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

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KEYWORDS

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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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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]

$$u'(t', y') = \frac{2 - \xi}{\xi} \lambda \frac{du'}{dy'},$$

$$T(y', t') = T_1 + T_2 Cos(\omega t) + \frac{2 - \sigma_T}{\sigma_T} \frac{2\phi}{\phi + 1} \frac{\lambda}{\Pr} \frac{dT}{dy'},$$

$$y' = -h \quad t' > 0 \tag{3}$$

and the non-moving wall and isothermal condition give

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

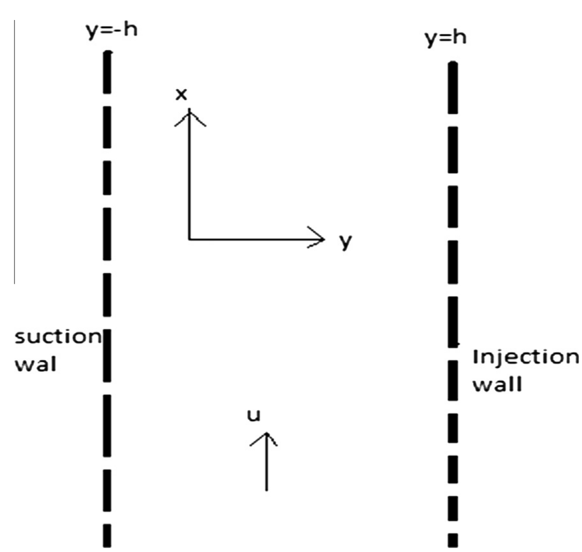

Figure 1 Channel geometry.

The following expressions are used in [8] to split the velocity and temperature into steady and unsteady part respectively.

$$\left.\begin{aligned} u'(t,y) &= \tfrac{g\beta h^2}{v}((T_1 - T_0)A(y) + T_2B(y)e^{iwt}) \\ T(t,y) &= T_0 + (T_1 - T_0)F(y) + T_2G(y)e^{i\omega t} \end{aligned}\right\} \quad (5)$$

together with the following dimensionless quantities and variables

$$\begin{aligned} &y = \tfrac{y'}{h}, \; St = \tfrac{h^2\omega}{v}, \; \Pr = \tfrac{\mu C_p}{k}, \; s = \tfrac{hV_0}{v} \\ &\delta = \tfrac{Q_0h^2}{k}, \; k_n = \tfrac{\lambda}{h}\left(\tfrac{2-\sigma_T}{\sigma_T}\right)\tfrac{2\phi}{\phi+1}, \; \gamma = \tfrac{(2-\xi)\lambda}{\xi h} \end{aligned} \quad (6)$$

gives

$$\begin{aligned} &iStT_2B(y)e^{iwt} - (T_1 - T_0)sA'(y) - T_2sB'(y)e^{iwt} \\ &\quad = (T_1 - T_0)A''(y) + T_2B''(y)e^{iwt} + (T_1 - T_0)F(y) \\ &\qquad + T_2G(y)e^{i\omega t} \end{aligned} \quad (7)$$

and

$$\begin{aligned} &i\Pr StT_2G(y)e^{i\omega t} - (T_1 - T_0)s\Pr F'(y) - T_2s\Pr G'(y)e^{i\omega t} \\ &\quad = (T_1 - T_0)F''(y) + T_2G''(y)e^{i\omega t} - \delta(T_1 - T_0)F(y) \\ &\quad - T_2\delta G(y)e^{i\omega t} \end{aligned} \quad (8)$$

Similarly, the boundary conditions yield

$$\begin{aligned} &(T_1 - T_0)A(y) + T_2B(y)e^{iwt} = \gamma k_n(T_1 - T_0)A(y) \\ &\quad + \gamma k_nT_2B(y)e^{iwt}, \; y = -1 \\ &(T_1 - T_0)A(y) + T_2B(y)e^{iwt} = 0 \quad y = 1 \end{aligned} \quad (9)$$

together with the boundary conditions

$$\begin{aligned} &(T_1 - T_0)F(y) + T_2G(y)e^{i\omega t} = T_1 - T_0 + T_2Cos(\omega t) \\ &\quad + \tfrac{k_n}{\Pr}((T_1 - T_0)F'(y) + T_2G'(y)e^{i\omega t}), \; y = -1 \\ &(T_1 - T_0)F(y) + T_2G(y)e^{i\omega t} = T_1 - T_0 + T_2Cos(\omega t), \quad y = 1 \end{aligned} \quad (10)$$

equating orders of $e^{i\omega t}$, in the steady regime we have

$$\begin{aligned} &A''(y) + sA'(y) = -F(y); \qquad A(-1) = \gamma A'(-1), \quad A(1) = 0 \\ &F''(y) + s\Pr F'(y) - \delta F(y) = 0, \; F(-1) = 1 + \tfrac{k_n}{\Pr}F'(-1), \; F(1) = 1 \end{aligned} \quad (11)$$

