# The Unsteady Magnetohydrodynamtc Flow and Heat Transfer between Two Non-Conducting Infinite Vertical Parallel Plates with Inclined Magnetic Field

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***Abstract***

The unsteady magnetohydrodynamic flow between two non-conducting infinite vertical plates in the presence of uniform inclined magnetic field has been studied. One of the plates is assumed to be in motion with constant velocity, whereas the other plate is considered to be adiabatic. By using transformation associated with decay factor, we have deduced a system of ordinary differential equations. And these equations are solved analytically for the velocity flow, induced magnetic field, temperature and concentration for various physical parameters. The results have beendiscussed through graphs.

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## 1. INTRODUCTION

MHD flow has seen a wide range of applications in the recent past and has gained considerable attention due to those in cosmic and geophysical fluid dynamics. The research of MHD flow with inclined magnetic field has attracted the attention of many researchers due to its use, for example, in extrusion of plastics in the manufacturing industries. The phenomenon of heat and mass transfer has a wide significance in chemical processing, geothermal systems, air conditioning, etc. It is therefore interesting to investigate the problem of the flow with the heat and mass transfer in presence of induced magnetic field.

Hazem Ali Attia, etal (2004),[1] considered Hall effect of unsteady Magnetohydrodynamic Coquette flow with the heat transfer of a Bingham fluid along with injection and suction. Magnetohydrodynamic mixed convection in a vertical channel was discussed by Umavathi and Malashetty (2005), [2].The study of an unsteady free convective MHD flow of dissipative fluid along with a vertical plate and constant heat flux was analyzed numerically by Joaquin Zueco Jordan(2006), [3]. Singha (2008), [4] determined the influence of heat transfer on unsteady hydromagnetic flow in a parallel plates of an electrically conducting , incompressible and viscous fluid. Singha &Deka (2009), [5] investigated on the magnetohydrodynamic two-phase flow with heat transfer in the presence of uniform inclined magnetic field. Analytical Solution to the problem of MHD free convective flow of an electrically conducting fluid between heated parallel plates along with an induced magnetic field was learned by Singha (2009), [6]. Marneni Narahari & Binay. K.Dutta (2011), [7] enumerated the free convection flow between two vertical plates with variable temperature atone boundary. Magnetic field effect on free convective oscillatory flow between two vertical plates with periodic temperature and dissipative heat is concentrated by Ahmed, et al (2012), [8]. Bishwaram Sharma, etal (2013), [9] investigated the impact of magnetic field and temperature gradient on separation of a binary fluid mixture in unsteady coquette flow. Unsteady MHD couette flow bounded between two parallel porous plates with heat transfer and inclined magnetic field was considered by Joseph, et al (2014), [10]. Kuiry & Surya Bahadur (2014), [11] presented the steady poiseuille flow between two parallel porous plates in presence of inclined magnetic field. SreeKala, Kesava Reddy (2014), [12] discussed the MHD couette flow of incompressible viscous fluid through a porous medium between two parallel plates under the influence of inclined magnetic field. Paneerselvi and Moheswari (2015), [13] learned the Soret effect on unsteady convective flow of a dusty viscous fluid between in finite parallel plates embedded by a porous medium with inclined magnetic field. Effect of mass and heat transfer on unsteady MHD Poiseuille flow between two parallel porous plates in presences of an inclined magnetic field is studied by Joseph, et al (2015), [14]. Unsteady MHD poiseuille flow with heat and mass transfer between two infinite parallel plates through porous medium in an inclined magnetic field was investigated by Rajput & Gaurav Kumar (2015), [15]. The influence of the inclined magnetic field and variable thermal conductivity on MHD plane poiseuille flow past non-uniform platet emperature was considered by Gupta, et al (2015), [16]. Agnes Mburu, Jackson Kwanza and Thomson Onyango, (2016), [17] discussed the MHD fluid flow between infinite parallel plates subjected to an inclined magnetic field and pressure gradient. MHD of incompressible fluid through parallel plates in inclined magnetic field with porous medium with mass and heat transfer was studied by Rishard Richard Hanvey,etal (2017), [18]. Nyariki, etal (2017),

[19] analysed the unsteady Hydro magnetic coquette flow in the presence of variable inclined

magnetic field. Unsteady magnetohydrodynamic flow of viscous, electrically conducting fluid bounded between two non-conducting vertical plates with inclined magnetic field was studied by Amarjyoti Goswami, etal (2017), [20]. Idrissa Kane1 et al [21] investigated the unsteady fluid flow between two moving plates in presence of an inclined applied magnetic field with magnetic fields lines fixed relative to the moving plates.

