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Hydromagnetic Free Convection Flow with Hall Effect and Mass Transfer

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Abstract. The study of magnetohydrodynamics (MHD) deals with the flow of an electrically conducting fluid in the presence of an electromagnetic field, which has many applications in astrophysics, geophysics and engineering. Objective of the present study in this paper is to consider the effect of dissipation and Hall current on the MHD free convection flow with mass transfer in a porous vertical channel. An exact solution of the governing equations is obtained by solving the complex variables. The effect of Hall parameter (m), Hartmann number (M), and Concentration parameter (S_c) on the velocity and temperature of the fluid is studied. Simulation results show that the shear stress of primary and secondary velocity for the lower plate increases with increase in the strength of Hall parameter (m) and decreases with increase in Hartmann number (M) and concentration parameter (S_c).

INTRODUCTION

Magnetohydrodynamics (MHD) or hydromagnetics is a simplified model of magnetized plasma in which plasma is treated as a single fluid and can carry an electric current. By saying single fluid, it is meant that there is only one density, i.e. the mass density and temperature, and there is also only one velocity, since electrons and ions cannot be treated separately. Though, an infinitesimal element of each fluid is assumed to contain an arbitrarily large number of charged particles of the corresponding species, it is too small compared to the spatial scale over which macroscopic thermodynamic or field quantity varies. Besides, the contribution of the electrons to fluid inertia could be neglected as the mass of an individual electron is so much smaller than that of an individual ion.

The magnetic field responding to the electric field as usual is actually adverted by the velocity field, since the latter is related in a constitutive way to the electric field, which is the ideal MHD model. The study of the problem of heat and mass transfer of an electrically conducting fluid through a channel has many engineering applications such as cooling of nuclear reactors, rocket technology etc. Authors in [1] have studied the hydromagnetics free convection flow of a viscous incompressible fluid. Authors in [2], [3], [4] have studied free convection flow with mass transfer in the presence or absence of magnetic field. However, authors in [5], and in [6] have studied the effect of Hall current on a steady hydromagnetics free convection flow.

The Hall effect on oscillatory hydromagnetics free convection flow past an infinite vertical porous flat plate has analyzed in [7]. Authors in [8] have studied the effect of viscous dissipation in natural convection in the absence of magnetic field. However, in the above investigations they have not considered the mass transfer and Hall effect simultaneously. Also, in the above studies the effect of viscous dissipation which plays an important role has been neglected. The objective of the present study is to consider the effect of dissipation and Hall current on the MHD free convection flow with mass transfer in a porous vertical channel.

The rest of the paper is organized as follows. Mathematical formulation of the said problem is made in Section II and possible solution is derived in Section III. Effect of viscous dissipation is analyzed in Section IV. Simulation results of various physical parameters on the flow are discussed in Section V and concluding remarks are made in Section VI.

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MATHEMATICAL FORMULATION

Consider the free convection flow of an electrically conducting fluid in a vertical channel, where the plates are separated by a distance of h units from each other. It is considered that the x'-axis is parallel to the plate and y'-axis is normal to it. There is a uniform suction V_0 on the wall $y=0$ and a uniform injection V_0 on the wall $y=h$. A uniform magnetic field H_0 acts normal to the channel neglecting the induced magnetic field. Considering the above assumptions, the magnetic field equation can be:

$$\vec{H}=(0,H_y,0) \tag{1}$$

This assumption is justifiable only when the magnetic Reynolds number is very small [9]. Using Maxwell's equation $div\,\vec{H}=0,$ we can have

$$H_y=H_0 \tag{2}$$

From the equation of conservation of electric charge, we have

$$div\,\vec{J}=0 \tag{3}$$

Neglecting the polarization effect, we take

$$\vec{E}=0 \tag{4}$$

Taking Hall current into account, the generalized Ohm's law is given by

$$\vec{J}+\frac{w_e\tau_e}{\beta_0}(\vec{J}\times\vec{B})=\sigma(\vec{E}+\vec{q}\times\vec{B}) \tag{5}$$

Taking equation of continuity, $div\,\vec{q}=0,$ it is obtained that $\frac{\partial v}{\partial y}=0.$ Hence,

$$v=constant=-V_0,\ V_0>0 \tag{6}$$

Now, using equation 3 and 6, we get,

$$\left.\begin{aligned}\vec{J}&=(J_x,0,J_y)\\ \vec{q}&=(u,-V_0,w)\end{aligned}\right\} \tag{7}$$

