# Natural Convective MHD Flow past an Inclined Porous Plate in the Presence of Chemical Reaction and Radiation with Constant Suction

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*Abstract*— An analysis is made for MHD flow of a viscous incompressible, electrically conducting fluid flow through a porous medium bounded by an inclined surface .The coupled non- linear partial differential equations are solved by perturbation techniques. The effects of various physical parameters on the dimensionless velocity, temperature and concentration profiles are depicted graphically and analyzed in detail. Skin-friction coefficient, Nusselt numbers and Sherwood number are tabulated for different physical parameters.

***Key words:*** Natural Convection, MHD, Radiation, Chemical Reaction, Inclined Surface

## I. INTRODUCTION

Natural convection is a mechanism, or type of heat transport, in which the fluid motion is not generated by any external source but only by density differences in the fluid occurring due to temperature gradients. Natural convection has attracted a great deal of attention from researchers because of its presence both in nature and engineering applications. In nature, convection is seen in the rising plume of hot air from fire, oceanic currents, and sea-wind formation. In engineering applications, convection commonly visualized in the formation of microstructures during the cooling of molten metals, and fluid flows around shrouded heat-dissipation fins, and solar ponds. Natural convection along an inclined plate has received less attention than the cases of vertical and horizontal plates. A number of researchers have considered an inclined, semi-infinite flat plate in their research because of its engineering applications. The study of natural convection flow of inclined plate is presented by authors Sivasankaran et al. [10] and Shit and Haldar [4]. Bhuvaneswari et al. [8] studied exact analysis of radiation convective flow heat and mass transfer over an inclined plate in a porous medium. Chen [1] presented the analysis to study natural convection flow over a permeable inclined surface with variable wall temperature and concentration. Reddy and Reddy [9] performed an analysis to study the natural convection flow over a permeable inclined surface with variable temperature, momentum and concentration.

The problem of natural convection MHD flow of an electrically conducting fluid past an inclined porous plate in the presence of chemical reaction and radiation with constant suction finds numerous applications in space technology and engineering. Kesavaiah et al. [2] studied the chemical reaction and radiation absorption effects of an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium with heat source and suction. Singh et al. [5] a study of the effect of chemical reaction and radiation absorption on MHD convective heat and mass transfer flow past a semi-infinite vertical moving plate with time dependent suction. Prakash et al. [6] studied the transient MHD free convection of a chemically reacting micro-polar fluid along with mass transfer in the presence of transverse magnetic field and variable suction. Seethamahalakshmi et al. [11] effects of the chemical reaction and radiation absorption on an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical moving in a porous medium with heat source and suction. Ibrahim et al. [3] presented the effect of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Sudheer Babu and Satyanarayan [7] presented the effect of chemical reaction and mass transfer on MHD unsteady free convection flow past semi-infinite vertical plate with constant/variable suction and heat sink.

The objective of present work is to study the natural convective MHD flow past an inclined porous plate in the presence of chemical reaction and radiation with constant suction .The method of solution applied here is perturbation method. The behaviour of velocity, temperature and concentration for different values of physical parameters has been discussed qualitatively and the results are presented graphically. The skin friction coefficient, Nusslet number and Sherwood number are also derived.

## II. MATHEMATICAL FORMULATION

Considered a steady natural convective MHD flow of a viscous, incompressible, electrically conducting fluid past a semi infinite tilted porous plate with an angle $\phi$ to the vertical in the presence of chemical reaction and radiation. The $x$-axis is taken along the plate and $y$-axis normal to plate .Since the plate is considered infinite in $x$-direction. Hence all the physical quantities will be independent of $x$ direction. The plate is maintained at a constant temperature $T_w$ and concentration $C_w$ higher than ambient temperature $T_\infty$ and concentration $C_\infty$ .it is assumed that there is no applied voltage which means there is no electric current. The Roseland 'approximation is used to describe the radiative flux .A transverse magnetic field and Reynolds number are assumed to be small, so that the induced magnetic field are neglected. Under the above assumptions, the governing equations are:

*1) Continuity equation:*

$$\frac{\partial v'}{\partial y'} = 0 \Rightarrow v' = -v_0 (const) \tag{1}$$

*2) Momentum equation:*

$$v'\frac{\partial u'}{\partial y'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g\cos\phi\beta_1(T' - T_\infty) + g\cos\phi\beta_2(C' - C_\infty) - \left(\frac{\sigma B_0^2}{\rho}\right)u' - \frac{\nu}{k}u' \tag{2}$$