In this paper we have studied the effect of mass transfer and heat transfer on the unsteady MHD flow of electrically conducting fluid between two parallel vertical plates with uniform magneticfield.

## 2. FORMATIONOFTHEPROBLEM

In the present work, the unsteady flow of an incompressible electrically conducting fluid bounded by two non-conducting vertical infinite parallel plates at a distance 2h apart is considered. The coordinate system is chosen such that X – axis is taken in upward direction and Y- axis is chosen perpendicular to the planes of the plates. The vertical plates of the channel are y = ± h and also, there is no pressure gradient in the flow field. An external magnetic field $B_0$ makes an angle θ with the positive X-axis which induces a magnetic field B(y) and also makes an angle θ to the free stream velocity .The left wall y = -h is kept atconstant temperature $T_0$ and the right wall y =+h is sustained at constant temperature $T_1$ , such that $T_1 > T_0$. The magnetic field distributions and velocity are given by

$\bar{\boldsymbol{B}} = B\{x, B_y, B_Z\} = \{\lambda B(y,t)\ \sqrt{1-\lambda^2}B_0, 0\}\ \bar{V} = \{u(y,t)\ 0, 0\}$, where $\lambda = cos\theta$ and 't' is the time.

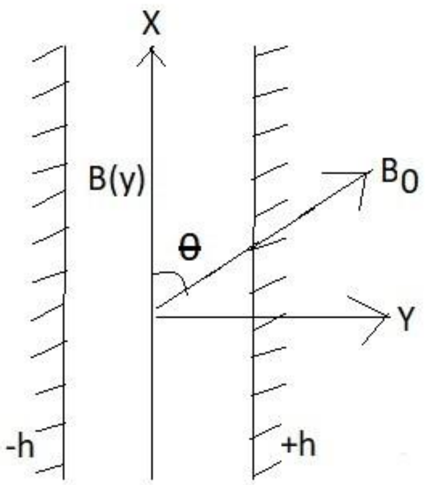


**Figure1**Schematicrepresentationoftheproblem

The following assumptions are made to frame the governing equations of the problem:

*(i)* The electrically conducting fluid is considered, viscous dissipation and Joule heat are neglected.

*(ii)* Polarization effect and Hall effect are negligible.

*(iii)* No pressure gradient.

*(iv)* The plates are infinitely long along X and Z directions. Therefore the velocity, concentration and temperature fields are the functions of y and t only.

## 3. GOVERNINGEQUATIONS

Equation of Continuity

$$div\bar{V} = 0 \quad (1)$$

Where $\bar{V}$ is the velocity.

Equation of Momentum

$$\left[\frac{\partial \bar{V}}{\partial t} + (\vec{V}\times\nabla)\vec{V}\right] = \frac{1}{\rho}\left[\mu\nabla^2 V + (\vec{J}\times\vec{B}) + g\beta(T - T_0) + g\beta^*(C - C_0)\right] \quad (2)$$

Equation of Magnetic Induction

$$\frac{\partial B}{\partial t} = \nabla\times\left(\overrightarrow{V\times B}\right) + \left(\frac{1}{\sigma\mu_e}\right)\nabla^2\vec{B} \quad (3)$$

Where $\mu_e$ is the permeability of the medium.

Energy Equation

$$\rho C_p\left(\frac{\partial T}{\partial t}\right) = \frac{d}{dy}\left(k\frac{\partial T}{\partial y}\right) \quad (4)$$

ρ–density and $C_p$-Specific heat at constant pressure.

Concentration Equation

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial y^2}\right) \quad (5)$$

D–Mass diffusion coefficient.

Here, $\bar{J}$ is the electric current density.

The generalized Ohm's law is,

$\bar{J}$=?($\bar{E}$+$\bar{V}$?$\bar{B}$), (6)

where σ–Electrical conductivity, B is the magnetic induction (6)

Neglecting the electric field $E$, equation (6) reduces to $J$=?($V$?$B$ )

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where, μ the coefficient of viscosity, k the thermal conductivity, t the time, β co-efficient of thermal expansion of the fluid and $\beta^*$ co-efficient of the mass transfer of the fluid.