Using relations given in equation 7 in equation 5, we have

$$\left.\begin{aligned}J_x&=\frac{\sigma\beta_0}{1+m^2}(mu-w)\\ J_z&=\frac{\sigma\beta_0}{1+m^2}(u+mw)\end{aligned}\right\} \tag{8}$$

For a fully developed steady free convection flow and mass transfer, the governing equations may now be written as

$$V_0\frac{du}{dy}=\gamma\frac{d^2u}{dy^2}-\frac{\sigma B_0^2\left(u+mw\right)}{\rho\left(1+m^2\right)}+g\beta T+g\beta^*C' \tag{9}$$

$$V_0\frac{dw}{dy}=\gamma\frac{d^2w}{dy^2}+\frac{\sigma\beta_0^2\left(mw-w\right)}{\rho\left(1+m^2\right)} \tag{10}$$

$$V_0\frac{dT}{dy}=\frac{k}{\rho C_p}\frac{d^2T}{dy^2}+\frac{\mu}{\rho C_p}[(\frac{du}{dy})^2+(\frac{dw}{dy})^2] \tag{11}$$

$$V_0\frac{dC'}{dy}=D\frac{d^2C'}{dy^2} \tag{12}$$

The boundary conditions are:

$$\left.\begin{aligned} u=0,\ w{=}0,\ T{=}T_1,\ C'=C_1 \quad \text{at } y=0 \\ u=0,\ w{=}0,\ T{=}T_2,\ C'=C_2 \quad \text{at } y=h \end{aligned}\right\} \tag{13}$$

On introducing the following dimensionless variables,

$$\left.\begin{aligned} \eta=\frac{y}{h}, u'=\frac{u}{V_0}, w=\frac{w'}{V_0}, \\ \theta=\left(\frac{T-T_2}{T_1-T_2}\right), C=\left(\frac{C'-C_2}{C_1-C_2}\right) \end{aligned}\right\} \tag{14}$$

equations 9-12, can be written in the dimensionless form (on dropping dashes) as

$$\left.\begin{aligned} \frac{1}{R}\frac{d^2u}{d\eta^2}+\frac{du}{d\eta}- \\ \left(\frac{RM}{1+m^2}\right)(u+mw)+RG\theta+RG_cC=0 \end{aligned}\right\} \tag{15}$$

$$\frac{1}{R}\frac{d^2w}{d\eta^2}+\frac{dw}{d\eta}-\left(\frac{RM}{1+m^2}\right)(mu-w)=0, \tag{16}$$

$$\frac{1}{R.P_r}\left(\frac{d^2\theta}{d\eta^2}\right)+\frac{d\theta}{d\eta}+\frac{E_c}{R}\left[\left(\frac{du}{d\eta}^2\right)+\left(\frac{dw}{d\eta}^2\right)\right]=0, \tag{17}$$

$$\frac{1}{RS_c}\left(\frac{d^2C}{d\eta^2}\right)+\frac{dc}{d\eta}=0 \tag{18}$$

where, the dimensionless parameters are $R=\frac{V_0h}{v}$ is the Reynolds's number, $G=\frac{g\beta(T_1-T_2)\gamma}{V_0^3}$ is the Grashof number, $G_c=\frac{g\beta^*(C_1-C_2)\gamma}{V_0^3}$ is the modified Grashof number, $P_r=\frac{\gamma\rho C_p}{k}$ is the Prandtl number, $E_C=V_0^2/(T_1-T_2)C_p$ is the Eckert number, $S_c=\frac{v}{D}$ is the Schmidt number. M is the Hartmann number.

The modified boundary conditions are:

$$\left.\begin{aligned} u=w=0,\ \theta=1,\ C=1 \quad \text{at } \eta{=}0 \\ u=w=0,\ \theta=0,\ C=0 \quad \text{at } \eta{=}1 \end{aligned}\right\} \tag{19}$$