 

*3) Energy equation:*

$$v'\frac{\partial T'}{\partial y'}=\frac{\alpha}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2}+\frac{\nu}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y'} \quad (3)$$

*4) Species diffusion equation*

$$v'\frac{\partial C'}{\partial y'}=D\frac{\partial^2 C'}{\partial y'^2}-D_1(C'-C_\infty) \quad (4)$$

With the following initial and boundary condition

$$u'=0,\ T'=T_w,\ C'=C_w \ at\ y'=0$$

$$u'\to 0,\ T'\to T_\infty,\ C'\to C_\infty \ as\ y'\to\infty \quad (5)$$

Under the Rosseland approximation , the radiative heat flux $q_r$ has the form:

$$q_r=-\frac{4\sigma^*}{3k_s}\frac{\partial T'^4}{\partial y'}, \quad (6)$$

Where $\sigma^*$ is the Stefan–Boltzmann constant and $k_s$ is the mean absorption coefficient. We assume that the temperature differences within the flow are sufficiently small such that $T'^4$ may be expressed as a linear function of the temperature $T'_\infty$. Expanding $T'^4$ in a Taylor series about $T'_\infty$ and neglecting higher-order terms, we have:

$$T'^4\approx 4T'^3_\infty T'-3T'^4_\infty \quad (7)$$

By using equations (6) and (7), equation (2) reduces to

$$v'\frac{\partial T'}{\partial y'}=\frac{\alpha}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2}+\frac{\nu}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2+\frac{16\sigma^* T'^3_\infty}{3k_s}\frac{\partial^2 T'}{\partial y'^2} \quad (8)$$

Introducing non-dimensional parameters:

$$u=\frac{u'}{v_0},\ y=\frac{v_0 y'}{\nu},\ \theta=\frac{T'-T_\infty}{T_w-T_\infty},\ C=\frac{C'-C_\infty}{C_w-C_\infty},\ \Pr=\frac{\rho\nu C_p}{\alpha}$$

$$Sc=\frac{\nu}{D},\ Gr=\frac{\nu g\beta_1(T_w-T_\infty)}{v_0^3},\ Gm=\frac{\nu g\beta_2(C_w-C_\infty)}{v_0^3}$$

$$E=\frac{v_0^2}{C_p(T_w-T_\infty)},K=\frac{v_0^2}{\nu^2}k,\ Kr=\frac{\nu}{v_0^2}D_1,\ R=\frac{16\sigma^* T'^3_\infty}{3k_s\alpha} \quad (9)$$

Equations (2), (4) and (8) reduce to

$$u''+u'=-Gr\cos\phi\theta-Gm\cos\phi C+\left(M+\frac{1}{K}\right)u \quad (10)$$

$$\theta''+\frac{\Pr}{1+R}\theta'+\frac{\Pr}{1+R}E(u')^2=0 \quad (11)$$

$$C''+ScC'=KrScC \quad (12)$$

The corresponding boundary conditions in dimensionless form are:

$$u=0,\ \theta=1,\ C=1,\ at\ y=0$$

$$u\to 0,\ \theta\to 0,\ C\to 0\ as\ y\to\infty \quad (13)$$

To solve the coupled nonlinear equations (10) to (12) with the boundary conditions (13), $u,\theta$ and $C$ are expanded in powers of the Eckert number(E<<1). So we can write

$$u=u_0+Eu_1+O(E^2)$$

$$\theta=\theta_0+E\theta_1+O(E^2) \quad (14)$$

$$C=C_0+EC_1+O(E^2)$$

Substituting (14) in equations (10) - (12) and equating the coefficient of the terms with the equal power of $E$, and neglecting higher order terms of $O(E^2)$, we obtain

$$u_0''+u_0'-\left(M+\frac{1}{K}\right)u_0=-Gr_1\theta_0-Gm_1C_0 \quad (15)$$

$$\theta_0''+\frac{\Pr}{1+R}\theta_0'=0 \quad (16)$$

$$C_0''+ScC_0'-KrScC_0=0 \quad (17)$$

$$u_1''+u_1'-\left(M+\frac{1}{K}\right)u_1=-Gr_1\theta_1-Gm_1C_1 \quad (18)$$

$$\theta_1''+\frac{\Pr}{1+R}\theta_1'=-\frac{\Pr}{1+R}E(u_0')^2 \quad (19)$$

$$C_1''+ScC_1'-KrScC_1=0 \quad (20)$$

and the corresponding boundary conditions are:

$$y=0:\begin{cases}u_0=0,\ u_1=0,\ \theta_0=1,\\ \theta_1=0,\ C_0=1,\ C_1=0\end{cases} \quad (21)$$

$$y\to\infty:\begin{cases}u_0\to 0,\ u_1\to 0,\ \theta_0\to 0\\ \theta_1\to 0,\ C_0\to 0\ C_1\to 0\end{cases}$$

