International Journal of Thermal Sciences 128 (2018) 15–27

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Convective heat transfer and entropy generation analysis of non-Newtonian power-law fluid flows in parallel-plate and circular microchannels under slip boundary conditions

Mehdi Kiyasatfar

School of Engineering and Applied Sciences, Khazar University, Baku, Azerbaijan

ARTICLE INFO

Keywords:
Micro flow
Slip flow
Power-law fluid
Nusselt number
Viscous dissipation
Entropy generation

ABSTRACT

This study deals with convective heat transfer and entropy generation analysis of slip flow of non-Newtonian power-law fluids through parallel-plate and circular microchannels. The microchannels were subjected to uniform heat flux boundary condition at the wall. The governing equations relevant to both hydrodynamically and thermally fully developed laminar flows were analytically solved using non-linear slip boundary condition while also including viscous dissipation. Analytical closed form solution of the velocity profiles, temperature distributions, Nusselt number, entropy generation rate and Bejan number in terms of different parameters such as slip coefficient, power-law index and Brinkman number were obtained. The results indicate that increase of the slip coefficient leads to an increase in Nusselt number and a decrease in average entropy generation rate. The effect of slip coefficient on Bejan number is strongly affected by Brinkman number. Low values of either power-law index or Brinkman number result in better working performance of microfluidic systems. Under same conditions, parallel-plate microchannel produce more entropy than circular microchannel. Viscous dissipation significantly affects heat transfer and entropy generation characteristics and cannot be neglected. The results of current study are helpful in deep understanding of flow and heat transfer rates and also designing more thermally efficient microfluidic devices which utilize non-Newtonian fluids.

1. Introduction

Microfluidic systems have found their importance in many scientific and industrial contexts. The extensive use of microchannel in micro-flow devices, has promoted abundant studies on its flow and heat transfer characteristics.

While the original focus is on Newtonian fluids [1–3], more recently interest in non-Newtonian fluids has increased due to its important multidisciplinary applications as biological and chemical fluids in lab on chip systems [4–9]. It is noteworthy to mention here that many fluids such as biological fluids, foams, suspensions, polymer melts and solutions in real-life applications obey non-Newtonian rheological characteristics, whose viscosities are basically a function of shear rate, different from those of conventional Newtonian fluids.

Commonly, for a simpler describing of conventional flow situations, the viscous dissipation terms are neglected in the governing energy conservation equation. However, these terms are of specific importance when it comes to microchannels, to the point that an appreciable rise in the fluid temperature happens based on the conservation of kinetic motion of the fluid to thermal energy. In particular, the effects of viscous dissipation play a significant role in the governing equations due to its large length-to-diameter ratio and existence of large velocity gradient, especially in fluids of low specific heat and high viscosity. There have been abundant studies, for examples see Refs. [10–15], investigating viscous dissipation effect on the heat transfer characteristic of fluids flow in microchannels.

Jambal et al. [16] studied the effects of viscous dissipation and fluid axial heat conduction on heat transfer for non-Newtonian fluids in parallel-plates and circular ducts subjected to uniform wall temperature. The effect of viscous dissipation, axial conduction and temperature dependent viscosity on the thermally developing flow of power-law liquids in a microchannel with uniform heat flux boundary condition were studied by Dehkordi and Memari [17]. They also proposed correlation for the entrance length as a function of power-law index and wall heat flux. Babaie et al. [18] numerically studied on heat transfer characteristics of mixed electroosmotic and pressure driven flow of power-law fluids in a slit microchannel. Their findings revealed that the thermal characteristics were strongly affected by governing parameters such as flow index, zeta potential and viscous dissipation. Ragueb and Mansouri [19] carried out a numerical analysis to study the heat

---

E-mail address: m.kiyasatfar@gmail.com.

https://doi.org/10.1016/j.ijthermalsci.2018.02.013
Received 29 November 2016; Received in revised form 10 February 2018; Accepted 11 February 2018
1290-0729/

Nomenclature

A_c	cross-sectional area
b	slip law exponent
Be	Bejan number
Br	Brinkman number
CC	circular channel
C_p	specific heat at constant pressure
C_1	constant defined in Eq. (20)
C_2	constant defined in Eq. (21)
C_3	constant defined in Eq. (22)
D	hydraulic diameter
f	slip-friction coefficient
F	dimensionless slip-friction coefficient
h	convective heat transfer coefficient
H_0	height of half parallel-plates channel
H_1	radius of circular channel
k	thermal conductivity of fluid
m	0 for parallel-plates channel and 1 for circular channel
n	power-law index
N_S	dimensionless entropy generated
N_S	average dimensionless entropy generated
Nu	Nusselt number
P	pressure
Pe	Peclet number
PP	Parallel-plates
q_w	heat flux at the wall
Re	Reynolds number
$\dot{S}_{gen}^{\prime\prime\prime}$	volumetric rate of entropy generation
T	temperature
U	dimensional velocity component in the X direction
u	dimensionless velocity component in the x direction
U_m	mean velocity
X	dimensional axial position in the coordinate system
x	dimensionless axial position in the coordinate system
Y	dimensional transverse position in coordinate system
y	normalized transverse position in coordinate system