SOLUTION

The solution of the governing equations 15-18 has been made using successive approximations. We first solve the system on neglecting the viscous dissipation in equation 17 and subsequently solve for the dimensionless temperature on inclusion of the viscous dissipation. Neglecting viscous dissipation, the equation 17 becomes

$$\frac{d^2\theta}{d\eta^2}+RP_r\frac{d\theta}{d\eta}=0 \tag{20}$$

The solution for θ and C satisfying the approximate boundary conditions from equation 19 is given by

$$\theta = \frac{1-e^{RP_r(1-\eta)}}{1-e^{RP_r}} \tag{21}$$

and

$$C = \frac{1-e^{RS_c(1-\eta)}}{1-e^{RS_c}} \tag{22}$$

Introducing $\psi = u + iw$, equations15 and 16 can be written together as

$$\frac{d^2\psi}{d\eta^2} + R\frac{d\psi}{d\eta} - \frac{MR^2\left(1-im\right)}{1+m^2}\psi = -R^2\left(G\theta + G_cC\right) \tag{23}$$

Substituting θ and C from equations 21 and 22 in equation 23 and solving for ψ , we can have

$$\begin{aligned}\psi = {}&[b_1e^{-a_5\eta}cos(a_6\eta) - b_2e^{-a_5\eta}sin(a_6\eta) + b_3e^{-a_7\eta}cos(a_8\eta) + b_4e^{-a_7\eta}sin(a_8\eta) - p_1e^{-a_1\eta} - q_1e^{a_2\eta} - s_1] \\ &+ i[b_1e^{-a_5\eta}sin(a_6\eta) + b_2e^{-a_5\eta}cos(a_6\eta) + b_3e^{-a_7\eta}sin(a_8\eta) - b_4e^{-a_7\eta}cos(a_8\eta) + p_2e^{-a_1\eta} + q_2e^{-a_2\eta} - s_2]\end{aligned} \tag{24}$$

$$u = b_1e^{-a_5\eta}cos(a_6\eta) - b_2e^{-a_5\eta}sin(a_6\eta) + b_3e^{-a_7\eta}cos(a_8\eta)x + b_4e^{-a_7\eta}sin(a_8\eta) - p_1e^{-a_1\eta} - q_1e^{-a_2\eta} - s_1 \tag{25}$$

The secondary velocity is given as:

$$w = b_1e^{-a_5\eta}sin(a_6\eta) + b_2e^{-a_5\eta}cos(a_6\eta) + b_3e^{-a_7\eta}sin(a_8\eta) - b_4e^{-a_7\eta}cos(a_8\eta) + p_2e^{-a_1\eta} + q_2e^{-a_2\eta} - s_2 \tag{26}$$

Where $a_5 = \frac{1}{2}\left[R + (a^2+b^2)^{1/4}cos\frac{\alpha}{2}\right]$ $a = R^2 + \frac{4MR^2}{1+m^2}$, $b = \frac{4MR^2}{1+m^2}$, $\alpha = tan^{-1}\left(\frac{b}{a}\right)$

EFFECTS OF VISCOUS DISSIPATION

Now considering the effect of viscous dissipation in the free convection flow, the energy equation can be written as:

$$\frac{d^2\theta}{d\eta^2} + RP_r\frac{d\theta}{d\eta} = -P_rE_c\left[\left(\frac{du}{d\eta}\right)^2 + \left(\frac{dw}{d\eta}\right)^2\right] \tag{27}$$

Using the non-dissipative solution for u and w, the right hand side terms of equation 27 becomes

$$\begin{aligned}-P_rE_c\left[\left(\frac{du}{d\eta}\right)^2 + \left(\frac{dw}{d\eta}\right)^2\right] = {}& p_3e^{-a_5\eta} + p_4e^{-a_7\eta} + p_5e^{-2a_1\eta} + p_6e^{-2a_2\eta} + p_7e^{-C_1\eta}sin(c_7\eta) \\ &+ p_8e^{-c_1\eta}cos(c_7\eta) + p_9e^{-c_2\eta}sin(a_6\eta) + p_{10}e^{-c_2\eta}cos(c_8\eta) + p_{11}e^{-c_3\eta}sin(a_6\eta) \\ &+ p_{12}e^{-c_3\eta}cos(a_6\eta) + p_{13}e^{-c_4\eta}sin(a_8\eta) - p_{14}e^{-c_4\eta}cos(a_8\eta) + p_{15}e^{-c_5\eta}sin(a_8\eta) \\ &- p_{16}e^{-c_5\eta}cos(a_8\eta) + p_{17}e^{-c_6\eta}\end{aligned} \tag{28}$$

