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Thermal transport of electromagnetohydrodynamic in a microtube with electrokinetic effect and interfacial slip

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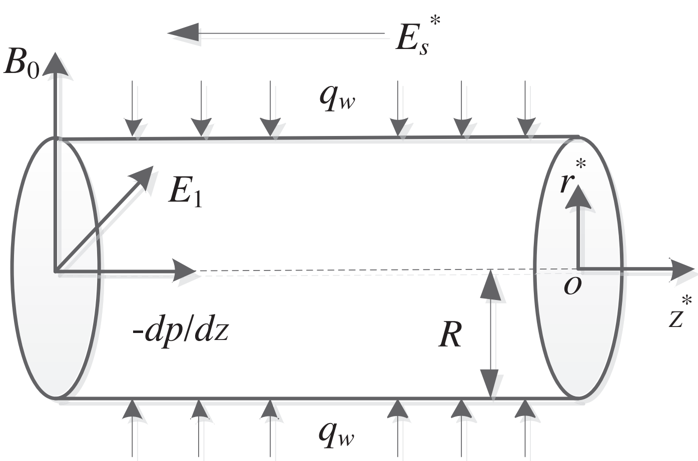
GRAPHICAL ABSTRACT

Schematic diagram of the physical model.



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ABSTRACT

Thermally fully developed flow characteristics are investigated through a microtube. The combined influences of pressure driven, induced streaming potential field and an additional vertical magnetic field are taken into account in the microflow system. Flow velocity can be obtained with consideration of the slip boundary, magnetic field and lateral electric field. Subsequently, the analytical expression of induced streaming potential field is also derived by considering the conservation of net electrical current. A comparison of streaming potential with the experimental result is conducted and a linear relationship is also obtained between the pressure and streaming potential. According to the obtained velocity and streaming potential fields, we further study the temperature distribution in the presence of the influence of viscous dissipation and Joule heating by finite difference method. The distributions of streaming potential, velocity and temperature are depicted graphically. Besides, a significant non-dimensional temperature parameter *Nu* is discussed in detail. Results show that the magnetic field and lateral electric field play a crucial role in the distributions of streaming potential, flow velocity and temperature. The present endeavor can be utilized to design the exquisite and efficient magnetofluid devices, especially within a specific regime of thermal transport characteristics.

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1. Introduction

Microfluidics devices have been significantly utilized in biology, drug delivery biochip, micro-electro-mechanical systems (MEMS) and thermal management of microelectronic systems [1–4]. When the electrolyte solution contacts with the microchannel wall, the chemical interaction generates in the solid-liquid interface, which ultimately results in an electric double layer (EDL) forming near the microchannel wall. Under the influence of the imposed axial electric field, the electrolyte solution filled with the whole microchannel will migrate and such flow phenomenon is so-called electroosmotic flow (EOF). Electroosmotic flow can be utilized as a promising process of transporting fluids through microfluidic devices mainly due to its numerous advantages such as ease of fabrication and control, absence of mechanical parts and high reliability, etc. Hence, the theoretical, numerical and experimental investigations of electroosmotic flow have been well studied, including the different fluid models [5,6], various geometric domains of microfluidic devices [7–9], rotating flow system [10–12] and multi-layer fluid system [13,14]. Due to the existence of the applied electric field, the Joule heating effect is important and cannot be ignored in the transport process of EOF. The analysis of thermal transport characteristics through microfluidic devices has attracted considerable attentions [15–17], especially in the field of the thermal engineering.

In the pure electroosmotic flow system, the magnitude of applied electric field is larger in order to drive the electrolyte solution flow in general. The larger electric field may result in larger Joule heating which is detrimental to thermally labile test samples and brings about the activity loss of some biological samples [18]. In order to minimize the Joule heating effect in EOF, the effect of magnetic field is considered in the microscale devices similar to the macroscale flow driven by the electromagnetic force. When the influence of EDL is ignored, the analysis of electromagnetohydrodynamics (EMHD) flow affected by the imposed electric and magnetic fields has been widely studied. Jang and Lee [19] experimentally investigated the EMHD flow in microfluidic systems and the results showed the average flow rates can be enhanced under the low-magnitude magnetic field. EMHD flow of a third grade fluid ignoring EDL effects was studied by Wang et al [20] and approximate analytical solutions of velocity and temperature were obtained. At the same time, they compared approximate analytical solutions to numerical solutions obtained by employing Chebyshev spectral collocation method. In practice, the roughness of the actual microchannel wall is always present in the manufacturing process and the fluid flow with slightly corrugated walls under the uniform electromagnetic field is studied in [21,22]. In addition, the more interesting phenomenon of microflow transmission using spatially non-uniform magnetic fields was also discussed in [23,24]. Jian and Chang [25] obtained the approximate analytical solutions and numerical solutions of EMHD velocity in a spatially varying non-uniform magnetic field through a microparallel channel. Considering the interaction between the electric double layer (EDL) and the imposed electric and magnetic fields, the transport phenomena of fluid flow has attracted considerable attentions since Joule heating can be reduced effectively. Chakraborty et al. [26] analyzed the thermal characteristics of EMHD flow under the act of electroosmotic effect through a microchannel and they discussed EMHD heat transfer characteristics under the influence of Joule heating and viscous dissipation. In a microchannel induced by peristaltic wave, an analytical solution of entropy generation in magnetohydrodynamic (MHD) electroosmotic flow was obtained by Ranjit and Shit [27]. Jian [28] used the method of Laplace transform to study the transient MHD heat transfer and entropy generation combined with unsteady pressure driven and electroosmotic effects in a microparallel channel.

