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Research Article

MDH Flow Past a Vertical Rotating Plate with Chemical Reaction and Mass Diffusion in the Presence of Hall Current

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Abstract

In the present paper, MHD flow past a vertical rotating plate with chemical reaction and mass diffusion in the presence of Hall current is studied. The fluid is electrically conducting and the flow is along the plate. The model under consideration is solved by Laplace transform method. This study is useful in magnetic field controlled material processing, planetary systems and MHD energy generators, etc.

Keywords : MHD flow; Hall current; Chemical reaction; Variable mass diffusion.

1 Introduction

The magneto hydrodynamic flow with Hall effect plays important role in engineering and astrophysics. Therefore, in view of its applications MHD flow has become an important topic of research. A large number of articles have been published on this topic, some of which are mentioned here. Das et al [18] have analyzed combined effects of Hall current and rotation on unsteady Couette flow in a porous channel. Datta and Jana [12] have studied oscillatory magneto hydrodynamic flow past a flat plate with Hall effects. Sarveshanand et al [7] have considered effect of Hall current and wall conductance on hydromagnetic natural convective flow between vertical walls. Further, effect of chemical reaction on MHD flow with different geometries and boundary conditions has been studied by a number of researchers. We would mention some of the articles here for reference. Sahin and Chamkha [3] have examined chemical reaction, heat and mass transfer and radiation effects on the MHD flow on a vertical porous wall with induced magnetic field. Chamkha et al [10, 19] focused their work on MHD rotating heat and mass transfer free convective flow past an exponentially accelerated isothermal plate with fluctuating mass Diffusion. Singh and Kumar, [9] have studied Combined effects of Hall current and rotation on free convection MHD flow in a porous channel. Effect of chemical reaction and heat on double-diffusive convection from a vertical truncated cone in porous media with variable viscosity was discussed by Mahdy [4]. Further, chemically reacting boundary layer MHD flow was studied by Ibrahim et al [17]. Raptis and Perdikis [1] have analyzed viscous flow on stretching sheet with chemical reaction. Abd [11] has studied effect of slip and variable thermal boundary con-

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ditions on hydromagnetic mixed convection flow and heat transfer from a non-linearly stretching surface. Venkateswarlu et al [15] have analyzed chemical reaction and heat source effects on MHD oscillatory flow in an irregular channel. Radiation and chemical reaction effects on isothermal vertical oscillating plate with variable mass diffusion was studied by Manivannan, et al [8]. Watanabe et al [14] have studied Hall effect on magneto hydrodynamic free convection about a semi infinite vertical plate. Effects of thermal diffusion and chemical reaction on MHD transient free convection flow past a porous vertical plate with radiation was studied by Suneetha, et al [20]. Jha and Apere [17] have analyzed combined effect of Hall and ion-slip currents on unsteady MHD Couette flows in a rotating system. Noor et al [13] have studied MHD flow and heat transfer in a thin liquid film on an unsteady stretching sheet. Pop et al [12] worked on Magnetohydrodynamic flow and heat transfer due to a stretching cylinder. Chemical reaction on unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate with heat absorption was presented by Mythreye et al [5]. Earlier we [16] have studied MHD flow past a vertical plate with variable temperature and mass diffusion in the presence of Hall current. The objective of the present paper is to study MHD flow past a vertical rotating plate with chemical reaction and mass diffusion in the presence of Hall current. The model has been solved by the Laplace transform technique. The effects of various parameters on velocity, concentration, skin friction and Sherwood number have been presented graphically and discussed quantitatively.

