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Unsteady MHD Flow through Porous Medium Past an Impulsively Started Inclined Plate with Variable Temperature and Mass Diffusion in the presence of Hall current

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ABSTRACT

Unsteady MHD flow through porous medium past an impulsively started inclined plate with variable temperature and mass diffusion in the presence of Hall current is studied here. The fluid considered is gray, absorbing-emitting radiation but a non-scattering medium. 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, Hall current parameter, permeability parameter, magnetic field parameter and Schmidt number, and the numerical values of skin-friction have been tabulated.

Introduction

The study of MHD flow through porous medium with heat and mass transfer plays important roles in different areas of science and technology, like chemical engineering, biological science, mechanical engineering, petroleum engineering, biomechanics, irrigation engineering and aerospace technology. Such problems frequently occur in petro-chemical industry, chemical vapour deposition on surfaces, heat exchanger design, cooling of nuclear reactors, 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. The response of laminar skin friction and heat transfer to fluctuations in the stream velocity was studied by Lighthill[1]. Free convection effects on the oscillating flow past an infinite vertical porous plate with constant Suction - I, was studied by Soundalgekar[3] which was further improved by Vajravelu et al[4]. The study of MHD flow past an impulsively started vertical plate with variable temperature and mass diffusion were studied by Rajput and Kumar[12]. MHD flow between two parallel plates with heat transfer was investigated by Attia et al[8]. Heat transfer in flow through a porous medium bounded by an infinite vertical plate under the action of magnetic field was studied by Raptis et al[6]. Raptis and Kafousias[7] have further studied flow of a viscous fluid through a porous medium bounded by a vertical surface. The researchers have studied the effect of Hall current in various flow models. Sulochana[14] has investigated Hall effects on unsteady MHD three dimensional flow through a porous medium in a rotating parallel plates channel with effect of inclined magnetic field. Attia[9] has considered the effect of variable properties on the unsteady Hartmann flow with heat transfer considering the Hall effect. Attia and Ahmed[10] have studied the Hall effect on unsteady MHD couette flow and heat transfer of a Bingham fluid with suction and injection. Deka[11] has considered Hall effects on MHD flow past an accelerated plate. Combined effects of radiation and Hall current on MHD flow past an exponentially accelerated vertical plate in the presence of rotation were studied by Thamizhsudar and Pandurangan[15]. Maripala and Naikoti[16] have analyzed Hall effects on unsteady MHD free convection flow over a stretching sheet with variable viscosity and viscous dissipation. Hall effects on free and forced convective flow in a rotating channel were studied by Rao et al[5]. Longitudinal vortices in natural convection flow on inclined plates were studied by Sparrow and Husar[2]. Heat and mass transfer in MHD boundary layer flow past an inclined plate with viscous dissipation in porous medium was analyzed by Singh[15]. We are considering the unsteady MHD flow through porous medium past an impulsively started inclined plate with variable temperature and mass diffusion in the presence of Hall current. The results are shown with the help of graphs.

Mathematical Analysis

In this paper we have consider MHD flow between two parallel electrically non conducting plates inclined at an angle α from vertical. x axis is taken along the plate and y normal to it. A transverse magnetic field B_0 of uniform strength is applied on the flow. The viscous dissipation and induced magnetic field has been neglected due to its small effect. Initially it has been considered that the plate as well as the fluid is at the same temperature T_∞ and the concentration level C_∞ everywhere in the fluid is same in stationary

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condition. At time t > 0, the plate starts moving with velocity u_0 in its own plane and temperature of the plate is raised to T_w and the concentration level near the plate is raised linearly with respect to time. Due to the Hall effects there will be two components of the momentum equation, the flow modal is as under:

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

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

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2}, \tag{3}$$

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2}, \tag{4}$$

with the corresponding initial and boundary conditions:

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

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 is the Hall parameter, T- temperature of the fluid, K- the permeability parameter, 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, σ - electrically 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:

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

where $\bar{u}$ is the dimensionless Primary velocity, $\bar{v}$ - the secondary velocity, $\bar{t}$ - dimensionless time, θ - the dimensionless temperature, $\bar{K}$ - the dimensionless permeability parameter, $\bar{C}$ - the dimensionless concentration, G_r - thermal Grashof number, G_m - mass Grashof number, μ - the coefficient of viscosity, P_r - the Prandtl number, S_c - the Schmidt number, M- the magnetic parameter.