While in the periodic regime, we get

$$\begin{aligned} &B''(y) + sB'(y) - iStB(y) = -G(y); \; B(-1) = \gamma B'(-1), \\ &B(1) = 0 \\ &G''(y) + s\Pr G'(y) - (\delta + i\Pr St)G(y) = 0; \\ &G(-1) = 1 + \tfrac{k_n}{\Pr}G'(-1), \quad G(1) = 1 \end{aligned} \quad (12)$$

Evidently, in the asymptotic case as $\gamma, k_n \to 0$ the boundary valued problem (11), (12) reduced to that in [8]. Observe that Eq. (12) is a generalized form of (11) and as such will give the same solution as (12) whenever $St = 0$. Hence, the solution of the (12) when $St \neq 0$ will be sufficient to describe the periodic fluid flow behaviour.

3. Method of solution

The exact solution of the boundary valued problem (12) can be written as

$$\begin{aligned} G(y) &= a_1e^{\frac{m_1}{2}y} + a_2e^{\frac{m_2}{2}y} \\ B(y) &= a_3e^{\frac{m_3}{2}y} + a_4e^{\frac{m_4}{2}y} - \tfrac{1}{n_0}\left(a_5e^{\frac{m_1}{2}y} + a_6e^{\frac{m_2}{2}y}\right) \end{aligned} \quad (13)$$

The rate of heat transfer is given by

$$Nu = -\frac{\partial G}{\partial y} = -\frac{a_1m_1}{2}e^{m_1y} - \frac{a_2m_2}{2}e^{m_2y} \quad (14)$$

while the shear stress is given by

$$\begin{aligned} S_f &= \frac{\partial B}{\partial y} \\ &= \frac{a_3m_3}{2}e^{\frac{m_3}{2}y} + \frac{a_4m_4}{2}e^{\frac{m_4}{2}y} - \frac{1}{n_0}\left(\frac{a_5m_1}{2}e^{\frac{m_1}{2}y} + \frac{a_6m_2}{2}e^{\frac{m_2}{2}y}\right) \end{aligned} \quad (15)$$

the constants are all defined in the Appendix.

4. Results and discussion

In this section, variation of parameters are carried out for different values of parameters such as the heat generation/absorption, temperature jump, suction/injection, Prandtl number, Knudsen number and Navier slip. To show the accuracy of the solution, Tables 1 and 2 show the comparison of the present result with previously obtained result in the literature in the asymptotic limit. Note that $\delta < 0$ is the internal heat generation while $\delta > 0$ implies the heat absorption. Fig. 2 shows the temperature profile at different values of the temperature jump parameter. It is observed from the plot that during fluid absorption, the temperature profile is decreased with an increase in the values of the temperature jump parameter k_n. This is due to the fact that the molecular distance of the fluid increases as k_n increases hence heat flux decreases within the channel.

Figs. 3 and 4, represent the effects of variation of heat generation/absorption parameter on the temperature profile. The result shows that as the internal generation parameter increases there is corresponding rise in the fluid temperature. This is due to the fall in thermal conductivity of the fluid. On the other hand if the fluid chemical interaction is endothermic then the fluid temperature decreases as seen in Fig. 4. In Fig. 5, the influence of fluid suction and injection on the fluid temperature is shown. From the figure, one observed that in the absence of suction/injection the temperature is symmetrical about the channel half width, further increase in this parameter shows that the temperature increases but the profile is observed to be skewed towards the wall with suction. However, a decrease in the fluid temperature is observed in Fig. 6 as the Strouhal number (oscillation parameter) increases. This is attributed to the reduction in the intensity of heating of the boundary plates as the frequency of heating increases. In Fig. 7, it is observed that an increase in the fluid Prandtl number decreases the fluid temperature. This is due to decrease in thermal conductivity of the fluid within the micro-channel.