Using magnetic field distribution and velocity as mentioned above, the equations (1) to (5) are:

$\partial u$ — $\partial t$ $\partial^2 u$

$$= v \frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}\left(\frac{1}{\lambda^2} - 1\right) u + g\beta (T - T_0) + g\beta^*(C - C_0) \qquad (7)$$

$$\frac{\partial B}{\partial t} - B_0 \left(\sqrt{\frac{1}{\lambda^2} - 1}\right)\frac{\partial u}{\partial y} = \left(\frac{1}{\sigma\mu}\right)\frac{\partial^2 B}{\partial y^2} = 0 \qquad (8)$$

$$\frac{\partial T}{\partial t} = \alpha_1 \left(\frac{\partial^2 T}{\partial y^2}\right) \qquad (9)$$

where

$$\alpha_1 = \frac{k}{\rho C_p}$$

$$\left(\frac{\partial C}{\partial t}\right) = D \left(\frac{\partial^2 C}{\partial y^2}\right) \qquad (10)$$

The boundary conditions are:

$$\left.\begin{array}{ll} u = 0, B = B_0, T = T_1, C = C_1 & at\ t = 0 \\ y = h, u = u_0\ B = B_0, T = T_1, C = C_1 & at\ t > 0 \\ y = -h, u = -u_0\ B = , \frac{\partial T}{} = 0, C = C & at\ t > \end{array}\right\}$$

—

(11)

0 0 $\partial y$ 1

—

Using the following dimensionless parameters in the governing equations of motion (7)–(10),

$u^* = \frac{u}{u_0}, y^* = \frac{y}{h}, t^* = \frac{tu_0}{h}, b = \frac{B}{B_0}, \bar{T} = \frac{T - T_0}{T_1 - T_0}, \bar{C} = \frac{C - C_0}{C_1 - C_0},$ (12)

Using the following dimensionless parameters in the governing equations of motion (7)–(10),

$$u^* = \frac{u}{u_0}, y^* = \frac{y}{h}, t^* = \frac{tu_0}{h}, b = \frac{B}{B_0}, \bar{T} = \frac{T - T_0}{T_1 - T_0}, \bar{C} = \frac{C - C_0}{C_1 - C_0}, \quad (12)$$

Neglect the asterisks, the dimensionless equations are:

$$\frac{\partial u}{\partial t} = \left(\frac{1}{R_e}\right)\frac{\partial^2 u}{\partial y^2} - \frac{H_a}{R_e}(1 - \lambda^2)u + \left(\frac{G_r}{R_e^2}\right)\bar{T} + G_m R_e \bar{C} \quad (13)$$

$$\frac{\partial b}{\partial t} - \left(\sqrt{\frac{1}{\lambda^2} - 1}\right)\frac{\partial u}{\partial y} - \left(\frac{1}{R_e R_m P_r}\right)\frac{\partial^2 b}{\partial y^2} = 0 \quad (14)$$

The dimensionless form of boundary conditions:

$$\left.\begin{array}{ll} u = 0,\ b = 1, \bar{T} = 1, \bar{C} = 1 & \text{at } t = 0 \\ y = 1, u = 1, b = 1, \bar{T} = 1, \bar{C} = 1 & \text{at } t > 0 \\ y = -1, u = -1, b = 1, \frac{\partial \bar{T}}{\partial y} = 0, \bar{C} = 0 & \text{at } t > 0 \end{array}\right\} \quad (17)$$

To solve the equation (13) – (16) by using equation (17), considerthe following variable transformation,

$$u = f(y)e^{-n\pi}, b = g(y)e^{-n\pi}, \bar{T} = F(y)e^{-n\pi},$$

$$\bar{C} = (\ )e^{-n\pi}, \quad (18)$$

where'n' denotes the decay constant.

Substituting (18)in equations(13),(14),(15)and (16),we have

$$\boldsymbol{f''(y) - R_e\{H_a R_e(1 - \lambda^2) - n\}f(y) + \left(\frac{G_r}{R_e}\right)F(y) - G_m R_e^2 G(y) = 0} \quad (19)$$

$$g''(y) + (n R_e R_m P_r g(y)) + ( ) R_e R_m P_r \left(\sqrt{\frac{1-\lambda^2}{\lambda^2}}\right)[f'(y)] = (20)$$

$$F''(y) + nP_e[F(y)] = 0 \qquad (21)$$

$$G''(y) + nS_C R_e G(y) = 0 \qquad (22)$$

The relevant boundary conditions are

$$\left.\begin{array}{l} f = 0,\ g = 1,\ F = 1,\ G = 1 \text{ at } t = 0 \\ y = 1, f = e^{nt}, g = e^{nt}, F = e^{nt}, G = e^{nt} \text{ at } t > 0 \\ y = -1, f = -e^{nt}, g = e^{nt}, \frac{\partial F}{\partial y} = 0, G = 0 \text{ at } t > 0 \end{array}\right\} \qquad (23)$$

