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Combined Effects of Hall Current and Chemical Reaction on Unsteady MHD Flow Past an Impulsively Started Vertical Plate with Constant Wall Temperature and Mass Diffusion

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Combined effects of Hall current and chemical reaction on unsteady MHD flow past a vertical plate with constant wall temperature and mass diffusion is studied here. The fluid considered is electrically conducting and heat generating. The Laplace transform technique has been used to find the solutions for the velocity and Skin friction. The velocity profile, temperature and mass diffusion have been studied for different parameters like Schmidt number, Hall parameter, magnetic parameter, chemical reaction parameter, mass Grashof number, thermal Grashof number, Prandtl number, and time. The effect of parameters is shown graphically, and the values of the skin-friction have been tabulated.

Keywords: *MHD flow, Chemical reaction, Constant temperature and Mass diffusion, Skin fraction, and Hall current.*

1. Introduction

Study of MHD and heat generation effect of moving fluid is important in view of several physical problems, such as fluid undergoing exothermic or endothermic chemical reactions. Chemical reaction can be codified as either homogeneous or heterogeneous process. MHD flow and Hall effect are encountered in powergenertors, refrigeration coils, and electric transfers etc. The researchers have studied the effect of Hall current in various flow models. . Mythreye et al. [5] have analysed chemical reaction on unsteady MHD convective heat and mass transfer past a semi infinite vertical permeable moving plate with heat absorption. Katagiri [1] has considered the effect of Hall current on the magneto hydrodynamic boundary layer flow past a semi-infinite plate. Kandasamy et al. [2] have studied effects of chemical reaction, heat and mass transfer along a wedge with heat source and concentration in the presence of suction or injection. Hossain et al. [6] have analysed MHD free convection and mass transfer flow through a vertical oscillatory porous plate with Hall, ion-slip current and heat source in a rotating system. Seth et al. [4] have studied Hall effect on unsteady MHD natural convection flow of a heat absorbing fluid past an accelerated moving vertical plate with ramped temperature. Shehzad et al. [7] have studied three-dimensional MHD flow of casson fluid in porous medium with heat generation. Gamal et al. [8] have analysed chemical entropy generation and MHD effects on the unsteady heat and fluid flow through a porous medium. Satya et al. [3] have studied the effects of Hall current and radiation absorption on MHD micropolar fluid in a rotating system. We are considering combined effects of Hall current and chemical reaction on unsteady MHD flow past a vertical plate with constant wall temperature and mass diffusion. The effect of Hall current on the velocity have been observed with the help of graphs, and the skin friction has been tabulated.

2. Mathematics Analysis.

The unsteady flow of an electrically conducting, incompressible, viscous fluid past a vertical plate has been considered. The x axis is taken in the direction of the motion and z normal to it. A transverse magnetic field B_0 of uniform strength is applied on the flow. Initially it has been considered that the plate as well as the fluid is at the same temperature T_∞. The species concentration in the fluid is taken as C_∞. At time t>0, the plate starts oscillating in its own plane with frequency ω, the temperature of the plate and the concentration of the fluid, respectively are raised to T_w and C_w. Using the relation $\nabla \cdot B = 0$ for the magnetic field $\overline{B} = (B_x, B_y, B_z)$, we obtain B_y (say B_0) = constant, i.e. $B = (0, B_0, 0)$, where B_0 is externally applied transverse magnetic field. The Geometry of the problem is given in figure 1_A.

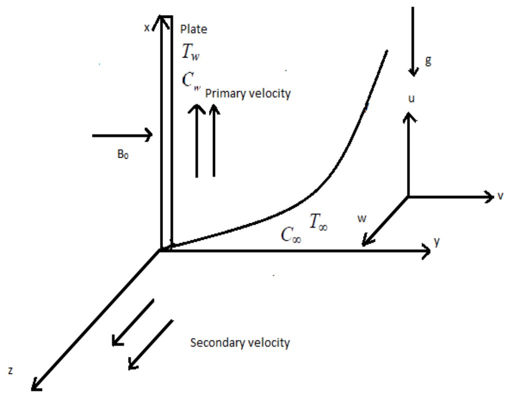

Figure 1$_A$ Geometry of the problem

Let V be the velocity vector, and u, v, w are respectively the velocity components along x, y and z-directions. The governing equation of continuity is

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

Since there is no variation of flow in the y- direction, therefore v = 0

The generalized ohm's law including the effect of Hall current according to cowling (1957) is given as

$$\bar{J}+\frac{\omega_e \tau_e}{B_0}(\bar{J}\times\bar{B})=\sigma(E+\bar{V}\times\bar{B})$$

The external electric field E = 0, since polarization of charges is negligible.