As observed in Fig. 8, the rate of heat transfers at the plate with suction decreases with increase in the temperature jump parameter. This is physically true since the fluid–plate interaction at the suction wall decreases. This consequently decreases the heat flux on the boundary plates as the temperature jump increases. In Fig. 9, it is observed that an increase in the Navier slip parameter enhances the flow at the plate with suction this is due to increased gas–molecule interaction with the suction wall. On the other hand as observed in Fig. 10, an increase

Table 1 Showing convergence of solution of $G(y)$ when $\gamma = 0, k_n = 0,\ St = 1 = s = \Pr = \delta$.

y	Previous result [8] for $G(y)$	Present result for $G(y)$	Absolute error
−1	1	1	4.44089×10^{-16}
−0.75	0.77398	0.77398	1.11022×10^{-16}
−0.5	0.648087	0.648087	2.22045×10^{-16}
−0.25	0.596908	0.596908	1.11022×10^{-16}
0	0.602555	0.602555	2.22045×10^{-16}
0.25	0.652739	0.652739	5.55112×10^{-16}
0.5	0.739168	0.739168	7.77156×10^{-16}
0.75	0.856242	0.856242	7.77156×10^{-16}
1	1	1	4.44089×10^{-16}

Table 2 Showing convergence of solution of $B(y)$ when $\gamma = 0, k_n = 0,\ St = 1 = s = \Pr = \delta$.

y	Previous result [8] for $B(y)$	Present result for $B(y)$	Absolute error
−1	-2.22045×10^{-16}	-4.44089×10^{-16}	2.22045×10^{-16}
−0.75	0.141466	0.141466	7.77156×10^{-16}
−0.5	0.213966	0.213966	2.22045×10^{-16}
−0.25	0.243139	0.243139	2.22045×10^{-16}
0	0.242830	0.242830	1.66533×10^{-16}
0.25	0.218953	0.218953	55.55112×10^{-16}
0.5	0.172309	0.172309	1.11022×10^{-16}
0.75	0.100621	0.100621	7.77156×10^{-16}
1	-6.66134×10^{-16}	-2.22045×10^{-16}	4.44089×10^{-16}

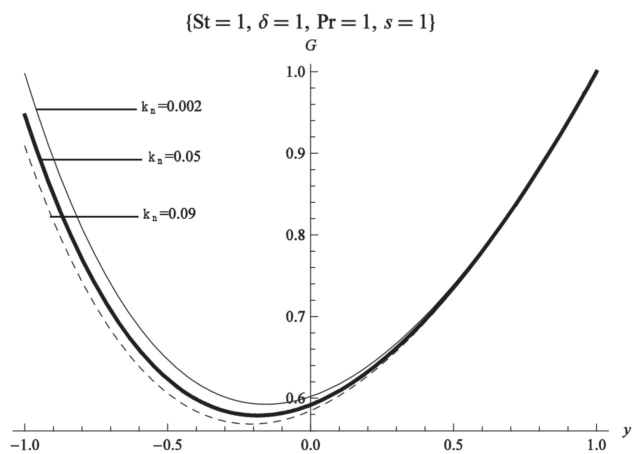

Figure 2 Temperature profile for different values of temperature jump parameter.

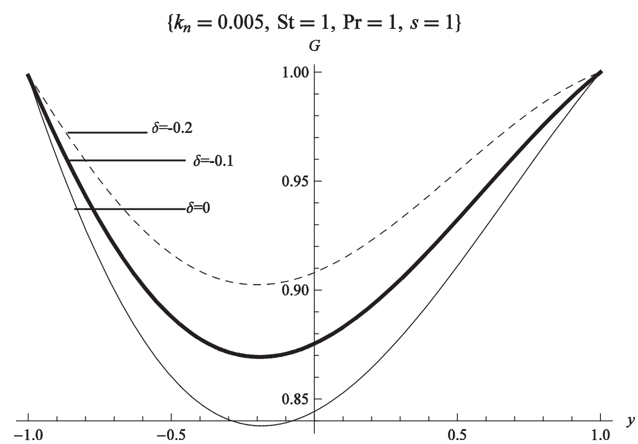

Figure 3 Temperature profile for different values of internal heat generation parameter.

in the temperature jump is seen to decrease the fluid velocity close to the suction wall as well as decreasing the fluid temperature maximum. This is physically correct since an increase in k_n implies an increase in the molecular distance in the fluid and this decreases the fluid temperature as shown in Fig. 2. This in turn weakens the convection currents and it is expected to decrease the fluid flow velocity.