Theequations(19)–(22) are solved with the boundary conditions equation (23). The velocity distribution of the field, temperature and species concentration are:

$$u(y) = A_{13}\cos(1+y)A_5 + B_3\sin(1+y)B_1 + C_1e^{-\sqrt{A_1}y} + C_2e^{\sqrt{A_1}y} \qquad (24)$$

$$b(y) = A_7e^{-\sqrt{A_1}y}(A_7e^{\sqrt{A_1}y}A_{14}\sin(1+y)A_5 - B_4e^{\sqrt{A_1}y}\cos(1+y)B_1 + A_{12}(A_{15} - A_{16}e^{2\sqrt{A_1}y} + e^{\sqrt{A_1}y}A_9(C_3\sin\sqrt{A_3}y + C_4\cos\sqrt{A_3}y))) \qquad (25)$$

$$\bar{T} = \left[\frac{\cos(1+y)A_5}{\cos 2A_5}\right] \qquad (26)$$

$$\bar{C} = \left[\frac{\sin(1+y)B_1}{\sin 2B_1}\right] \qquad (27)$$

Where

$$A_1 = R_e\{H_a R_e(1 - \lambda^2 - n)\}$$

$$A_2 = \left(\frac{G_r}{R_e}\right)$$

$$B_1 = \sqrt{nS_cR_e}$$

$$B_2 = G_m \; 2R_e$$

$$A3 = nR_eR_mP_r$$

$$A4 = \left( R_eR_mP_r\sqrt{\frac{1}{\lambda^2} - 1} \right)$$

$$A5 = \sqrt{nP_e}$$

$$A_6 = \frac{A_2cose(2A_5)}{A_1 + A_5^2}$$

$$B_3 = \frac{B_2cose(2B_1)}{A_1 + B_1^2}$$

$$B_4 = (A_1 + A_3)(A_3 - A_5^2)_4B_3B_1$$

$$A_7 = \frac{1}{(A_1 + A_2)(A_3 - A_5^2)(A_3 - B_1^2)}$$

$$A_8 = (A_1 + A_3)_4A_5A_6$$

$$A_9 = A_1 + A_3$$

$$A10 = \sqrt{A1}A4C3$$

$$A11 = \sqrt{A1}A4C4$$

$$A_{12} = (A_3 - A_5^2)(A_3 - B_1^2)$$

$$A_{13} = \frac{A_2\sec(2A_5)}{A_1 + A_5^2}$$

$$A_{14} = (A_1 + A_3)(A_3 - B_1^2)A_4A_5A_{13}$$

$$A15 = \sqrt{A1}A4C1$$

$$A16 = \sqrt{A1}A5C2$$

## 1. RESULTSANDDISCUSSION

Equation(24)-(27) are solved numerically for different values of λ, where θ varies as θ=$30^0$,$45^0$,$60^0$,$75^0$. Plotting of all such cases is carried out by using 'MATLAB'.

From figure 2 it is noted that the velocity profile increases with increase in the angle of inclination θ.

The velocity profile variations with the thermal Grashof number $G_r$ are shown in figure 3. The magnitude of the velocity degrades the flow with the increase in the Grashof number Gr. Figure 4 depicts the effect of modified Grashof number Gm and it is clearly seen that the velocity enhances the flow, when the modified Grashof number Gm is incremented.

Figure 5 to figure 7 explains the effect of Prandtl number $P_r$, Hartmann number $H_a$ and Schmidt number Sc on the velocity profile. It is determined that the velocity profile shows progress by increasing these pertinent parameters.

Figure 8 communicates the effect of magnetic Reynolds number $R_m$. It has been noticed that the velocity gradually increases when the magnetic Reynolds number $R_m$ is increased.

Figure 9 reveals that the effect of decay factor n. The increase in decay factor reduces the velocity of the flow.

Figure10 to figure 17 illustrates the effect of induced magnetic field.

Figure10 indicates the increase of angle of inclination θ of the flow, increases the intensity of the magnetic field. Figure 11 communicates the impact of thermal Grashof number Gr on the induced magnetic field. It is observed that, when Gr is increased, the intensity of the magnetic field is also increased.

Figure 12 depicts the effect of modified Grashof number $G_m$. With the increase in modified Grashof number Gm there appears a sharply increasing change in the intensity of the magnetic field. Figure 13 indicates the cause of Hartmann number Ha. The induced magnetic field increases gradually when the Hartmann number $H_a$ is increased.