Thus the model becomes

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

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

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

$$\frac{\partial \theta}{\partial \bar{t}} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial \bar{z}^2}, \tag{10}$$

with the following boundary conditions:

$$\left.\begin{array}{ll} \bar{t} \le 0: \bar{u} = 0, \bar{v} = 0, \theta = 0, \bar{C} = 0, & \text{for all } \bar{z}, \\ \bar{t} > 0: \bar{u} = 1, \bar{v} = 0, \theta = \bar{t}, \bar{C} = \bar{t}, & \text{at } \bar{z} = 0, \\ \bar{u} \to 0, \bar{v} \to 0, \theta \to 0, \bar{C} \to 0, & \text{as } \bar{z} \to \infty. \end{array}\right\} \tag{11}$$

Dropping bars in the above equations, we get

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

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

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}, \tag{14}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{P_r}\frac{\partial^2 \theta}{\partial z^2}, \tag{15}$$

with the following boundary conditions:

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

Writing the equations (12) and (13) in Combined form:

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

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\frac{\partial^2 C}{\partial z^2}, \tag{18}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{P_r}\frac{\partial^2 \theta}{\partial z^2}, \tag{19}$$

where q = u + i v,
with the following boundary conditions:

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

Here, $a=\frac{M(1-im)}{1+m^2}+\frac{1}{K}.$

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:

$$\begin{aligned} q=&\frac{1}{2}e^{-\sqrt{a}z}A_{15}+\frac{Cos\alpha}{4a^2\sqrt{\pi}}[\sqrt{\pi}G_r\{-A_9 z+\sqrt{a}e^{-\sqrt{a}z}A_2 z\\ &+\frac{1z}{2zA_{13}A_3}+2e^{-\sqrt{a}z}A_1P_r+2A_{13}A_3P_r\}-G_rP_r\{-aA_{10}z\\ &+\frac{1}{z\sqrt{P_r}}A_{13}\sqrt{\pi}A_4z+\frac{2\sqrt{\pi}A_{11}}{\sqrt{P_r}}-\frac{2a\sqrt{\pi}tA_{11}}{\sqrt{P_r}}+\frac{1}{A_{13}\sqrt{\pi}A_8\sqrt{P_r}}\\ &-2\sqrt{\pi P_r}A_{11}\}-\sqrt{\pi}G_m\{A_9z-\sqrt{a}e^{-\sqrt{a}z}A_2z-2e^{-\sqrt{a}z}A_1S_c\\ &+2A_{14}A_5S_c\}+\sqrt{S_c}G_m\{-aA_{16}z+\frac{1}{\sqrt{\pi S_c}A_{14}A_7}+\frac{2\sqrt{\pi}A_{12}}{\sqrt{S_c}}\\ &+\frac{1}{A_{14}\sqrt{\pi S_c}A_6}-2A_{12}\sqrt{\pi S_c}\}]. \end{aligned}$$

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

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

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

Skin friction

The dimensionless skin friction at the plate z=0:

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

Separating real and imaginary part in $\left(\frac{dq}{dz}\right)_{z=0}$, the dimensionless skin – friction component $\tau_x=\left(\frac{du}{dz}\right)_{z=0}$ and $\tau_y=\left(\frac{dv}{dz}\right)_{z=0}$ can be computed.

Result and Discussion

The velocity profile for different parameters like, thermal Grashof number Gr, magnetic field parameter M, Hall parameter m, Prandtl number Pr and time t is shown in figures 1.1 to 2.9. It is observed from figures 1.1 and 2.1 that the primary and secondary velocities of fluid decrease when the angle of inclination (α) is increased. It is observed from figure 1.2 and 2.2, when the mass Grashof number is increased then the primary and secondary velocities of fluid are increased. From figures 1.3 and 2.3 it is deduced that when thermal Grashof number Gr is increased then the primary and secondary velocities of fluid are increased. If Hall current parameter m is increased then the velocities are increased (figures 1.4 and 2.4). It is observed from figures 1.5 and 2.5 that the effect of increasing values of the parameter M results in decreasing u and increasing v. Further, it is observed that velocities decrease when Prandtl number is increased (figures 1.6 and 2.6). When the Schmidt number is increased then the velocities get decreased (figures 1.7 and 2.7). When the permeability parameter increases then the velocities increase (figures 1.8 and 2.8). Further, from figures 1.9 and 2.9 it is observed that velocities increase with time.