While in Fig. 11, increasing the heat generation parameter is observed to improve the fluid flow. This is due to the physical fact that temperature within the channel grows with increase in heat generation parameter (Fig. 3) due to chemical interaction of the fluid particles and this strengthens the convection currents which consequently increases the fluid velocity while the reverse is the case during fluid absorption as shown in Fig. 12. In Fig. 13, it is observed that an increase in Prandtl number leads to a decrease in the flow velocity. This is true due to fluid thickening associated with rise in fluid viscosity as the Prandtl number increases. As seen in Fig. 14, an increase in fluid suction/injection increases the flow velocity and the increase breaks the symmetry in the flow, which is skewed towards the plate with suction. While in Fig. 15, the effect of oscillation on the flow velocity is seen to reduce the flow velocity. Finally, the effect of the velocity slip on the skin friction is presented in Fig. 16. From the graph it is observed that an increase in the Navier slip parameter weakens the skin friction at the suction wall.

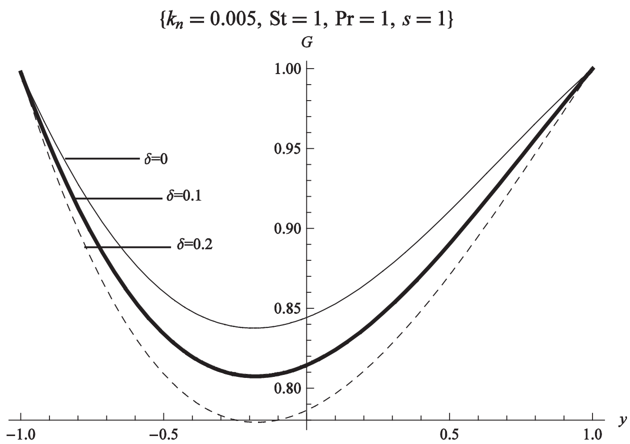

Figure 4 Temperature profile for different values of internal heat absorption parameter.

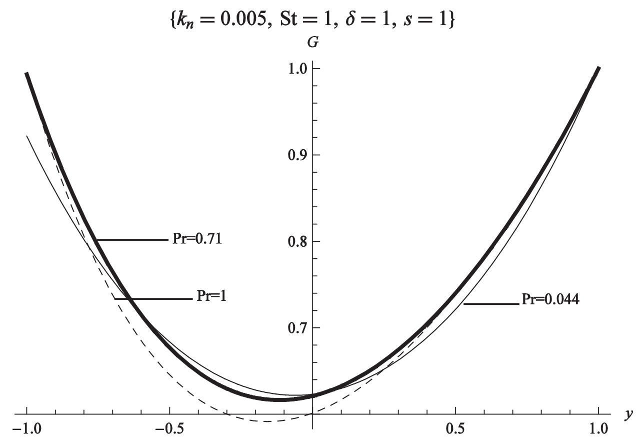

Figure 7 Temperature profile for different values of Prandtl number.

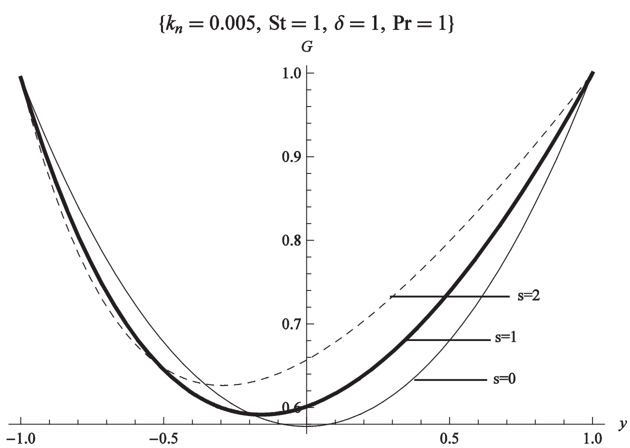

Figure 5 Temperature profile for different values of wall injection parameter.

