JJMIE

Volume 11 Number 1, January. 2017
ISSN 1995-6665
Pages 41 -49

Jordan Journal of Mechanical and Industrial Engineering

Chemical Reaction Effect on Unsteady MHD Flow Past an Impulsively Started Inclined Plate with Variable Temperature and Mass Diffusion in the Presence of Hall Current

U. S. Rajput * , Gaurav Kumar

Department of Mathematics and Astronomy, University of Lucknow, Lucknow, U.P, India.

Received JAN, 21, 2016   *Accepted MAY, 7, 2017*

Abstract

The present study is carried out to examine the combined effects of Hall current and chemical reaction on flow model. The model consists of unsteady flow of a viscous, incompressible and electrically conducting fluid. The flow is along an impulsively started inclined plate with variable wall temperature and mass diffusion. The magnetic field of uniform strength is applied perpendicular to the flow. The model contains equations of motion, diffusion equation and equation of energy. The Governing equations involved in the present analysis are solved by the Laplace-transform technique. The velocity profile is discussed with the help of graphs drawn for different parameters, like thermal Grashof number, mass Grashof number, Prandtl number, chemical reaction parameter, Hall parameter, the magnetic field parameter and Schmidt number. The numerical values obtained for skin-friction were tabulated. We found that the values obtained for velocity, concentration and temperature are in concurrence with the actual flow of the fluid.

Keywords:

1. Introduction

MHD flow problems associated with heat and mass transfer plays important roles in different areas of science and technology, like chemical engineering, mechanical engineering, biological science, petroleum engineering and biomechanics. Such problems frequently occur in petro-chemical industry, chemical vapor deposition on surfaces, cooling of nuclear reactors, heat exchanger design, forest fire dynamics and geophysics. The influence of magnetic field on viscous, incompressible and electrically conducting fluid is of great importance in many applications such as magnetic material processing, glass manufacturing control processes and purification of crude oil. Attia along with Ahmed [1] studied the Hall effect on unsteady MHD Couette flow and heat transfer of a Bingham fluid with suction and injection. Further, Attia [2] considered the effect of variable properties on the unsteady Hartmann flow with heat transfer considering the Hall effect. Effect of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction was investigated by Deka *et al.* [3]. Chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate with suction was investigated by Ibrahim and Makinde [4]. The effect of Hall current on the magneto hydrodynamic boundary layer flow past a semi-infinite fast plate was studied by Katagiri [5]. Muthucumarswamy [6] considered effect of chemical reaction on a moving isothermal vertical surface with suction. Further, Muthucumarswamy along with Ganesan [7] investigated first order chemical reaction on flow past an impulsively started vertical plate with uniform heat and mass flux. Maripala and Naikoti [8] analyzed Hall effect on unsteady MHD free convection flow over a stretching sheet with variable viscosity and viscous dissipation. MHD oscillatory channel flow, heat and mass transfer in a physiological fluid in the presence of chemical reaction was developed by Misra and Adhikary [9]. Pop [10] investigated the effect of Hall current on hydromagnetic flow near an accelerated plate. Pop and Watanabe [11] further studied Hall effect on MHD boundary layer flow over a continuous moving flat plate. Viscous flow over a non-linearly stretching sheet in the presence of a chemical reaction and magnetic field was studied by Raptis and Perdikis [12]. Raptis and Kafousias [13] studied flow of a viscous fluid through a porous medium bounded by a vertical surface. The study of MHD flow past an impulsively started vertical plate with variable temperature and mass diffusion was done by Rajput and Kumar [14]. Further, Rajput and kumar [15] worked on effect of chemical reaction on free convection MHD flow through a porous medium bounded by vertical surface. Ziyauddin and Kumar [16] investigated MHD heat and mass transfer free convection flow near the lower stagnation point of an isothermal cylinder imbedded in

* Corresponding author e-mail: rajputgauravlko@gmail.com.

porous domain with the presence of radiation. Combined effects of radiation and Hall current on MHD flow past an exponentially accelerated vertical plate in the presence of rotation was studied by Thamizhsudar and Pandurangan [17]. Tripathy *et al.* [18] analyzed chemical reaction effect on MHD free convective surface over a moving vertical plate through porous medium. Earlier, we [19] studied unsteady MHD flow past an impulsively started inclined plate with variable temperature and mass diffusion in the presence of Hall current. The main purpose of the present investigation is to study the effects of chemical reaction on unsteady MHD flow past an impulsively started inclined plate with variable wall temperature and mass diffusion in the presence of Hall current. The results are shown with the help of graphs and table.

2. Mathematical Analysis

The geometrical model of the problem is shown in figure-A

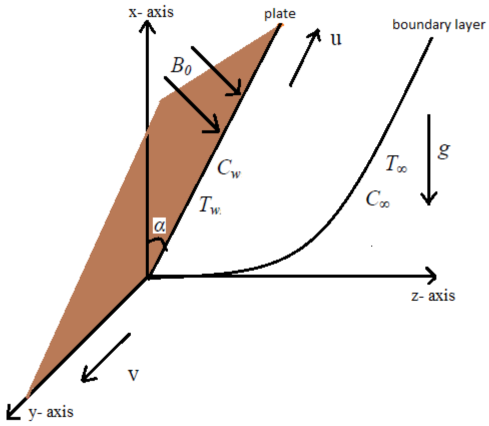

Figure A. Physical model

The x axis is taken along the vertical plane and z normal to it. Thus the z axis lies in the horizontal plane. The plate is inclined at an angle α from vertical. A transverse magnetic field B_0 of uniform strength is applied on the flow. The viscous dissipation and induced magnetic field was neglected due to its small effect. Initially it has been assumed that the plate and the fluid are at the same temperature T_∞. Further, the species concentration is C_∞ everywhere in the fluid in stationary condition. At time $t > 0$, the plate starts moving with a velocity u_0 in its own plane and temperature of the plate is raised to T_w; also the concentration level near the plate is raised linearly with respect to time. Due to the Hall effect there will be two components of the momentum equation. The flow model is as under:

3. Equations of motion

$$\frac{\partial u}{\partial t} = \upsilon \frac{\partial^2 u}{\partial z^2} + g\beta Cos\alpha\,(T - T_\infty) + g\beta^* Cos\alpha\,(C - C_\infty) - \frac{\sigma B_0^2 (u + mv)}{\rho(1+m^2)} \quad (1)$$

$$\frac{\partial v}{\partial t} = \upsilon \frac{\partial^2 v}{\partial z^2} + \frac{\sigma B_0^2 (mu - v)}{\rho(1+m^2)} \quad (2)$$

Diffusion equation

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - K_C (C - C_\infty) \quad (3)$$

Equation of energy

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \quad (4)$$

The initial and boundary conditions are

$$\left.\begin{array}{l} t \le 0 : u = 0,\ v = 0,\ T = T_\infty,\ C = C_\infty, \text{ for every } z, \\ t > 0 : u = u_0, v = 0, \\ T = T_\infty + (T_w - T_\infty)\dfrac{u_0^2 t}{\upsilon}, \quad \text{at } z=0, \\ C = C_\infty + (C_w - C_\infty)\dfrac{u_0^2 t}{\upsilon}, \\ u \to 0,\ v \to 0,\ T \to T_\infty,\ C \to C_\infty \text{ as } z \to \infty, \end{array}\right\} \quad (5)$$

where u is the primary velocity, v - the secondary velocity, g- the acceleration due to gravity, β - volumetric coefficient of thermal expansion, t-time, m - Hall parameter, T-temperature of the fluid, β^*- volumetric coefficient of concentration expansion, C- species concentration in the fluid, ν - 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, T_w - temperature of the plate at $z = 0$, C_w - species concentration at the plate $z = 0$, B_0 - the uniform magnetic field, K_c - chemical reaction and σ is electrical conductivity. Here $m = \omega_e \tau_e$ with ω_e - cyclotron frequency of electrons and τ_e - electron collision time.

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

$$\left.\begin{array}{l} \bar{z} = \dfrac{z u_0}{\upsilon},\ \bar{u} = \dfrac{u}{u_0},\ \bar{v} = \dfrac{v}{u_0}, S_c = \dfrac{\upsilon}{D}, \mu = \rho\upsilon, \\ M = \dfrac{\sigma B_0^2 \upsilon}{\rho u_0^2}, \bar{C} = \dfrac{(C - C_\infty)}{(C_w - C_\infty)}, P_r = \dfrac{\mu c_p}{k}, \\ G_r = \dfrac{g\beta\upsilon(T_w - T_\infty)}{u_0^3}, K_0 = \dfrac{\upsilon K_C}{u_0^2}, \bar{t} = \dfrac{t u_0^2}{\upsilon}, \\ G_m = \dfrac{g\beta^*\upsilon(C_w - C_\infty)}{u_0^3}, \theta = \dfrac{(T - T_\infty)}{(T_w - T_\infty)} \end{array}\right\} \quad (6)$$

The symbols in dimensionless form are as under:

$\bar{u}$ - the primary velocity, $\bar{V}$ - the secondary velocity, $\bar{t}$ - time, θ - the temperature, $\bar{C}$ - the concentration, G_r - thermal Grashof number, G_m - mass Grashof number, μ- the coefficient of viscosity, K_0 the chemical reaction parameter, P_r- the Prandtl number, S_c- the Schmidt number, M- the magnetic parameter.

The flow model in dimensionless form is

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} + G_r Cos\alpha\,\theta + G_m Cos\alpha\,\bar{C} - \frac{M(\bar{u}+m\bar{v})}{(1+m^2)} \quad (7)$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} = \frac{\partial^2 \bar{u}}{\partial \bar{z}^2} + \frac{M(m\bar{u}-\bar{v})}{(1+m^2)} \quad (8)$$

$$\frac{\partial \bar{C}}{\partial \bar{t}} = \frac{1}{S_c}\frac{\partial^2 \bar{C}}{\partial \bar{z}^2} - K_0\bar{C} \quad (9)$$

$$\frac{\partial \theta}{\partial \bar{t}} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial \bar{z}^2} \quad (10)$$

The corresponding boundary conditions (5) become:

$$\left.\begin{aligned} &\bar{t} \le 0 : \bar{u} = 0,\ \bar{v} = 0,\ \theta = 0,\ \bar{C} = 0, \text{ for every } \bar{z}, \\ &\bar{t} > 0 : \bar{u} = 1,\ \bar{v} = 0,\ \theta = \bar{t},\ \bar{C} = \bar{t}, \text{ at } \bar{z} = 0, \\ &\bar{u} \to 0,\ \bar{v} \to 0,\ \theta \to 0,\ \bar{C} \to 0, \text{ as } \bar{z} \to \infty. \end{aligned}\right\} \quad (11)$$

Dropping bars in the above equations, we get:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} + G_r Cos\alpha\,\theta + G_m Cos\alpha\,C - \frac{M(u+mv)}{(1+m^2)} \quad (12)$$

$$\frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial z^2} + \frac{M(mu-v)}{(1+m^2)} \quad (13)$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial z^2} - K_0 C \quad (14)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial z^2} \quad (15)$$