Solving equations (15)-(20) with the help of (21) we get

$$u=t_4\exp(-m_2y)+t_2\exp(-t_1y)+t_3\exp(-m_1y)+E\begin{pmatrix}t_{25}\exp(-m_2y)+t_{18}\exp(-t_1y)+t_{19}\exp(-2m_2y)+\\ t_{20}\exp(-2t_1y)+t_{21}\exp(-2m_1y)+t_{22}\exp(-m_5y)+\\ t_{23}\exp(-m_3y)+t_{24}\exp(-m_4y)\end{pmatrix} \quad (22)$$

$$\theta=\exp(-t_1y)+E\begin{pmatrix}t_{17}\exp(-t_1y)+t_{11}\exp(-2m_2y)+\\ t_{12}\exp(-2t_1y)+t_{13}\exp(-2m_1y)+\\ t_{14}\exp(-m_5y)+t_{15}\exp(-m_3y)+\\ t_{16}\exp(-m_4y)\end{pmatrix} \quad (23)$$

$$C=\exp(-m_1y) \quad (24)$$

Skin friction, Nusselt number and Sherwood number

Skin-friction in non-dimensional form is given by

$$\tau=\left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$=-m_2t_4-t_1t_2-m_1t_3-E\begin{pmatrix}t_{25}m_2+t_{18}t_1+2t_{19}m_2+2t_1t_{20}+\\ 2m_1t_{21}+m_5t_{22}+t_{23}m_3+m_4t_{24}\end{pmatrix}$$

The dimensionless local surface heat flux (i.e. Nusselt number) and local mass flux (i.e. Sherwood number) are given by

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

$$=t_1+E\begin{pmatrix}t_1t_{17}+2m_2t_{11}+2t_1t_{12}+\\ 2m_1t_{13}+t_{14}m_5+m_3t_{15}+m_4t_{16}\end{pmatrix}$$

$$Sh=-\left(\frac{\partial C}{\partial y}\right)_{y=0}=m_1$$

## III. Results and Discussion

Equations (10), (11) and (12) subjected to boundary condition (13) are solved numerically by perturbation

 

method. A study of velocity, temperature and concentration of a viscous incompressible electrically conducting fluid flow past an inclined plate has carried out in present research. Fig.1 shows the effect of magnetic field parameter ( $M$ ) .It can be seen that as the Hartman number increases, the velocity decreases .As $M$ increases, a restrictive type force (Lorentz force) similar to drag force resists the fluid flow and reducing the velocity. The effect of thermal radiation parameter ( $R$ ) is exhibited in Fig.2 and Fig.11. It is observed that both velocity and temperature decrease with an increase in $R$ . Fig.3 and Fig.5 show the effect of thermal Grashof number ( $Gr$ ) and mass Grashof number ( $Gm$ ) on the velocity profile. As expected fluid velocity increases as the $Gr$ increases due to enhancement in thermal buoyancy force it is also noticed that the velocity increases with increasing value of $Gm$ Fig.4 depicts the effect of Prandtl number ( $\Pr$ ) on velocity profile. It is seen that velocity decreases with an increase in $\Pr$ . The effect of viscous dissipation parameter ( $E$ ) shown in Fig.6 and Fig. 12. We observed that the increasing $E$ is increase both velocity and temperature profile. The influence of chemical reaction parameter ( $Kr$ ) on velocity and concentration profiles are plotted in Fig.7 and Fig.16. It is seen that $Kr$ has a reducing effect on both velocity and concentration profile. For different values of angle of inclination ( $\phi$ ), the velocity and temperature profiles plotted in Fig.8 and Fig.13. We observe that an increasing $\phi$ the velocity and temperature profile decreases. Fig.9 and Fig.15 described the behaviour of velocity and concentration with change in values of Schmidt number

( $Sc$ ). As the $Sc$ increase velocity and concentration profiles decrease. Fig.10 displays the variation of velocity and permeability parameter ( $K$ ). It is observe that an increase in $K$ leads to increase velocity profile.Fig.14 exhibits the effect of Prandtl number ( $\Pr$ ) on temperature profile respectively. It is observed that the temperature profile has a significant reduction for increasing values of $\Pr$ .