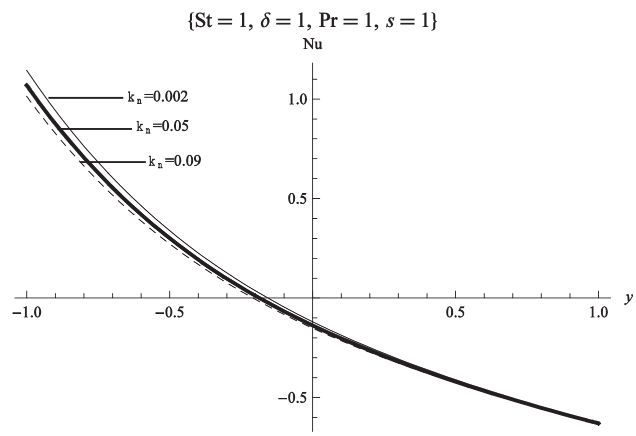

Figure 8 Heat transfer rate for different values of temperature jump parameter.

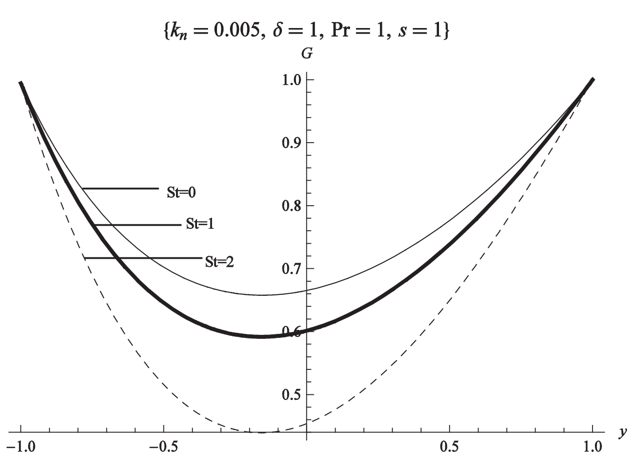

Figure 6 Temperature profile for different values of oscillation parameter.

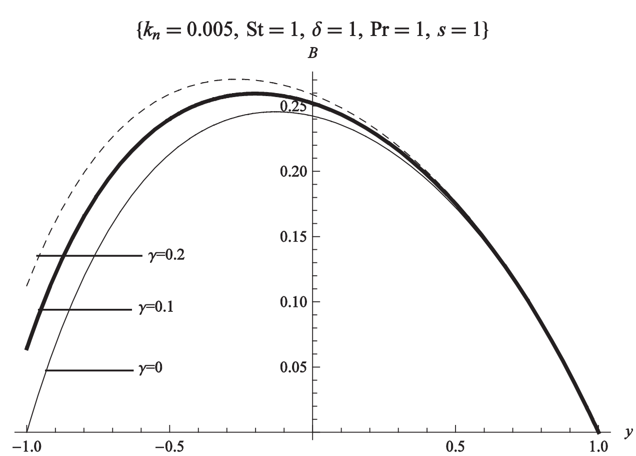

Figure 9 Velocity profile for different values of velocity slip parameter.

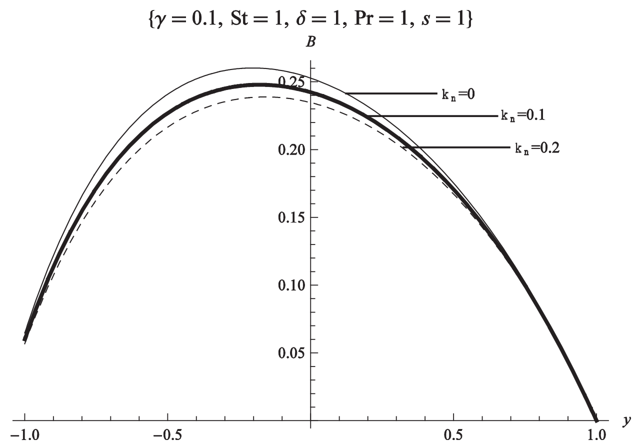

Figure 10 Velocity profile for different values of temperature jump parameter.

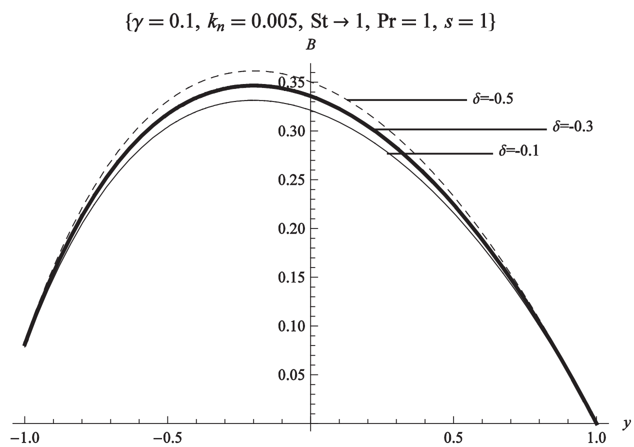

Figure 11 Velocity profile for different values of internal heat generation parameter.

