Ain Shams Engineering Journal (2015) 6, 1045–1052

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Ain Shams Engineering Journal

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ENGINEERING PHYSICS AND MATHEMATICS

Free convective flow of heat generating fluid through a porous vertical channel with velocity slip and temperature jump

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Received 19 June 2014; revised 4 November 2014; accepted 14 December 2014
Available online 7 February 2015

KEYWORDS

Oscillatory flow;
Velocity slip;
Temperature jump;
Micro-channel

Abstract This paper investigates the unsteady free convective flow of heat generating/absorbing fluid through a porous vertical channel with velocity slip and temperature jump. Exact solution of the oscillatory flow problem is obtained in the slip flow regime through a microchannel. The effects of various flow parameters on the temperature and velocity profiles together with the influence of the velocity slip and temperature jump on the rate of heat transfer and the skin friction are presented and discussed.

1. Introduction

The study of convective heat transfer to viscous incompressible slip flow through a channel has gained a lot of attention because of its importance in physiological flows, electronic cooling, drying processes, heat exchangers and many more. An appreciable number of studies have been reported on these flows under different flow conditions by Hayat and his collaborators. For instance, Hayat et al. [1] obtained closed form solutions of momentum and energy equations with slip and heat transfer on the peristaltic flow through an asymmetric channel. Hayat et al. [2] investigated the slip effects on the flow and heat transfer of a third grade fluid past a porous plate. More interesting result on slip flow can be seen in [3–5] to mention just a few. Moreover, Mehmood and Ali [6] (and references therein) showed that the no-slip boundary condition may not be suitable for hydrophilic flows over hydrophobic boundaries at both the micro- and nanoscale. Also in mechanical engineering, partial slip can occur in a channel with a coated or polished surface like polished artificial heart valves. The phenomenon also common in the flow of blood, paint and foam to mention just a few.

In order to improve the cooling of electronic components subjected to periodic cooling several investigations on oscillatory flow problems have been conducted. For example, Jha and Ajibade [7–9] presented some results on the free convective motion of a viscous incompressible fluid between two periodically heated infinite vertical parallel plates. In all the studies in [7–9], the effects of velocity slip and temperature jump were neglected by assuming that the fluid velocity is zero relative to the solid boundary. However, with the influx of microelectronic devices over the last few years, all these studies may not

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Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2014.12.008
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Nomenclature

t'	time	Q	is the term due to internal heat generation
u'	velocity	k	represents the thermal conductivity
v_0	constant horizontal velocity	ϕ	is the specific heat ratio
ρ	fluid density	T	fluid temperature
v	kinematic viscosity	T_0, T_1 and T_2	referenced fluid temperature respectively
σ_T	is the thermal accommodation coefficient	k_n	is the Knudsen number
λ	is the molecular mean free path	St	is the Strouhal number
ξ	is the tangent momentum accommodation coefficient intensity	s	is the suction/injection parameter
g	gravitational acceleration	Pr	is the Prandtl number
β	volumetric expansion	δ	is the heat generating parameter
C_p	is the specific heat capacity at constant pressure	γ	is the Navier slip parameter

accurately guarantee the efficient and effective removal of heat generated within the high performance electronic devices. According to Dharaiya and Kandlikar [10], Hung and Ru [11] micro-channels are the most efficient way of high heat flux removal from small areas.

It is known that for flows through a micro-channel, $k_n = 0$ represents the no slip condition and $k_n < 0.001$ is valid for continuum flow while $0.001 < k_n < 0.1$ is the slip regime which can be modelled using the Navier stokes equation taking the slip velocity and temperature jump into consideration for accurate results. Motivated by Zheng et al. [12], the main objective of this paper was to investigate the combined effects of partial slip and temperature jump on the free convective flow of heat generating and absorbing fluid through a micro-channel thereby extending the work done in [8] to a micro-channel. More details on velocity slip and temperature jump can be found in the work by Haddad et al. [13,14], Hooman et al. [15], Chen [16] and Aziz [17].

