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Joule heating, viscous dissipation and convective heat transfer of pressure-driven flow in a microchannel with surface charge-dependent slip

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ABSTRACT

The present work develops closed form expressions of Joule heating, viscous dissipation and Nusselt number for steady, laminar, hydrodynamically and thermally fully developed pressure-driven flow (PDF) in a microchannel considering the combined effect of surface charge-induced electric double layer (EDL) and surface charge-dependent slip. On basis of these, the effects of zeta potential in a large range limited by the steric effect of free ions to valid the nonlinear Poisson-Boltzmann equation, surface charge-dependent slip, ionic concentration of the electrolyte and the microchannel height on the Joule heating, viscous dissipation and Nusselt number of the PDF are analyzed. The results reveal that the electric field strength generated from the motion of the net free charges within the EDL moving with the PDF shows a valley trend with the continually increasing absolute value of zeta potential, and it is a key factor to affect the thermal performances of the PDF. Both the Joule heating and viscous dissipation of the PDF show a non-monotonic variation with the continually increasing zeta potential because of the non-monotonic electric field strength. Additionally, the zeta potential can lead to the reduction of Nusselt number by reducing the velocity of PDF. However, when the magnitude of zeta potential increases to a high value, the Nusselt number shows a non-monotonic variation because of the non-monotonic velocity field of the PDF arising from the non-monotonic electric field strength. Furthermore, slip, ionic concentration and microchannel height can also significantly affect the Joule heating, viscous dissipation and the Nusselt number of the PDF in different manners. The underlying mechanisms of the corresponding results are analyzed. The subject of the paper is the theoretical results and the corresponding analysis.

1. Introduction

Micro/nano fluidic systems are widely used in various kinds of applications, such as, micro/nanofluidic lab-on-chip and cooling of Micro- Electro- Mechanical Systems (MEMS) and Nano-Electro- Mechanical Systems (NEMS) [1–3]. In these applications, the thermal properties of the liquid flow are significant factors to affect the performances of the micro/nano fluidic system, for example, the temperature of the liquid flow can affect the liveness of biological and medical samples [4,5] and the formation and stability of nanobubbles at the solid-liquid interface [6]. Among many different thermal properties, Joule heating, viscous dissipation and Nusselt number are three important thermal properties in fluidic systems, where Joule heating is the heat generated from the electrical current arising from the flowing liquid with net free charges, which is common for the electrokinetic flow at the micro/-nanoscale, the viscous dissipation is the transfer of mechanical energy to thermal energy due to the friction during flow, and Nusselt number can be used to describe the activity of the convective heat transfer. Joule heating, viscous dissipation and Nusselt number of the fluid flow over the micro/nano scale have inspired much scientific interest [1,5].

With the deepening of the studies, scientists began to find that surface charge generated spontaneously at some solid-liquid interfaces and boundary slip condition characterizing the relative motion condition between the solid surface and the liquid adjacent to the solid surface are two important interfacial properties to affect the thermal properties of micro/nano fluid flow. For a certain solid-liquid interface, it can be spontaneously charged due to different mechanisms, and then the free ions within the liquid will

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be re-distributed because of their electrostatic interaction with the charged interface and their thermal motion. Finally, an electric double layer (EDL) with local net charge is formed near the charged interface [7–9]. At the meantime, when the liquid flows over a solid surface, there may be a relative motion between liquid adjacent to the solid surface and solid, that is, there is a finite velocity of the fluid-solid interface. This boundary condition of velocity is the so-called boundary slip, and it can be characterized by slip length in the mathematical format of $v_w = b(dv/dy)|_{y=0}$ (where v_w is the velocity of the liquid at the wall, $(dv/dy)|_{y=0}$ is the velocity gradient of the liquid at the wall, and b is the slip length), which is typically in a range from several nanometers to tens of micrometers [10–13]. Previous studies showed that the EDL and slip can significantly affect the fluidic behavior of the liquid flow over the micro/nanoscale [7,14–16]. For example, when the liquid flows in a microchannel under the driving of external pressure, that is the pressure-driven flow (PDF), the existence of EDL can apply an electrical body force, which is in the opposite direction of the driven pressure, on the fluid flow and reduce its velocity. This is the so-called electroviscous effect [7]. However, the existence of slip can increase the velocity of the fluid flow and reduce the fluid drag [14,15]. Additionally, the existence of EDL with net local charge can also be used as a potential method to achieve the transportation of the liquid by applying an electrical voltage, such as the electroosmotic flow (EOF) [17–19].