From figures 14, 15 and 16 the effect of Schmidt number Sc, Prandtl number $P_r$, magnetic Reynolds number Rm and Prandtl number Pr, are observed. It illustrates that the intensity of the magnetic field is more when the parameters Sc ,$R_m$ and $P_r$, are increased.

Figure 17 communicates that the increase in the decay factor n, degrades the magnetic field intensity.

In figure 18, it is observed that the progress in the Prandtl number Pr leads to the increasein the fluid temperature. In figure 19, it is noted that the concentration field increases with the step forward in the Schmidt

## 5. CONCLUSION

The problem of the effect of inclined magnetic field on unsteady magnetohydrodynamic vertical flow between two infinite non conducting vertical plates with heat and mass transfer has been investigated. From the analysis the following conclusions were made. The velocity upgrades with increase of angle of inclination θ of the magnetic field. The velocity for the flow increases with the increase in $G_m$, $P_r$, $H_a$ and Sc, while it retards with increase in thermal Grashof number Gr and the decay factor n. The induced magnetic field increases with the increase in the angle of inclination θ, thermal Grashof number Gr, modified Grashof Gm, Hartmann number Ha, Prandtl number Pr, magnetic Reynolds number Rm and Schmidt Sc and also it reduces with the increase of decay factor n. The temperature distribution was seen to progress due to rise in the Prandtl number Pr.

Concentration profile increases with the increment values of Schmidt number Sc

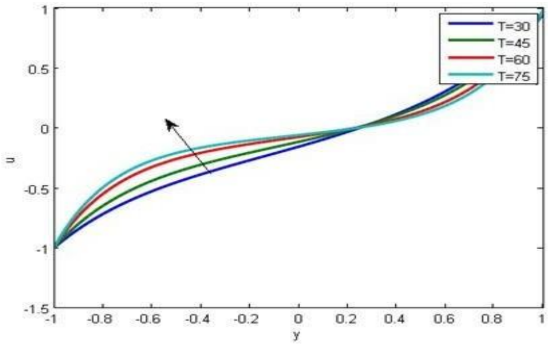


**Figure 2**: Velocity Profile for distinct values of θ, [n=1,$R_m$=.2,$R_e$=1.5,Pr=.71, $H_a$=7,$G_m$=2,$G_r$=2 and $S_c$=. 3]

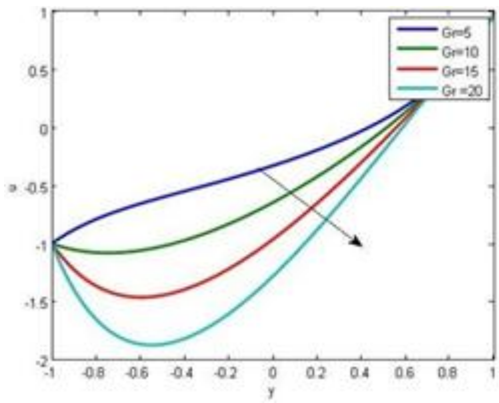


**Figure 3**:Velocity Profile for different values of $G_r$, [n=1,λ =.5 , $R_m$=.2,$R_e$=1.5,$H_a$=7, $G_m$=2 ,$S_c$=.3 andPr=.71]

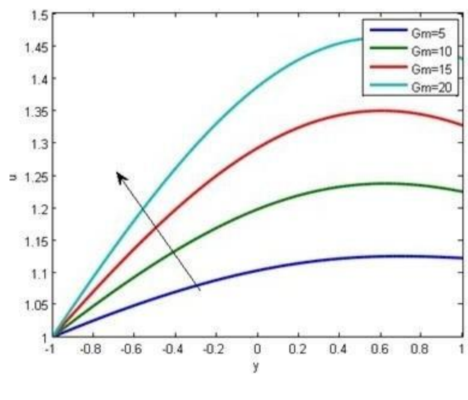


**Figure4**:Graph of velocity Profile for different values of $G_m$,[n=1,$R_m$=.2,λ =.5,$R_e$=1.5,$H_a$=7,Pr=.71,$S_c$=.3and$G_r$=2]