Let (j_x, j_y, j_z) be the components of current density J. Here j_x, j_y, and j_z are the components of current density in the x, y, and z directions, respectively . Using above assumption, we get

$$J_x=\frac{\sigma B_0{}^2}{1+m^2}(u+mw) \text{ and } J_z=\frac{\sigma B_0{}^2}{1+m^2}(mu-w).$$

The fluid model is as under –

$$\frac{\partial u}{\partial t} = \upsilon \frac{\partial^2 u}{\partial y^2} + g\beta (T - T_\infty) + g\beta^* (C - C_\infty) - \frac{\sigma B_0^2 (u + mw)}{\rho(1+m^2)}, \tag{1}$$

$$\frac{\partial w}{\partial t} = \upsilon \frac{\partial^2 w}{\partial y^2} + \frac{\sigma B_0^2 (mu - w)}{\rho(1+m^2)}, \tag{2}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial y^2} - K_C (C - C_\infty), \tag{3}$$

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial y^2} + Q_0 (T - T_\infty) \tag{4}$$

The initial and boundary conditions are

$$\left.\begin{aligned} &t \le 0: u = 0,\ w = 0,\ T = T_\infty,\ C = C_\infty, \ \text{for all } y. \\ &t > 0: u = u_0 \cos \omega t,\ w = 0,\ T = T_w,\ C = C_w, \ \text{at } y=0. \\ &u \to 0,\ w \to 0,\ T \to T_\infty,\ C \to C_\infty \ \text{as } y \to \infty, \end{aligned}\right\} \tag{5}$$

Here u and w are the primary and the secondary velocities along x and z respectively, v- the kinematic viscosity, ρ- the density, C_p- the specific heat at constant pressure, k- thermal conductivity of the fluid, D- the mass diffusion coefficient, g- gravitational acceleration, β- volumetric coefficient of thermal expansion, t- time, m- the Hall current parameter, T- temperature of the fluid, β^* - volumetric coefficient of concentration expansion, C- species concentration in the fluid, T_W- temperature of the plate, C_w- species concentration, B_0 - the uniform magnetic field, σ - electrical conductivity.

The following non-dimensional quantities are introduced to transform equations (1), (2), (3) and (4) into dimensionless form:

$$\left.\begin{aligned} &\bar{u} = \frac{u}{u_0}, \bar{w} = \frac{w}{u_0}, \bar{y} = \frac{yu_0}{\upsilon}, Sc = \frac{\upsilon}{D}, \Pr = \frac{\mu C_P}{k}, Q = \frac{Q_0 \upsilon}{u_0^2 \rho C_p}, \\ &M = \frac{\sigma B_0^2 \upsilon}{\rho u_0^2}, \bar{t} = \frac{t u_0^2}{\upsilon}, \bar{\omega} = \frac{\omega \upsilon}{u_0^2}, Gm = \frac{g\beta \upsilon (C_w - C_\infty)}{u_0^3}, \\ &Gr = \frac{g\beta \upsilon (T_w - T_\infty)}{u_0^3}, \bar{C} = \frac{C - C_\infty}{C_w - C_\infty}, \theta = \frac{(T - T_\infty)}{(T_w - T_\infty)}, K_0 = \frac{\upsilon K_c}{u_0^2}. \end{aligned}\right\} \tag{6}$$

The symbols in dimensionless form are as under:

$\bar{u}$ - dimensionless velocity of the fluid in x- direction, $\bar{w}$ - dimensionless velocity of the fluid in z- direction, θ - the dimensionless temperature, $\bar{C}$ - the dimensionless concentration, Gr- thermal Grashof number, Gm - mass Grashof number, μ - the coefficient of viscosity, $\Pr$ - the Prandtl number, Sc - the Schmidt number, M - the magnetic parameter, K_0 - chemical reaction, $\bar{t}$ - time, Q - heat generation parameter.