2 Mathematical Modeling

The Geometric model of the flow problem is shown in Figure 1. The flow is incompressible and unsteady. A vertically moving and electrically non-conducting plate with constant wall temperature is taken here. The x axis is considered along the fluid motion. Initially it has been considered that the fluid and the plate are at the same temperature T_∞. C_∞ is the species concentration within the fluid. The plate starts oscillating after t = 0

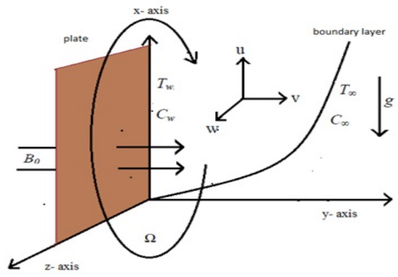

Figure 1

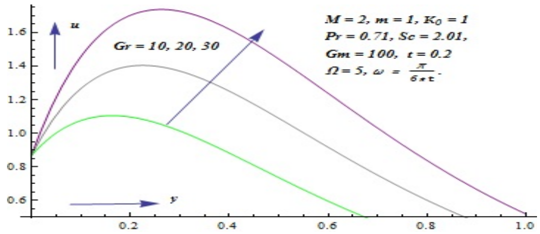

Figure 2: u vs y for different values of Gr.

with frequency ω. The species concentration and temperature of the plate are raised to C_w and T_w,respectively. The force due to inertia is neglected. A uniform magnetic field is taken on the flow. Using the relation $\triangle \cdot$ B, 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. Due to Hall effect, there will be two parts of the momentum equation. With usual assumptions the fluid model is as under:

$$\begin{aligned}
\frac{\partial u}{\partial t} - 2\Omega w &= \upsilon\frac{\partial^2 u}{\partial y^2} + g\beta cos\alpha(T - T_\infty) \qquad (2.1)\\
&+ g\beta^* cos\alpha(C - C_\infty)\\
&- \frac{\sigma B_0^2}{\rho(1+m^2)}(u + mw)\\
\frac{\partial w}{\partial t} + 2\Omega u &= \upsilon\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2(w - mu)}{\rho(1+m^2)} \qquad (2.2)\\
\frac{\partial C}{\partial t} &= D\frac{\partial^2 C}{\partial y^2} - K_0(C - C_\infty) \qquad (2.3)\\
\rho C_p\frac{\partial T}{\partial t} &= k\frac{\partial^2 T}{\partial y^2} \qquad (2.4)
\end{aligned}$$

Table 1: Sherwood number

Sc	K_0	t	Sh
0.16	1.0	0.2	-0.2150
0.3	1.0 0	0.2	-0.2944
0.6	1.0 0	0.2	-0.4164
2.01	10 0	0.2	–1.1182
2.01	20 0	0.2	-1.4264
2.01	1.0 0	0.1	-0.5225
2.01	1.0 0	0.2	-0.7621

Table 2: Skin Friction.

m	Gr	Gm	M	K_0	Sc	Ω	Pr	t	ω**t**	τ_x	τ_z
2.0	10	100	2.0	1.0	2.01	5.0	0.7	0.2	30	3.51	-3.03
3.0	10	100	2.0	1.0	2.01	5.0	0.7	0.2	30	3.53	-3.03
1.0	20	100	2.0	1.0	2.01	5.0	0.7	0.2	30	5.76	-3.60
1.0	30	100	2.0	1.0	2.01	5.0	0.7	0.2	30	8.13	-2.94
1.0	10	20	2.0	1.0	2.01	5.0	0.7	0.2	30	3.43	-3.08
1.0	10	30	2.0	1.0	2.01	5.0	0.7	0.2	30	3.35	-2.65
1.0	10	100	2.0	10	2.01	5.0	0.7	0.2	30	2.99	-2.78
1.0	10	100	2.0	20	2.01	5.0	0.7	0.2	30	2.70	-2.72
1.0	10	100	2.0	1.0	2.01	5.0	0.7	0.1	30	1.27	-1.76
1.0	10	100	2.0	1.0	2.01	5.0	0.7	0.3	30	5.32	-3.91
1.0	10	100	2.0	1.0	2.01	1.0	0.7	0.3	30	4.26	-0.35
1.0	10	100	2.0	1.0	2.01	3.0	0.7	0.3	30	3.98	-1.70
1.0	10	100	2.0	1.0	2.01	1.0	0.7	0.2	45	3.96	-2.68
1.0	10	100	2.0	1.0	2.01	3.0	0.7	0.2	90	6.30	-1.81

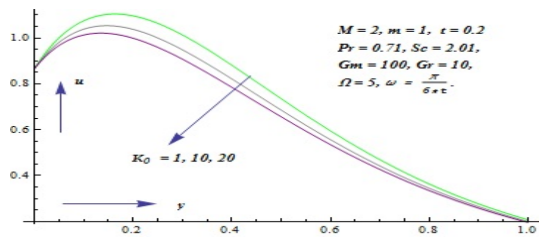

Figure 3: u vs y for different values of K_0.