Table 1.The skin friction ( $\tau$ ) increases under the influence of thermal Grashof number, mass Grashof number, Eckert number, permeability parameter, but decreases with an increase in the values of Schmidt number, Prandtl number, magnetic field parameter , radiation parameter, chemical reaction parameter and angle of inclination. It is observed that the effect of magnetic field with low diffusivity of heavier species reduces the shearing stress at the plate.

The influence of $\Pr$ , $E$ and $R$ on rate of heat transfer i.e. $Nu$ at the plate surface is tabulated in Table 2 it is evident that $Nu$ at plate gets increased due to Eckert number ( $E$ ) and reverse effect is observed in case of Prandtl number

( $\Pr$ )and radiation parameter ( $R$ ).

From Table 3 it can be seen that rate of mass transfer i.e. Sherwood number ( $Sh$ ) at the plate increases with an increase in Schmidt number ( $Sc$ ) and chemical reaction parameter ( $Kr$ ).

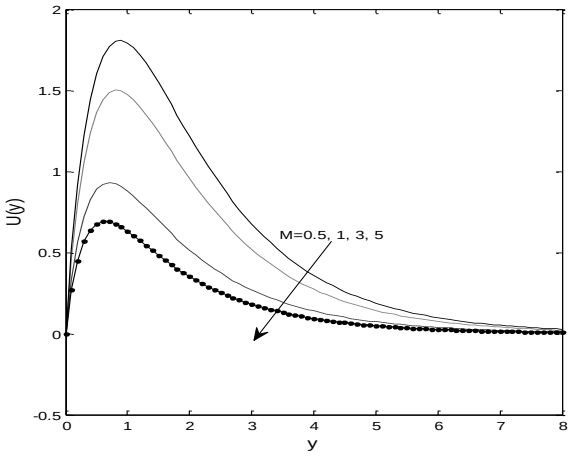


Fig. 1: Hartman Number Effects On Velocity When
$Gr = 5, Gm = 5, \Pr = 0.71,$

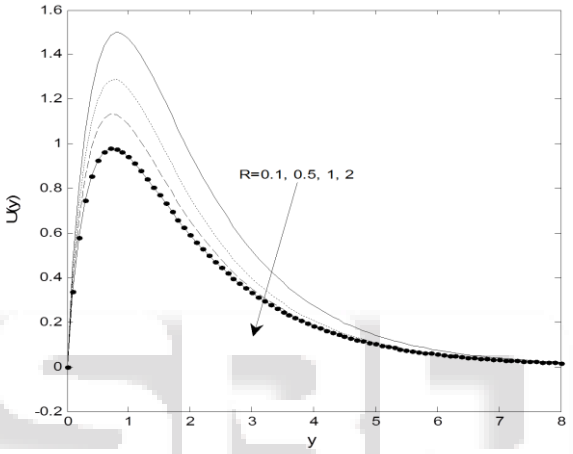


Fig. 2: Radiation Effects On Velocity When
$Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22, Kr = 1, K = 1$
$E = 0.05, \phi = \Pi / 6, M = 1$

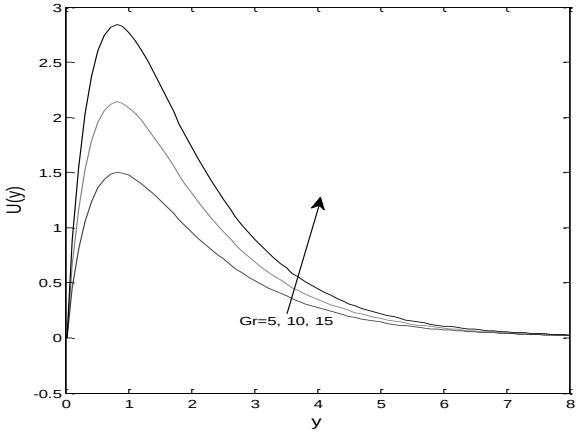


Fig. 3: Thermal Grashof Number Effects On Velocity When
$Gm = 5, \Pr = 0.71, Sc = 0.22$
$Kr = 1, K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