The dimension less flow model becomes

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + G_r\,\theta + G_m\,\bar{C} - \frac{M(\bar{u} + m\bar{w})}{(1+m^2)}, \tag{7}$$

$$\frac{\partial \bar{w}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + \frac{M(m\bar{u} - \bar{w})}{(1+m^2)}, \tag{8}$$

$$\frac{\partial \bar{C}}{\partial \bar{t}} = \frac{1}{S_c}\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} - K_0\bar{C}, \tag{9}$$

$$\frac{\partial \theta}{\partial \bar{t}} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial \bar{y}^2} + Q\theta. \tag{10}$$

The corresponding boundary conditions become

$$\left.\begin{array}{l} \bar{t} \le 0 : \bar{u} = 0,\ \bar{w} = 0,\ \theta = 0,\ \bar{C} = 0, \quad \text{for all } \bar{y}. \\ \bar{t} > 0 : \bar{u} = \cos\omega t,\ \bar{w} = 0,\ \theta = 1,\ \bar{C} = 1, \quad \text{at } \bar{y} = 0. \\ \bar{u} \to 0,\ \bar{w} \to 0,\ \theta \to 0,\ \bar{C} \to 0, \quad \text{as } \bar{y} \to \infty. \end{array}\right\} \tag{11}$$

Dropping the bars and combining equations (7) and (8), we get

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial y^2} + Gr\theta + GmC - \left(\frac{M}{1+m^2}(1-mi)\right)q, \tag{12}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} - K_0 C, \tag{13}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial y^2} + Q\theta, \tag{14}$$

where $q = u + iw,$ with corresponding boundary conditions

$$\left.\begin{array}{l} t \le 0 : q = 0, \theta = 0, C = 0, \text{for all values of y}, \\ t < 0 : q = \cos \omega t, q = 0, \theta = 1, C = 1, \text{at } y = 0, \\ q \to 0, C \to 0, \theta \to 0, \text{as} y \to \infty . \end{array}\right\} \quad (15)$$

The solutions of the above equations are obtained by the Laplace transform method, which are as under

$$\theta = \frac{1}{2} e^{-\sqrt{-Q\Pr} y} (1 + A_9 + e^{2\sqrt{-Q\Pr} y} A_{10})$$

$$C = \frac{1}{2} e^{-y\sqrt{ScK_0}} (B_4 + e^{2y\sqrt{ScK_0}} A_{14})$$

$$q = [\frac{1}{4} e^{-it\omega} (P_1 + P_2 - e^{-y\sqrt{a-i\omega}} P_3 - e^{y\sqrt{a-i\omega}} P_4 - e^{-yP_0} P_5 - e^{yP_0} P_6)$$
$$+ \frac{1}{2(a + Q\Pr)} Gr[\{-e^{-\sqrt{a}y} (A_1 + e^{2\sqrt{a}y} A_2) + e^{B_0 - B_1} (A_3 + e^{2B_1} A_4)\}$$
$$- \{e^{B_0 - B_1} (1 + e^{2B_1} + A_7 - e^{2B_1} A_8) - e^{-y\sqrt{-Q\Pr}} (1 + A_9 + e^{2y\sqrt{-Q\Pr}} A_{10})\}] +$$
$$\frac{1}{2(a - K_0 Sc)} Gm\{-e^{\sqrt{a}y} (1 + A_1 + e^{2\sqrt{a}y} A_2) + e^{B_2 - B_3} (A_5 + e^{2B} A_6)$$
$$- e^{B_2 - B_3} (1 + e^{2B_3} + A_{11} - e^{2B_3} A_{12})\} + Gm \frac{1}{2(-a + K_0 Sc)} e^{-y\sqrt{K_0 Sc}} (1 + A_{13} +$$
$$e^{2y\sqrt{K_0 Sc}} A_{14})]$$

3. Skin friction

The dimensionless skin friction at the plate $y = 0$ is computed by

$$\left(\frac{dq}{dy} \right)_{y=0} = \tau_x + i\tau_z .$$

4. Sherwood number

The dimensionless Sherwood number at the plate $y = 0$ is computed by

$$Sh = \left(\frac{\partial C}{\partial y}\right)_{y=0}$$

$$-\frac{1}{2}e^{-y\sqrt{ScK_0}}\{B_6 + e^{2y\sqrt{ScK_0}}A_{14}\}\sqrt{ScK_0} + \frac{1}{2}e^{-y\sqrt{ScK_0}}\{\frac{e^{-B_7}\sqrt{Sc}}{\sqrt{\pi t}}(-1 - e^{2y\sqrt{ScK_0}}) + 2e^{2y\sqrt{ScK_0}}A_{14}\sqrt{ScK_0}\}$$

