers. In 1981, Tuckerman and Pease [2] began their pioneering work on microscale flow and heat transfer phenomena, and they found that decreasing liquid cooling channel dimensions to the micron scale will lead to increase in the heat transfer rates. Ren et al. [3] investigated the velocity distribution, friction coefficient, apparent viscosity and heat transfer in parallel silicon plates and rectangular microchannels; they found that the analytical and experimental results of volume flow rates are significantly lower than those predicted by the classical theory. They attributed this discrepancy to the influence of electrical double layer (EDL). Peng and Peterson [4] performed experimental investigations on the pressure drop and convective heat transfer of water in rectangular microchannels; their experimental results show that the flow friction and convective heat transfer are greatly influenced by the cross sectional aspect ratio. In practice, hydrophobic surfaces are widely used in microchannels for liquid flow. Experimental studies [5] show the existence of significant liquid slip at the walls when hydrophobic surfaces are involved even at low Reynolds numbers($Re < 10$); slip flow will obviously influence heat transfer in microchannels [6].

The presence of the EDL causes additional flow resistance compared to the macroscale theory. This is usually referred to as the streaming potential effect (or called the electroviscous effect) [7]. The electrical potential distribution of the EDL can be described by the non-linear Poisson–Boltzmann (PB) equation. The PB equation is commonly solved by using the Debye–Huckel (D–H) linear approximation [8–10]. This assumption is only valid in case of low surface electrical potential condition [11], i.e., zeta potential $|\zeta| < 25$mV, however, if the value of the zeta potential is large, for example, the surface zeta potential in dilute electrolyte solutions can be up to several hundred millivolts, then the linear approximation is no longer valid.

With the progress of micro/nano-measurement technology, many studies experimentally observed that the boundary slip could occur in many situations [12]. Except experimental studies, the literature [13,14] also proved the existence of slippage in solid–liquid interface using the molecular dynamics (MD) simulation. The slip effect is significant in microfluidic systems and it should be taken into account. Especially hydrophobic materials (polymers such as polydimethylsiloxane, PDMS) become widespread in the fabrication of microfluidic devices [15], and velocity slip at hydrophobic surface is very remarkable. Hence, it is necessary to consider the slip effect in the mathematical modeling of fluid flow in such hydrophobic microchannels.

From the above review, we can see that most research works mainly focused on the effect of EDL on liquid flow, and less research pays

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attention to the streaming potential effect on heat transfer in pressure-driven microchannel flows. However, it has great significance to study the fluid flow and convective heat transfer characteristics in microchannels, which can provide valuable reference for engineering application, such as high-performance microchannel heat sink for very-large-scale integrated circuits, microfluid pumps, microvalves, and Lab-On-Chip devices for chemical and biomedical analysis instruments [16,17]. The aim of this paper is to carry out the investigation on the fluid flow and convective heat transfer considering wall slip and streaming potential effects simultaneously.

2. Problem description and mathematical model

Consider the pressure-driven flow through a microchannel formed between two parallel plates with a channel half width of H; the physical model is shown in Fig. 1. The bottom and upper wall are both made of hydrophobic materials and bear the same zeta potential ζ. At the same time the channel walls are subject to constant and uniform heat flux q. According to the assumptions presented in reference [18], the governing equations are given in the non-dimensional form as follows:

The Poisson–Boltzmann (PB) equation

$$\frac{d^2\psi}{dY^2} = K^2 \sinh(\psi) \tag{1}$$

The modified Navier–Stokes equation

$$\frac{d^2\overline{u}}{dY^2} + 2 - \frac{2G_1 Re}{K^2} \cdot \overline{E_s} \cdot \frac{d^2\psi}{dY^2} = 0 \tag{2}$$

The energy equation

$$\frac{\partial^2\theta}{\partial Y^2} = \frac{\overline{u}}{\overline{u}_m} \tag{3}$$

where the dimensionless variables and dimensionless groups are defined:

$$\begin{aligned} &Y = y/H, \psi = ez\Psi/(k_b T_r), \kappa = \left(2n_0 e^2 z^2 \big/ (\varepsilon_r \varepsilon_0 k_b T_r)\right)^{1/2}, \\ &K = \kappa H, G_1 = k_b T_r n_0 \big/ \left(\rho U_r^{\,2}\right) \\ &Re = \rho U_r \cdot 2H/\mu, \overline{u} = u/U_r, \\ &P_x = -dp/dx, \theta = (T - T_m)/(Hq/k), \overline{u}_m = u_m/U_r \end{aligned} \tag{4}$$

Here, Ψ is the EDL electrical potential, u is the velocity, T is the local temperature, κ is the Debye–Huckel parameter, K is the electrokinetic parameter, P_x is the pressure gradient in x direction, $U_r = P_x \cdot H^2/(2\mu)$ is the reference velocity, Re is the Reynolds number, k is the thermal conductivity. T_m is the bulk mean temperature, and u_m is the mean flow velocity.

