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# Chemical Reaction and Hall Effects on MHD Convective Flow along an Infinite Vertical Porous Plate with Variable Suction and Heat Absorption

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## Abstract

In this paper an attempt is made to study the chemical reaction and combined buoyancy effects of thermal and mass diffusion on MHD convective flow along an infinite vertical porous plate in the presence of Hall current with variable suction and heat generation. A uniform magnetic field is applied in a direction normal to the porous plate. The equations governing the fluid flow are solved using the perturbation technique and the expressions for the velocity, the temperature and the concentration distributions have been obtained. Dimensionless velocity, temperature and concentration profiles are displayed graphically for different values of the parameters entering into the problem like Prandtl number $Pr$, Hartmann number $M$, Grashof number $G$, modified Grashof number $Gc$, Hall parameter $m$, Heat source parameter $\delta$, Schmidt number $Sc$, and Chemical reaction parameter $Kr$. The Skin-friction coefficient, rate of heat transfer and mass transfer at the plate have been obtained and also discussed through tables. It has been observed that an increase in the Prandtl number leads to a decrease in the primary and secondary velocities, and also a decrease in the primary and secondary temperatures. The primary and secondary velocities decrease with increase in the Chemical reaction parameter or Magnetic field parameter.

**Keywords**: Magnetic field, Heat generation/absorption, Chemical reaction, Heat transfer, Mass transfer

**MSC 2010 No.:** 74F25, 76W05, 76E15, 80A20

## Nomenclature

$u, v$ - Velocity components
$x, y$ - Cartesian coordinates
$t$ - Time
$g$ - Acceleration due to gravity
$\rho$ - Density
$w$ - Velocity ratio parameter
$\omega$ - Frequency parameter
$U_0^{'}$ - Mean velocity
$\theta$ - Dimensionless temperature
$C$ - Dimensionless concentration
$\beta$ - Coefficient of volume expansion due to temperature
$\beta^*$ - Coefficient of volume expansion due to concentration
$C_p$ - Specific heat at constant pressure
$\nu$ - Kinematic viscosity
$k$ - Thermal conductivity
$M$ - Magnetic field parameter
$Pr$ - Prandtl number
$G$ - Thermal Grashof number
$Gc$ - Mass Grashof number
$m$ - Hall parameter
$Sc$ - Schmidt number
$\delta$ - Heat source parameter
$Kr$ - Chemical reaction rate constant
$\varepsilon$ - Small reference parameter <<1
$D$ - Chemical molecular diffusivity
$D_1$ - Chemical reaction coefficient
$Q$ - Rate of heat absorption per unit volume per degree Kelvin
$\tau$ - Skin friction coefficient
$Nu$ - Nusselt number
$Sh$ - Sherwood number

## 1. Introduction

In many engineering applications, natural convective flows play an important role and have attracted the attention of many research workers. The phenomenon of mass transfer is very common in the theories of stellar structure and observable effects are easily detectable at least on the solar surface. On the other hand, the results of the effects of a magnetic field on the flow of an electrically-conducting viscous fluid in the presence of mass transfer are also useful in a stellar atmosphere.

Gebhart and Pera (1971) have studied the vertical natural convection flows resulting from the combined buoyancy effects of thermal and mass diffusion. Pop and Soundalgekar (1974) investigated the effect of Hall current on steady hydromagnetic flow past a porous plate.

Georgantopoulos et al. (1981*)* studied the effects of mass transfer on free-convective flow of an electrically-conducting viscous liquid past an impulsively started infinite vertical limiting surface, when the magnetic Reynolds number of the flow is small, so that the induced magnetic field is neglected. Agarwal et al. (1984) have studied the effect of Hall current on MHD natural convective flow past an infinite vertical porous plate. Takhar et al (1992) presented the Hall effects on heat and mass transfer flow with variable suction and heat generation. Aboeldhab and Elbarbary (2001) studied the Hall current effect on magneto hydrodynamic free convection flow past a semi-infinite vertical plate with mass transfer. Acharya et al. (2001) presented Hall current effect with simultaneous thermal and mass diffusion on unsteady hydromagnetic flow near an accelerated vertical plate.