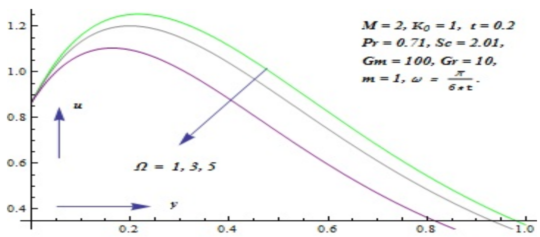

Figure 4: u vs y for different values of Ω.

The boundary conditions considered for the model are as follows:

$$\left\{\begin{array}{l} t \leq 0 : u = 0, w = 0, T = T_\infty, \\ C = C_\infty, \forall y \\ t > 0 : u = u_0 cos\omega t, w = 0, T = T_w, \\ C = C + (C_w - C_\infty)\frac{u_0^2 t}{\upsilon} \quad \text{at} \quad y = 0 \\ u \to 0, w \to 0, T \to T_\infty, \\ C \to C_\infty, \text{as} \quad y \to \infty \end{array}\right\} \quad (2.5)$$

Definition of symbols: u fluid velocity along x, w fluid velocity along z, m - Hall parameter, g - gravity, β - coefficient of thermal expansion, β^* - coefficient of concentration expansion, t - time, C_∞ - the species concentration away from the plate, C - species concentration in the fluid, Cw - species concentration at the plate, D - mass diffusion, C_∞ - fluid temperature near the plate, T_w - plate temperature, T - fluid temperature, k - the thermal conductivity, υ - the kinematic vis-

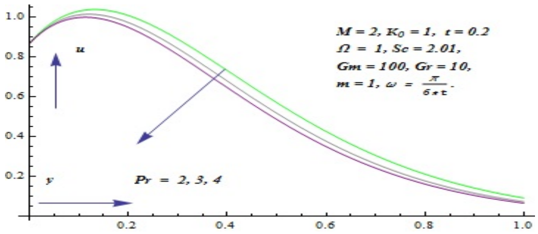

Figure 5: u vs y for different values of Pr.

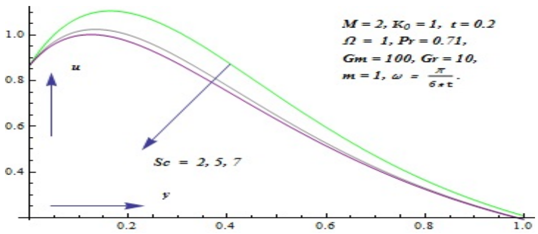

Figure 6: u vs y for different values of Sc.

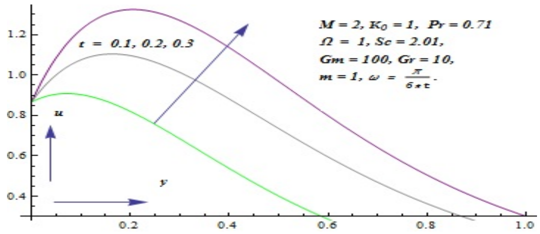

Figure 7: u vs y for different values of t.