5. Nusselt number

The dimensionless Nusselt number at the plate $y = 0$ is computed by

$$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$

$$-\frac{1}{2}e^{-\sqrt{-Q\Pr}y}\sqrt{-Q\Pr}\,y\{1 + A_9 + e^{2\sqrt{-Q\Pr}y}A_{10}\} +$$
$$\frac{1}{2}e^{-\sqrt{-Q\Pr}y}\{\frac{e^{-B_5}\sqrt{\Pr}}{\sqrt{\pi t}}(1 - e^{2\sqrt{-Q\Pr}y}) + 2e^{2\sqrt{-Q\Pr}y}A_{10}\sqrt{-Q\Pr}\}$$

4. Results and Discussion

The numerical values of velocity, and skin friction are computed for different parameters. The values of the main parameters considered are

M = 1, 1.5, 2; Gm = 5, 10, 15; Sc = 2, 5, 7; t = 0.1, 0.2, 0.3; Q = 1, 5, 10; $\omega t = 30^\circ, 45^\circ, 60^\circ$; Gr =10, 20, 30; K_0 = 1, 10, 20; M = 1, 3, 5; Pr = 2, 3, 5.

It has been observed from figures 1, 2, 3, 7, and 9 that primary velocity (u) increases when Gm, Gr, m, t, and Q are increased. It means, Hall current has increasing effect on the flow of the fluid along the plate. However, figures 4, 5, 6, 8 and 10 show that u decreases when M, Pr, Sc, K_0 and ωt are increased. Almost similar pattern is observed for secondary velocity. Figures 11, 12, 14, 17, and 19 show that the secondary velocity (w) increases when Gm, Gr, M, t and Q are increased. However, figures 13, 15, 16, 18 and 20 show that w decreases when m, Pr, Sc, K_0 and ωt are increased. This implies that the Hall parameter slows down the transverse velocity. Figure 21 shows that concentration decreases when K_0 is increased. And figure 22 shows that temperature increases when Q is increased. Table 1- shows that Skin fraction τ_x decreases with increase in Sc, Pr K_0 and M and it increases with Gr, Gm, m, t, Q, and ωt. Further, τ_z increases with the increase in Gr, Gm, t, Q, and M; and it decreases with Pr, m, Sc, K_0 and ωt.

The results obtained are in agreement with the actual flow.

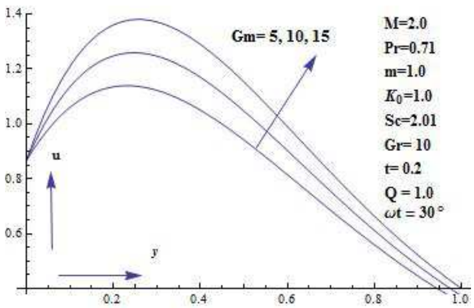

Figure 1. The effect of Gm on velocity u.

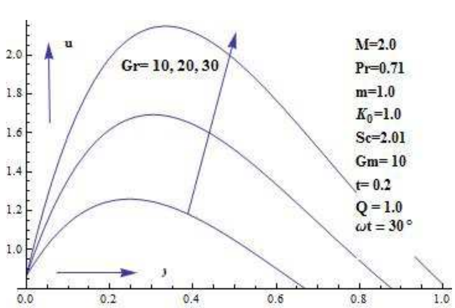

Figure 2. The effect of Gr on velocity u.

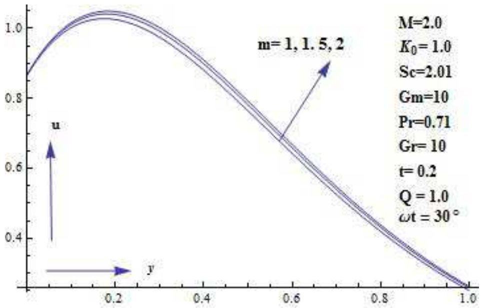

Figure 3. The effect of m on velocity u.

