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Thermally developing combined magnetohydrodynamic and electrokinetic transport in narrow confinements with interfacial slip

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ABSTRACT

In this article, we investigate the combined consequences of magnetohydrodynamic forces and interfacial slip on the heat transfer characteristics of streaming potential mediated flow in narrow fluidic confinements by following a semianalytical formalism. Going beyond the celebrated Debye–Hückel linearization, we obtain a closed form analytical expression for velocity and induced streaming potential through the consistent description of finite conductance of the immobilized Stern layer. We report an augmentation in the streaming potential field as attributable to the wall slip activated enhanced electromagnetohydrodynamic transport of the ionic species within the EDL. In particular, we demonstrate the key role of induced streaming potential in altering thermal transport and Nusselt number variation considering the concurrent interplay of hydrodynamic slip lengths, magnetic effects, viscous dissipation, and Joule heating. We also show the implications of Stern layer conductivity and magnetohydrodynamic influence on system irreversibility through entropy generation analysis due to fluid friction and heat transfer. Finally, our results have significant scientific and technological consequences in the novel design of future generation energy efficient devices and could be useful in further advancement of theory, simulation, and experimental work.

1. Introduction

Research investigations on the magnetohydrodynamic (MHD) transport phenomena have intensified progressively over the past few years, primarily motivated by the interesting and significant implication of magnetic field-driven actuation mechanism in a wide spectrum of scientific and technological applications [1–8]. There are several important applications where externally imposed magnetic field has been successfully used to control and manipulate liquid flow, examples being industrial reactors, advanced materials processing, micro/nano-electromechanical devices, magnetophoresis, flow augmentation in micropumps, chemical and biomedical processes, magnetohydrodynamic flow control [5], to name a few. The flow and heat transfer characteristics in such devices can be effectively controlled through alterations of the imposed magnetic field. Several studies of MHD effect in varied systems and applications are available and reported in the literature [9–12]. It has been observed experimentally that the average flow rates in micropumps can be substantially augmented by employing low-magnitude magnetic fields.

In recent years, researchers have demonstrated the modality of using combined magnetohydrodynamic and electrokinetic phenomena for driving fluid in devices with different geometries and shapes. Of particular interest are the situations when fluid flow and heat transfer is encountered in extreme narrow passages and confinements, which are often used in modern industries and instruments. Transport phenomena at the microscale exhibit distinctly different characteristics, as compared to the macroscale transport behavior, primarily due to the interfacial effects such as electric double layer (EDL) [13–15]. There have been a number of studies on the hydrodynamic and thermal transport in electrokinetically driven flow in narrow fluidic confinements. Studies on heat transfer characteristics of electrokinetic flows have assumed great importance primarily because of the inherent importance of thermal transport in micro-electro-mechanically actuated flows in modern age industrial applications. Maynes and Webb [16,17] investigated thermally fully developed flow situation in microchannels for pure electroosmotic and combined pressure-driven and electroosmotic flows. Horiuchi and Dutta [18] provided analytical solutions for temperature distribution and Nusselt number for thermally developing electroosmotic flows through straight microchannels. Chakraborty [19] analyzed hydrodynamically and thermally fully developed heat transfer in microtubes under

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Nomenclature

a	half height of the confinement
B_Y	strength of the magnetic field
Br	Brinkman number
E_X	induced streaming potential field
e	protonic charge
F_B	body force per unit volume
Ha	Hartmann number
$\vec{j}$	electric current density vector
I_{net}	net ionic current
k_B	Boltzmann constant
P	hydrostatic pressure
Pe_T	thermal Peclet number
Nu	Nusselt number
Re	Reynolds number
T	dimensional temperature
u, v	non-dimensional velocity components in x and y directions
x, y	non-dimensional coordinates

Greek symbols

β	dimensionless slip coefficient
σ_e	electrical conductivity of the fluid
ζ	dimensionless zeta potential
ψ	dimensionless EDL potential
ε	dielectric constant of the liquid
ε_0	permittivity of the free space
μ	viscosity of a fluid
κ	Debye length
θ	non-dimensional temperature

combined action of electroosmotic forces and imposed pressure gradients. In another study, Dey et al. [20,21] reported thermal transport characteristics for both thermally fully developed and thermally developing flows in microchannel in the presence of thick electrical double layer.

