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Convective heat transfer and entropy generation analysis on Newtonian and non-Newtonian fluid flows between parallel-plates under slip boundary conditions

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ABSTRACT

In this study, convective heat transfer and entropy generation in Newtonian and non-Newtonian fluid flows between parallel-plates with velocity slip boundary condition were analytically investigated for both isoflux and isothermal thermal boundary conditions. Accordingly, the governing equations of hydrodynamically and thermally fully developed laminar flows were analytically solved using wall slip boundary conditions while also including viscous dissipation. As a result of this analysis, some closed form expressions for velocity, local and mean temperature distributions, Nusselt number, entropy generation and Bejan number in terms of different parameters such as slip coefficient, power-law index, and Brinkman number were obtained. According to the results, it was found that heat transfer characteristics of non-Newtonian micro flows are strongly influenced by these governing parameters. The derived expressions can be also generalized to Newtonian fluids and to macro scale by letting the power-law index equal to unity and the slip coefficient equal to zero, respectively. The results indicated that an increase in the slip coefficient leads to an increase in both Nusselt number and Bejan number, whereas it gives rise to a decrease in global entropy generation rate. Brinkman number and power-law index had opposite effects on Nusselt number, Bejan number, and entropy generation rate compared to slip coefficient.

1. Introduction

Rapid progress in microfabrication techniques has resulted in micro devices involving heat and fluid flow. Experimental and analytical studies investigating parametric effects on convective heat transfer and entropy generation rate are of cardinal significance to successfully assess heat and fluid flow characteristics in micro- and nano-scale and to identify their differences from conventional scale. One of the most important parameters in micro and nano flows is the slip effect, which strongly influences fluid motion at the fluid–solid interface. Under certain conditions such as very low pressure, hydrophobic surfaces, and small-size channels with characteristic lengths between 1 μm and 1 mm, the continuum assumption may not be accurate, particularly in micro devices, which find applications in medicine, fuel cells, biomedical reaction chambers, Lab-On-a-Chip technology and heat exchangers for electronics cooling. Therefore, it is important to investigate slip flows in order to provide useful prediction tools for convective heat transfer in micro devices.

When the characteristic length (or size of channel) is reduced down to micro-and nano scale, the slip effect becomes apparent, which leads to discontinuities in velocity and temperature (only for gases) profiles at the fluid–solid interface. For flows of polymers, this effect may even occur in macro scale [1,2]. Knudsen number (*Kn*), the ratio of the mean free path to the characteristic length of the channel, is a benchmark to classify flow regimes of gases. *Kn* in the range of $0.001 < Kn < 0.1$ is in the slip flow regime, where fluid velocity at wall is non-zero (velocity slip condition), and wall temperature and adjacent fluid temperature are not the same (temperature jump condition). Heat and fluid flow characteristics for gas microflows have been investigated in many experimental studies [3–6] as well as in numerical and theoretical studies taking temperature-jump and velocity-slip effects into account [7–16].

For liquid flows in macro scale, no-slip boundary condition on solid surface is widely assumed, which may not be always correct in micro and nano fluidic systems. Recent experimental studies of microflows revealed that boundary conditions at the channel wall depend on both flow length scale and surface properties. Hydrophobic smooth surfaces such as in polydimethylsiloxane (PDMS materials) made channels [17–19] or hydrophobic liquids could lead to slip conditions at the channel wall [20] for liquid flows, while slip conditions in liquid flows may also occur when liquid moves over surfaces with microscopic roughnesses [21]. Studies reporting slip lengths for liquid microflows are already present in

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Nomenclature

A	constant defined by Eq. (15)
a	defined by Eq. (32)
b	defined by Eq. (32)
Be	Bejan number
Br	Brinkman number
$C_1, \ldots, C_4$	constant defined in Eq. (22)
c_p	specific heat at constant pressure
D	hydraulic diameter
f	friction factor
H	height of channel
k	thermal conductivity of fluid
l	slip length
L	dimensionless slip length
m	consistency factor
$\dot{m}$	mass flow rate
n	power-law index
N_s	dimensionless entropy generation number
$\langle N_s \rangle$	global entropy generation rate
Nu	Nusselt Number
Pe	Peclet Number
Po	Poiseuille number
p	pressure
q''	heat flux
Re	Reynolds number
S	cross-section area
$\dot{S}$	entropy generation
T	temperature
U, V	dimensional velocity component in the X, Y directions
u, v	dimensionless velocity component in the X, Y directions
U_m	mean velocity
X,Y	dimensional position in coordinate system
x,y	dimensionless position in coordinate system