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

Table. Skin friction for different parameters

α	M	m	Pr	Sc	Gm	Gr	K	t	τ_x	τ_y
15°	2	0.5	0.71	2.01	100	10	0.2	0.2	0.106602	0.1696
30°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.17756	0.166477
45°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.6296	0.161509
60°	2	0.5	0.71	2.01	100	10	0.2	0.2	-1.21871	0.155035
30°	1	0.5	0.71	2.01	100	10	0.2	0.2	-0.00560	0.0864674
30°	3	0.5	0.71	2.01	100	10	0.2	0.2	-0.34444	0.240704
30°	5	0.5	0.71	2.01	100	10	0.2	0.2	-0.66377	0.374156
30°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.17756	0.166477
30°	2	0.5	5.00	2.01	100	10	0.2	0.2	-0.28861	0.16400
30°	2	0.5	7.00	2.01	100	10	0.2	0.2	-0.30619	0.163728
30°	2	1.0	0.71	2.01	100	10	0.2	0.2	-0.05289	0.21397
30°	2	2.0	0.71	2.01	100	10	0.2	0.2	0.079090	0.176259
30°	2	3.0	0.71	2.01	100	10	0.2	0.2	0.12487	0.133534
30°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.17756	0.166477
30°	2	0.5	0.71	3.00	100	10	0.2	0.2	-0.40746	0.161746
30°	2	0.5	0.71	4.00	100	10	0.2	0.2	-568469	0.158766
30°	2	0.5	0.71	2.01	10	10	0.2	0.2	-2.14411	0.145554
30°	2	0.5	0.71	2.01	50	10	0.2	0.2	1.27009	0.154853
30°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.17756	0.166477
30°	2	0.5	0.71	2.01	100	20	0.2	0.2	0.100766	0.170301
30°	2	0.5	0.71	2.01	100	50	0.2	0.2	0.935747	0.181773
30°	2	0.5	0.71	2.01	100	100	0.2	0.2	2.32738	0.200893
30°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.17756	0.166477
30°	2	0.5	0.71	2.01	100	10	0.5	0.2	0.493818	0.193325
30°	2	0.5	0.71	2.01	100	10	1.0	0.2	0.741891	0.204282
30°	2	0.5	0.71	2.01	100	10	0.2	0.2	-0.17756	0.166477
30°	2	0.5	0.71	2.01	100	10	0.2	0.4	3.8391	0.268724
30°	2	0.5	0.71	2.01	100	10	0.2	0.6	8.41871	0.409066