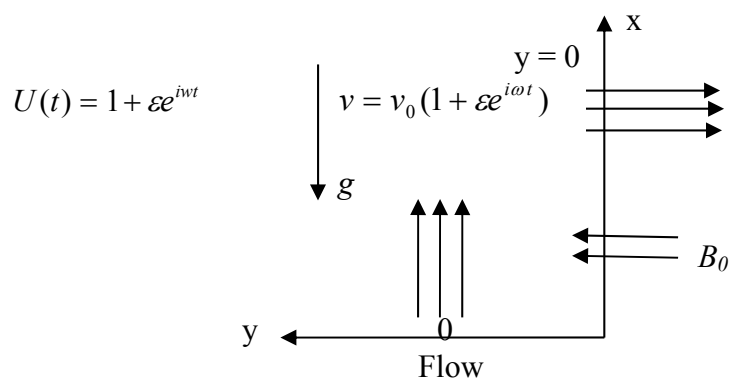
The study of heat generation or absorption in moving fluids is important in problems dealing with chemical reactions and those concerned with dissociating fluids. Heat generation effects may alter the temperature distribution and this in turn can affect the particle deposition rate in nuclear reactors, electronic chips and semi-conductor wafers. Although exact modeling of internal heat generation or absorption is quite difficult, some simple mathematical models can be used to express its general behavior for most physical situations. Heat generation or absorption can be assumed to be constant, space-dependent or temperature-dependent. Several interesting computational studies of reactive MHD boundary layer flows with heat and mass transfer in the presence of heat generation or absorption have appeared in recent years. Patil and Kulkarni (2008) studied the effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. Salem and El-Aziz (2008) studied the effects of hall currents and chemical reaction on hydromagnetic flow of a stretching vertical surface with internal heat generation/absorption.

Makinde and Sibanda (2008) studied MHD convective flow and heat and mass transfer past a vertical plate in a porous medium with constant wall suction. Recently, Shateyi et al. (2010) presented the effects of thermal radiation, hall currents, soret and dufour on MHD flow by mixed convection over a vertical surface in porous medium. Shankar et al. (2010) presented a numerical solution for radiation and mass transfer effects on unsteady MHD free convective fluid flow embedded in a porous medium with heat generation/absorption using the Galerkin finite element method. Makinde and Olanrewaju (2011) investigated unsteady mixed convection with Soret and Dufour effects past a vertical porous plate moving through a binary mixture of a chemically reacting fluid.

The purpose of the present investigation is to study the effects of chemical reaction and hall current on the combined effects of thermal and mass diffusion of an electrically conducting fluid past an infinite vertical porous plate. Here we assume that (i) the plate is subjected to variable suction velocity, (ii) the heat source $Q^*$ is of the type $Q^* = Q(T'_\infty - T')$, and (iii) the free-stream velocity of the fluid vibrates about a constant mean value. The equations governing the fluid flow are solved using perturbation technique. Dimensionless velocity, temperature and concentration profiles are displayed graphically for different values of the parameters entering into the problem like *Pr, M, G, Gc, m, δ, Sc,* and *Kr*. The variations in skin friction, Nusselt number and Sherwood number for different physical parameters are presented.

## 2. Formulation of the Problem

The transient MHD free connection flow of an electrically conducting fluid over a porous vertical infinite plate with variable suction and heat generation has been considered. The $x'$ axis is assumed to be along the plate and the $y'$ axis is normal to the plate.




