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Nanofluid flow and heat transfer in a microchannel with interfacial electrokinetic effects

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ABSTRACT

The behaviour of microchannel flow of a nanofluid between two parallel flat plates in the presence of the electrical double layer (EDL) is investigated in this paper. The problem is formulated based on the Buongiorno nanofluid model with the electrical body force due to the EDL being considered in the momentum equation. As one of the highlights of the present investigation, the unphysical assumption introduced in previous studies often leading to the discontinuities of flow field that the electrostatic potential in the middle of the channel has to be equal to zero is eliminated. In addition, the inappropriate assumption that the pressure constant is treated as a known condition is also rectified. The new model is developed with the governing equations being reduced by a set of dimensionless quantities to a set of coupled ordinary differential equations. Based on the analytical approximations, the influences of various physical parameters on the flow field and temperature field, and the important physical quantities of practical interests are analysed and discussed in detail.

1. Introduction

The research of fluid flow and heat transfer in microchannel is of significant interest to engineers and scientists in industrial applications such as microchannel heat sinks for cooling high power very large scale integration circuitry and laser diode arrays, heat transfer augmentation in aerospace technology, microreactors for the analysis of biological cells and micro fluid pumps [1,2]. However, conventional transport theories are insufficient to explain many phenomena associated with microscale flow. Experimental observations [3–5] have shown that flow and heat transfer behaviours in microscale are quite different from those in macroscale. Particularly, Wang and Peng [5] noticed that transition and laminar heat transfer in microchannels are highly strange and complicated compared with the conventionally sized situation. They conjectured that this unusual behaviour of microchannel flow may be largely due to electrical double layer (EDL) effects. If the liquid contains very small number of ions, the electrostatic charges on the solid surface will attract the counterions in the liquid to establish an electrical field. The rearrangement of the electrostatic charges on the solid surface and the balancing charges in the liquid is called the EDL [6]. When a liquid is forced through a microchannel under hydrostatic pressure, the ions in the diffuse layer of the EDL are carried towards the downstream end. This causes an electrical current, called streaming current. The accumulation of ions downstream sets up an electrical field with an electrical potential called the streaming potential. This field causes a current, called conduction current, to flow back in the opposite direction. When conduction current is equal to the streaming current a steady state is reached. It is easy to understand that, when the ions are moved in the diffuse double layer, they pull the liquid along with them. However, the motion of the ions in the diffuse double layer is subject to the electrical potential of the double layer. Thus the liquid flow and associated heat transfer are affected by the presence of the EDL.

Generally, for macrochannel flow the EDL effects can be neglected since the EDL thickness is very small as compared to the channels' characteristic length. While for microchannel flow, the thickness of the EDL is comparable to the characteristic length of channels and its effect has to be considered. It is noted that the EDL effects originated from the interfacial electrokinetic effects [7] by the variation of electric potential near a surface and could have a significant influence on the behaviour of fluid flow. Therefore, it

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Nomenclature

A_1, A_2	constants
A_c	cross-sectional area of the microchannel [m]
c	specific heat at constant pressure[J kg^{-1} K^{-1}]
C	nanoparticle volume fraction
C_0	nanoparticle volume fraction at the microchannel entrance
C_w	nanoparticle volume fraction on the microchannel wall surface
C_{f2}	local skin friction coefficients on the lower wall of the microchannel [kg m^{-3}]
D_B	Brownian diffusion coefficient [m^2 s^{-1}]
D_T	thermophoretic diffusion coefficient [m^2 s^{-1}]
e	charge of a proton [C]
Ec	Eckert number
E_s	streaming potential [V]
$\bar{E}_s$	non-dimensional streaming potential
E_x	electric field strength [V m^{-1} or N C^{-1}]
$\mathbf{F}$	electrical body force [N m^{-3}]
G_1	non-dimensional parameter, represents the ratio of the mechanical force to viscous force
G_2	non-dimensional parameter, represents the ratio of EDL force to viscous force
G_3	non-dimensional parameter, represents the ratio of streaming current to conduction current
H	half distance between the upper and lower microchannel walls [m]
I_c, I_s	conduction and streaming currents, respectively [A]
k	Debye-Hückel parameter [m^{-1}]
k_b	Boltzmann constant [J mol^{-1} K^{-1}]
k_f	thermal conductivity of the fluid [W m^{-1} K^{-1}]
L	length of the microchannel [m]
Le	Lewis number
n_i	ionic number concentration of the ith species
n_{0i}	the bulk ionic concentration of type i ions [m^{-3}]
Nb	Brownian motion parameter
Nt	thermophoresis parameter
Nu_2	local Nusselt number on the lower wall of the microchannel
p	pressure [Pa]
Pr	Prandtl number
q_{wT2}	wall heat flux on the lower wall of the microchannel [W m^{-2}]
q_{wC2}	local wall flux of nanoparticles on the lower wall of the microchannel [kg m^{-2} s^{-1}]
Re	Reynolds number
Sh_2	local Sherwood number on the lower wall of the microchannel
T	temperature [K]
T_0	temperature at the microchannel entrance [K]
T_w	temperature on the microchannel wall surface [K]
$\hat{T}$	absolute temperature [K]
u	velocity of the fluid [m s^{-1}]
U	non-dimensional velocity of the fluid
U_m	average velocity of the fluid [m s^{-1}]
x, y, z	Cartesian coordinates [m]
X, Y	non-dimensional Cartesian coordinates
$\hat{z}_i$	the valence of type i ions

