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Electroviscous effects on thermal transport of electrolytes in pressure driven flow through nanoslit

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ABSTRACT

Fluid flow through micro/nanofluidics is of utmost importance in analyzing mechanical, biological and medical systems. Biological liquids are often electrolytes that produce spontaneous electrokinetic effects when flowing through pores and channels. The streaming potential which is resultant of this electrokinetic phenomenon drives the ions in the channel to move in the direction opposite to the pressure-driven flow and causes a resistance against fluid flow along the channel. It is simply similar to the case when the viscosity of the fluid is slightly increased. It is expected to have a lower flow rate in the presence of the electroviscous effects; however, understanding of these effects on thermal transport characteristics would be interesting. The present study attempts to present a theoretical investigation of the electroviscous effects on heat transfer in nanofluidics based on continuum fluid mechanics while boundary slip is assumed on the walls. Results show that the presence of electroviscous effects will remarkably enhance the heat transfer rate.

1. Introduction motion through or past structures

Ever increasing utilization of micro/nanofluidic systems in engineering, biology and medicine has made this field one of the most attractive area of research in fluid mechanics throughout the last decade. The microscale and nanoscale fluidics refer to the fluidic structures with a size smaller than 100 µm and 100 nm, respectively. Since the Reynolds number of pressure driven flow in micro/nanofluidics is extremely small, the inertial terms in the Navier–Stokes equations can be neglected and the flow is assumed to be Stokes flow.

In the case of fluid flow through nanochannels, the Knudsen number is generally used to evaluate the validity of the assumption of continuum model. The definition of Knudsen number is $Kn = l/L$ with l as the mean free path of molecules and L as the characteristic length [1–4]. When the electrolyte flows in a channel, the walls become charged due to the dissociation and adsorption of ions in the region close to the walls resulting in the development of a layer with a net charge density in this region that is called electric double layer (EDL) [5,6].

The first layer which is strongly attracted to the wall has an opposite charge on the charged wall. However, the second layer which is the mobile part of the EDL is poorly attracted to the wall and can transport along the channel. Therefore the ions presented in the diffuse layer of the EDL migrate and drive the electrolyte along with them, thereby engendering the fluid flow. Thus, internal electric field is induced due to the relative motion between the charged surface and the diffuse layer.

Although the main source of flow is the axial pressure gradient, the induced electric field stimulates the ionic species to move in the pressure gradient direction, resulting in an electric current known as streaming current and a potential difference known as streaming potential. This potential difference urges the ionic species to move in the opposite direction of the pressure driven flow that causes an ionic current called conduction current. So the EDL engenders an electrical drag force opposed to the pressure driven flow. When the fluidic dimensions become smaller than the characteristic length the surprising phenomena are expected to happen. These phenomena, which are predominant in nanochannels, come from the interfacial interactions at the interface of the electrolyte and the wall including boundary slip, surface tension and electrical interactions. Since there is extremely few molecules in nanofluidic channels, electrokinetic transport through such channels distincts from microchannels. The majority of studies have been focused on channels in microscale.

The study of pure electroosmotic flow in a microscale slit channel was conducted by Wei et al. [7]. They reported that their analytical results match acceptably with the experimental data. Some researchers focused on the combination of pressure driven and electroosmotic flows in microchannels [8–11]. In comparison to

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Nomenclature

Br	Brinkman number
e	proton change
E_x	induced electric field
h	heat transfer coefficient
H	height of channel
k	thermal conductivity
k_B	onstant Boltzmanc
K	Debye–Hückel parameter
n	concentration ionic number
Nu	Nusselt number
p	pressure field
q	wall heat flux
T	temperature
T_{av}	average temperature
T_w	wall temperature
Re	Reynolds number
Sc	Schmidt number
u	axial velocity
u_m	mean velocity
y	transverse coordinate
z	valence number of ions
x	axial coordinate