Putting equation 28 in equation 27, the complete solution of this equation becomes

$$\begin{aligned}\theta = {}& c_3 + c_4e^{-a_1\eta} + q_3e^{-a_5\eta} + q_4e^{-a_7\eta} + q_5e^{-2a_1\eta} + q_6e^{-2a_2\eta} - q_7e^{-c_1\eta}cos(c_7\eta) + q_8e^{-c_1\eta}sin(c_7\eta) \\ &+ q_9e^{-c_1\eta}sin(c_7\eta) + q_{10}e^{-c_1\eta}cos(c_7\eta) + q_{11}e^{-c_2\eta}sin(a_6\eta) - q_{12}e^{-c_2\eta}cos(a_6\eta) \\ &+ q_{13}e^{-c_2\eta}sin(a_6\eta) + q_{14}e^{-c_2\eta}cos(a_6\eta) - q_{15}e^{-c_3\eta}cos(a_6\eta) + q_{16}e^{-C_3\eta}sin(a_6\eta) \\ &+ q_{17}e^{-C_3\eta}sin(a_6\eta) + q_{18}e^{-C_3\eta}cos(a_6\eta) - q_{19}e^{-C_4\eta}cos(a_8\eta) + q_{20}e^{-C_4\eta}sin(a_8\eta) \\ &- q_{21}e^{-C_4\eta}cos(a_8\eta) - q_{22}e^{-C_4\eta}cos(a_8\eta) - q_{23}e^{-C_5\eta}cos(a_8\eta) + q_{24}e^{-c_5\eta}sin(a_8\eta) \\ &- q_{25}e^{-C_5\eta}sin(a_8\eta) - q_{26}e^{-C_5\eta}cos(a_8\eta) + q_{27}e^{-c_6\eta}\end{aligned} \tag{29}$$

Using the boundary conditions given in equation 19 in equation 29 and solving for the constant c_3 and c_4, we have

$$\theta = \frac{(\xi e^{-a_1} - \xi^*) + (\xi^* - \xi)e^{-a_1\eta}}{(e^{-a_1} - 1)} + q_3 e^{-a_5\eta} + q_4 e^{-a_7\eta} + q_5 e^{-2a_1\eta} + q_6 e^{-2a_2\eta} + [q_8 sin(c_7\eta)$$
$$-q_7 cos(c_7\eta) + q_9 sin(c_7\eta) + q_{10} cos(c_7\eta)]e^{-c_1\eta} + [q_{11} sin(a_6\eta) - q_{12} cos(a_6\eta) + q_{13} sin(a_6\eta)$$
$$+q_{14} cos(a_6\eta)]e^{c_2\eta} + [q_{16} sin(a_6\eta) - q_5 cos(a_6\eta) + q_{17} sin(a_6\eta) + q_{17} sin(a_6\eta) + q_{18} cos(a_6\eta)]e^{-c_3\eta} \quad (30)$$
$$+[q_{20} sin(a_8\eta) - q_{21} cos(a_8\eta) - q_{22} cos(a_8\eta) - q_{19} cos(a_8\eta)]e^{-c_4\eta} + [q_{24} sin(a_8\eta) - q_{23} cos(a_8\eta)$$
$$-q_{25} sin(a_8\eta) - q_{26} cos(a_8\eta)]e^{c_5\eta} + q_{27} e^{-c_6\eta}$$

A. Shear stress

For the primary flow, the shear stress at the lower plate $(\eta = 0)$ is given as

$$\tau_p = \left(\frac{\partial u}{\partial \eta}\right)_{\eta=0} \quad (31)$$

Hence, $$\tau_p = p_1 a_1 + q_1 a_2 + b_4 a_8 - b_1 a_5 - -b_2 a_6 - b_3 a_7 \quad (32)$$

For the primary flow, the shear stress at the upper plate $(\eta = 1)$ is given by

$$\tau_p^* = \frac{\partial u}{\partial \eta}]_{\eta=1} \quad (33)$$

$$\tau_p^* = p_1 a_1 e^{-a_1} + q_1 a_2 e^{-a_2} + [b_2 a_5 sin(a_6) - b_2 a_6 cos(a_6) - b_1 a_5 cos(a_6) - b_1 a_6 sin(a_6)]e^{-a_5}$$
$$+ b_4 a_8 cos(a_8) - b_3 a_7 cos(a_8) - b_3 a_8 sin(a_8) - b_4 a_7 sin(a_8)]e^{-a_7} \quad (34)$$