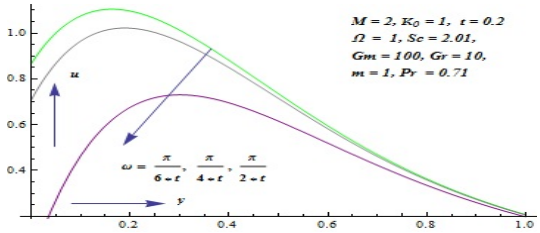

Figure 8: u vs y for different values of ωt.

cosity, ρ- the fluid density, K_c-chemical reaction parameter σ- electrical conductivity, μ-the magnetic permeability, and C_P- specific heat at constant pressure. Here $m= \omega_e \tau_e$ with ω_e- cyclotron frequency of electrons and τ_e- electron collision time. To transform the equations (2.1) - (2.4) in dimensionless form, the following non - dimensional quantities are used:

$$\left\{ \begin{array}{l} \overline{y} = \frac{yu_0}{\upsilon}, \overline{u} = \frac{u}{u_0}, \overline{w} = \frac{w}{u_0}, Sc = \frac{\upsilon}{D}, \\ \theta = \frac{T-T_\infty}{T_w-T_\infty}, Pr = \frac{\mu C_p}{K}, H = \frac{Q\upsilon}{u_0^2 \rho C_p}, \\ \overline{\Omega} = \frac{Q\upsilon}{u_0^2}, \overline{t} = \frac{tu_0^2}{\upsilon}, \overline{C} = \frac{C-C_\infty}{C_w-C_\infty} \\ M = \frac{\sigma B_0^2 \upsilon}{\rho u_0^2}, Gr = \frac{g\beta \upsilon cos\alpha(T_w-T_\infty)}{u_0^3}, \\ Gm = \frac{g\beta^* \upsilon cos\alpha(C_w-C_\infty)}{u_0^3} \end{array} \right\} \quad (2.6)$$

The symbols in dimensionless form are: $\overline{u}$ - primary velocity, $\overline{w}$- secondary velocity, θ - temperature, $\overline{C}$ - 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, Ω- rotation parameter, K_0 - the chemical reaction parameter. The dimensionless forms of equations (2.1), (2.3), (2.4) and (2.4) are as follows

$$\frac{\partial \overline{u}}{\partial \overline{t}} - 2\overline{\Omega}\overline{w} = \frac{\partial^2 \overline{u}}{\partial \overline{y}^2} + Gr\theta + Gm\overline{C} - \frac{M(\overline{u} - m\overline{w})}{(1+m^2)} \quad (2.7)$$

$$\frac{\partial \overline{w}}{\partial \overline{t}} + 2\overline{\Omega}\overline{u} = \frac{\partial^2 \overline{w}}{\partial \overline{y}^2} - \frac{M(\overline{w} - m\overline{u})}{(1+m^2)} \quad (2.8)$$

$$\frac{\partial \overline{C}}{\partial \overline{t}} = \frac{1}{Sc}\frac{\partial^2 \overline{C}}{\partial \overline{y}^2} - K_0\overline{C} \quad (2.9)$$

$$\frac{\partial \theta}{\partial \overline{t}} = \frac{1}{Pr}\frac{\partial^2 T}{\partial \overline{y}^2} \quad (2.10)$$

The corresponding boundary conditions are:

$$\left\{ \begin{array}{l} \overline{t} \leq 0 : \overline{u} = 0, \overline{w} = 0, \overline{\theta} = 0, \overline{C} = 0 \forall y \\ \overline{t} > 0 : \overline{u} = \overline{u}_0 cos\omega t, \overline{w} = 0, \theta = 1, \\ \overline{C} = \overline{t} \quad \text{at} \quad y = 0 \\ \overline{u} \to 0, \overline{w} \to 0, \theta \to 0, \overline{C} \to 0, \quad \text{as} \quad \overline{y} \to \infty \end{array} \right\}. \quad (2.11)$$

Dropping the bars and combining the equations (2.8) and (2.9), we get

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial y^2} + Gr\theta + GmC - \frac{(M(1-im) + 2i\Omega)q}{(1+m^2)} \quad (2.12)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - K_0 C \quad (2.13)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 T}{\partial y^2} \quad (2.14)$$

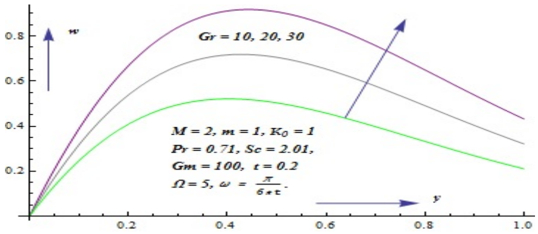

Figure 9: w vs y for different values of Gr.