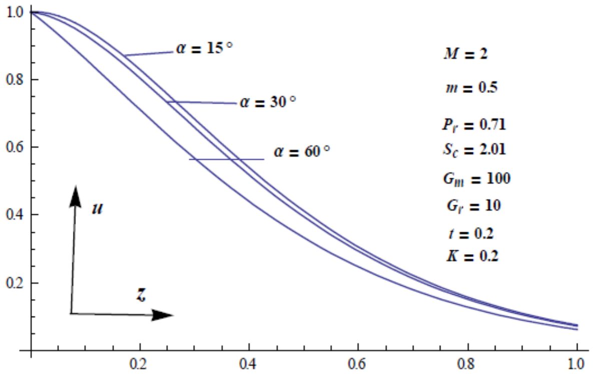

Figure 1.1. Velocity u for different values of α

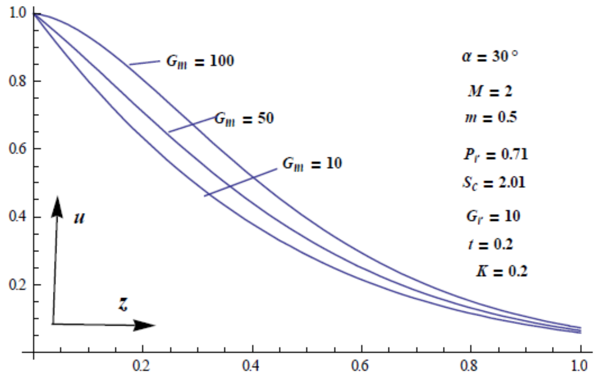

Figure 1.2. Velocity u for different values of Gm

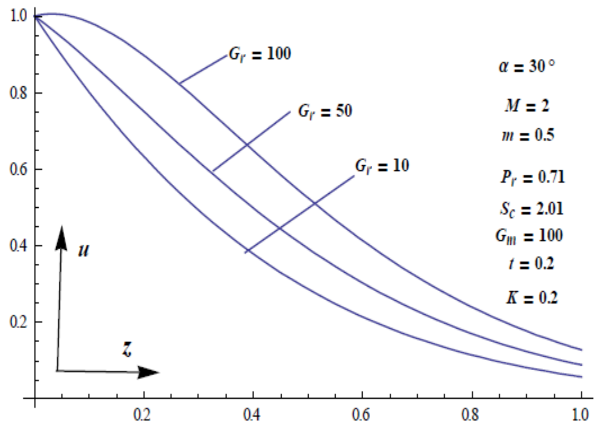

Figure 1.3. Velocity u for different values of Gr

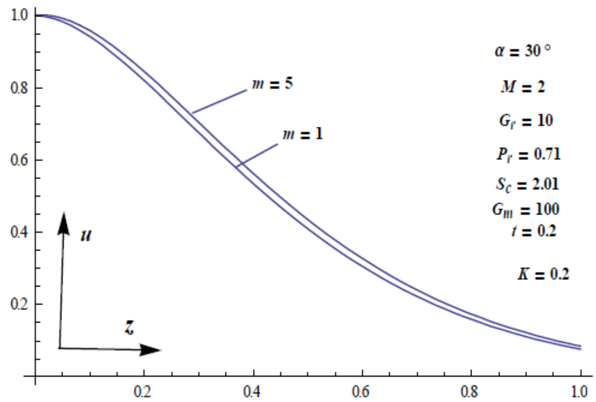

Figure 1.4. Velocity u for different values of m

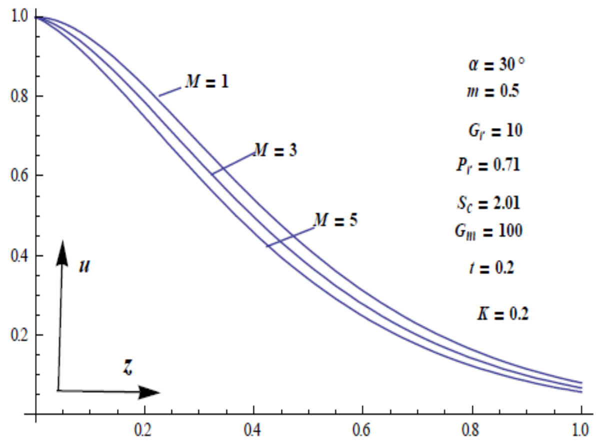

Figure 1.5. Velocity u for different values of M

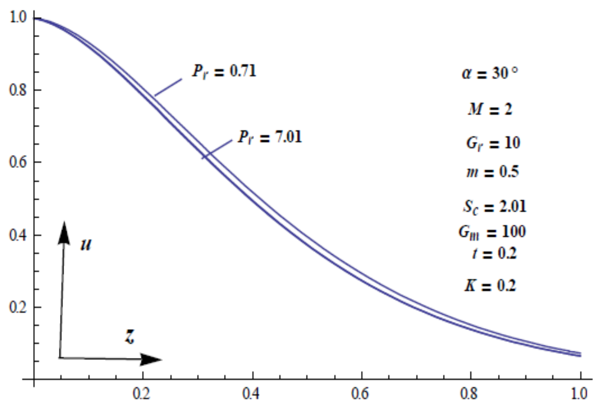

Figure 1.6. Velocity u for different values of Pr

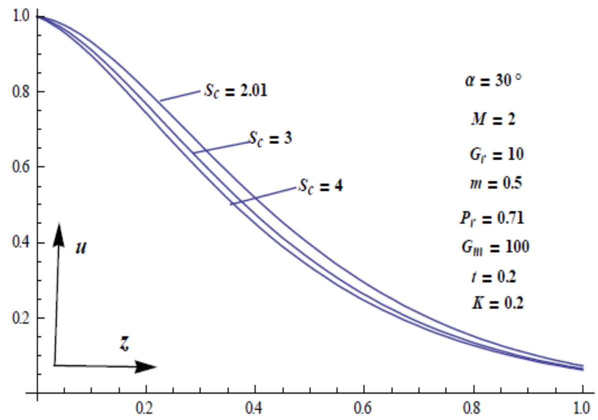

Figure 1.7. Velocity u for different values of Sc

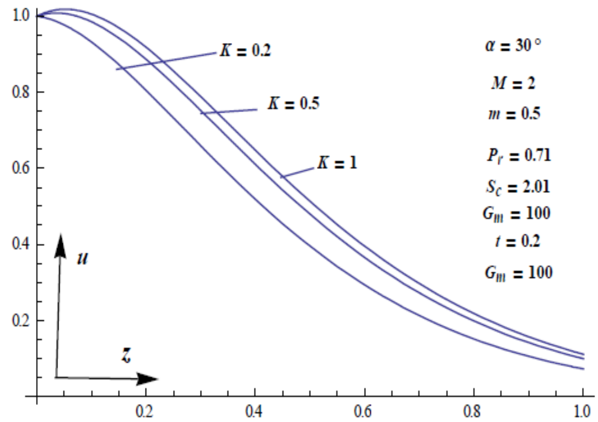

Figure 1.8. Velocity u for different values of K

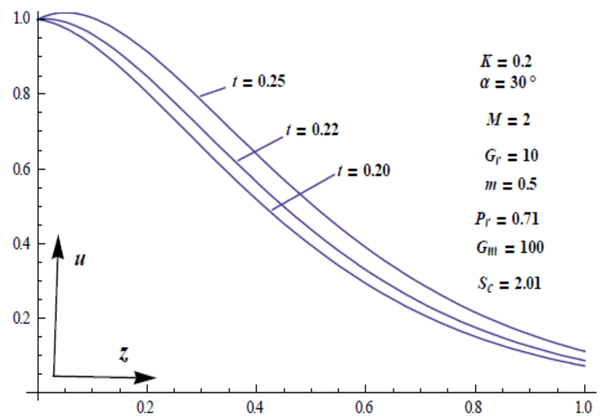

Figure 1.9. Velocity u for different values of t

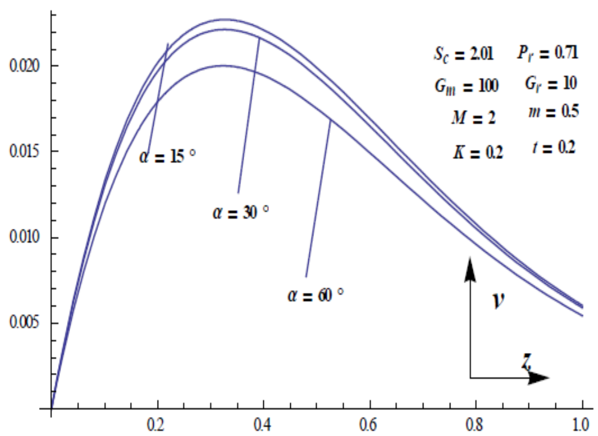

Figure 2.1. Velocity v for different values of α

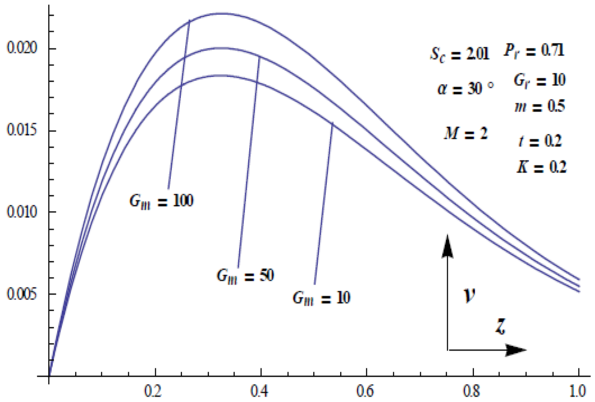

Figure 2.2. Velocity v for different values of Gm