Greek symbols

α	thermal diffusivity of the nanofluid [m^2 s^{-1}]
ε	dielectric constant of the medium
ε_0	permittivity of vacuum [C V^{-1} m^{-1}]
κ	non-dimensional electrokinetic separation distance between the upper and lower wall of the microchannel
λ_0	electrical conductivity of the fluid [Ω^{-1} m^{-1}]
μ	dynamic viscosity of the fluid [kg m^{-1} s^{-1}]
ν	kinematic viscosity of the fluid [m^2 s^{-1}]
Θ	non-dimensional temperature distribution
Φ	non-dimensional nanoparticle volume fraction
ρ_e	charge density [C m^{-3}]
ρ_f	density of the fluid [kg m^{-3}]
τ	ratio of the heat capacity of the nanoparticle to that of the fluid
τ_{w2}	shear stress on the lower wall of the microchannel [Pa]
ζ	zeta potential [V]
ψ	electrostatic potential [V]
Ψ	non-dimensional electrostatic potential

is necessary to investigate the fundamental characteristics of these phenomena in order to develop the high quality products. Recently, Mala et al. [8] analyzed the effects of the EDL at the solid-liquid interface on liquid flow and heat transfer through a microchannel between two parallel plates. Mala et al. [9] reported experimental results on flow of distilled water and aqueous solutions through silicon and glass microchannels between two parallel plates. Ren *et al.* [10] further investigated the electro-viscous effect caused by the EDL near a solid–liquid interface in microchannels. Zhang et al. [11] experimentally studied the streaming potentials across a porous membrane in various organic-aqueous solutions.

On the other hand, increasing research effort has been devoted to study the mechanism of nanofluids owing to their great potentials in thermal engineering [12–14]. Many experiments were carried out to investigate convective flow and heat transfer features of various nanofluids [15–17]. Among those studies, Wen and Ding [15] experimentally confirmed that the heat transfer enhancement is prominent when pure heat transfer fluids are replaced by nanofluids. Similar conclusions were drawn by other researchers [18,19]. Theoretically, several mathematical models such as the homogenous flow model [20], the dispersion model [21], the Buongiorno's model [22] have been suggested to predict nanofluids' behaviours. Among these models, the Buongiorno's model received great attention [23] since it explains well the slip mechanisms between the nanoparticles and the base fluid. Since the volumetric distributions of nanoparticles can be altered by virous physical processing, such as fluid flow, heat transfer, electric field, it is very attractive to investigate such multiple physical phenomena with consideration of how these physical processing interacts each other. For example, the EDL modifies the fluid motion obviously, which could affect heat transfer, and also play an important role in the volumetric distribution of the nanoparticles. Therefore, it is necessary to investigate the influence of EDL on liquid flow of nanofluids.

This paper is to examine a steady-state, fully-developed, laminar nanofluid flow in a horizontal microchannel with the interfacial electrokinetic effects. The electrical body force resulting from the electrical double layer (EDL) and the electrokinetic fields are considered in the momentum equation. The energy and the volumetric concentration of the nanoparticles equations are established based on the Buongiorno's model. One nonphysical assumption by Mala et al. [8,9] that the electrostatic potential in the middle of the channel has to be equal to zero is corrected since it can lead to the discontinuities of the flow field. The other inappropriate assumption by Mala et al. [8,9] and Ren *et al.* [10] that