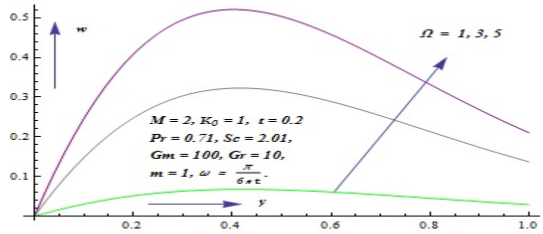

Figure 11: w vs y for different values of Ω.

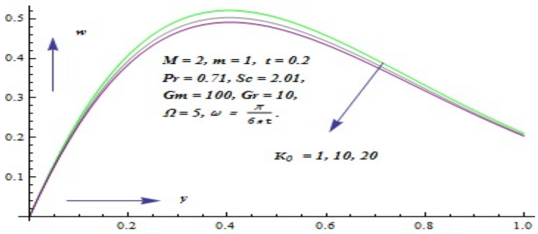

Figure 10: w vs y for different values of K_0.

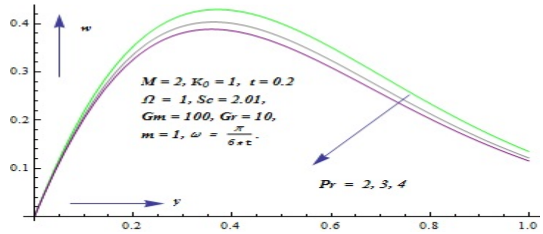

Figure 12: w vs y for different values of Pr.

Here $(q = u+iw)$ The corresponding boundary conditions become

$$\left\{\begin{array}{l} t \le 0 : q = 0, \theta = 0, C = 0 \forall \quad y \\ t > 0 : q = q\cos\omega t, \theta = 1, C = t \quad \text{at} \quad y = 0 \\ q \to 0, \theta \to 0, C \to 0, \quad \text{as} \quad y \to \infty \end{array}\right\} \tag{2.15}$$

Solving analytically using Laplace transform method, equations (2.12), (2.13) and (2.14) are changed to

$$\begin{aligned} sq^*(y', s) - q(y', 0) &= \frac{\partial^2 q^*}{\partial t^2} \\ &+ Gr\theta^* + GmC^* \\ &- \frac{[M(1-im)]q^*}{(1+m^2)} \\ &- \frac{2i\Omega q^*}{(1+m^2)} \end{aligned} \tag{2.16}$$

$$\begin{aligned} sC^*(y', s) - C(y', 0) &= [\frac{\partial^2 C^*(y', s)}{\partial y'^2} \\ &\frac{1}{Sc}] - K_0 C^* \end{aligned} \tag{2.17}$$

$$\begin{aligned} s\theta^*(y', s) - \theta(y', 0) &= [\frac{\partial^2 \theta^*(y', s)}{\partial y'^2} \\ &\frac{1}{Pr}] \end{aligned} \tag{2.18}$$

where s is a parameter of Laplace transformation. After solving equations .(2.16), (2.17), and (2.18) are changed to

$$\begin{aligned} q^* &= \frac{e^- \sqrt{(s+a)}y}{s^2+\omega^2} + \frac{Gre^- \sqrt{(s+a)}y}{sPr-(s+a)} \\ &+ \frac{Gme^- \sqrt{(s+a)}y}{s^2(s+K_0)Sc-(s+a)} \\ &- \frac{Gre^- \sqrt{Pr}y}{s^2(sPr)-(s+a)} \\ &- \frac{Gme^- \sqrt{(s+K_0)Sc}y}{s^2(s+K_0)Sc-(s+a)} \end{aligned} \tag{2.19}$$