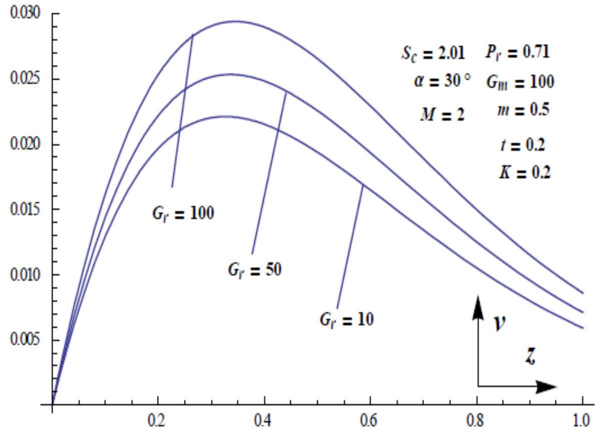

Figure 2.3. Velocity v for different values of Gr

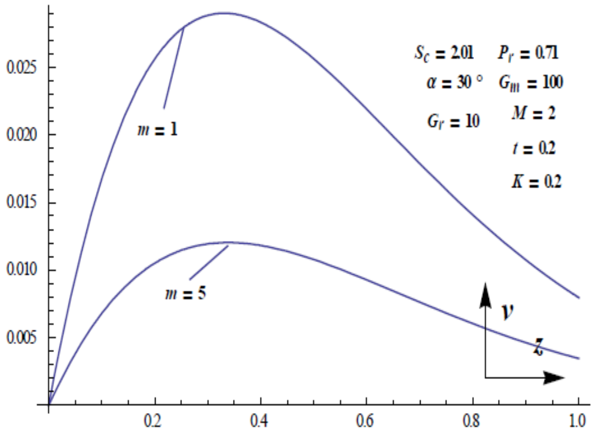

Figure 2.4. Velocity v for different values of m

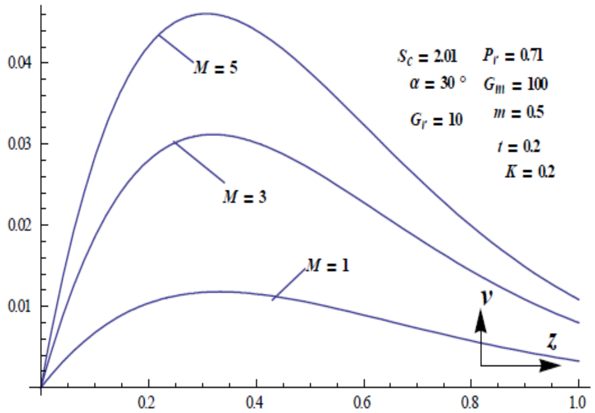

Figure 2.5. Velocity v for different values of M

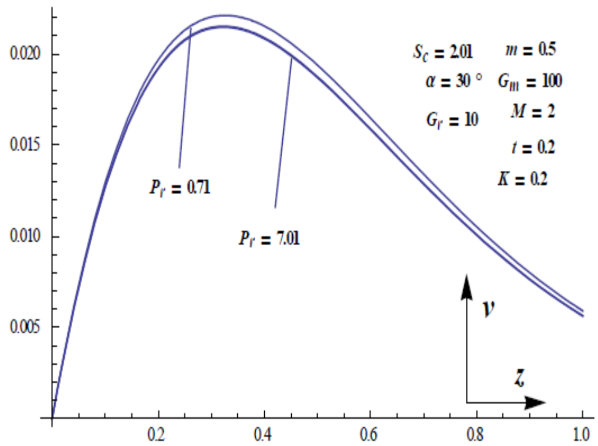

Figure 2.6. Velocity v for different values of Pr

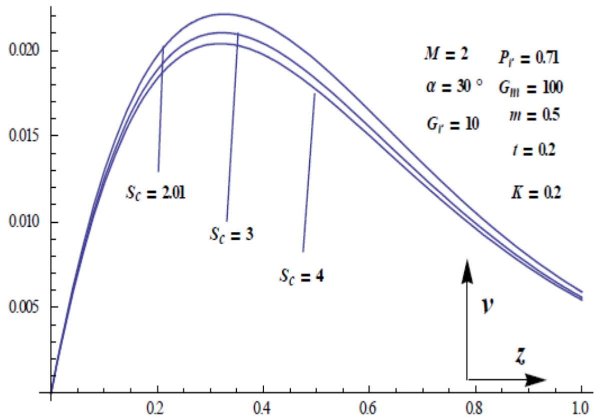

Figure 2.7. Velocity v for different values of Sc

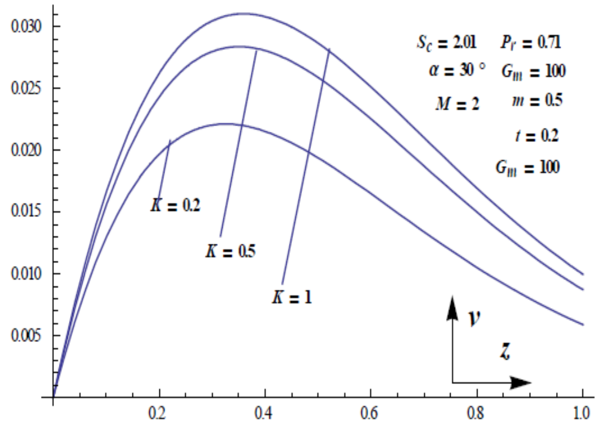

Figure 2.8. Velocity v for different values of K

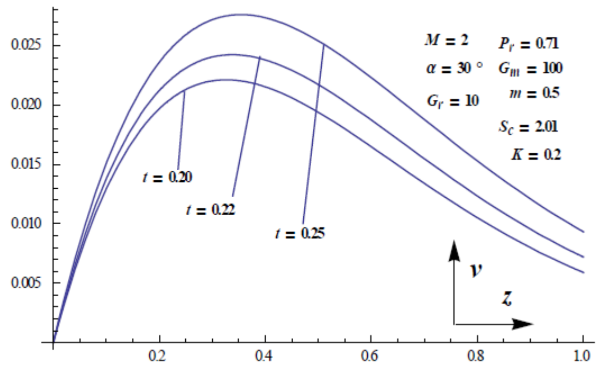

Figure 2.9. Velocity v for different values of t

Conclusion

The conclusions of the study are as follows:

- Primary Velocity increases with the increase in thermal Grashof number, mass Grashof Number, permeability, Hall current parameter, and time.
- Primary Velocity decreases with the angle of inclination of plate, the magnetic field, Prandtl number and Schmidt number.