Considering some thermal properties of the fluid flow, such as viscous dissipation and convective heat transfer are directly related to its fluidic behavior, thus, the surface charge-induced EDL and slip inevitably affect the thermal properties of the fluid flow by affecting its fluidic behavior. The effects of surface charge and slip on the thermal properties of the fluid flow over the micro/nanoscale deserve deep study to achieve the wide applications of micro/nanofluidic devices and improve their performances and lifetime [1,5]. The separate effect of surface charge and slip and their combined effect on the Joule heating, viscous dissipation and convective heat transfer of PDF or EOF even their combination have been studied [20–25]. Nevertheless, these effects still need in-depth studies. For example, the Joule heating of EOF has been widely and systematically studied [5,20–22], however, the Joule heating of PDF, which arises from the transportation of net local free charges within the EDL moving with PDF (the so-called streaming current), has not received much attention. Additionally, although the combined effect of surface charge and slip on the thermal properties of the micro/nano fluid flow has been studied, most of these previous studies assumed that the surface charge and boundary slip are independent. However, the relevant studies reported that the surface charge at the solid-liquid interface can enhance the attractive electrostatic interaction between the solid and the liquid molecules near the charged interface and then reduces the slip length [14,15,26]. The dependence of slip on surface charge can reduce the fluid velocity of the PDF based on our previous study [15] and then inevitably affect the corresponding thermal properties of the micro/nanofluidic flow, thus, it is necessary to consider the coupling effect between surface charge and slip when analyzing the Joule heating, the viscous dissipation and convective heat transfer of the PDF. It is believed that the considering of the dependence of slip on surface charge can make the revelant analysis more accurate, and the studies of these fundamental phenomena and their mechanisms are helpful for the optimal design, excellent performances and broad applications of micro/nanofluidic systems.

To address these problems, in this paper, theoretical models of Joule heating, viscous dissipation and convective heat transfer of the steady, laminar and thermally fully developed PDF in a parallel-plate microchannel considering the effect of both surface charge-induced EDL and surface charge-dependent slip are established. On basis of these models, the effect of zeta potential, slip, ionic concentration of the electrolyte and microchannel height on the Joule heating, viscous dissipation and convective heat transfer of the PDF in the microchannel are systematically investigated. The underlying mechanisms of the corresponding results are analyzed.

2. Theoretical models

To analyze the effect of surface charge and slip on the Joule heating, viscous dissipation and convective heat transfer of PDF over the microscale, a steady, laminar, hydrodynamically and thermally fully developed PDF through a microchannel formed by two infinitely parallel plates with a separation distance of $2h$ is considered. Here, the zeta potential is used to characterize the surface charge density at the microchannel walls. Fig. 1 gives a simplified schematic of the physical problem in this present work. Throughout the analysis, the following assumptions are used.

- The channel walls are subject to uniform zeta potential, constant heat flux and no-slip condition or surface charge-dependent slip condition. There is no internal heat source in the microchannel.
- Constant thermophysical properties of the electrolyte based on a small and negligible temperature variation.
- The free ions within the EDL satisfies the nonlinear Poisson-Boltzmann distribution. Additionally, considering the free ion is not point-like without any size, the steric effect [27,28] is used to limit the maximum absolute value of zeta potential to valid the nonlinear Poisson-Boltzmann.
- The channel size is assumed to be much larger than the Debye length of the liquid, which is a symmetric electrolyte, that is, the EDLs separately formed near the upper wall and the lower wall are not overlapped with each other.

In order to analyze the Joule heating, viscous dissipation and convective heat transfer of PDF in the microchannel with the combined effect of surface charge and slip, the ions and electrical potential distributions within the EDL governed by the nonlinear

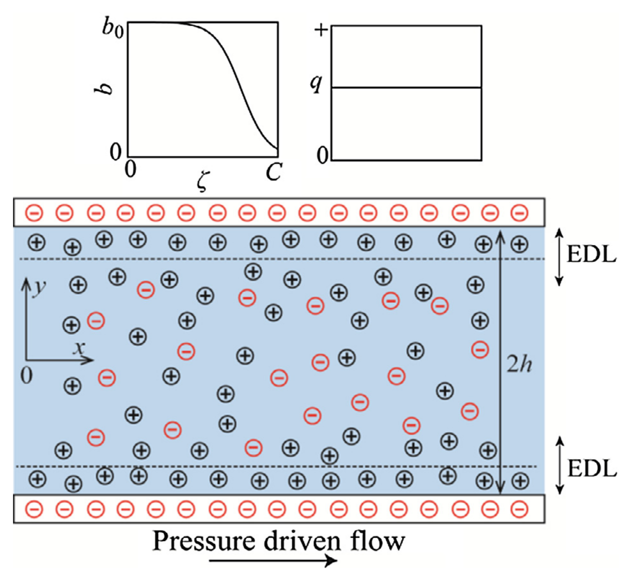

Fig. 1. Schematic of PDF in a microchannel with various boundary conditions and the coordinate system. ζ is the zeta potential to characterize the surface charge density at the microchannel wall, C is a non-zero value of zeta potential, b is surface charge-dependent slip length, b_0 is the original slip length in the case of zero surface charge density, q is the heat flux which is a constant, h is the half height of the microchannel, and x and y are the coordinate axes.