The boundary conditions become

$$\left.\begin{aligned} &t \le 0 : u = 0,\ v = 0,\ \theta = 0,\ C = 0, \text{ for all z,} \\ &t > 0 : u = 1,\ v = 0,\ \theta = t,\ C = t, \text{ at z=0,} \\ &u \to 0,\ v \to 0,\ \theta \to 0,\ C \to 0, \text{ as } z \to \infty. \end{aligned}\right\} \quad (16)$$

Writing the equations (12) and (13) in combined form

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial z^2} + G_r Cos\alpha\,\theta + G_m Cos\alpha\,C - qa \quad (17)$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial z^2} - K_0 C \quad (18)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial z^2} \quad (19)$$

Finally, the boundary conditions become

$$\left.\begin{aligned} &t \le 0 : q = 0, \theta = 0, C = 0, \text{ for every z,} \\ &t > 0 : q = 1, \theta = t, C = t, \text{ at z=0,} \\ &q \to 0,\ \theta \to 0,\ C \to 0, \text{ as } z \to \infty. \end{aligned}\right\} \quad (20)$$

Here $q = u + i\,v$, $a = \frac{M(1-im)}{1+m^2}$

The dimensionless governing equations (17) to (19) subject to the boundary conditions (20) are solved by the usual Laplace transform technique. The solution obtained is as under:

$$\theta = t\left\{(1+\frac{z^2 P_r}{2t})erfc[\frac{\sqrt{P_r}}{2\sqrt{t}}] - \frac{z\sqrt{P_r}}{\sqrt{\pi}\sqrt{t}}e^{-\frac{z^2}{4t}P_r}\right\},$$

$$C = \frac{e^{-z\sqrt{S_c K_0}}}{4\sqrt{K_0}}\{erfc[\frac{z\sqrt{S_c}-2t\sqrt{K_0}}{2\sqrt{t}}](-z\sqrt{S_c} + 2t\sqrt{K_0}) + e^{2z\sqrt{S_c K_0}}erfc[\frac{z\sqrt{S_c}+2t\sqrt{K_0}}{2\sqrt{t}}](z\sqrt{S_c}+2t\sqrt{K_0})\}$$

$$q = \frac{e^{-\sqrt{a}z}A_{15}}{2} + \frac{G_r Cos\alpha}{4a^2}\{zA_{11} + 2e^{-\sqrt{a}z}A_2 P_r + 2A_{14}A_4(1-P_r)\} + \frac{G_m Cos\alpha}{4(a-K_0 S_c)^2}[zA_{11} + 2A_{13}A_5(1-S_c) + 2e^{-\sqrt{a}z}A_2 S_c(1-tK_0) - \frac{ze^{-\sqrt{a}z}A_3 K_0 S_c}{\sqrt{a}}] + \frac{G_r Cos\alpha}{2a^2\sqrt{\pi}}[2zae^{\frac{-z^2 P_r}{4t}}\sqrt{tP_r} + \sqrt{\pi}A_{14}(A_6 + A_7 P_r) + \sqrt{\pi}A_{12}(az^2 P_r - 2 + 2at + 2P_r)] + \frac{G_m Cos\alpha}{4\sqrt{\pi}(a-K_0 S_c)^2}[\frac{e^{-\sqrt{K_0 S_c}}\sqrt{\pi}A_9\sqrt{S_c}}{2\sqrt{K_0}}(S_c K_0 - az) + A_{13}\sqrt{\pi}A_{10}(S_c - 1) + e^{-\sqrt{K_0 S_c}}\sqrt{\pi}A_8(1 - at - S_c + tK_0 S_c)]$$

The expressions for the symbols involved in the above equations are given in the appendix.

4. Skin Friction

The dimensionless skin friction at the plate is

$$\left(\frac{dq}{dz}\right)_{z=0} = \tau_x + i\tau_y .$$

The numerical values of τ_x and τ_y, for different parameters are given in table-1.

5. Results and Discussion

In the present paper, we studied the effects of Hall current and chemical reaction on unsteady MHD flow. The velocity profile for different parameters, like thermal Grashof number *Gr*, magnetic field *M*, Hall parameter *m*, chemical reaction K_0, Prandtl number *Pr*, Schmidt number *Sc* and time *t* are shown in figures from 1.1 to 2.9. The concentration profile for different parameters, like chemical reaction, Schmidt number and time are shown in figures from 3.1 to 3.3. The numerical values of skin-friction are presented in Table–1. Due to gravity component $gCos\alpha$, the fluid flows with higher velocity when plate is vertical as compared to flow when plate is horizontal. It is observed in figures 1.1 and 2.1 that the primary and secondary velocities of fluid decrease when the angle of inclination (α) is increased. From figures 1.2 and 2.2, we observe that if mass Grashof number is increased then the velocities got increased. From figures 1.3 and 2.3 it is deduced that when thermal Grashof number Gr is increased then the velocities are increased. If Hall current parameter m is increased then u is increased and v is decreased (figures 1.4 and 2.4). The influence of magnetic field on flow is observed from figures 1.5 and 2.5. It is seen that the effect of increasing values of the parameter (*M*) results in decreasing u and increasing v. It is in agreement since the magnetic field establishes a force which acts against the main flow resulting in slowing down the velocity of fluid. If K_0 the chemical reaction parameter is increased then the velocities are increased throughout the boundary layer region (figures 1.6 and 2.6). Further, it is observed that velocities decrease when Prandtl number is increased (figures 1.7 and 2.7). When the Schmidt number is increased then the velocities get decreased (figures 1.8 and 2.8). Further, from figures 1.9 and 2.9 it is observed that velocities increase with time. If reaction parameter and Schmidt number are increased then concentration is decreased (figures 3.1 and 3.2). Physically, the increase of *Sc* means decrease of molecular diffusivity (*D*). That is the process of diffusion will decrease. It is observed that velocities increase with time (figures 3.3).