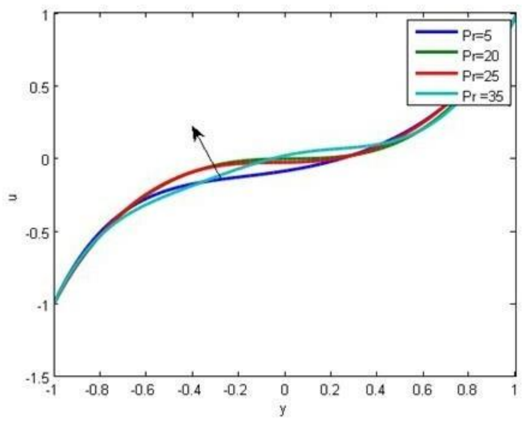


**Figure 5**: Velocity Profile for unlike values of $P_r$,[$G_m$=2,$R_e$=1.5, n=1,$R_m$ =.2,$H_a$=7,λ =.5, $G_r$=2,$S_c$=.3and$R_m$=0.2]

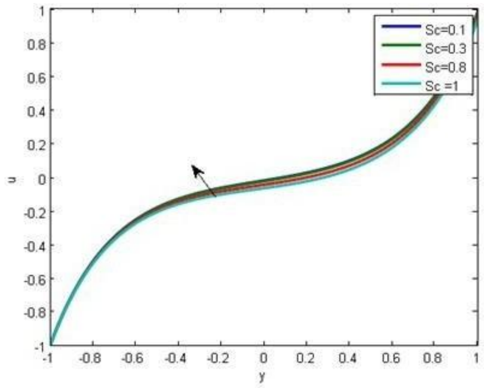


**Figure 6**: Velocity graph for various values of Ha,[ Re=1.5, Rm =.2, λ =.5, Gm=2,Gr=2,Sc=.3, n=1andPr=.71]

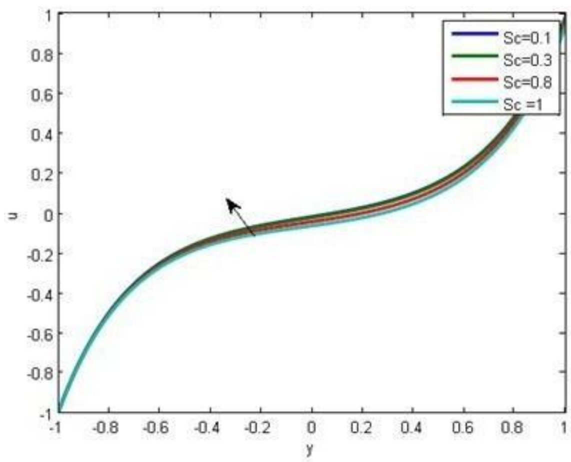


**Figure** 7:Velocity Profile for different values of Sc,[Re=1.5, n=1,Ha=7,λ =.5,Rm =0.2,Pr=.71,Gr=2,Sc=.3and Gm=2]

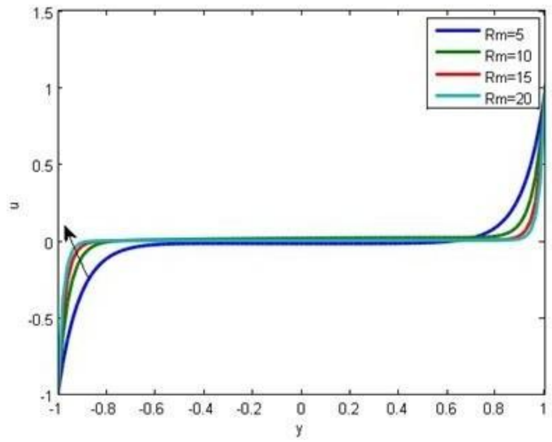


**Figure 8**: Velocity Profile for diverse $R_m$ values,[n=1,$R_e$=1.5,$G_m$=2, $H_a$=7,λ =.5, $S_c$=.3, $G_r$=2 and$P_r$=.71]

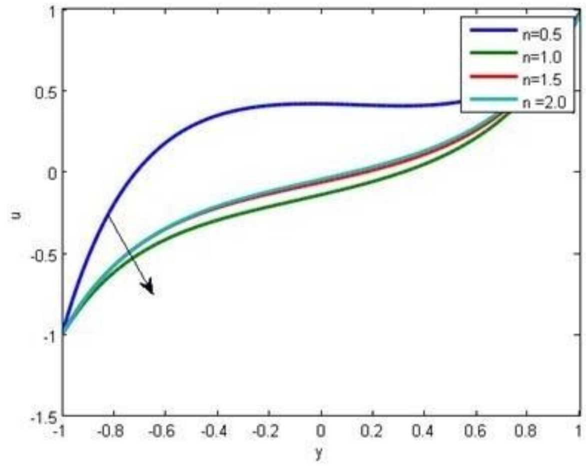


**Figure 9**:Velocity graph for different values of n,[$R_m$ =.2,Pr=.71,$R_e$=1.5,$S_c$=.3, λ =.5 ,$G_m$=2,$G_r$=2 and$H_a$=7]