Greek symbols

β	slip coefficient
η	consistency factor
τ	shear stress
ρ	density of fluid
θ	dimensionless temperature
ψ	dimensionless heat flux
ϕ	irreversibility distribution ratio

Subscripts

FF	fluid friction
HT	Heat transfer
m	Mean or refers to pp and cc
w	wall
ws	Wall slip

transfer characteristics of a laminar flow of a power-law fluid with viscous dissipation. They found that in the fully developed region, Nusselt number increases with increase in aspect ratio. Kiyasatfar and Pourmahmoud [20] investigated the effects of viscous dissipation on heat transfer characteristics of power-law fluids flow through a microchannel at the presence of transverse magnetic field. Their results indicated that the Nusselt number strongly depends on the values of flow behavior index and Brinkman number.

It is accepted in fluid mechanics that the velocity of fluid immediately adjacent to a solid is equal to that of the solid [21,22]. Such an absence of a jump in the velocity of a simple liquid at a surface seems to be a confirmed fact in macroscopic experiments. However, at macro level, wall slip can occur by instabilities at high stress level in polymer extrusion processes [23]. Here the wall slip affects the quality of the final product. The phenomena of wall slip has many industrial and practical application, especially in micro scales. Therefore slip effect is the one of the most important parameters in micro and nano flow, which strongly influences fluid motion at the fluid–solid interface. The flow of liquid in microchannel is different from that of a gas in the same microchannel [24]. The flow regimes of gases are classified according to a parameter called Knudsen number Kn, which is the ratio of mean free path to characteristic length of channel. Gas flows in microsystems are often in the slip flow regime, with Knudsen number of the order of $10^{-3} \sim 10^{-1}$ [25]. In this regime, velocity slip and temperature jump at the walls play a major role in heat transfer. For micro-flows of liquids, the boundary conditions are depended on both flow length scale and surface properties. Channels with hydrophobic surfaces (like PDMS) [26–28] or hydrophobic liquids could lead to slip conditions at the channel wall [29] for liquid flows. Also, slip conditions in liquid flows may occur when liquid moves over surfaces with micro-scale roughnesses [30].

The possibility of slippage in non-Newtonian fluids have been extensively studied [31–39]. Denn [40] presented a review of mechanisms of slip in non-Newtonian fluids and also explores the relation between slip and extrusion instabilities. Pereira [41] studied microfluidic flows under slip of Newtonian, generalized Newtonian and viscoelastic fluids governed by the linearized White–Metzner model using the Navier slip boundary condition. Ferras et al. [42] solved analytically the Couette and Poiseuille flow of Newtonian as well as inelastic non-Newtonian fluids using slip boundary conditions. They considered the various slip boundary conditions such as Navier's linear slip law, non-linear slip law, Hatzikiriakos slip law and asymptotic slip law.

In recent years the practical application of entropy generation concept has been realized in many areas of research. A comprehensive review of applications of the entropy concepts in various research areas can be found in Refs. [43,44]. The minimization of entropy generation is a key design objective, especially in microsystems such as micro-scale heat exchangers, cooling of electronic devices and microfluidic lab on chip systems. Considering that microchannels are the fundamental part of this systems, the analysis of entropy generation mechanism in microchannels is very important to optimize the second law performance of these microscale devices.

To obtain the desired functions through microfluidic systems, it is inherently necessary to control the fluid flow and heat transfer in microchannels. A widely applied optimization criterion is the maximization of ratio of heat transfer to pressure drop. This criterion can be misleading in studying the problems such as natural convection. In general, identifying an appropriate thermal performance metric for a technically important problem like electronic cooling can be very difficult [45].

All industrial and engineering flow processes and thermal systems induce entropy generation and thus destroy system available work and reduce its energy efficiency. Therefore, in addition to the analysis based on the basic conservation laws, entropy analysis is a technique to quantify the thermodynamic irreversibility in any fluid flow and heat transfer processes in microfluidics devices. This technique is an outcome of second law of thermodynamics and is useful for determining optimized operation conditions that lead to a minimum dissipation consistent with the physical constraints demanded by the system. The method which was first devised by Bejan [46,47] is referred to as