$$C^* = \frac{e^- \sqrt{(s+K_0)Sc}y}{s^2} \tag{2.20}$$

$$\theta^* = \frac{e^- \sqrt{(Prs)}y}{s} \tag{2.21}$$

Taking inverse Laplace, the solution obtained is as under

$$\begin{aligned} q &= \frac{1}{2}\exp(\sqrt{-}i\omega)(P_1+P_2-P_3-P_4-P_5 \\ &- P_6) + \frac{1}{2a}(-\exp(\sqrt{-}ay)(A_0 \\ &+ exp\frac{at}{-1+Pr}y\sqrt{\frac{at}{-1+Pr}}(A_{13} \\ &+ exp2y\sqrt{\frac{at}{-1+Pr}}A_{14}))Gr \\ &+ \frac{1}{4(a-K_0Sc)^2}yGm((\frac{2exp\sqrt{-}ayA_{01}}{y}) \\ &(1-a_0) + \sqrt{a}exp\sqrt{-}ay(A_0 - exp2\sqrt{a}yA_{12}) \end{aligned}$$

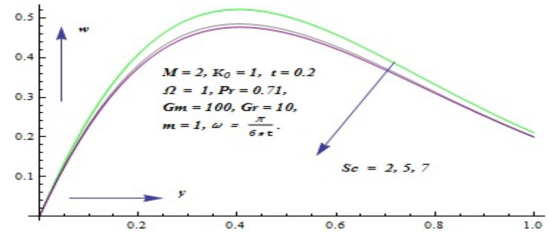

Figure 13: w vs y for different values of Sc.

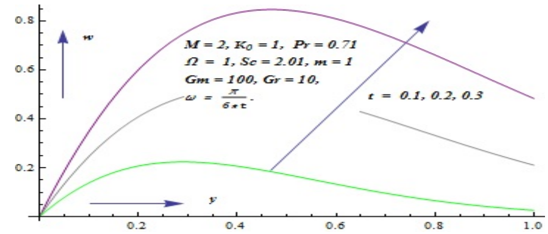

Figure 14: w vs y for different values of t.

$$
\begin{aligned}
+ \quad & \frac{1}{y}2exp(\frac{at}{-1+Sc} - \frac{tk_0Sc}{-1+Sc} - yA_{17}) \\
& (-1 - exp(2yA_{17}) + A_{15}exp(2yA_{17}A_{16}) \\
* \quad & [1 - Sc] + \frac{1}{y}2exp\sqrt{-a}y \\
* \quad & (-1 - exp\sqrt{a}y - A_{11} + exp2\sqrt{a}yA_{12})Sc \\
& [1 - tK_0] - \frac{1}{\sqrt{a}}exp - \sqrt{a}y(A_0 \\
& -exp2\sqrt{a}y)K_0Sc) \\
- \quad & \frac{1}{2a}(exp(\frac{at}{-1+Pr} - y\sqrt{\frac{at}{-1+Pr}})(1 + A_{18} \\
+ \quad & exp(2y\sqrt{\frac{at}{-1+Pr}})A_{19}) - 2erfc[\frac{y\sqrt{Pr}}{2\sqrt{t}}])Gr \\
+ \quad & \frac{1}{4(a-K_0Sc)^2}yGm \\
& \sqrt{Sc}(-\frac{1}{K_0}aexp(-y\sqrt{K_0Sc} \\
& (-1 - exp(y\sqrt{K_0Sc}) + A_{20} \\
+ \quad & exp(2y\sqrt{K_0Sc}A_{21}) \\
+ \quad & \frac{1}{y}\sqrt{Sc}2exp(-y\sqrt{K_0Sc}(-1 - \\
& exp(2y\sqrt{K_0Sc} + A_{20} \\
+ \quad & exp(2y\sqrt{K_0Sc}A_{21})[1 - t - Sc]) \\
- \quad & \frac{1}{y\sqrt{Sc}}(\frac{at}{-1+Sc} \\
& 2exp - yA_{17}\frac{tK_0SC}{-1+Sc})(1 - exp(2yA_{17} - A_{22} \\
+ \quad & 2exp(2y\sqrt{\frac{a-K_0}{-1+Sc}}\sqrt{Sc})[1 - Sc] \\
+ \quad & exp(-y\sqrt{K_0Sc}))
\end{aligned}
$$