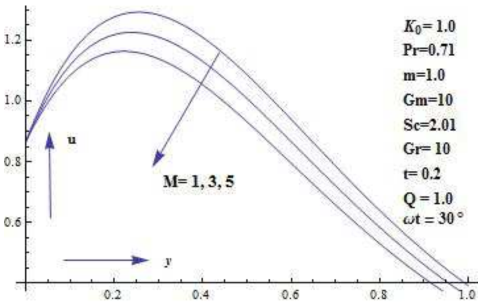

Figure 4. The effect of M on velocity u.

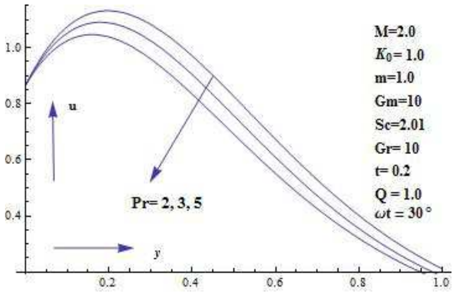

Figure 5. The effect of Pr on velocity u

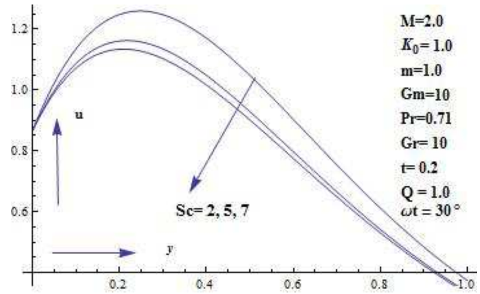

Figure 6. The effect of Sc on velocity u.

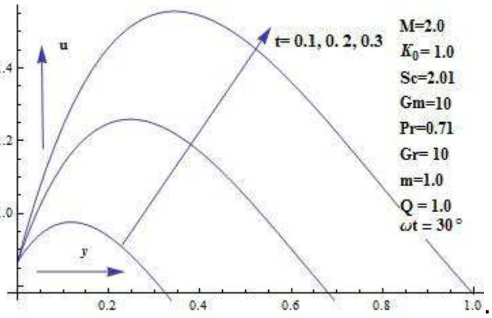

Figure 7. The effect of t on velocity u.

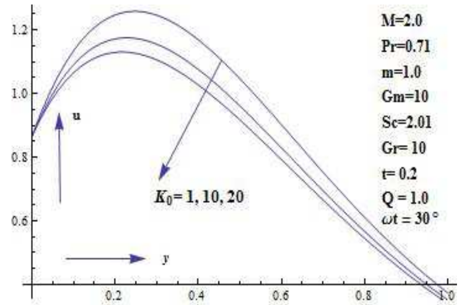

Figure 8. The effect of K_0 on velocity u.

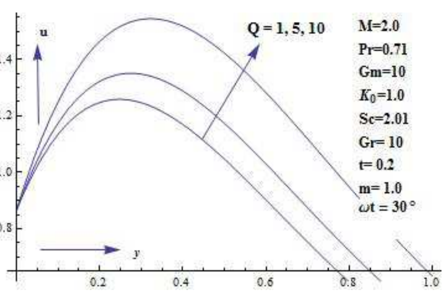

Figure 9. The effect of Q on velocity u.

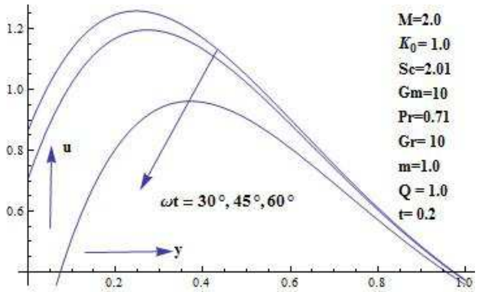

Figure 10. The effect of ωt on velocity u

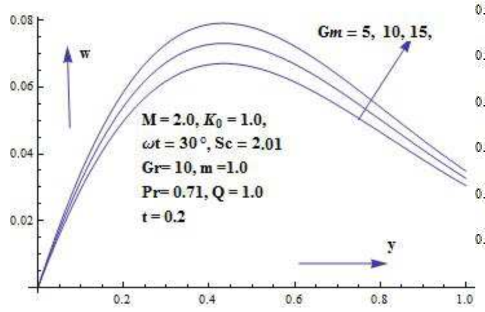

Figure 11. The effect of Gm on velocity w.