Skin friction is given in table1. The value of τ_x increases with the increase in angle of inclination of plate, thermal Grashof number, and Hall currents parameter; and it decreases with angle of inclination of plate, mass Grashof Number, magnetic field, chemical reaction parameter, Prandtl number, Schmidt number and time. The value of τ_y increases with the increase in angle of inclination of plate, thermal Grashof number and the magnetic field; and it decreases with mass Grashof number, Hall current parameter, the chemical reaction parameter, Prandtl number, Schmidt number and time.

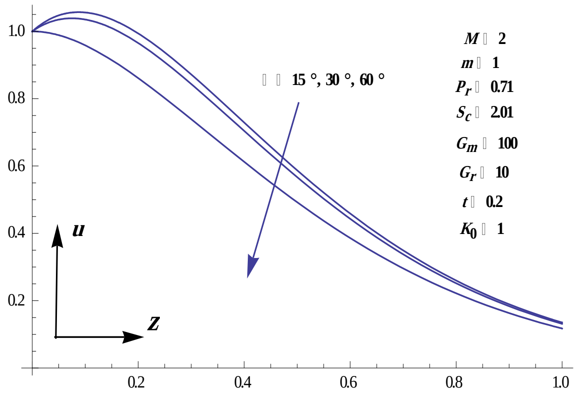

Figure 1.1: velocity *u* for different values of α

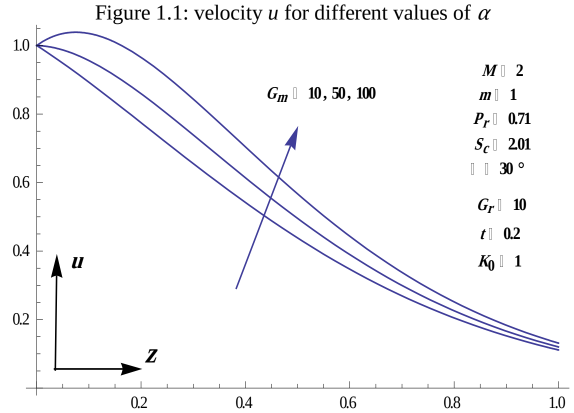

Figure 1.2: velocity *u* for different values of *Gm*

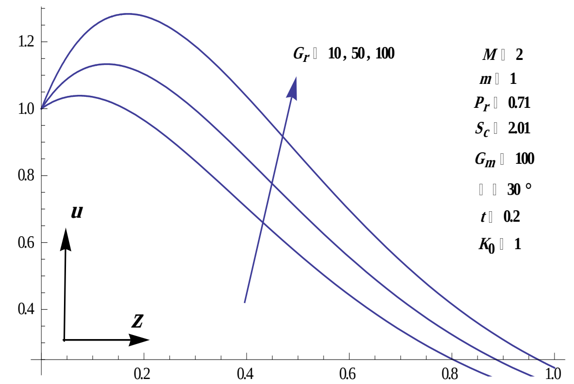

Figure 1.3: velocity u for different values of *Gr*

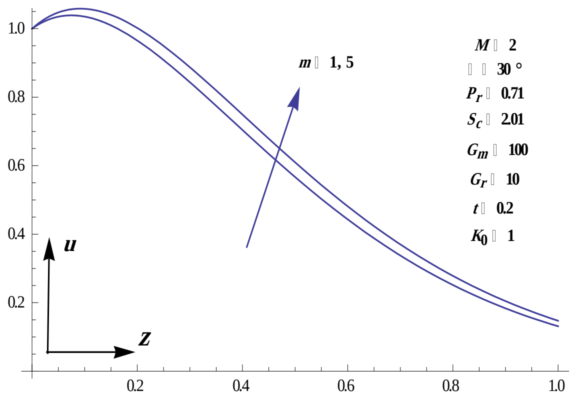

Figure 1.4: velocity *u* for different values of *m*

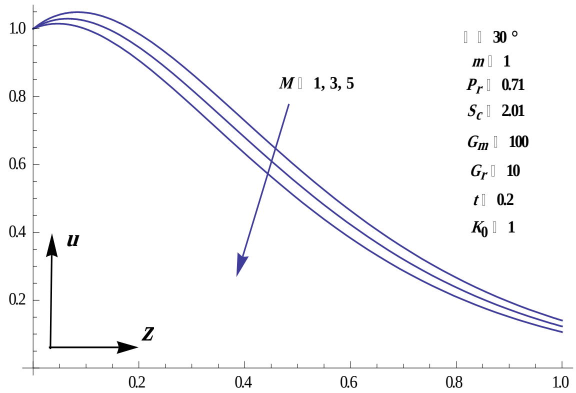

Figure 1.5: velocity *u* for different values of *M*

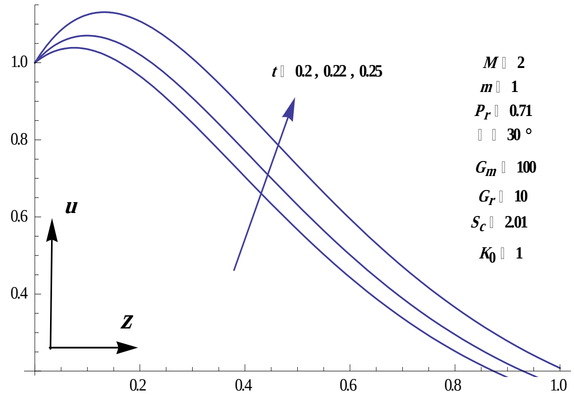

Figure 1.9: velocity u for different values of t

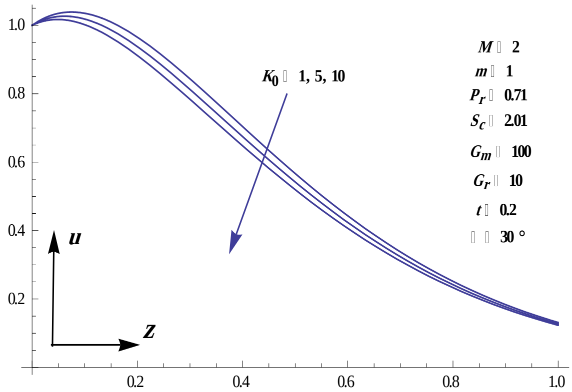

Figure 1.6: velocity *u* for different values of K_0

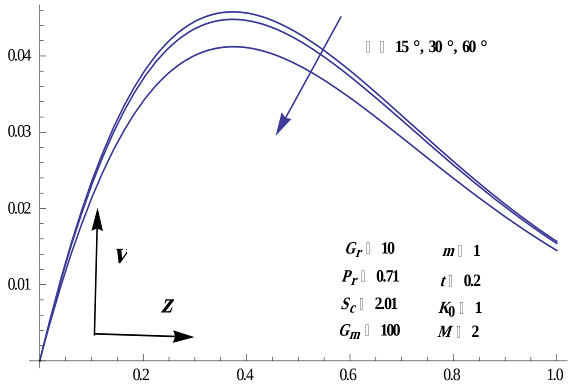

Figure 2.1: velocity *v* for different values of *α*

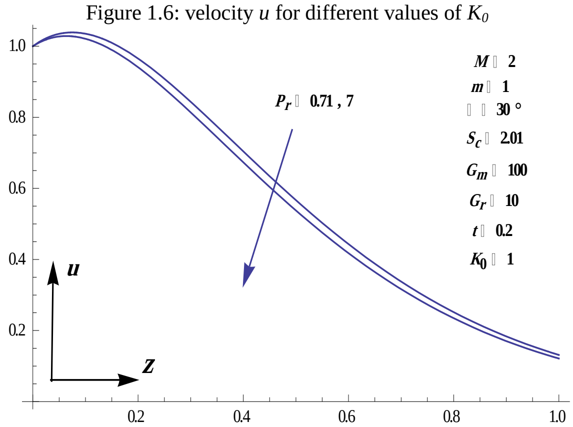

Figure 1.7: velocity *u* for different values of *Pr*

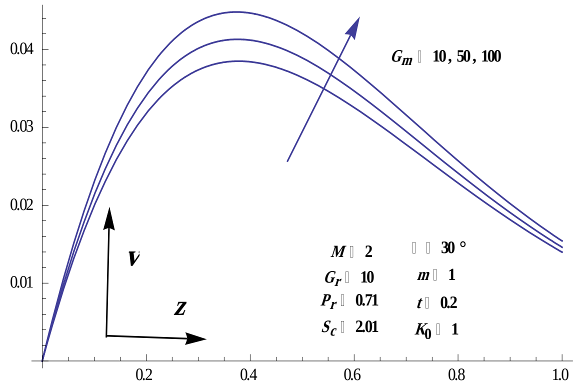

Figure 2.2: velocity v for different values of Gm

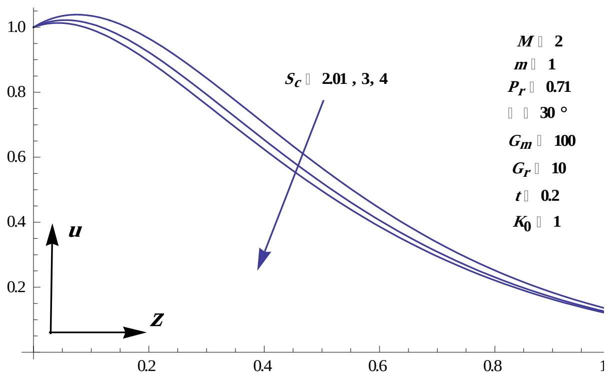