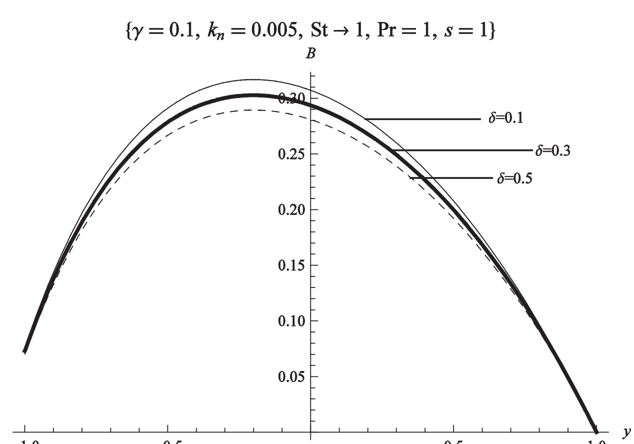

Figure 12 Velocity profile for different values of internal heat absorption parameter.

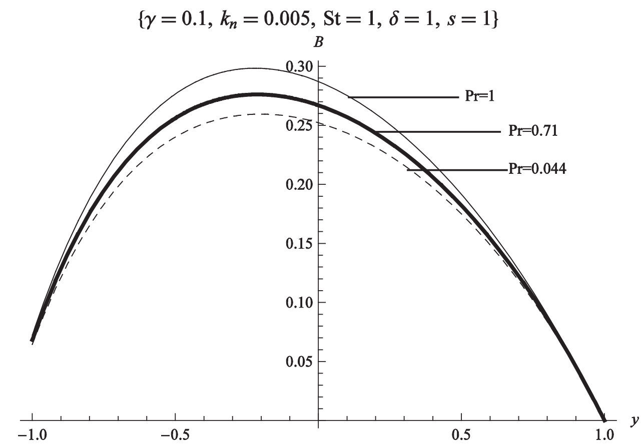

Figure 13 Velocity profile for different values of Prandtl number.

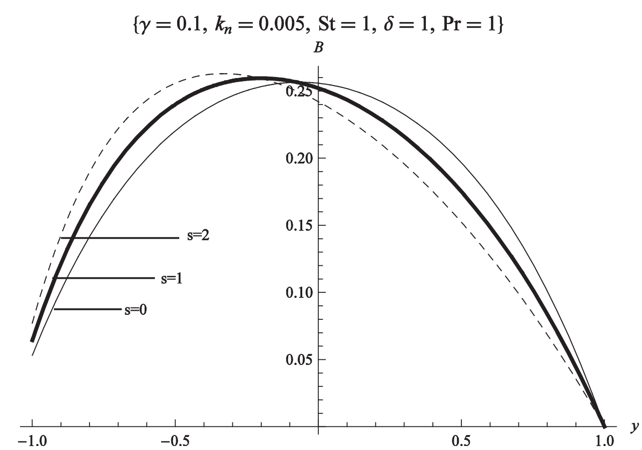

Figure 14 Velocity profile for different values of wall injection parameter.

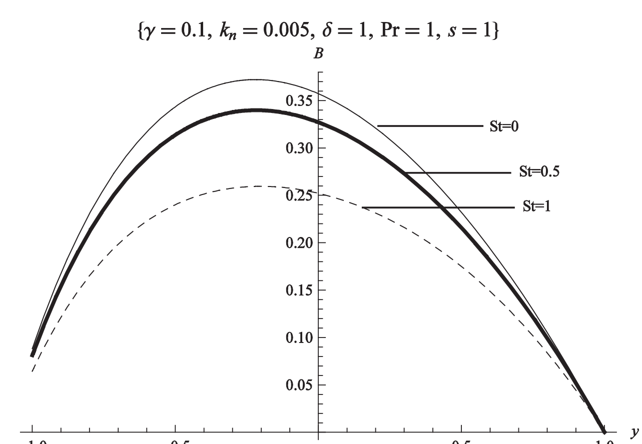

Figure 15 Velocity profile for different values of Strouhal number.