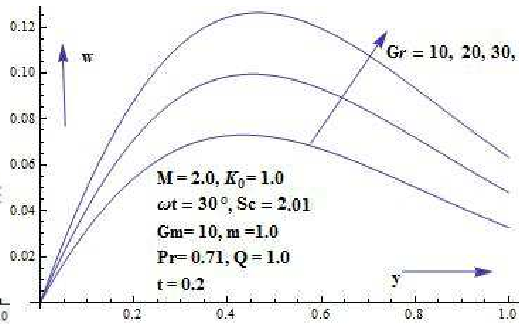

Figure 12. The effect of Gr on velocity w.

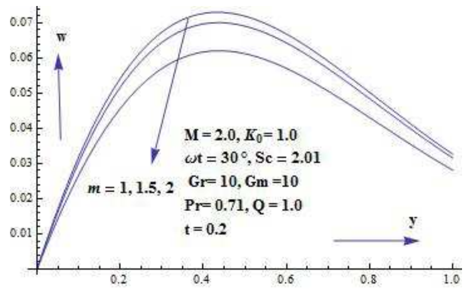

Figure 13. The effect of m on velocity w.

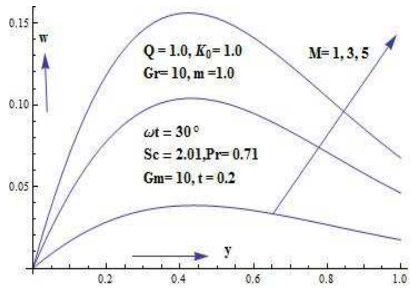

Figure 14. The effect of M on velocity w.

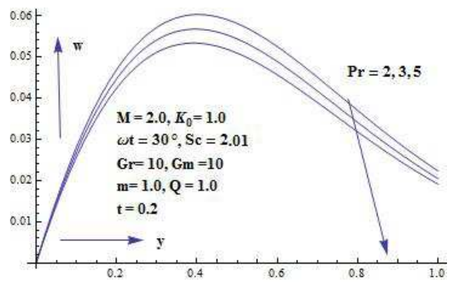

Figure 15. The effect of Pr on velocity w.

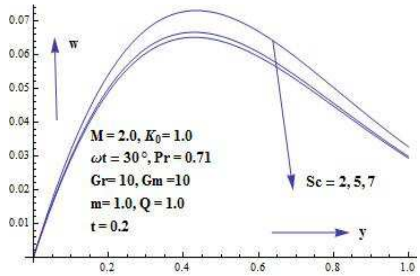

Figure 16. The effect of Sc on velocity w.

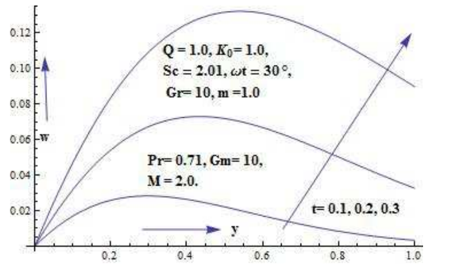

Figure 17. The effect of t on velocity w.

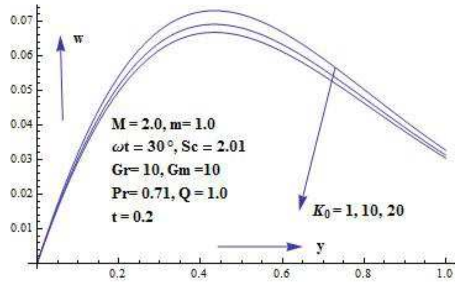

Figure 18. The effect of K_0 on velocity w.

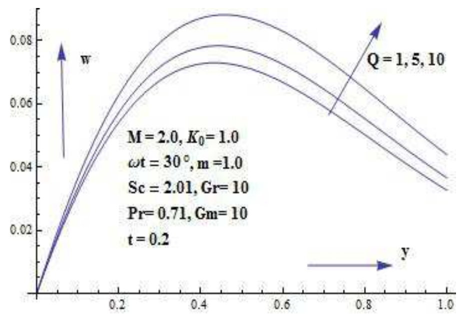

Figure 19. The effect of Q on velocity w.