Figure 1.8: velocity *u* for different values of *Sc*

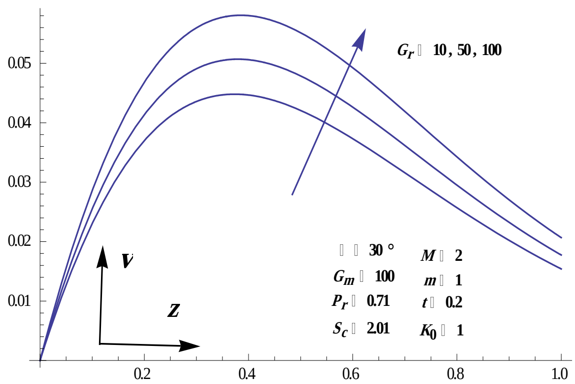

Figure 2.3: velocity v for different values of Gr

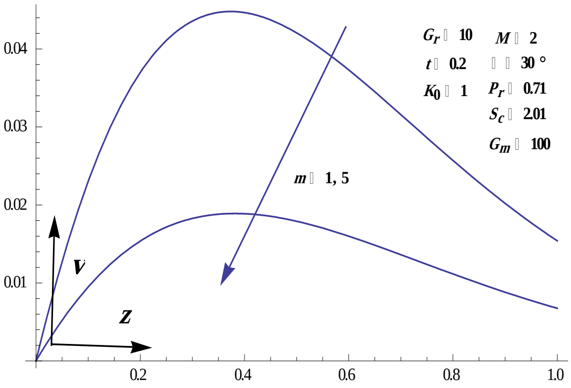

Figure 2.4: velocity v for different values of m

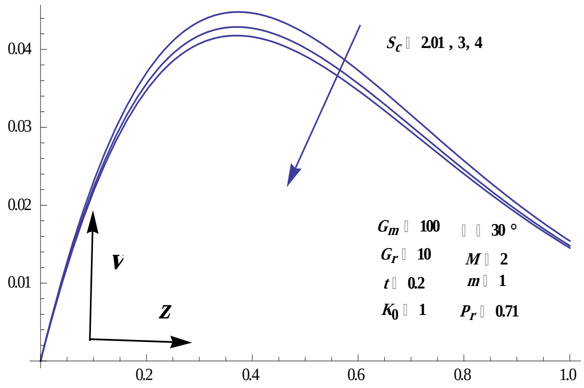

Figure 2.8: velocity v for different values of Sc

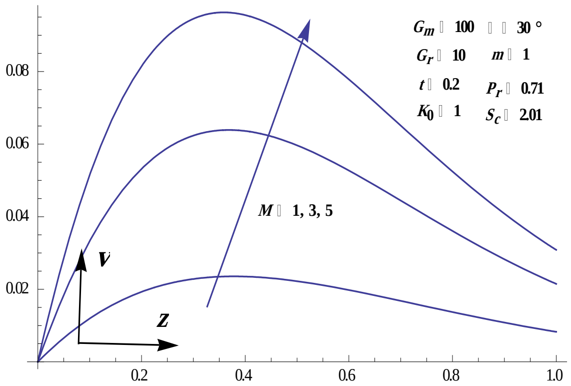

Figure 2.5: velocity v for different values of M

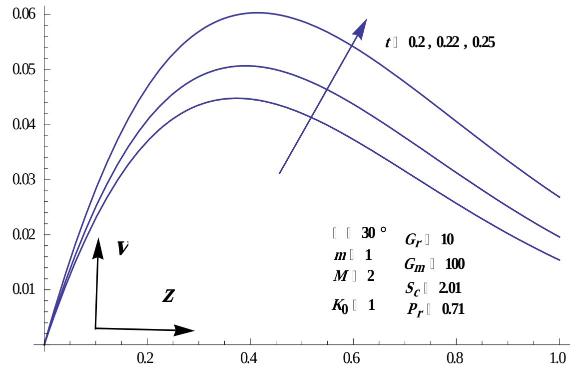

Figure 2.9: velocity v for different values of t

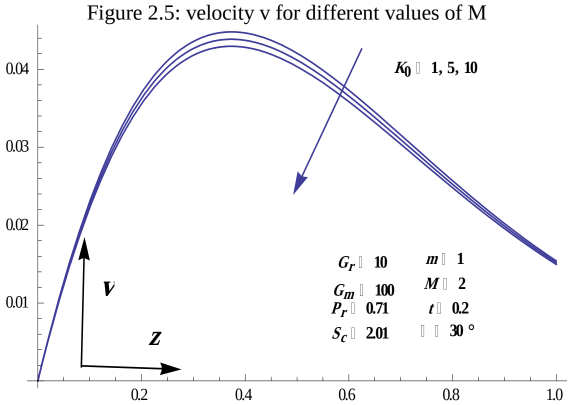

Figure 2.6: velocity v for different values of K0

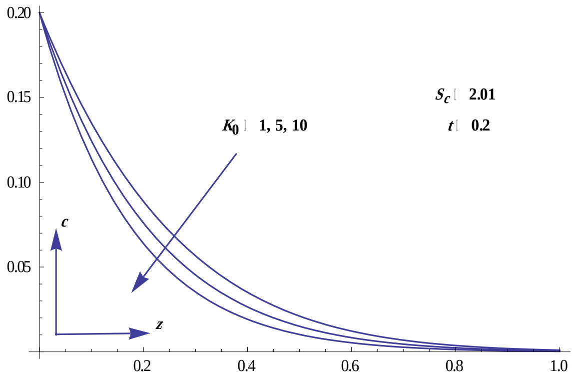

Figure 3.1: c for different values of Ko

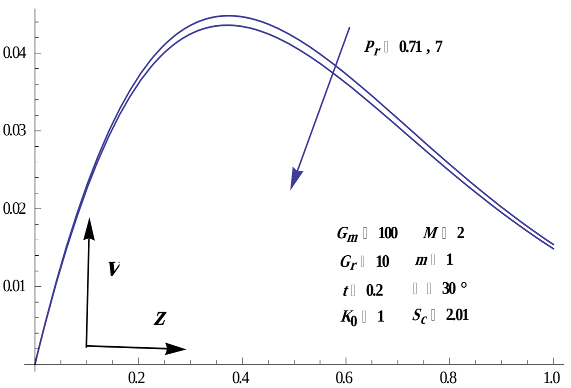

Figure 2.7: velocity v different values of Pr

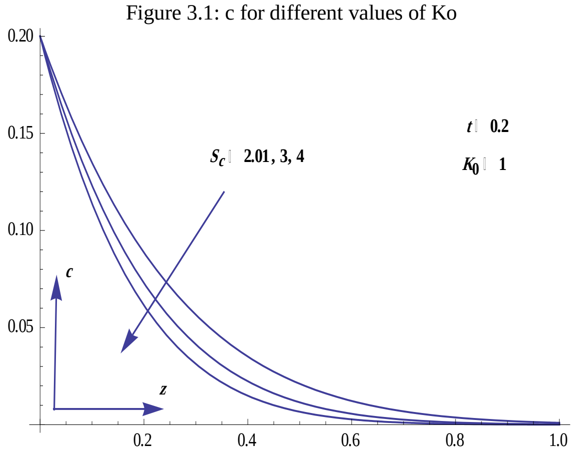

Figure 3.2: c for different values of Sc

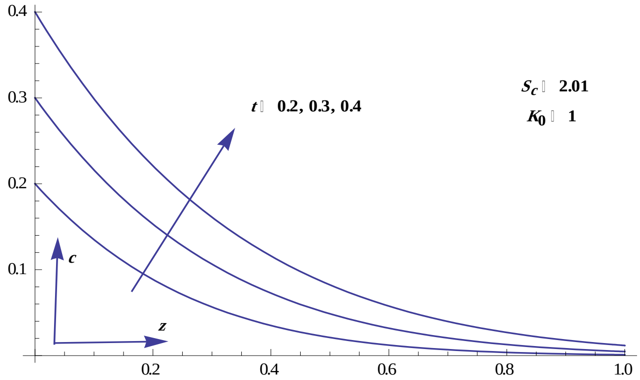

Figure 3.3: c for different values of t

Table1: Skin friction for different Parameters.
(α in degree)

α	M	m	Pr	Sc	Gm	Gr	K_0	t	τ_x	τ_y
15	02	0.5	0.71	2.01	100	10	01	0.2	-18.8529	-6.69686
30	02	0.5	0.71	2.01	100	10	01	0.2	-170596	-5.97981
45	02	0.5	0.71	2.01	100	10	01	0.2	-14.2068	-4.83916
60	02	0.5	0.71	2.01	100	10	01	0.2	-10.4889	-3.35263
30	01	0.5	0.71	2.01	100	10	01	0.2	-11.3213	-8.64095
30	03	0.5	0.71	2.01	100	10	01	0.2	-19.0148	7.66727
30	02	2.0	0.71	2.01	100	10	01	0.2	-10.0720	-7.42215
30	02	3.0	0.71	2.01	100	10	01	0.2	-8.74910	-9.98736
30	02	0.5	7.00	2.01	100	10	01	0.2	-17.2109	-5.98460
30	02	0.5	0.71	3.00	100	10	01	0.2	-4.55355	-7.52869
30	02	0.5	0.71	4.00	100	10	01	0.2	-1.06865	-4.92974