The assessment of transport characteristics in narrow fluidic confinements, under the influence of combined electromagnetohydrodynamic effect, however, is rarely found in the literature. There have been wide spectrums of micro/nanofluidic applications where magnetic field-driven actuation mechanism has been successfully employed to enhance overall efficiency of the system [3]. Jang and Lee [5] experimentally demonstrated the novelty of combined electromagnetic effect in microfluidic flow transport characteristics. In-depth applications of magnetophoresis for such narrow confinement flows have been elaborated in the seminal text book of Jones [22]. In an another perspective, Andreu et al. [1] and Pamme [11] demonstrated the possibility of employing magnetic field for the separation of biological and chemical moieties. The influence of electromagnetic fields on the flow characteristics in a parallel plate narrow confinement has been examined recently by Tso and Sundaravadivelu [4]. In their study [4], authors have considered externally applied transverse electric field interacting with imposed magnetic field acting in the longitudinal vertical plane of flow, thereby producing a net driving axial body force to enhance the flow rates. Although, electrical double layer effects were not considered in their study. Chakraborty and Paul [23] studied the implications of electromagnetohydrodynamic field towards controlling the microfluidic transport. Recently, Jian [24] carried out an analytical study to investigate the effect of transient magnetic field on heat transfer and entropy generation in a microparallel channel combined with pressure and electroosmotic effects. Munshi and Chakraborty [25] in a subsequent study investigated the influences of axial pressure gradients and transverse magnetic fields on hydroelectrical energy conversion mechanisms in narrow fluidic confinements. Although no external electric field was present in this study, electrokinetic transport was induced through streaming potential field which is developed due to the convective ionic transport in the mobile part of the EDL under the influence of pressure and magnetic fields. As such, the intricacies of microscale transport characteristics in the presence of a combined interplay of electrokinetic effect and magnetic fields have still remained unclear. Also, elaborate studies on heat transfer characteristics of combined magnetohydrodynamic and streaming potential mediated flow in narrow confinements are yet to be reported in the literature. In addition, consideration of interfacial slip in conjunction with the combined electromagnetohydrodynamic influence is also not reported till date. On the other hand, liquid slip at hydrophobic surfaces in narrow channels has frequently been reported by the research community [26–30]. It is now well recognized that slip imparts a strong influence on fluid motion by altering the interfacial hydrodynamics at the micro/nano-scale [31–34]. However, the interactions between the developed EDL and the imposed electromagnetic field, the resultant streaming potential field, slippage phenomena on the consequent hydrodynamic and thermal transport behavior are still not fully understood. In general, in the vicinity of the walls of the confinement the highly concentrated counterion renders a somewhat inconsequential coupling between the ionic and thermofluidic transport phenomena, which become substantially more involved for increasing EDL thickness [27]. The primary consideration that influence strongly on the ensuing nontriviality is a possible aberration of the interfacial transport from the traditional paradigm of a no-slip boundary condition. As such, the local entrapment of the fluid elements within the surface asperities as attributable to the inherent roughness characteristics of the solid surface is often accredited as the no-slip boundary condition [27]. Therefore, as a result of an otherwise the dense molecular packing, the fluid molecules fail to escape from that trapping. The liquid slips over a molecularly smooth boundary due to the absence of the surface asperity barriers. Furthermore, for high shear rates, the fluid molecules adhering to the solid surface must experience appropriate straining for overcoming the van der Waals forces of attraction. Additionally, rough surfaces comprised of hydrophobic materials may trigger the formation of depleted gas layers or nano-bubbles stick to the walls. This, in turn, provides the liquid to smoothly sail over the intervening vapor layer shield without exposing directly to the rough surface asperities. Therefore, the liquid may effectively “slip” on the rough wall surface instead of “sticking” in it. In mathematical models employing continuum-based approach, this phenomena is generally accounted through an interfacial boundary condition of the form $U|_{slip} = \beta^{*}[dU/dm]_{wall}$, where U is the fluid velocity, β^{*} being the dimensional slip coefficient (defined as a distance beyond the surface that extrapolates bulk velocity to zero), and m is the direction normal to the surface. Experimental measurements reported slip lengths ranging from no-slip (zero) to the order of 100 nm [31]. On the other hand, mass transport measurements on carbon nanotube filters have reported very high value of slip length as $\beta^{*} = 33$ mm [39,40].