Physical model of the problem

Under the Boussinesq's approximation and the boundary layer theory, the governing equations for the problem under consideration are

Continuity equation:

$$\frac{\partial v'}{\partial y'} = 0, \tag{1}$$

Momentum equation:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \frac{\partial U'}{\partial t'} + g\beta(T' - T'_\infty) + g\beta^*(c' - c'_\infty) + \nu\frac{\partial^2 u}{\partial y'^2} - \frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}(u' - U' + mw'), \tag{2}$$

$$\frac{\partial w'}{\partial t'} + v'\frac{\partial w'}{\partial y'} = \nu\frac{\partial^2 w'}{\partial y'^2} + \frac{\sigma\mu_e^2 H_0^2}{\rho(1+m^2)}[m(u' - U') - w'], \tag{3}$$

Energy equation:

$$\frac{\partial T}{\partial t'}+v'\frac{\partial T}{\partial y'}=\frac{K}{\rho C_p}\frac{\partial^2 T}{\partial y'^2}+\frac{Q}{\rho C_p}(T'_\infty-T'). \tag{4}$$

Concentration equation:

$$\frac{\partial c'}{\partial t'}+v'\frac{\partial c'}{\partial y'}=D\frac{\partial^2 c'}{\partial y'^2}+D_1(c'-c'_\infty). \tag{5}$$

The boundary conditions are given by

$$\left.\begin{array}{llll} u=0, & w=0, & T=T_w, & c=c_w \quad at\ \ y=0, \\ u'\to U'(t'), w'\to 0, & T'\to T'_\infty, & c'\to c'_\infty & as\ y'\to\infty, \end{array}\right\} \tag{6}$$

where the dashes denote the dimensional quantities.

Equation (1) gives $v'=v'(t)$.

The plate is subjected to a variable suction velocity with time so that we can replace $v'=-v'_0(1+\varepsilon e^{i\omega' t'})$ ($\varepsilon << 1$), where $v'_0$ is the steady suction velocity. Now, introducing the following non-dimensional parameters in equations (2), (3), (4) and (5),

$$\left.\begin{array}{l} y=\frac{y'v'_0}{\nu},\quad t=\frac{t'v'^2_0}{4\nu},\quad \omega=\frac{4\nu\omega'}{v'^2_0},\quad u=\frac{u'}{U'_0},\delta=\frac{Q\nu^2}{k\,v'^2_0},\quad Kr=\frac{v'}{v'^2_0}D_1, \\ w=\frac{w'}{U'_0},\quad U=\frac{U'}{U'_0},\quad \theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},\quad C=\frac{c'-c'_\infty}{c'_w-c'_\infty},M^2=\frac{\sigma\nu\mu_e^2H_0^2}{\rho v'^2_0}, \\ Sc=\frac{\nu}{D},\quad \Pr=\frac{\rho\nu C_p}{k},\quad G=\frac{\nu g\beta(T'_w-T'_\infty)}{U'_0v'^2_0},\quad Gc=\frac{\nu g\beta^*(c'_w-c'_\infty)}{U'_0v'^2_0}. \end{array}\right\} \tag{7}$$

We obtain the following equations in dimensionless form.

$$\frac{1}{4}\frac{\partial q}{\partial t}-(1+\varepsilon\, e^{i\omega t})\frac{\partial q}{\partial y}-\frac{\partial^2 q}{\partial y^2}+\frac{M^2(1-im)}{1+m^2}(q-U)=\frac{1}{4}\frac{\partial U}{\partial t}+G\theta+GcC\ , \tag{8}$$

$$\frac{\Pr}{4}\frac{\partial\theta}{\partial t}-\Pr(1+\varepsilon\, e^{i\omega t})\frac{\partial\theta}{\partial y}=\frac{\partial^2\theta}{\partial y^2}+\delta\theta\ , \tag{9}$$

$$\frac{Sc}{4}\frac{\partial C}{\partial t} - Sc(1+\varepsilon e^{i\omega t})\frac{\partial C}{\partial y} = \frac{\partial^2 C}{\partial y^2} + ScKrC\ , \tag{10}$$

where

$q = qr + i(qi)$.