- Secondary Velocity increases with the increase in thermal Grashof number, mass Grashof Number, the magnetic field, permeability, and time.
- Secondary Velocity decreases with the angle of inclination of plate, Hall currents parameter, Prandtl number and Schmidt number.
- τ_x increases with the increase in Gr, Gm, K, m and t, and it decreases with angle of inclination of plate, M, Pr and Sc.
- τ_y increases with the increase in Gr, Gm, M, K and t, and it decreases with angle of inclination of plate, m, Pr and Sc.

Appendex

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

$$A_2 = -1 + A_{16} - e^{2\sqrt{a}z}(1 - A_{17}),\ A_8 = -A_4,$$

$$A_3 = -1 + A_{20} - A_{18}(1 - A_{21}),$$

$$A_4 = 1 + A_{23} + A_{18}(1 - A_{24}),\quad A_5 = -1 + A_{25} - A_{19}(1 - A_{26}),$$

$$A_6 = -1 - A_{27} - A_{19}(1 + A_{28}),$$

$$A_7 = -A_6,\ A_9 = \frac{2e^{-\sqrt{a}z}A_1}{z}(1 - at)$$

$$A_{10} = (2e^{\frac{-z^2 P_r}{4t}}\sqrt{t} + \sqrt{\pi}zA_{11})\sqrt{P_r}$$

$$A_{11} = -1 + erf\left[\frac{z\sqrt{P_r}}{2\sqrt{t}}\right],$$

