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Thermal transport of magnetohydrodynamic electroosmotic flow in circular cylindrical microchannels

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ABSTRACT

Thermal transport phenomena of magnetohydrodynamic electroosmotic flow are investigated through a circular cylindrical microchannel. The fluid flow can be actuated by the interactions of imposed pressure-gradient, electroosmosis and additional electromagnetic field. Under the appropriate assumptions, the distributions of the non-dimensional flow velocity can be obtained. Based upon the achieved velocity field, heat transfer characteristics, explained by the non-dimensional temperature and Nusselt number, are discussed graphically by taking into account the effects of viscous dissipation and Joule heating under the constant wall heat flux circumstance. Concisely, the results show, in the absence of lateral electric field, the flow velocity decreases with the increasing magnitudes of Hartmann number resulting in the decrease of non-dimensional temperature, which ultimately culminates in increasing the Nusselt number. However, the profiles of non-dimensional flow velocity, non-dimensional temperature and Nusselt number are demarcated into two regions based on the value of critical Hartmann number and exhibit an adverse trend among different regions due to the existence of lateral electric field. The present endeavor can be utilized to design the exquisite and efficient electromagnetic devices, especially within a specific regime of thermal transport characteristics.

1. Introduction

Recently, microfluidics transport processes have received considerable attention due to their manifold applications in a broad spectrum of fields, such as micro-electro-mechanical systems (MEMS), biochemical engineering, drug delivery biochip, biomedical diagnostic techniques, chemical separation devices and thermal management of microelectronic systems [1–5]. Initially, similar to the macroscale flow, the liquid flows were actuated by conventional and simplistic pressure-driven mechanisms through the microscale devices pertaining to the above mentioned microfluidic applications [6–8]. However, due to the reduction of the microfluidic device length-scale, there are certain inherent disadvantages towards the fluid flow driven by pressure, including the power loss owing to the effect of the friction, lack of precise flow control and poor reconfigurability with microscale devices. In view of the above-mentioned detrimental attributes, the optimizing actuation mechanisms should be provided for the fluid flow through microfluidic conduits.

With the advent of electrokinetic flows, the electroosmotic flow has attracted extensive attention in the applications of microfluidic devices primarily due to its relative advantages such as simple design requirement, lack of moving components, minimized sample dispersion and efficient reconfigurability with electrical circuitry [9,10]. In this regard, the electroosmosis actuation mechanism can be utilized as a viable alternative for the liquid flow through the microchannel. Many studies of EOF in a microchannel for both Newtonian fluids [11–14] and non-Newtonian fluids [15–19] have been well investigated. In various microfluidic applications, like lab-on-a-chip [20,21], especially in biological and non-biological applications, a combination of pressure-driven mechanism and electroosmosis actuation mechanism [22] is frequently implemented to manipulate and analyze the microfluidic flow. Furthermore, the thermal transport process of combined pressure-driven and electroosmosis actuation in microscale devices, including thermally fully-developed flows [23–28] and thermally developing flows [29–31], has been studied by the contemporary researchers. Due to the minimized microscale devices, the viscous dissipation, unlike the macroscale devices, can no longer be trivially precluded from the analysis of the microscale thermal characteristics. Moreover, the effects of Joule heating have also played a very significant role in the analysis of heat transfer processing pertaining to microscale electroosmotic flows.

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Generally, Joule heating effects are detrimental and unavoidable for the processing of thermally labile biological samples and the loss of test samples [32,33]. This necessitated more efficient microscale flow actuation mechanisms should be alternative to minimize the Joule heating effects.

Recently, the combined electric and magnetic fields driven mechanism has been extensively utilized for analyzing the transport characteristics through the microfludic devices due to its many advantages, such as simple manufacture, lack of moving parts and lower voltage of operation [34–37]. Electromagnetohydrodynamics (EMHD) describes the liquid flow affected by the imposed electric and magnetic fields, which can induce a Lorentz force to push the liquid flow. The average flow rates of the microfludic devices for pumping liquids can be enhanced by implementing EMHD flows [38], especially under the low-magnitude magnetic field. Hence, the EMHD micropump, mainly driven by Lorentz force, has been widely used in biological and chemical fields to control the microfluidics flow. Research on the motion characteristics through microfluidic devices in the presence of electric and magnetic fields has gained extensive popularity. Lemoff and Lee [39] have constructed an alternating current (AC) MHD micropump in which the electrolytic solution is actuated by the Lorentz force. Subsequently, they reported a microfluidic switch which is propelled by the electromagnetic force and the flow of the electrolytic solution could be shifted in a Y-shaped microfluidic circuit [40]. A simplified two-dimensional fully developed MHD flow model [41] has been numerically studied by finite difference method. The results showed the fluid velocity has been strongly affected by the Lorentz force induced by the interaction between electric and magnetic fields. The above mentioned references on the MHD flow have been centered on the smooth microchannel. In practice, the roughness always exists on the real microchannel wall during the fabrication process and the fluid flows under the uniform electric and magnetic fields with slightly corrugated walls have been studied in [42,43]. In addition, more interesting phenomena of the microflow transport triggered by utilizing a spatially non-uniform magnetic field have been achieved [44–47]. Jian and Chang [48] have obtained the approximate analytical EMHD velocity through a microparallel channel, subjected to a spatially varying non-uniform magnetic field. The flow velocities have been compared with the numerical solutions obtained by the Chebshev spectral collocation method. Considering the interaction between the electric double layer (EDL) and the imposed electric and magnetic fields, the transport phenomena of fluid flow through a microparallel channel have been studied by Chakraborty and Paul [49]. Although the EMHD flow characteristics have been adequately investigated by the contemporary researchers, the microfluidics thermal behavior should also be studied due to the significant effects of heat transfer and entropy generation in practical engineering, especially for the EMHD flow combined the influence of EDL.