 

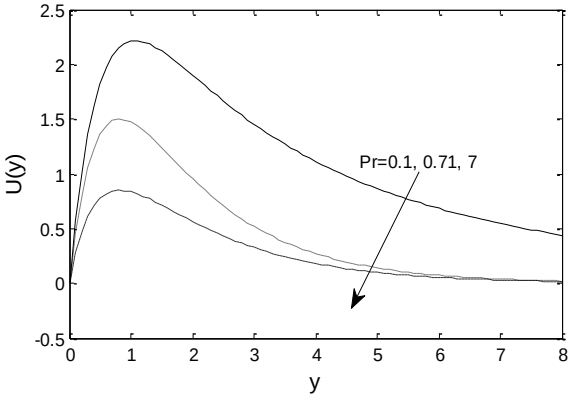


Fig. 4: Prandtl number effects on velocity when
$Gr = 5, Gm = 5, Sc = 0.22, Kr = 1$
$K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

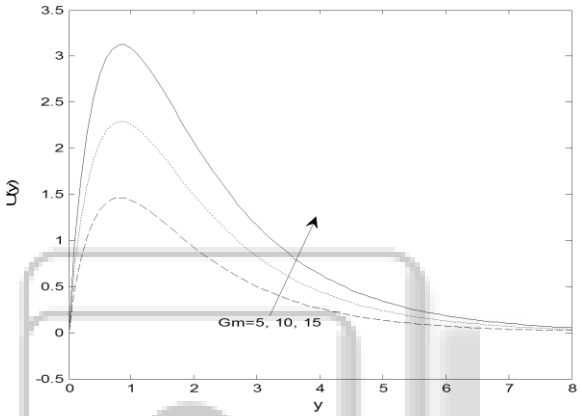


Fig. 5: Mass Grashof Number Effects On Velocity When
$Gr = 5, \Pr = 0.71, Sc = 0.22,$
$Kr = 1, K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

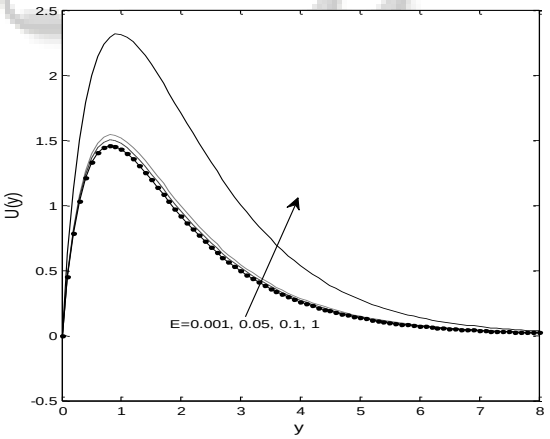


Fig. 6: Eckert Number Effects On Velocity When
$Gr = 5, Gm = 5, \Pr = 0.71,$
$Sc = 0.22, Kr = 1, K = 1, R = 1, \phi = \Pi / 6, M = 1$

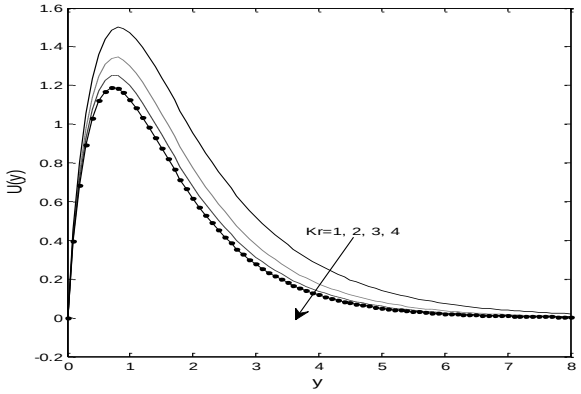


Fig.7: Chemical reaction parameter effects on velocity when $Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22,$
$K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

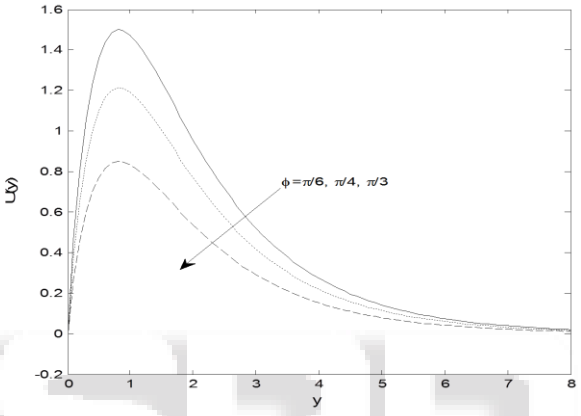


Fig. 8: Angle Of Inclination Effects On Velocity When
$Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22, Kr = 1,$
$K = 1, E = 0.05, R = 1, M = 1$