To achieve this objective, the problem is formulated and the dimensionless analysis is performed in the Section 2 of the paper. Based on the oscillatory nature of the flow, exact solution of the problem is presented. It is interesting to note that when velocity slip and temperature jump are neglected in the present problem, the result coincides with what is obtained in [8]. The real part of the results is presented and discussed in Section 4 of the paper while Section 5 concludes the work.

2. Mathematical analysis

Consider the laminar free convective flow of a viscous incompressible heat generating/absorbing fluid in a vertical channel due to heating of the porous channel plates with slip and temperature jump at the lower wall. The micro-channel walls are taken vertically and parallel to the x-axis at $y = \pm h$. It is assumed that on one plate ($y = h$), fluid is injected into the channel with certain constant velocity (v_0) and that it is sucked off from the other plate ($y = -h$) at the same rate (see Fig. 1). It is further assumed that interfacial interaction between the gas molecules and the surface atoms exists. In other words, the gas molecules are assumed to interact with the surface of the solid via a long range attractive force. As a result of this interaction, the gas molecules can be adsorbed onto the surface which are then reflected after some time lag. This time lag leads to macroscopic velocity slip and temperature jump [17]. The flow is induced by the periodic heating introduced on both walls. The governing equations for the fully developed flow and heat transfer can be written as [8]:

$$\left.\begin{aligned} \frac{\partial u'}{\partial t'} - v_0\frac{\partial u'}{\partial y'} &= v\frac{\partial^2 u'}{\partial y'^2} + g\beta(T - T_0) \\ \frac{\partial T}{\partial t'} - v_0\frac{\partial T}{\partial y'} &= \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y'^2} + \frac{Q}{\rho C_p}(T_0 - T) \end{aligned}\right\} \tag{1}$$

together with appropriate initial condition

$$u'(t', y') = 0,\ T(t', y') = T_0 \quad t' = 0 \tag{2}$$

For rarefied flow with temperature jump, the appropriate initial-boundary conditions can be written as [8,12 and 17]

$$\begin{aligned} &u'(t', y') = \frac{2-\xi}{\xi}\lambda\frac{du'}{dy'}, \\ &T(y', t') = T_1 + T_2 Cos(\omega t) + \frac{2-\sigma_T}{\sigma_T}\frac{2\phi}{\phi+1}\frac{\lambda}{\Pr}\frac{dT}{dy'}, \\ &y' = -h \quad t' > 0 \end{aligned} \tag{3}$$

and the non-moving wall and isothermal condition give

$$u'(t', y') = 0,\ T(y', t') = T_1 + T_2 Cos(\omega t) \quad y' = h \qquad t' > 0 \tag{4}$$

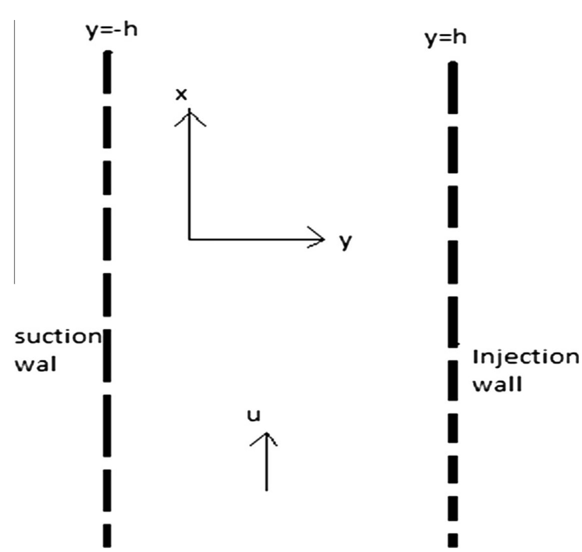

Figure 1 Channel geometry.