The thermal analysis of the EMHD flow through a rectangular microchannel has been studied by Duwairi and Abdullah [50]. They analytically obtained the distributions of the velocity and temperature and discussed the influences of relative parameters on the velocity and temperature fields. However, the effects of viscous dissipation have been ignored in their study. Wang et al. [51] have investigated the EMHD flow and heat transfer of a non-Newtonian fluid considering the viscous dissipation effects and discussed the variation trends of Nusselt number with the magnetic field in detail. The electric double layer (EDL) effects can be considered in the analysis of the EMHD flow. In this case, the flow actuation mechanisms include the electroosmotic body force resulting from the EDL effects and the Lorentz force induced by the interaction between electric and magnetic fields. Chakraborty et al. [52] have analyzed the thermal characteristics of EMHD flow in a microparallel channel considering the electrokinetics effects (electroosmotic effects) and they have discussed the Joule heating and viscous dissipation effects on the EMHD heat transfer characteristics. Subsequently, Jian [53] studied the transient MHD heat transfer and entropy generation through a microchannel with the combined pressure and electroosmotic effects. The influence of electromagnetic interaction has been taken into account in the analysis of the temperature distribution. In addition, other relevant references on thermofluidic characteristics of combined electroosmotic effects in the presence of magnetic field have been performed [54–56]. In the practical EMHD applications, the heat transfer characteristics, for all the essential aspects of microscale physics, should be further study in-depth in order to design the efficient electromagnetic devices, especially thermal management devices which can diminish the Joule heating effects.

Thermally fully developed magnetohydrodynamic electroosmotic flow in a circular microtube has been delineated in the present paper, by taking into account the interactions of imposed pressure-gradient, electroosmosis and additional electromagnetic fields. Based on the liquid flow features (the velocity distributions), thermal transfer phenomena, explained by the temperature distribution and Nusselt number, have been analyzed in detail under the constant wall heat flux condition. Moreover, the effects of Joule heating and viscous dissipation are considered in the analysis of heat transfer characteristics and these effects cannot be ignored in the microscale devices. The results of the present study can be utilized as a valuable guideline in the design of the thermodynamic microdevices.

2. Mathematical modeling

The transport characteristic of thermally fully developed magnetohydrodynamic flow in a circular cylindrical microchannel has been sketched in this study under the combined effects of electroosmosis and imposed pressure gradient. The radius of the circular microtube is R and the length is L. The length of the microtube is much larger than its diameter, i.e. ($L \gg 2R$). The physical model is delineated detailed in Fig. 1. An external electric field E_1 and pressure gradient are imposed along the principle axis of the circular microtube (i.e. along positive z-axis), which can provide driving force for liquid flow. Another electric field E_2 is applied in the lateral direction from outside to inside and a uniform magnetic field B_0 is implemented perpendicular to the direction of flow, from bottom to top. The interplay of the electric field E_2 and the magnetic field B_0 can induce an electromagnetic body force which pushes the liquid flow along z-axis direction. Moreover, a cylindrical coordinate system (r, θ, z) is established at the central part of the microtube, r, θ and z are the radial, the angular, and the axial coordinates, respectively.

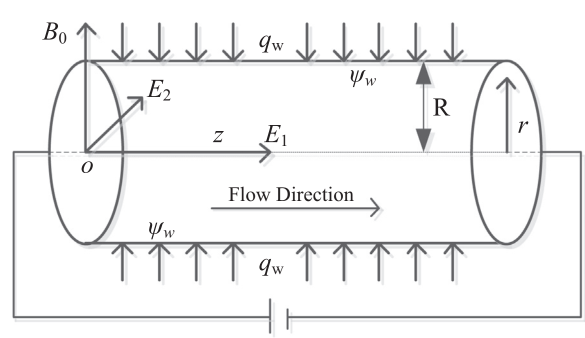

Fig. 1. Schematic diagram of the physical model.