30	02	0.5	0.71	2.01	010	10	01	0.2	-2.78945	-0.37961
30	02	0.5	0.71	2.01	050	10	01	0.2	-9.13173	-2.86859
30	02	0.5	0.71	2.01	100	50	01	0.2	-15.8221	-5.95394
30	02	0.5	0.71	2.01	100	100	01	0.2	-14.2752	-5.92160
30	02	0.5	0.71	2.01	100	10	02	0.2	-0.63278	-4.87585
30	02	0.5	0.71	2.01	100	10	0.5	0.3	-23.8595	-8.99461
30	02	0.5	0.71	2.01	100	10	1	0.4	-30.4292	-11.9803

6. Conclusion

The conclusions of the present study are as follows:

- Primary velocity increases with the increase in thermal Grashof number, mass Grashof Number, Hall current parameter and time.
- Primary velocity decreases with the angle of inclination of plate, the magnetic field, chemical reaction parameter, Prandtl number and Schmidt number.
- Secondary velocity increases with the increase in thermal Grashof number, mass Grashof Number, the magnetic field and time.
- Secondary velocity decreases with the angle of inclination of plate, Hall currents, chemical reaction parameter, Prandtl number and Schmidt number.
- τ_x increases with the increase in angle of inclination of plate, Gr, and m; and it decreases with angle of inclination of plate, Gm, M, K_0, Pr , Sc and t.
- τ_y increases with the increase in angle of inclination of plate, *Gr* and *M*, and it decreases with Gm, m, K_0, *Pr, Sc* and *t*.
- Concentration of the fluid near the plate increases with time and it decreases with K_0, and Sc.

References

[1] Attia Hazem Ali and Ahmed Mohamed Eissa Sayed, "The Hall effect on unsteady MHD Couette flow with heat transfer of a Bingham fluid with suction and injection", Applied Mathematical Modelling 28, pp.1027-1045, (2004).