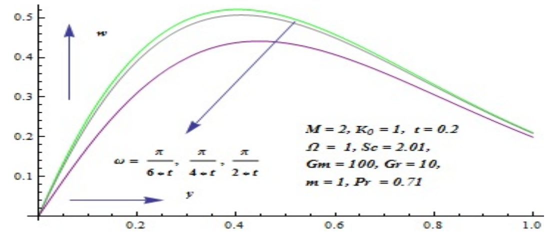

Figure 15: w vs y for different values of ωt.

$$
\begin{aligned}
C \quad = \quad & \frac{1}{4\sqrt{K_0Sc}}exp(-y\sqrt{ScK_0})[B_{11}] \\
& (-Scy + 2t\sqrt{ScK_0}) \\
+ \quad & exp(2y\sqrt{ScK_0})[B_{12}] \\
& (Scy + 2t\sqrt{ScK_0}) \\
\theta \quad = \quad & Ercf[\frac{\sqrt{Pr}y}{2\sqrt{t}}]
\end{aligned}
$$

2.1 Skin fraction

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

$$\frac{\partial q}{\partial y}_{y=0} = \tau_x + i\tau_z$$

2.2 Sherwood Number

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

$$Sh = \frac{\partial C}{\partial y}_{y=0}$$

$$
\begin{aligned}
Sh \quad = \quad & \frac{-1}{4}exp(-y\sqrt{ScK_0})(B_{11}(-Scy \\
+ \quad & 2t\sqrt{ScK_0})) + exp(2y\sqrt{ScK_0}) \\
& (B_{12}Scy + 2t\sqrt{ScK_0})) + \frac{1}{4\sqrt{ScK_0}} \\
& exp(-y\sqrt{ScK_0})(-ScB_{11} \\
& exp(2y\sqrt{ScK_0})ScB_{12}) - \frac{\sqrt{Sc}}{\sqrt{t}} \\
& exp(B_{11}^2)(Sc + 2t\sqrt{ScK_0}) \\
+ \quad & exp(-B_{11}^2 + 2y\sqrt{ScK_0}) \\
& (Sc + 2t\sqrt{ScK_0}) + 2exp(2y\sqrt{ScK_0}) \\
& B_{12}(Sc + 2t\sqrt{ScK_0})
\end{aligned}
$$

3 Interpretation of Results

The velocity, skin friction and Sherwood number have been computed for different parameters. Figure 2 and 7 show that u increases when Gr and t are increased. Figures 3, 4, 5, 6, 8, and 9 show that u decreases when K_0, Ω, Pr, Sc and ωt are increased. Further, it is deduced from figure 9, 11 and 14 that w increases when Gr, Ω, and t are increased. Figures 10, 12, 13, and 15 show that w decreases when K_0, Pr, Sc and ωt are increased. These results are in agreement with the actual flow of the fluid. Figures 14 and 15 show that concentration decreases when K_0, and Sc are increased. From table 1 it is deduced that Sherwood number decreases with increase in Sc, K_0, and t. From table 2 it is deduced that τ_x decreases with increase in M, Ω, and K_0. Further, it increases with increase in Gm, Gr, m, t and ωt. The value of τ_z increases with increase in M, K_0 and . Further, it decreases when Gm, Gr, m, t, and Ω are increased. Effectively it is as per the expectations of the boundary layer theory.

4 Conclusion

It has been observed that both the velocities, primary (u) and secondary (w), increase when thermal Grashof number and time are increased. However, these decrease with the increase in chemical reaction parameter, Prandtl number, Schmidt number and phase angle. Further concentration decreases when chemical reaction parameter and Schmidt number are increased. The value of τ_x decreases with increase in the magnetic parameter, rotation parameter and chemical reaction parameter; and it increases with increase in mass Grashof number, thermal Grashof number, Hall current parameter, time and phase angle. The value of τ_z increases with increase in the magnetic parameter, chemical reaction parameter and phase angle; and it decreases when mass Grashof number, thermal Grashof number, Hall current parameter, time and rotation parameter are increased. Sherwood number decreases with increase in Schmidt number, chemical reaction parameter and time.