The corresponding boundary conditions are

$$\left.\begin{array}{l} q = 0, \quad \theta = 1, \quad C = 1, \quad at\ y = 0, \\ q \to v(t),\ \theta \to 0, \quad C \to 0 \quad as\ y \to \infty. \end{array}\right\} \tag{11}$$

## 1. Method of Solution

To solve the nonlinear equations (8) to (10) with the boundary conditions (11), we assume that

$$\begin{array}{l} q = (1-q_0) + \varepsilon(1-q_1)e^{i\omega t}, \quad U = 1 + \varepsilon e^{i\omega t}, \quad \theta = \theta_0 + \varepsilon\theta_1 e^{i\omega t}, \\ C = C_0 + \varepsilon C_1 e^{i\omega t}. \end{array} \tag{12}$$

We now substitute equation (12) into equations (8) to (10) and equating the like terms, neglecting higher order terms in $\varepsilon$, we obtain

$$q_0'' + q_0' - M_1 q_0 = G\theta_0 + GcC_0, \tag{13}$$

$$q_1'' + q_1' - \left(M_1 + \frac{i\omega}{4}\right)q_1 = -\frac{\partial q_0}{\partial y} + G\theta_1 + G_c C_1, \tag{14}$$

$$\theta_0'' + \Pr\theta_0' - \delta\theta_0 = 0, \tag{15}$$

$$\theta_1'' + \Pr\theta_1' - \left(\delta + \frac{i\omega\Pr}{4}\right)\theta_1 = -\Pr\frac{\partial\theta_0}{\partial y}, \tag{16}$$

$$C_0'' + ScC_0' + ScKrC_0 = 0, \tag{17}$$

$$C_1'' + ScC_1'' + Sc\left(Kr - \frac{i\omega}{4}\right)C_1 = -Sc\frac{\partial C_0}{\partial y}. \tag{18}$$

The boundary conditions are

$$\left.\begin{array}{l} q_0 = 1, \quad q_1 = 1, \quad \theta_0 = 1, \quad \theta_1 = 0, \quad C_0 = 1, \quad C_1 = 0 \qquad at \quad y = 0, \\ q_0 \to 0, \quad q_1 \to 0, \quad \theta_0 \to 0, \quad \theta_1 \to 0, \quad C_0 \to 0, \quad C_1 \to 0 \qquad as \quad y \to \infty, \end{array}\right\} \tag{19}$$

In Equations (13) to (18), the primes denote the derivatives with respect to $y$. Solving equations (13) to (18) subject to the boundary conditions (19), we get

$$\theta_0 = e^{-\delta_2 y}, \tag{20}$$

$$\theta_1 = \frac{\Pr \delta_2}{a_3}(e^{-\delta_2 y} - e^{-\delta_3 y}), \tag{21}$$

$$C_0 = e^{-\delta_4 y}, \tag{22}$$

$$C_1 = \frac{\delta_4 S_c}{a_4}\left[e^{-\delta_4 y} - e^{-\delta_5 y}\right], \tag{23}$$

$$q_0 = A_1 e^{-\delta_2 y} + A_2 e^{-\delta_4 y} + A_3 e^{-M_3 y}, \tag{24}$$

$$q_1 = A_4 e^{-\delta_2 y} - A_5 e^{-\delta_3 y} + A_6 e^{-\delta_4 y} - A_7 e^{-\delta_5 y} + A_8 e^{-M_3 y} + A_9 e^{-M_4 y}. \tag{25}$$

The constants involved in the above discussion are given in the Appendix.