[2] Attia H A, "The effect of variable properties on the unsteady Hartmann flow with heat transfer considering the Hall effect", Appl. Math. Model. 27, (7), pp. 551–563, (2003).

[3] Das U N, Deka R K and Soundalgekar V M, "Effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction". Forsch. Ingenieurwes 60, pp.284-287, (1994).

[4] Ibrahim S Y and Makinde O D, "Chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate with suction", Scientific Research and Essays, 5(19), pp. 2875-2882, (2010).

[5] Katagiri M, "The effect of Hall current on the magneto hydrodynamic boundary layer flow past a semi-infinite fast plate". Journal of the Physical Society of Japan, Vol. 27(4), pp. 1051-1059, (1969).

[6] Muthucumarswamy R, "Effects of chemical reaction on a moving isothermal vertical surface with suction", Acta Mech.155, pp. 65-70,(2002).

[7] Muthucumarswamy R and Ganesan P, "First order chemical reaction on flow past an Impulsively started vertical plate with uniform Heat and Mass Flux." Acta Mechanica, Vol. 147, No. 1-4, pp. 45-57, (2001).

[8] Maripala Srinivas and Naikoti Kishan "Hall effects on unsteady MHD free convection flow over a stretching sheet with variable viscosity and viscous dissipation" World Applied Sciences Journal 33 (6), pp. 1032-1041, (2015).

[9] Misra J C, Adhikary S D, "MHD oscillatory channel flow, heat and mass transfer in a physiological fluid in presence of chemical reaction" Alexandria Engineering Journal,55, pp. 287–297, (2016).

[10] Pop I. "The effect of Hall currents on hydromagnetic flow near an accelerated plate", J. Math. Phys. Sci. 5, pp. 375-379, (1971).