Greek Symbols

β	slip coefficient
γ	specific heat ratio of fluid
μ	dynamic viscosity of fluid
ξ	defined by Eq. (9a)
ρ	density of fluid
θ	dimensionless temperature
Φ	defined by Eq. (22)
Ω	defined as $q''D/T_ik$
Ψ	defined by Eq. (45)
Γ	perimeter

Subscripts

i	fluid properties at the inlet
m	mean or bulk
s	fluid properties at the surface
w	wall

the literature. Joseph and Tabeling [22] reported slip lengths below 100 nm in water flowing inside 10 μm × 100 μm × 1 cm microchannels in velocity profiles obtained using the particle image velocimetry (PIV) technique. According to the numerical predictions given by El-Genk and Yang [23], slip lengths in the experiments on water flows through microchannels conducted by Celata et al. [24] and Rands et al. [25] were estimated as 1 μm and 0.7 μm, respectively. Tretheway and Meinhart [26] reported that the slip length in water flow in a 30 × 300 μm^2 channel coated with a monolayer of hydrophobic octadecyltrichlorosilane was approximately 1 μm. Slip lengths ranging from 6 μm to 8 μm were measured by Chun and Lee [19] in their experimental study on 1 mM KCl electrolyte flow with fluorescent polystyrene latex of radius 1.05 μm and dilute concentration of 0.48 ppm in a slit-like channel of 3 cm length, 90 μm width and 1000 μm depth. For Newtonian fluids, such as air and water, the wall slip happens when the scale of channel reduces to the order of molecular dimensions or fractions of a micrometer. However, there exist some investigations on thermal and fluid characteristics of Newtonian liquid in microchannels, considering both slip [27–29] and no-slip [30–32] conditions at the surface interface. It has been also observed that slip conditions existed at the channel walls for non-Newtonian fluids, such as polymer solutions and extrusions of polymer melts in capillary tubes because of instabilities induced at sufficiently high stress levels [1,33]. These instabilities were attributed to chain polymer disentanglement [34] and debonding at the interface of wall and polymer [35] and resulted in wall slips for these types of fluids. Bhagavatula and Castro [36] proposed a mathematical model, which used linear Navier slip boundary condition at wall and Carreau viscosity for explaining the rheological behavior corresponding to the coating material. They employed a micro slit rheometer to measure rheological and slip parameters corresponding to the coating material and found that their predictions of pressure and coating thicknesses agreed well with the experimental results.

Since there are many practical applications related to non-Newtonian fluids, the assessment of their heat transfer characteristics is vital for accomplishing successful thermal designs. Hung [37] provided an analytical solution for entropy generation rate of fluid flows through circular microchannels under power law assumption. The author reported that viscous dissipation is significant and should be taken into consideration in the entropy generation analysis.

Chen et al. [38] studied heat transfer characteristics of power-law fluid flow in a microchannel and presented dimensionless temperature distributions and fully developed Nusselt numbers for different parameters such as flow behavior index, ratio of Debye length to half channel height, ratio of Joule heating to surface heat flux, and Brinkman number. Babaie et al. [39] performed a numerical study on heat transfer characteristics of hybrid electroosmotic and pressure driven power-law fluid flows in a microchannel. Their findings revealed that the thermal characteristics were strongly affected by governing parameters such as flow behavior index, zeta potential, and viscous dissipation. Sunarso et al. [40] performed numerical simulations to examine wall slip effects on Newtonian and non-Newtonian fluid flows in microchannels. They found that different vortex growth could be observed in micro scale due to the inclusion of wall slip, which qualitatively matched with experimental results. Barkhordari and Etemad [41] conducted a numerical study on convective heat transfer of non-Newtonian fluid flows in microchannels at both constant temperature and constant heat flux boundary conditions. Their computational results showed that a change in the slip coefficient decreased Poiseuille number while increasing local Nusselt number.

To the authors' best knowledge, few analytical studies on forced convection heat transfer of non-Newtonian fluid in microchannels with slip conditions exist in the literature. This paper aims at proving an analytical solution for non-Newtonian fluid flows between parallel-plates in micro scale subject to isoflux and isothermal thermal wall boundary conditions, while taking the effects of wall