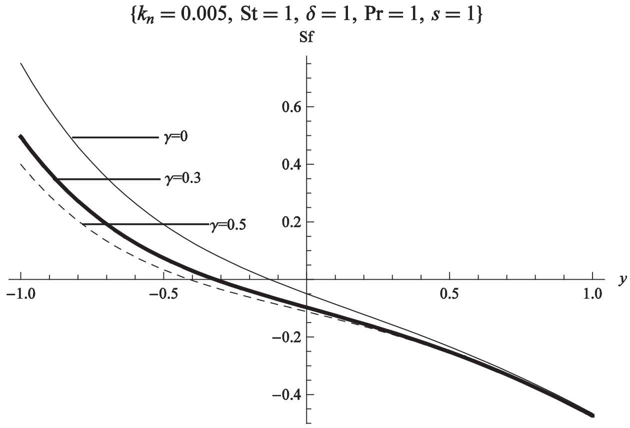

Figure 16 Wall shear stress for different values of slip parameter.

5. Conclusion

In this paper, the free convective flow of heat generating/absorbing fluid through porous vertical micro-channel with velocity slip and temperature jump is studied. Exact solutions are obtained for the velocity and temperature profiles. The present result reduced to that obtained in [8] in the absence of Navier slip and temperature jump. In addition, an increase in the slip parameter is shown to increase the flow velocity and decrease the shear stress at the suction wall. Moreover, an increase in the temperature jump parameter increases the fluid temperature and decreases the rate of heat transfer at the suction wall. The result obtained here is significant in the cooling of electronic devices.

Acknowledgement

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Appendix A

$$m_1 = -\Pr\, s - \sqrt{\Pr^2\, s^2 + 4i\,\Pr\, St + 4\delta}$$

$$m_2 = -\Pr\, s + \sqrt{\Pr^2\, s^2 + 4i\,\Pr\, St + 4\delta}$$

$$a_1 = -\frac{e^{\frac{m_1}{2}}(-2\Pr + 2e^{m_2}\,\Pr + k_n m_2)}{2e^{m_1}\,\Pr - 2e^{m_2}\,\Pr + e^{m_2}k_n m_1 - e^{m_1}k_n m_2}$$

$$a_2 = -\frac{e^{\frac{m_2}{2}}(-2\Pr + 2e^{m_2}\,\Pr + k_n m_2)}{-2e^{m_1}\,\Pr + 2e^{m_2}\Pr - e^{m_2}k_n m_1 + e^{m_1}k_n m_2}$$

$$a_5 = 4\left(-4iSta_1 + 2sa_1m_2 + a_1m_2^2\right)$$

$$a_6 = 4\left(2sa_2m_1 + a_2m_1^2 - 4iSta_2\right)$$

$$n_0 = \left(-s + \sqrt{s^2 + 4iSt} - m_1\right)\left(s + \sqrt{s^2 + 4iSt} + m_1\right) \times \left(-s + \sqrt{s^2 + 4iSt} - m_2\right)\left(s + \sqrt{s^2 + 4iSt} + m_2\right)$$

$$n_1 = n_0(-2e^{m_3} + 2e^{m_4} - \gamma m_3 e^{m_4} + \gamma m_4 e^{m_3})$$

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$$a_3 = \frac{4e^{-\frac{1}{2}(m_1+m_2-m_3)}\left\{\left(e^{m_4+\frac{1}{2}m_2}(2-\gamma m_1) + e^{m_1+\frac{1}{2}m_2}(\gamma m_4 - 2)\right)a_5 + \left(e^{m_2+\frac{1}{2}m_1}(\gamma a_6 m_4 - 2) + e^{m_4+\frac{1}{2}m_1}(2-\gamma m_2)\right)a_6\right\}}{n_1}$$

$$a_4 = -\frac{4e^{-\frac{1}{2}(m_1+m_2-m_4)}\left\{(e^{m_1+\frac{1}{2}m_2}(\gamma m_3 - 2) + e^{m_3+\frac{1}{2}m_2}(2-\gamma m_1))a_5 + \left(e^{m_2+\frac{1}{2}m_1}(\gamma m_3 - 2) + e^{m_3+\frac{1}{2}m_1}(2-\gamma m_2)\right)a_6\right\}}{n_1}$$

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