Greek symbols

α	flow rate ratio
η	Nusselt number ratio
θ	dimensionless temperature
λ	EDL thickness
ρ	density
ρ_e	net electric charge density
μ	dynamic viscosity
ρC_p	heat capacitance
σ	electrical resistivity
ψ	electric potential
Γ	pressure driven parameter

the microchannels there is a paucity of works published on the nanochannels. What is generally accepted is that fabrication of nanochannels is more expensive and difficult than channels in microscale and it might be the reason that the nanochannels have made less contribution to the accomplished researches in this research area. An overview on the fabrication technologies of nanofluidic devices and their applications was performed by Abgrall and Nguyen [12] to describe the transport phenomena in nanochannels. A review on conventional methods and approaches for fabrication of nanostructured channels was presented by Perry and Kandlikar [13]. In their review article, Schoch et al. [14] studied physical mechanisms of the nanostructures such as nanometer-sized openings in order to realize the physical properties and integrated sample preparation and analysis systems. Yuan et al. [15] prepared a review on theoretical and experimental investigations pertained to electrokinetic effects in nanofluidics. They evaluated the EDL effect on the electrophoresis and electroosmosis in charged analytes.

Pennathur and Santiago [16] presented analytical and numerical data based on continuum model for electrophoretic transport in nanoscale channels with characteristic depths on the order of the Debye length. They pointed out that the effective mobility governing electrophoretic transport of charged species in nanochannels depends on electrolyte mobility values, zeta potential, ion valence, and background electrolyte concentration.

The presence of streaming potential for flow of a viscoelastic fluid through nanofluidics was theoretically examined by Habibi Matin and Khan [17]. They reported that increasing the EDL thickness or wall potential have and increasing impact on induced electric field. They also pointed out that that assuming no slip boundary condition will bring a considerable error in modeling of the flow in such fluidics.

In the literature it is repeatedly stated that for $Kn < 0.01$ the continuum model for the flow is applicable and for $0.01 < Kn < 0.1$, the slip boundary condition has to be considered to use continuum model for the flow [3]. Since nanofluidic channels might deal with Knudsen numbers smaller than 0.01 the slip boundary condition is implemented here.

One formulation that accurately predicts the boundary slip was first introduced by Navier [18]. In his method, Navier included the relative movement between the liquid and solid boundary, and he showed that the tangential velocity in the flow field is proportional to the velocity gradient in the direction perpendicular to the boundary. The EDL in nanochannels is usually very thin in comparison to the channel height and in such a case the Navier slip boundary condition on the wall is realistic.

Since the thermal conditions will definitely affect the fluid flow, studying the electrolyte flow through the channel when different thermal conditions are applied would be of interest. Thermal analysis of combined pressure driven and electroosmotic flow inside a circular microchannel was carried out by Maynes and Webb [19]. They also studied the effect of viscous dissipation on the heat transfer of purely electro-osmotic flow in microchannels [20] and claimed that viscous dissipation effect is negligible for most practical electro-osmotic flow applications. There have been some other works which focused on electrokinetic effects in heat flow inside microchannels [21–26]. The impact of joule heating on the thermal transport for a combined electroosmotic and pressure driven flow in micro/nanochannels was investigated by Chen [27]. It was shown that joule heating effects have to be taken into consideration in modeling the heat transport phenomenon in micro and nanochannels. Balaj et al. [28] employed direct numerical simulation to study the effect of velocity slip on non-equilibrium heat transfer in pressure driven flow through micro/nanochannels.

In the open literature all the studies have focused on heat transfer in electroosmotic flow through microchannels. Understanding of the thermal transport characteristics for pressure driven flow through micro/nanochannels considering the streaming potential has never been addressed.

The streaming potential which is resultant of this electrokinetic phenomenon drives the ions in the channel to move in the direction opposite to the pressure-driven flow and caused a resistance against fluid flow along the channel. It is simply similar to the case when the viscosity of the fluid is slightly increased. It is expected to have a lower flow rate in the presence of the electroviscous effects.

This study focuses on theoretical investigation of the electroviscous effects on heat transfer in nanofluidics based on continuum model. The non-dimensional conservative equations are derived and simplified assuming the constant properties for the electrolyte. Since the width of the channel is much larger than the height of the rectangular shaped channel, it may be presented by a two dimensional slit. The flow is assumed to be hydro dynamically and thermally fully developed and a linear slip is modeled on the walls using the Navier's law. The walls of the channel are exposed to a