**Skin-friction, Rate of Heat and Mass Transfer**

The **s**kin-friction coefficient ( $\tau$ ) at the plate is:

$$\tau = \left|\left(\frac{\partial u}{\partial y}\right)_{y=0}\right| = \left|\begin{array}{l} A_1\delta_2 - A_2\delta_4 - A_3 M_3 + \varepsilon(A_4\delta_2 - A_5\delta_3 \\ + A_6\delta_4 - A_7\delta_5 + A_8 M_3 + A_9 M_4)e^{iwt} \end{array}\right|. \tag{26}$$

The rate of heat transfer in terms of the Nusselt number at the plate is given by:

$$N_u = \left|\left(\frac{\partial \theta}{\partial y}\right)_{y=0}\right| \left|-\delta_2 + \varepsilon \frac{\Pr \delta_2}{a_3}(\delta_3 - \delta_2)e^{i\omega t}\right|. \tag{27}$$

The rate of mass transfer coefficient in term of the Sherwood number at the plate is given by:

$$S_h = \left| \left( \frac{\partial C}{\partial y} \right)_{y=0} \right| \left| -\delta_4 + \varepsilon \frac{Sc\delta_4}{a_4} (\delta_5 - \delta_4) e^{i\omega t} \right|. \tag{28}$$

## 2. Results and Discussion

In order to get a physical insight into the problem numerical calculations are carried out for the transient primary velocity *qr*, the secondary velocity *qi*, the primary temperature *Tr* , the secondary temperature *Ti*, the primary concentration *Cr* and the secondary concentration *Ci,* in terms of the parameters *M, Kr, Sc,* $\delta$ *,Pr, m* respectively. Throughout the computations we employ the Prandtl number $Pr = 0.71$, Grashoff number $G = 5.0$, Modified Grashoff number $Gc = 2.0$, Schmidt number $Sc = 0.3$, Magnetic field parameter $M = \sqrt{10}$ , $\omega = 5.0$, $\varepsilon = 0.01$, and $\omega t = \frac{\pi}{2}$.

### 4.1. Velocity Profiles

Figures 1 to 12 display the effects of a Magnetic field parameter (*M*), a Chemical reaction parameter (*Kr*), Schmidt number (*Sc*), Heat absorption parameter ($\delta$), Prandtl number (*Pr*), hall parameter (*m*) on primary and secondary velocity distributions respectively. From Figures 1 and 2, it is observed that an increase of Magnetic field parameter leads to decrease in primary and secondary velocity fields. It is because that the application of transverse magnetic field will result a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. The nature of velocity profiles in the presence of foreign species is shown in Figures 3 and 4. The flow field suffers a decrease in the primary velocity and secondary velocity at all points in the presence of heavier diffusing species. The behavior of the primary velocity and secondary velocity for different values Prandtl number is shown in Figures 5 and 6. The numerical results show that the effect of increasing values of Prandtl number results in decreasing both primary and secondary velocity fields. Figures 7 and 8 discuss the effect of Heat absorption parameter on the velocity of the flow field. It is found that an increase in Heat absorption parameter leads to a reduction in the primary and secondary velocity fields. The velocity for different values of the Chemical reaction parameter is shown in Figures 9 and 10. It is observed that both primary velocity and secondary velocity decrease with an increase of the Chemical reaction parameter. It is seen from Figures 11 and 12 that hall parameter accelerates the both primary and secondary velocity field.