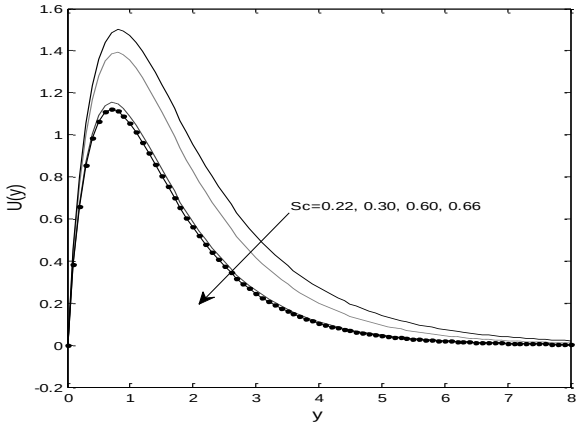


Fig. 9: Schmidt Number Effects On Velocity When
$Gr = 5, Gm = 5, \Pr = 0.71,$
$Kr = 1, K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

 

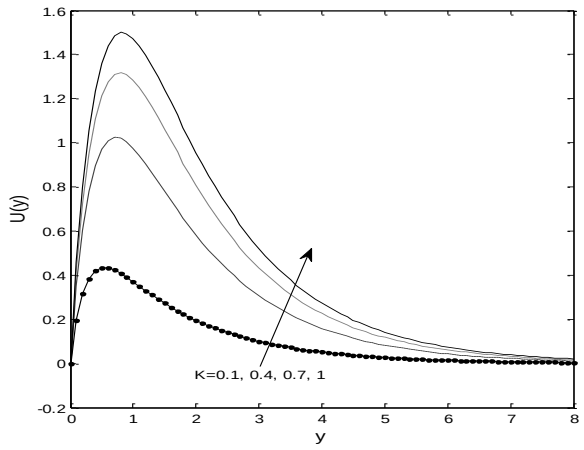


Fig. 10: Permeability Parameter Effects On Velocity When
$Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22,$
$Kr = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

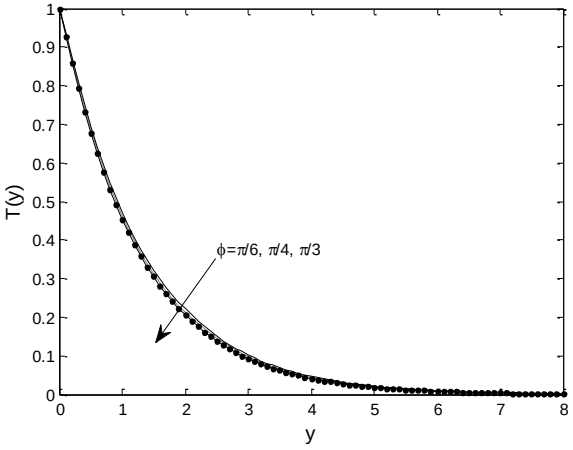


Fig. 13: The Effects Of Angle Of Inclination On Temp.
$Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22, Kr = 1,$
$K = 1, E = 0.05, R = 1, M = 1$

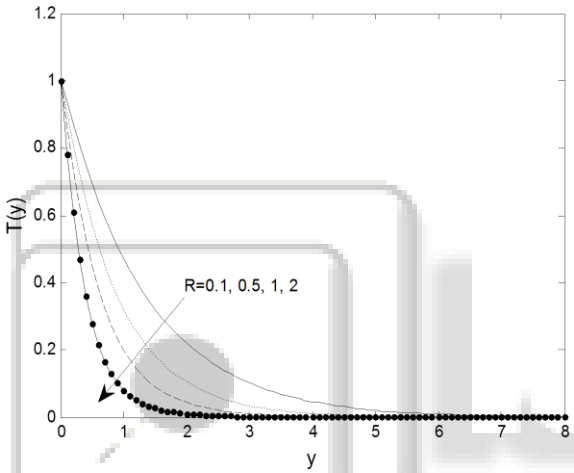


Fig. 11: The Effects Of Radiation On Temp. When
$Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22, Kr = 1,$
$K = 1, E = 0.05, \phi = \Pi / 6, M = 1$