For the secondary flow, the shear stress at the lower plate is

$$\tau_s = \frac{\partial w}{\partial \eta}]_{\eta=0} \quad (35)$$

Hence, $$\tau_s = b_1 a_6 - b_2 a_5 + b_3 a_8 + b_4 a_7 - p_2 a_1 - q_2 a_2 \quad (36)$$

For the secondary flow, the shear stress at the upper plate is

$$\tau_s^* = \frac{\partial w}{\partial \eta}]_{\eta=1} \quad (37)$$

$$\tau_s^* = [b_1 a_6 cos(a_6) - b_1 a_5 sin(a_6) - b_2 a_5 cos(a_6) - b_2 a_6 sin(a_6)]e^{-a_5} + [b_3 a_8 cos(a_8)$$
$$+ b_4 a_7 cos(a_8) - b_3 a_7 sin(a_8) + b_4 a_8 sin(a_8)]e^{-a_7} - p_2 a_1 e^{-a_1} - q_2 a_2 e^{-a_2} \quad (38)$$

B. Rate of Heat transfer

The dimensionless rate of heat transfer at the lower plate $(\eta = 0)$ is

$$Nu = -\frac{\partial \theta}{\partial \eta}]_{\eta=0} = -\left(\frac{a_1 e^{a_1}}{1 - e^{a_1}}\right) \quad (39)$$

The dimensionless rate of heat transfer at the upper plate $(\eta = 1)$ is

$$Nu^* = -\frac{\partial \theta}{\partial \eta}]_{\eta=1} = -\left(\frac{a_1}{1 - e^{a_1}}\right) \quad (40)$$

C. Concentration gradient

The concentration gradient at the lower plate is

$$C_G = \frac{-\partial c_0}{\partial \eta}]_{\eta=0} = -\left(\frac{a_2 e^{a_2}}{1-e^{a_2}} \right) \tag{41}$$

The concentration gradient at the upper plate is

$$C_G = -\frac{\partial c}{\partial \eta}]_{\eta=1} = -\left(\frac{a_2}{1-e^{a_2}} \right) \tag{42}$$

RESULTS AND DISCUSSION

The effect of various physical parameters on the flow of the viscous fluid in the presence of magnetic field is studied by means of several graphs and numerical tables. The velocity and temperature profiles for different values of Hall parameter (m), Hartmann number (M), Grashof number (G), Reynolds number (R), Eckert number (E_c), Concentration parameter (S_c), and Prandtl number (P_r) are shown in Figures 1 to 6.

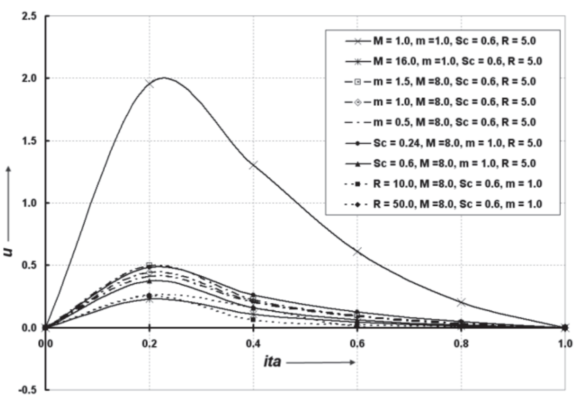

FIGURE 1. Primary velocity profile for different values of m, S_c, R and M, When $P_r = 1.0$, $E_c = 0.01$ $G_c = 2.0$, $G = 5.0$

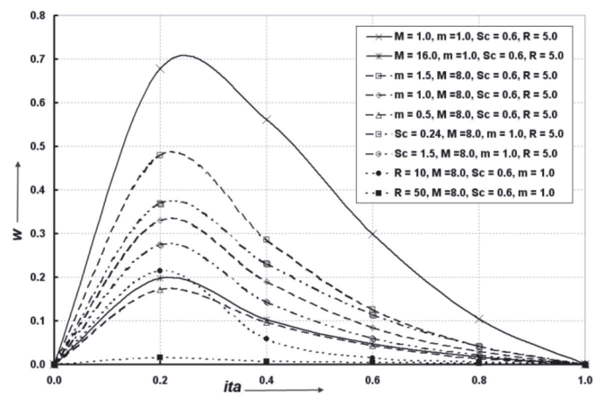

FIGURE 2. Secondary velocity profile for different values of m, S_c, R and M, When $P_r = 1.0$, $E_c = 0.01$ $G_c = 2.0$, $G = 5.0$