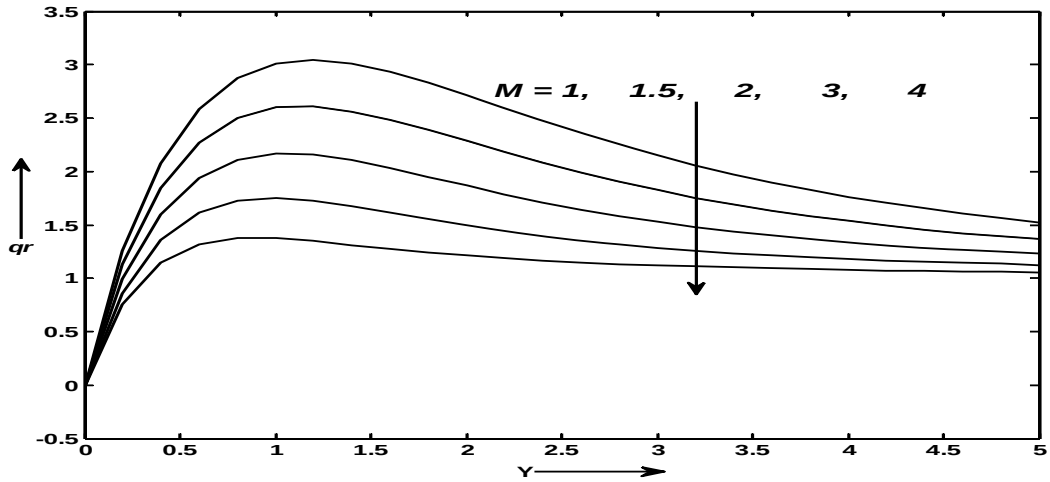



**Figure 1.** Effect of *M* on primary velocity *qr*

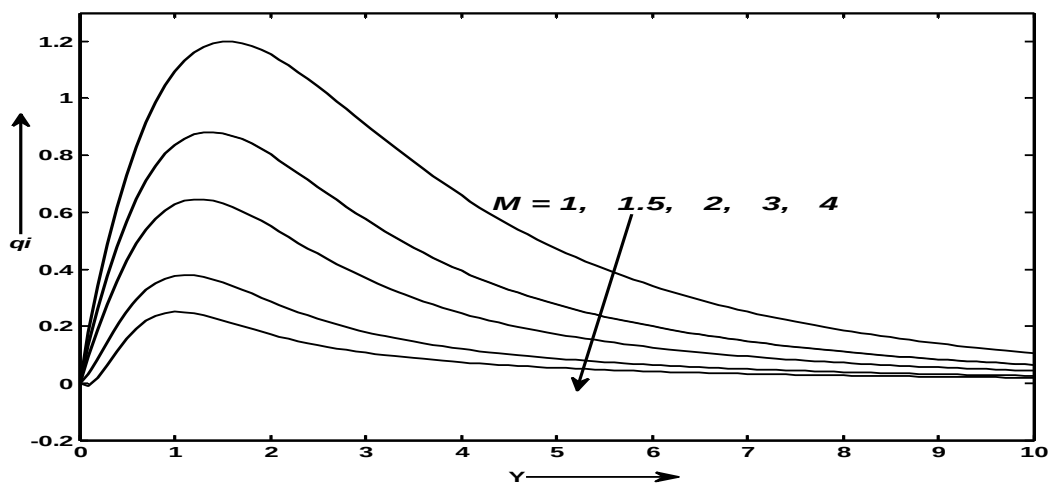



**Figure 2.** Effect of *M* on secondary velocity *qi*

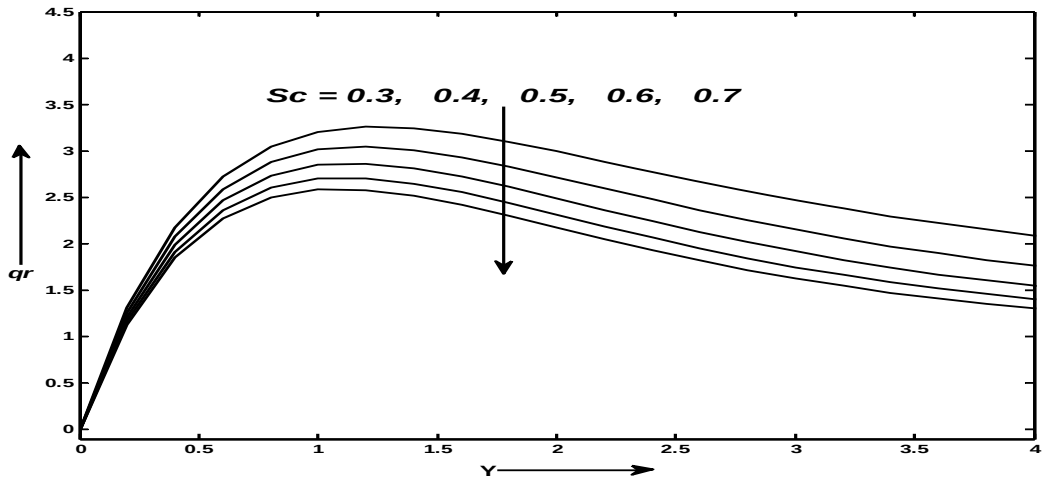