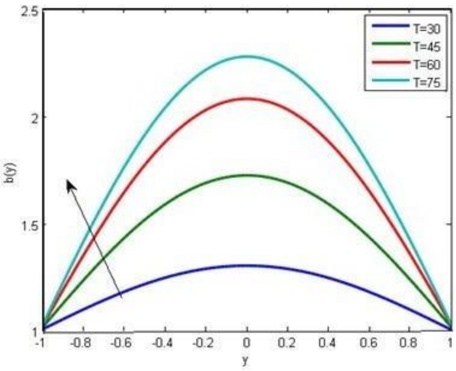


Fig10:Magnetic Field graph for different values of T,[$R_m$=2,$S_c$=.3,$R_e$=1.5,$G_m$=2,$H_a$=7,λ =.5,n=1,Pr=.71and$G_r$=2]

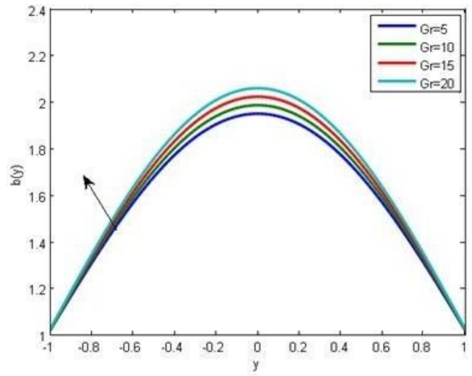


**Figure11**:Magnetic Field Profile for distinct values of $G_r$,[Pr=.71,$H_a$=7,$R_e$=1.5,λ=.5,$R_m$=.2,$S_c$ =.3,$G_m$=2andn=1]

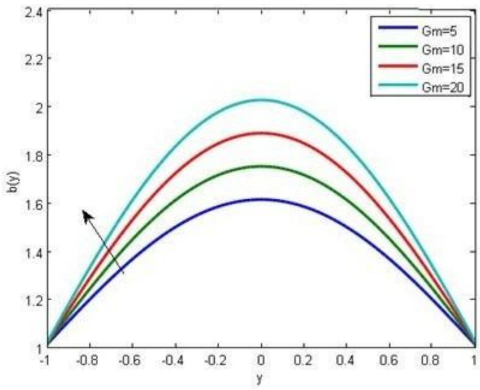


**Figure12**: Magnetic Field Sketch for distinct values of $G_m$, [Pr=.71 n=1,$R_e$=1.5,$H_a$=7, λ =.5,$G_r$=2.,$G_m$=2,$S_c$=.3and$R_m$=.2]

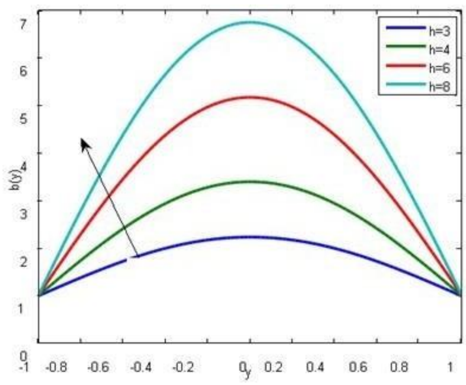


**Figure13**:Magnetic Field Graph for suitable values of h,[$S_c$=.3,Pr=.71,$G_m$=2,n=1,$R_e$=1.5,$H_a$=7,λ =.5,$R_m$=.2,$G_r$=2,$S_c$=.3and$R_e$=1.5]