When applied electric field is ignored in the electrokinetic flow system, the pressure is the main source to drive fluid flow. Along the pressure gradient direction, net charge ions will be triggered to migrate and gather at the downstream of microchannel, ultimately forming a reverse induced electric field (also known streaming potential field). The existence of the induced streaming potential field will generate a reverse electroosmosis force which can resist against fluid motion since it is always opposite to the flow direction. Such resistance can be characterized in term of an enhanced viscosity and this flow phenomenon is traditionally known as electroviscous effect [29–31]. A large number of studies are carried out to investigate the electrokinetic effects for the pressure driven flow through microchannels. Mala et al. [32] studied the effects of the streaming potential field on characteristics of pressure driven flow through a micoparallel channel and a feasible experiment were conducted to compare the theoretical results. They found the volume flow rates for the steady pressure driven flow with the consideration of EDL effects were agree well with the experimental data. Subsequently, Ren et al. [33] extended the theoretical results of Mala et al. [32] in a rectangular microchannel and gave the analytical expression of streaming potential field. The electroviscous effects of power-law fluids in a slit microchannel were studied by Vasu and De [34]. They obtained the analytical expressions of velocity and streaming potential field for three specific values of power-law fluids behavior index ($n = 1,\ 1/2,\ 1/3$). Simultaneously, the numerical simulation is used to carry out the velocity and streaming potential for all values of power-law fluids behavior index. In addition, the electrokinetic flow with no application of electric field can also be utilized as an alternative method to carry out energy conversion between mechanical energy and electric energy, especially in the nanoscale devices. Hence, the analysis of the flow transport properties with electrokinetic effects through nanochannel is well studied [35–37]. Jian et al. [38] provided the analytical solutions of streaming potential field for the pressure driven flow of viscoelastic fluids in a nanochannel and discussed the influences of related dimensionless parameters on the electrokinetic energy conversion efficiency in detail. The thermal transport characteristics on pressure driven flow considering the influence of streaming potential have been researched through micro/nanochannels as well. Mala et al. [39] investigated heat transfer characteristics of pressure driven flow with the consideration of electroviscous effects. They gave the analytical distributions of flow velocity and streaming potential field and discussed the temperature distribution in a finite difference method. Although the analysis of streaming potential in pure pressure driven flow is widely investigated, the transport characteristics with a combined interaction of streaming potential field and magnetic field are still remained unclear. Recently, Zhao et al. [40] studied the streaming potential of nanofluids in the presence of magnetic field and obtained the analytical solutions of velocity and streaming potential field ignoring the effects of lateral electric field and interfacial slip. The above mentioned theoretical studies are mainly confined within the micro/nanoscale field in the analysis of streaming potential field. Although the experimental study of the measurement of streaming potential has not been conducted under the influence of electric and magnetic fields, the streaming potential field can be measured by the electric potential difference of a pair of electrodes in purely pressure driven flow [41,42]. Very recently, Ghommem et al. [43] conducted an experimental study to measure the streaming potential field of pressure driven flow and obtained the value of the streaming potential coupling coefficient. The linear relationship of the streaming potential and the pressure difference is predicted. Besides, other experimental studies of measuring the streaming potential field can also be conducted in Refs [44,45].

The effects of fluid slip with the hydrophobic surfaces have been frequently studied in microflow system [46,47]. It is recognized that the fluid flow through micro/nanochannel can be effectively controlled by altering the liquid-solid interfacial hydrodynamic parameters. Experimental investigation showed the slip length at the microchannel wall can reach micron level. In addition, it is should be noted that the influence of interface slip can be amplified in the electrokinetic flow (considering the streaming potential field) [48]. Yang and Kwok [49] studied the effect of liquid slip on the transport of electrokinetic flow and found the flow rate can be enhanced dramatically. Matin [50]