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5 Appendix

$$P_1 = exp(-y\sqrt{a-i\omega} + exp(y\sqrt{a-i\omega}),$$
$$P_2 = exp(-y\sqrt{a-i\omega} - 2it\omega + exp(y\sqrt{a-i\omega} + 2it\omega),$$
$$P_3 = exp(-y\sqrt{a-i\omega})Erf\left[\frac{y-2t\sqrt{a-i\omega}}{2\sqrt{t}}\right],$$
$$P_4 = exp(-y\sqrt{a-i\omega})Erf\left[\frac{y+2t\sqrt{a-i\omega}}{2\sqrt{t}}\right],$$
$$P_5 = exp(-y\sqrt{a-i\omega} + 2it\omega)Erf\left[\frac{y-2t\sqrt{a-i\omega}}{2\sqrt{t}}\right],$$
$$P_6 = exp(-y\sqrt{a-i\omega} + 2it\omega)Erf\left[\frac{y+2t\sqrt{a-i\omega}}{2\sqrt{t}}\right],$$
$$A_0 = 1 + A_{11} + exp(2\sqrt{a}y)A_{12}, A_{01} = 1 + exp(2\sqrt{a}y)$$
$$+ A11 - exp(2\sqrt{a}y)A_{12}, A_{11} = Erf\left[\frac{2a\sqrt{t}-y}{2\sqrt{t}}\right],$$
$$A_{12} = Erf\left[\frac{2a\sqrt{t}+y}{2\sqrt{t}}\right],$$
$$A_{13} = Erf\left[\frac{y-2t\sqrt{a(1+\frac{1}{-1+Pr})}}{2\sqrt{t}}\right],$$
$$A_{14} = Erf\left[\frac{y+2t\sqrt{a(1+\frac{1}{-1+Pr})}}{2\sqrt{t}}\right],$$

$$A_{15} = Erf\left[\frac{y - 2t\sqrt{y - \frac{(a-K_0Sc)}{-1+Sc}}}{2\sqrt{t}}\right]$$

$$A_{16} = Erf\left[\frac{y + 2t\sqrt{y - \frac{(a-K_0Sc)}{-1+Sc}}}{2\sqrt{t}}\right],$$

$$A_{17} = \sqrt{\frac{(a - K_0Sc)}{-1 + Sc}},$$

$$A_{18} = Erf\left[\frac{2t\sqrt{\frac{a}{-1+Pr}} - y\sqrt{t}}{2\sqrt{t}}\right],$$

$$A_{19} = Erf\left[\frac{2t\sqrt{\frac{a}{-1+Pr}} + y\sqrt{t}}{2\sqrt{t}}\right],$$

$$A_{20} = Erf\left[\frac{2t\sqrt{K_0} - y\sqrt{Sc}}{2\sqrt{t}}\right],$$

$$A_{21} = Erf\left[\frac{2t\sqrt{K_0} + y\sqrt{Sc}}{2\sqrt{t}}\right],$$

$$A_{22} = Erf\left[\frac{2t\sqrt{\frac{a-K_0}{-1+Sc}} - y\sqrt{Sc}}{2\sqrt{t}}\right],$$

$$A_{23} = Erf\left[\frac{2t\sqrt{\frac{a-K_0}{-1+Sc}} + y\sqrt{Sc}}{2\sqrt{t}}\right],$$

$$B_{11} = Erfc\left[\frac{y\sqrt{K_0} - 2t\sqrt{K_0}}{2\sqrt{t}}\right],$$

$$B_{12} = Erfc\left[\frac{y\sqrt{K_0} + 2t\sqrt{K_0}}{2\sqrt{t}}\right],$$

$$a = \frac{M}{1 + m^2}(1 - im) + 2i\Omega.$$

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