Figure 1 shows the effect of Hall parameter (m), Hartmann number (M), Concentration parameter (S_c), and Reynolds number (R) on primary velocity (u) on keeping other parameters constant. It is observed that the primary velocity increases with increase in Hall parameter (m), but decreases with increase in Hartmann number (M), Concentration parameter (S_c), and Reynolds number (R). It is found that for higher values of R $(R > 50)$, the primary velocity (u) approaches to zero. Figure 2 displays the profiles of secondary velocity (w) for different values of m, M, R and S_c. Similar effects are observed on the secondary velocity as in the primary velocity. However, the secondary velocity has larger values than the primary one for the same value of the above parameters.

Figure 3 and 4 represent the primary and secondary velocities for different values of Prandtl number (P_r) and Grashof number, i.e., heating or cooling effect of the plates. In both figures, velocity increases on heating the plates $(G > 0)$, but decreases on cooling it $(G < 0)$. In increasing the Prandtl number (P_r), the primary as well as secondary velocities decrease.

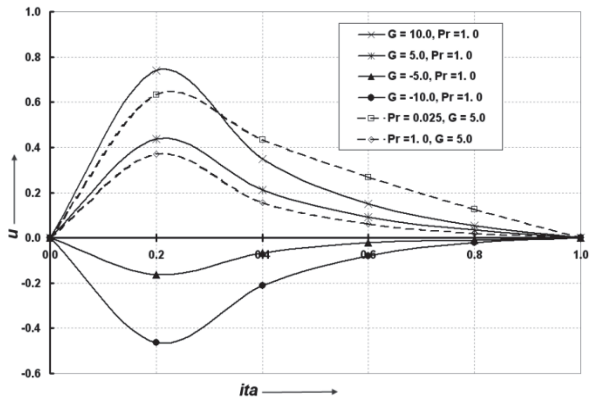

FIGURE 3. Primary velocity profile due to cooling and heating of the plates for different values of G and P_r, when $G_c = 2.0$, $S_c = 0.6$, $R = 5.0$, $m = 1.0$, $M = 8.0$.

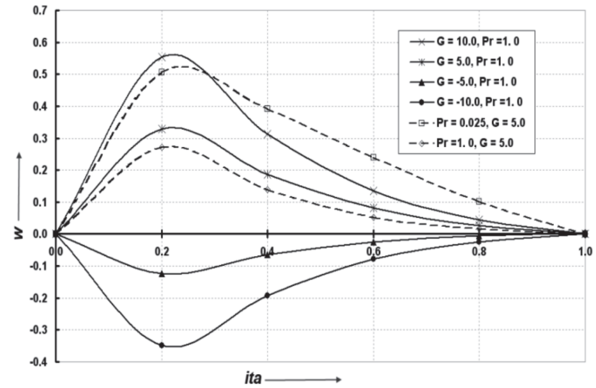

FIGURE 4. Secondary velocity profile due to cooling and heating of the plates for different values of G and P_r, when $G_c = 2.0$, $S_c = 0.6$, $R = 5.0$, $m = 1.0$, $M = 8.0$.

Figure 5 shows the temperature profiles for various values of Eckert number (E_c). The temperature increases with increase in Eckert number. The temperature profiles corresponding to E_c = 0.001, 0.01 and 0.1 represent the temperature distribution on considering viscous dissipation, but the curve corresponding to E_c =0.0 shows the temperature without dissipation. In the same figure, it is observed that temperature falls with increase in Reynolds numbers. Figure 6 shows the concentration profiles for different values of concentration parameter (S_c) and Reynolds number (R). It is observed that concentration of the fluid decreases with increase in the value of S_c or R.

The numerical values of the shear stress for both primary and secondary flows, i.e. τ_p, τ_p^*, τ_s and τ_s^* are tabulated in Tables 1 and 2. Table 1 represents the effect of m, M, S_c on the shear stresses, when all other physical parameters are fixed. It is observed that the shear stress of primary and secondary velocity for the lower plate increases with increase in the strength of Hall parameter (m) and decreases with increase in Hartmann number (M) and concentration parameter (S_c). However, the result is reverse from both the shear stresses at the upper plate of the channel.