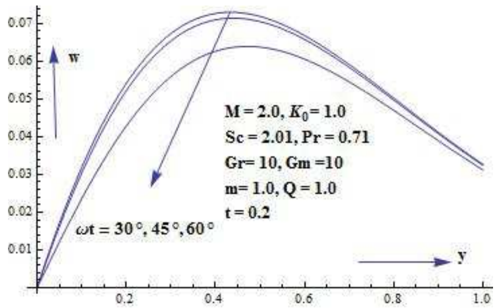

Figure 20. The effect of ωt on velocity w.

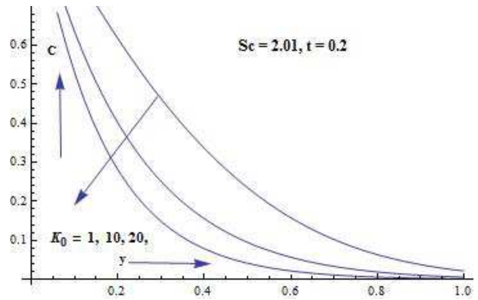

Figure 21. The effect of K_0 on Concentration C

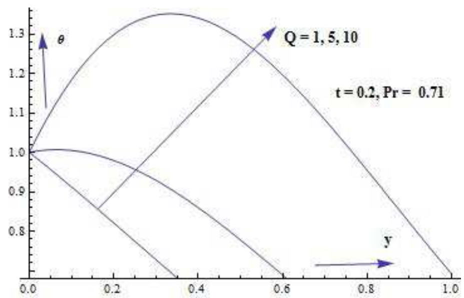

Figure 22. The effect of Q on temperature θ.

5. Conclusion

The effects of Hall current, heat generation, and chemical reaction are observed on both, the primary and secondary velocities. It has been observed that the primary velocity increases with heat generation, and Hall parameter. However it decreases with chemical reaction. Further, secondary velocity increases when heat generation parameter is increased. However it decreases with Hall parameter and chemical reaction parameter. Similar effect is observed for drag at boundary. That is τ_x increases with heat generation parameter, permeability of the medium and Hall parameter, and it decreases with chemical reaction parameter. Further, τ_z decreases when Hall and chemical reaction parameters are increased.

Table 1. Skin friction for different parameter

M	*m*	*Pr*	*Sc*	*Gm*	*Gr*	*Q*	K_0	*t*	ωt [°]	τ_x	τ_z
3.0	1.0	0.71	2.01	10	10	1.0	1.0	0.2	30	3.4349	0.5266
5.0	1.0	0.71	2.01	10	10	1.0	1.0	0.2	30	3.0542	0.8165
2.0	1.5	0.71	2.01	10	10	1.0	1.0	0.2	30	3.7722	0.3455
2.0	2.0	0.71	2.01	10	10	1.0	1.0	0.2	30	3.8562	0.1889
2.0	10	3.00	2.01	10	10	1.0	1.0	0.2	30	2.7871	0.3138
2.0	1.0	5.00	2.01	10	10	1.0	1.0	0.2	30	2.5065	0.3014
2.0	1.0	0.71	5.00	10	10	1.0	1.0	0.2	30	3.1349	0.3416
2.0	1.0	0.71	7.00	10	10	1.0	1.0	0.2	30	2.9709	0.3355
2.0	1.0	0.71	2.01	05	10	1.0	1.0	0.2	30	2.6515	0.3386
2.0	1.0	0.71	2.01	15	10	1.0	1.0	0.2	30	4.6056	0.3897
2.0	1.0	0.71	2.01	10	20	1.0	1.0	0.2	30	6.3514	0.4587
2.0	1.0	0.71	2.01	10	30	1.0	1.0	0.2	30	9.0742	0.5533
2.0	1.0	0.71	2.01	10	10	5.0	1.0	0.2	30	4.0376	0.3808
2.0	1.0	0.71	2.01	10	10	10	1.0	0.2	30	4.8040	0.4105
2	1.0	0.71	2.01	10	10	1.0	10	0.2	30	3.1619	0.3487
2	1.0	0.71	2.01	10	10	1.0	20	0.2	30	2.8861	0.3394
2	1.0	0.71	2.01	10	10	1.0	1.0	0.1	30	2.0408	0.2133
2	1.0	0.71	2.01	10	10	1.0	1.0	0.3	30	4.6922	0.5169
2	1.0	0.71	2.01	10	10	1.0	1.0	0.2	45	4.1697	0.3430
2	1.0	0.71	2.01	10	10	1.0	1.0	0.2	60	6.3961	0.2442