$$A_{12} = -1 + erf\left[\frac{z\sqrt{S_c}}{2\sqrt{t}}\right],\ A_{13} = e^{\frac{at}{-1+P_r} - z\sqrt{\frac{aP_r}{-1+P_r}}},$$

$$A_{14} = e^{\frac{at}{-1+S_c} - z\sqrt{\frac{aS_c}{-1+S_c}}},$$

$$A_{15} = 1 + A_{16} + e^{2\sqrt{a}z} erfc\left[\frac{2\sqrt{at} + z}{2\sqrt{t}}\right],$$

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

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

$$A_{20} = erf[\frac{z - 2t\sqrt{\frac{aP_r}{-1+P_r}}}{2t}],$$

$$A_{21} = erf[\frac{z + 2t\sqrt{\frac{aP_r}{-1+P_r}}}{2t}],$$

$$A_{22} = erf[\frac{2t\sqrt{\frac{a}{-1+P_r}} - z\sqrt{P_r}}{2t}],\ A_{23} = erf[\frac{2t\sqrt{\frac{a}{-1+P_r}} - z\sqrt{P_r}}{2t}],$$

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

$$A_{25} = erf[\frac{z - 2t\sqrt{\frac{aS_c}{-1+S_c}}}{2t}],\ A_{26} = erf[\frac{z + 2t\sqrt{\frac{aS_c}{-1+S_c}}}{2t}],$$

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

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

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