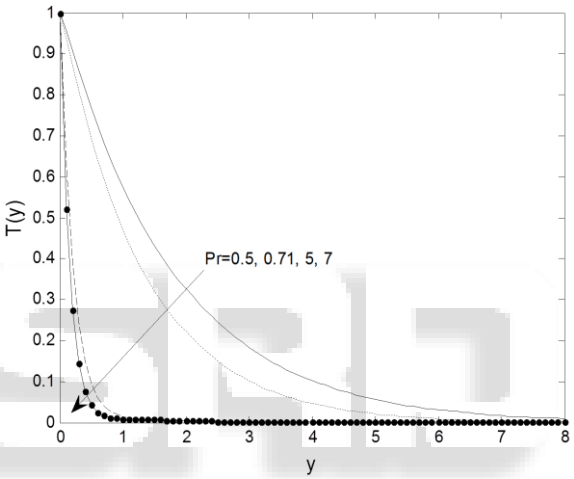


Fig. 14: The Effect Of Prandtl Number On Temp. When
$Gr = 5, Gm = 5, Sc = 0.22, Kr = 1,$
$K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

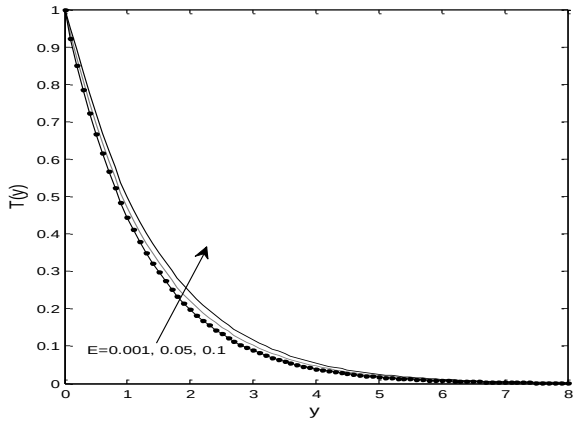


Fig. 12: The Effects Of Eckert Number On Temp. When
$Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22, Kr = 1, K = 1, R = 1,$
$\phi = \Pi / 6, M = 1$

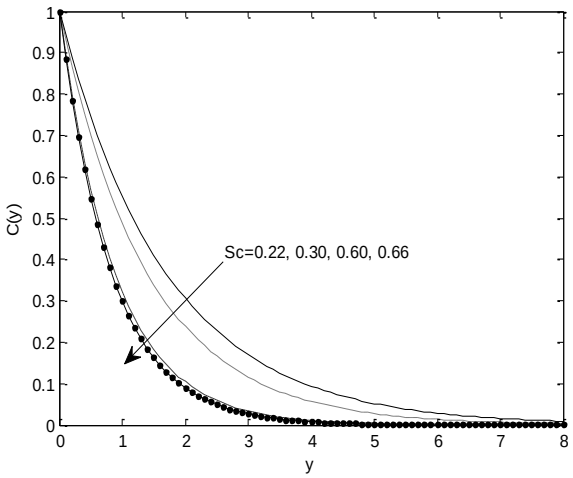


Fig. 15: Concentration Profile For Different Schmidt Number
when $Gr = 5, Gm = 5, \Pr = 0.71, Kr = 1,$
$K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

 

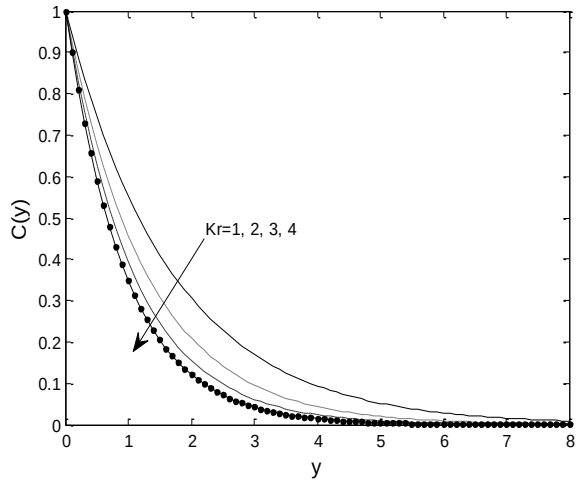


Fig. 16: Concentration Profile For Different Chemical reaction parameter $Gr = 5, Gm = 5, \Pr = 0.71, Sc = 0.22,$ $K = 1, E = 0.05, R = 1, \phi = \Pi / 6, M = 1$