Appendex

$$P_0 = \sqrt{a+i\omega} + 2it\omega,\ P_1 = e^{-y\sqrt{a-i\omega}} + e^{y\sqrt{a-i\omega}},\ P_2 = e^{-yP_0} + e^{yP_0},$$

$$P_3 = Erf[\frac{y-2t\sqrt{a-i\omega}}{2\sqrt{t}}],\ P_4 = Erf[\frac{y+2t\sqrt{a-i\omega}}{2\sqrt{t}}],\ P_5 = Erf[\frac{y-2t\sqrt{a+i\omega}}{2\sqrt{t}}],$$

$$P_6 = Erf[\frac{y+2t\sqrt{a+i\omega}}{2\sqrt{t}}],\ A_1 = Erf[\frac{2t\sqrt{a}-y}{2\sqrt{t}}],\ A_2 = Erf[\frac{2t\sqrt{a}+y}{2\sqrt{t}}],$$

$$A_3 = Erfc[\frac{y-2t\sqrt{\frac{(a+Q)\Pr}{-1+\Pr}}}{2\sqrt{t}}],\ A_4 = Erfc[\frac{y+2t\sqrt{\frac{(a+Q)\Pr}{-1+\Pr}}}{2\sqrt{t}}],\ A_5 = Erfc[\frac{y-2t\sqrt{\frac{(a+K_0)Sc}{-1+Sc}}}{2\sqrt{t}}],$$

$$A_6 = Erfc[\frac{y-2t\sqrt{\frac{(a-K_0)Sc}{-1+Sc}}}{2\sqrt{t}}],\ A_7 = Erf[\frac{2t\sqrt{\frac{(a+Q)}{-1+\Pr}} - y\sqrt{\Pr}}{2\sqrt{t}}],\ A_8 = Erf[\frac{2t\sqrt{\frac{(a+Q)}{-1+\Pr}} + y\sqrt{\Pr}}{2\sqrt{t}}],$$

$$A_9 = Erf[\frac{2\sqrt{-Q}t - y\sqrt{\Pr}}{2\sqrt{t}}],\ A_{10} = Erf[\frac{2\sqrt{-Q}t + y\sqrt{\Pr}}{2\sqrt{t}}],\ A_{11} = Erf[\frac{2t\sqrt{\frac{(a-K_0)}{-1+Sc}} - y\sqrt{Sc}}{2\sqrt{t}}],$$

$$A_{12} = Erf[\frac{2t\sqrt{\frac{(a-K_0)}{-1+Sc}} + y\sqrt{Sc}}{2\sqrt{t}}],\ A_{13} = Erf[\frac{2t\sqrt{K_0} - y\sqrt{Sc}}{2\sqrt{t}}],\ A_{14} = Erf[\frac{2t\sqrt{K_0} + y\sqrt{Sc}}{2\sqrt{t}}],$$

$$B_0 = \frac{at}{-1+\Pr} + \frac{Qt\Pr}{-1+\Pr},\ B_1 = y\sqrt{\frac{(a+H)\Pr}{-1+\Pr}},\ B_2 = \frac{at}{-1+Sc} - \frac{tK_0Sc}{-1+Sc},\ B_3 = y\sqrt{\frac{(a-K_0)Sc}{-1+Sc}},$$

$$B_4 = Erfc[\frac{y\sqrt{Sc} - 2t\sqrt{K_0}}{2\sqrt{t}}],\ B_5 = \frac{(2\sqrt{-Qt} - \sqrt{\Pr}\,y)^2}{4t},\ B_6 = Erfc[\frac{y\sqrt{Sc} - 2t\sqrt{K_0}}{2\sqrt{t}}],$$

$$B_7 = \frac{(\sqrt{Sc}\,y - 2t\sqrt{K_0})^2}{4t},\ a = \frac{M}{1+m^2}(1-im),$$

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