[11] Pop I and Watanabe T, "Hall effects on magnetohydrodynamic boundary layer flow over a continuous moving flat plate",Acta Mech.,Vol. 108, pp. 35–47, (1995).

[12] Raptis A and Perdikis C, "Viscous flow over a non-linearly stretching sheet in the presence of a chemical reaction and magnetic field". International Journal of Non- Linear Mechanics 41, pp. 527-529, (2006).

[13] Raptis A and Perdikis C, "Flow of a viscous fluid through a porous medium bounded by a vertical surface", Int. J. Eng. Sci. 21, pp. 1327–1330, (1983).

[14] Rajput U S and Kumar Surendra, "MHD flow past an impulsively started vertical plate with variable temperature and mass diffusion", Applied Mathematical Sciences, Vol. 5, no. 3, pp. 149 – 157,(2011)

[15] Rajput U S and Kumar Surendra, "Effect of chemical reaction on free convection MHD flow through a porous medium bounded by vertical surface", Elixir Appl. Math 41, pp. 5957-5962, (2011).

[16] Ziyauddin and Kumar Manoj, "MHD heat and mass transfer free convection flow near the lower stagnation point of an isothermal cylinder imbedded in porous domain with the presence of radiation" Jordan Journal of Mechanical and Industrial Engineering(JJMIE), Volume 5,Issue 2,pp. 133 - 138 , (2011).

[17] Thamizhsudar M and Pandurangan J, "Combined effects of radiation and Hall current on MHD flow past an exponentially accelerated vertical plate in the presence of rotation" International Journal of Innovative Research in Computer and Communication Engineering Vol. 2, Issue 12, December (2014).

[18] Tripathy R S, Dash G C, Mishra S R and Baag S, "Chemical reaction effect on MHD free convective surface over a moving vertical plate through porous medium" Alexandria Engineering Journal (2015) 54, pp. 673–679, (2015).

[19] Rajput U S and Kumar Gaurav, " Unsteady MHD Flow Past an Impulsively Started Inclined Plate with Variable Temperature and Mass Diffusion in the presence of Hall current" Applications and Applied Mathematics, Vol. 11, Issue 2, pp. 693 – 703, (2016).

Appendix

$$A_1 = 1 + A_{16} + e^{2\sqrt{a}z}(1 - A_{17}),\ A_2 = -A_1,$$

$$A_3 = A_{16} - A_1,\ \ A_4 = -1 + A_{22} + A_{18}(A_{23} - 1),$$

$$A_5 = -1 + A_{24} + A_{19}(A_{25} - 1),$$

$$A_6 = -1 - A_{26} + A_{18}(A_{27} - 1),\ A_7 = -A_6,$$

$$A_8 = -1 - A_{20} + A_{30}(A_{21} - 1),$$

$$A_9 = A_8 + 2(A_{20} + 1),$$

$$A_{10} = -1 - A_{28} + A_{19}(A_{29} - 1),$$

$$A_{11} = \frac{e^{-\sqrt{a}z}}{z}(2A_1 + 2atA_2 + \sqrt{a}A_3),$$

$$A_{12} = -1 + erf\left[\frac{z\sqrt{P_r}}{2\sqrt{t}}\right],$$

$$A_{13} = e^{\frac{at}{-1+S_c} - z\sqrt{\frac{(a-K_0)S_c}{-1+S_c} - \frac{tK_0S_c}{-1+S_c}}},$$

$$A_{14} = e^{\frac{at}{-1+P_r} - z\sqrt{\frac{(a)P_r}{-1+P_r}}},\ A_{15} = 1 + A_{16} + e^{2\sqrt{az}}A_{17},$$

$$A_{16} = erf[\frac{2\sqrt{at} - z}{2\sqrt{t}}],\ A_{17} = erf[\frac{2\sqrt{at} + z}{2\sqrt{t}}],$$

$$A_{18} = e^{-2z\sqrt{\frac{aP_r}{-1+P_r}}},\ A_{19} = e^{-2z\sqrt{\frac{(a-K_0)S_c}{-1+S_c}}},$$

$$A_{20} = erf\left[\sqrt{tK_0} - \frac{z\sqrt{S_c}}{2\sqrt{t}}\right],$$

$$A_{21} = erf\left[\sqrt{tK_0} + \frac{z\sqrt{S_c}}{2\sqrt{t}}\right],$$

$$A_{22} = erf[\frac{z - 2t\sqrt{\frac{aP_r}{-1+P_r}}}{2t}],$$

$$A_{23} = erf[\frac{z + 2t\sqrt{\frac{aP_r}{-1+P_r}}}{2t}],$$

$$A_{24} = erf[\frac{z - 2t\sqrt{\frac{(a-K_0)S_c}{-1+S_c}}}{2t}],$$

$$A_{25} = erf[\frac{z + 2t\sqrt{\frac{(a-K_0)S_c}{-1+S_c}}}{2t}],$$

$$A_{26} = erf[\frac{2t\sqrt{\frac{a}{-1+P_r}} - z\sqrt{P_r}}{2\sqrt{t}}],$$

$$A_{27} = erf[\frac{2t\sqrt{\frac{a}{-1+P_r}} + z\sqrt{P_r}}{2\sqrt{t}}],$$

$$A_{28} = erf[\sqrt{t}\sqrt{\frac{(a-K_0)}{-1+S_c}} - \frac{zS_c}{2\sqrt{t}}],$$

$$A_{29} = erf[\sqrt{t}\sqrt{\frac{(a-K_0)}{-1+S_c}} + \frac{zS_c}{2\sqrt{t}}],$$

$$A_{30} = erf[e^{2z\sqrt{K_0\sqrt{S_c}}}],$$