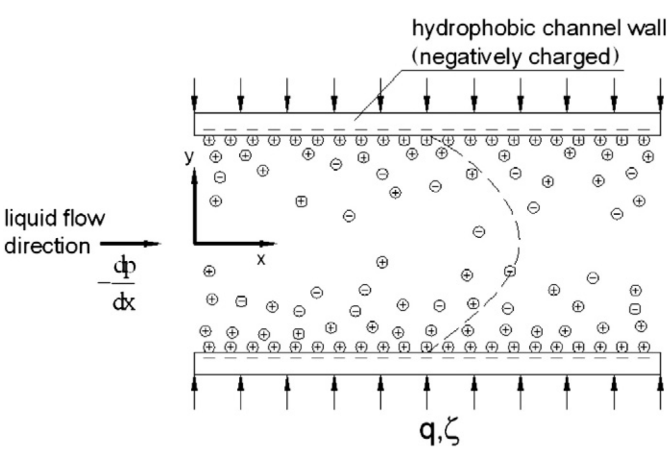

Fig. 1. Schematic diagram of planar microchannel.

The dimensionless forms of the corresponding boundary conditions are:

$$\begin{aligned} &\text{At the channel wall } (Y = \pm 1) \quad \psi = \overline{\zeta} \quad \overline{u} = \mp\beta \frac{d\overline{u}}{dY} \quad \frac{\partial\theta}{\partial Y} = \pm 1 \\ &\text{At the center line of the microchannel } (Y = 0) \quad \frac{\partial\psi}{\partial Y} = 0 \quad \frac{\partial\overline{u}}{\partial Y} = 0 \end{aligned} \tag{5}$$

where $\overline{\zeta} = ez\zeta/(k_b T_r)$ denotes the dimensionless zeta potential on channel wall, and β is the dimensionless slip coefficient.

D–H linear assumption is not valid anymore at high zeta potential. Therefore, if the electrical potential distribution asymptotically goes to zero far away from the flat plate, the analytical solution of Eq. (3) can be given by [19]:

$$\psi = 2\ln\left[\frac{1 + \tanh\left(\overline{\zeta}/4\right)e^{-KY}}{1 - \tanh\left(\overline{\zeta}/4\right)e^{-KY}}\right] \tag{6}$$

At steady state, the net electrical current should be zero, i.e., $I_s + I_c = 0$, thereby the dimensionless streaming potential $\overline{E_s}$ in Eq. (2) can be determined as

$$\overline{E_s} = G_2 \int_0^1 \overline{u} \frac{\partial^2\psi}{\partial Y^2} dY \tag{7}$$

where $G_2 = \varepsilon_r \varepsilon_0 U_r/(\lambda H)$ is a dimensionless parameter, and λ is the electrical conductivity of the electrolyte solution, which can be calculated by

$$\lambda = \frac{De^2 z^2}{k_b T_r}(n_+ + n_-). \tag{8}$$

Here, D is the species diffusion coefficient.

3. Results and discussion

We consider the 1:1 symmetrical electrolyte solution as the working fluid. The channel height is H = 25 μm, and the channel length is L = 5 cm. A pressure gradient of P_x = 5 × 10^3 Pa/cm is applied. At a typical room temperature T_r = 298 K, the physical properties of this electrolyte are $\varepsilon_r = 80$, $\varepsilon_0 = 8.854 \times 10^{-12}$ C^2 J^{-1} m^{-1}, $\mu = 0.9 \times 10^{-3}$ kg m^{-1} s^{-1}, and $D = 1.334 \times 10^{-9}$ m^2 s^{-1}.

3.1. Velocity field

The flow-induced streaming potential retards the pressure-driven main flow, while wall slip tends to increase the flow velocity. Their influences on velocity distribution are shown in Fig. 2. The dimensionless velocity distribution only in the upper half channel is plotted due to the symmetry. It can be seen that the streaming potential reduces the flow velocity when there is no slip at the microchannel wall (the dotted line); however, the boundary slip promotes the liquid flow, and thus leads to higher velocity (the dash-dotted line). The velocity distribution under the combined effects of streaming potential and wall slip (the short-dashed line) is very close to the case of no slip and no EDL (the solid line). This indicates that the streaming potential effect predominates over the slip effect to retard the liquid flow. Although the slip increases the flow velocity, it also assists the streaming potential to decrease the flow velocity. Therefore, streaming potential plays a more significant role when the above two effects appear in microchannels simultaneously.