| *Gr* | *Gm* | Pr | *Sc* | *M* | *K* | *E* | *R* | *Kr* | $\phi$ | $\tau$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 5 | 0.71 | 0.22 | 1 | 1 | 0.05 | 1 | 1 | $\pi/6$ | 4.3978 |
| 10 | 5 | 0.71 | 0.22 | 1 | 1 | 0.05 | 1 | 1 | $\pi/6$ | 6.185 |
| 5 | 10 | 0.71 | 0.22 | 1 | 1 | 0.05 | 1 | 1 | $\pi/6$ | 7.2723 |
| 5 | 5 | 7 | 0.22 | 1 | 1 | 0.05 | 1 | 1 | $\pi/6$ | 3.2609 |
| 5 | 5 | 0.71 | 0.3 | 1 | 1 | 0.05 | 1 | 1 | $\pi/6$ | 4.1888 |
| 5 | 5 | 0.71 | 0.22 | 2 | 1 | 0.05 | 1 | 1 | $\pi/6$ | 3.7633 |
| 5 | 5 | 0.71 | 0.22 | 1 | 2 | 0.05 | 1 | 1 | $\pi/6$ | 4.8957 |
| 5 | 5 | 0.71 | 0.22 | 1 | 1 | 0.1 | 1 | 1 | $\pi/6$ | 4.4775 |
| 5 | 5 | 0.71 | 0.22 | 1 | 1 | 0.05 | 2 | 1 | $\pi/6$ | 3.9547 |
| 5 | 5 | 0.71 | 0.22 | 1 | 1 | 0.05 | 1 | 2 | $\pi/6$ | 4.0935 |
| 5 | 5 | 0.71 | 0.22 | 1 | 1 | 0.05 | 1 | 1 | $\pi/4$ | 3.5691 |

Table 1: Skin Friction ( $\tau$ ) For The Value Of Different Physical Parameters $Gr, Gm, \Pr, Sc, M, K, E, R, \phi$ And $Kr$

| Pr | *E* | *R* | *Nu* |
|---|---|---|---|
| 0.71 | 0.05 | 1 | 1.4472 |
| 7 | 0.05 | 1 | 7.3617 |
| 0.71 | 0.1 | 1 | 1.1845 |
| 0.71 | 0.05 | 2 | 2.3922 |

Table 2: Rate Of Heat Transfer ( *Nu* ) Values For Different Physical Parameter Pr, *E* And *R*

| *Sc* | *Kr* | *Sh* |
|---|---|---|
| 0.22 | 1 | 0.5918 |
| 0.3 | 1 | 0.7179 |
| 0.6 | 1 | 1.1307 |
| 0.22 | 2 | 0.7824 |
| 0.22 | 3 | 0.9298 |

Table 3: Rate Of Heat Transfer ( *Sh* ) Values For Different Physical Parameter *Sc* And *Kr*

## IV. Conclusion

A study of velocity, temperature, concentration, skin friction, mass transfer and heat transfer for natural convective MHD flow of a viscous incompressible electrically conducting fluid past an inclined plate in presence of chemical reaction and radiation with constant suction has been carried out in the present study.

(1) Increasing angle of inclination is to decrease velocity profile as well as temperature profile.
(2) An increase in radiation parameter leads to decrease both in velocity and temperature profile.
(3) Velocity increases with the increase in thermal Grashof number, mass Grashof number and permeability parameter and velocity decreases when chemical reaction parameter, Schmidt number and magnetic field parameter.
(4) Both velocity and temperature profile increase with increasing values of Eckert number and decreases with increasing values of Prandtl number.
(5) The concentration decrease with increasing the chemical reaction parameter, Schmidt number.
(6) The skin friction increases with an increase in thermal Grashof number, mass Grashof number, permeability parameter and Eckert number but decreases as Prandtl number, Schmidt number, magnetic field parameter, radiation parameter, chemical reaction parameter and angle of inclination increase.
(7) The rate of heat transfer increases with increasing of Prandtl number and radiation and decreases with increasing of Eckert number.
(8) The rate of mass transfer increases with increasing of Schmidt number and chemical reaction parameter.

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