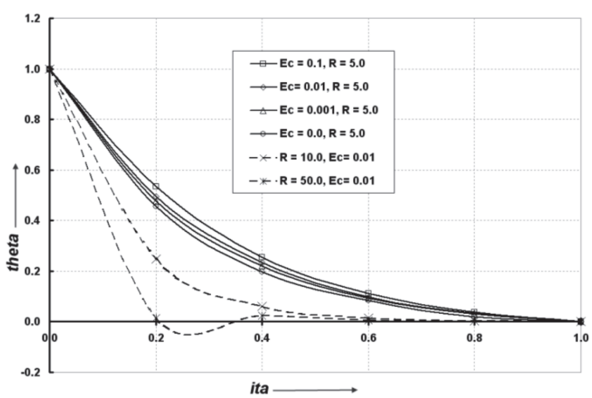

FIGURE 5. Temperature profile for different values of E_c and R, when $G = 5.0$, $G_c = 2.0$, $S_c = 0.6$, $\mathrm{P_r} = 1.0$,

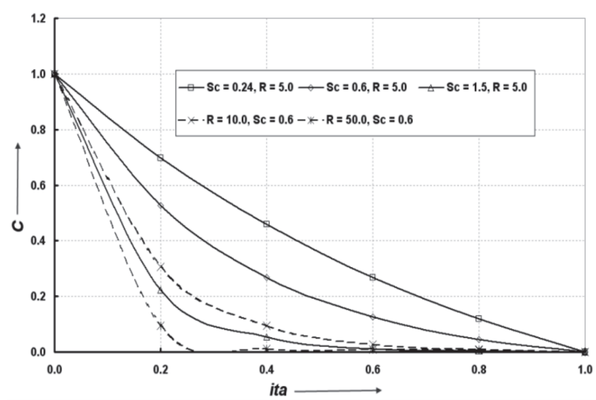

FIGURE 6. Concentration profile for different values of S_c and R, when $G = 5.0$, $G_c = 2.0$, $m = 1.0$, $M = 8.0$,

$m = 1.0$ and $M = 8.0$. $E_c = 0.01$, $P_r = 1.0$,.

TABLE 1. Effect of m, M and S_c on shear stress of primary and secondary flows, when G = 5.0, R = 5.0, P_r = 1.0, E_c =0.01.

m	M	S_c	τ_p	τ_p^*	τ_s	τ_s^*
0.5	8.0	0.6	11.7269	-0.0933	2.4711	-0.0452
1.0	8.0	0.6	12.6102	-0.0968	4.5552	-0.0809
1.0	16.0	0.6	9.1355	-0.0496	3.4667	-0.0450
1.0	8.0	0.24	12.9677	-0.1681	4.8794	-0.1233
1.0	8.0	1.5	11.7914	-0.0623	3.9733	-0.0538

Table 2 represents the effect of R and G on shear stresses. It shows that the shear stresses for both primary and secondary flows on both the plates of the channel increase with increase in Reynolds number. However, the shear stress at the upper plate vanishes for higher value of R (i.e. $R \geq 5.0$). Also, it is found that on heating the plates, shear stress for both primary and secondary flow at the lower plate increases, whereas those at the upper plate decreases. Reverse effect is observed on cooling the plate.

TABLE 2. Effect of R and G on shear stress of primary and secondary flows, when m = 1.0, M = 8.0, P_r = 1.0, S_c = 0.06, E_c = 0.01.

R	G	τ_P	τ_P^*	τ_S	τ_S^*
50.0	5.0	127.2309	0.0000	16.7757	0.0000
10.0	5.0	25.4382	-0.0068	9.3465	-0.0064
5.0	5.0	12.102	-0.0968	4.5552	-0.0809
5.0	10.0	21.5373	-0.1580	7.7432	-0.1331
5.0	-5.0	-5.2440	0.0256	-1.8207	0.0235
5.0	-10.0	-14.1711	0.0868	-5.0086	0.0758

CONCLUSION

In this paper, effect of various physical parameters such as R, S_c and P_r on concentration gradients C_G and C_G^* also on the rates of heat transfer Nu and Nu^* are studied. It is observed that the rate of heat transfer and concentration gradient at the lower plate increase with increase in value of Reynolds's number, whereas those at the upper plate decrease. The concentration gradient at the lower plate increases with increase in concentration parameter (S_c), whereas the same at the upper plate decreases. Similarly, the rate of heat transfer at the lower plate increases with increase in P_r, but at the upper plate decreases.

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