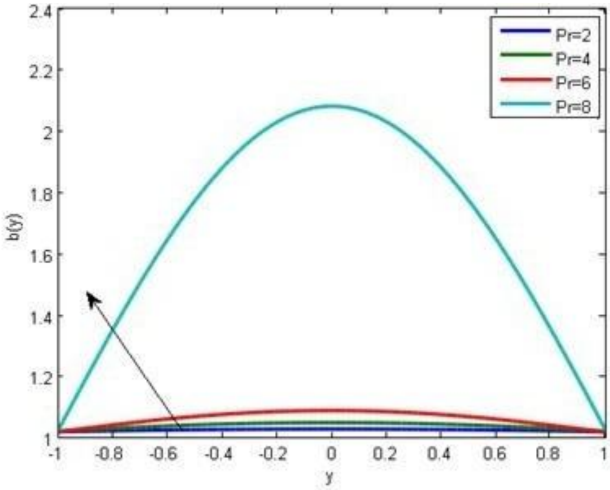


**Figure14**:MagneticFieldGraphforvariousvaluesofPr, [$H_a$=7,n=1,$R_e$=1.5,$R_m$=.2,$G_r$=2,$G_m$=2,$S_c$=.3andλ=.5].

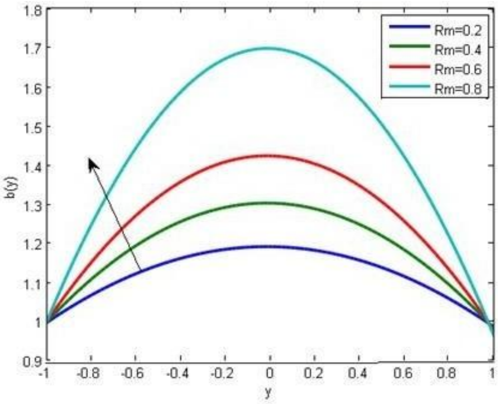


**Figure15**: Magnetic Field Profile for distinct values of $R_m$,[n=1,$G_r$=2, $R_e$=1.5,$H_a$=7,Pr=.71, $G_m$=2,$S_c$=.3andλ=.5]

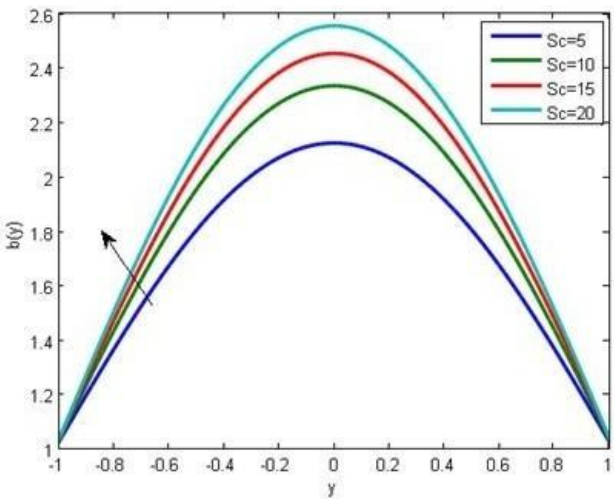


**Figure16**:Graph of Magnetic Field for different values of Sc, [$P_r$=.71,$H_a$=7,$G_m$=2,$R_e$=1.5,$G_r$=2,λ =.5,n=1 and $R_m$=0.2]

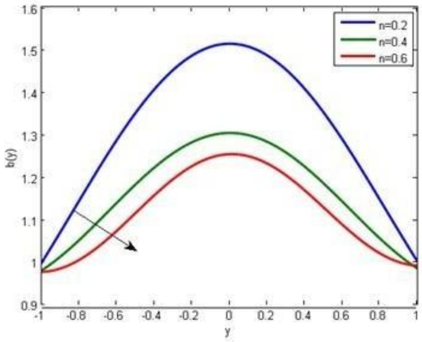


**Figure17**:Magnetic Field Profile for various values of n,[Re=1.5,Sc=.3,Pr=.71,Ha=7,λ =.5,$R_m$=.2,$G_r$=2,$G_m$=2 and $H_a$=7].

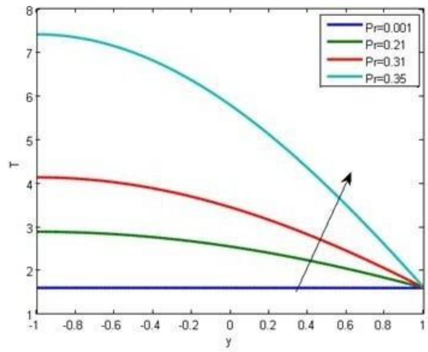


**Figure18**:A Graph of Temperature Field Profile for suitable values of Pr,[$R_e$=1.5andn=1]

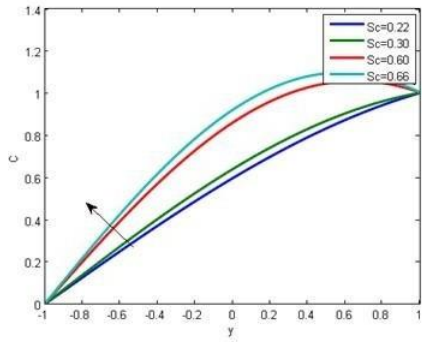


**Figure19**:Sketchof Concentration for various values of Sc,[n=1,Re=1.5]

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