**Figure 3.** Effect of *Sc* on primary velocity *qr*

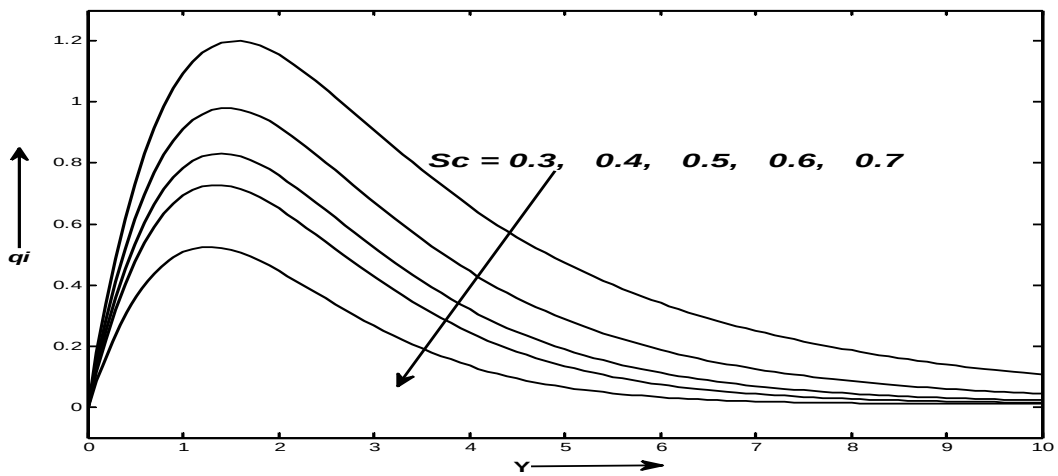



**Figure 4.** Effect of *Sc* on secondary velocity *qi*

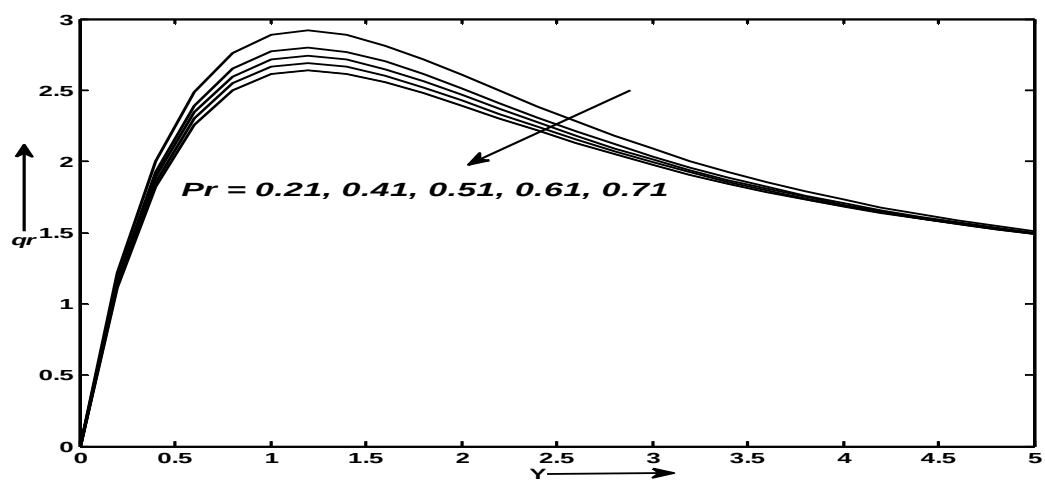



**Figure 5.** Effect of *Pr* on primary velocity *qr*

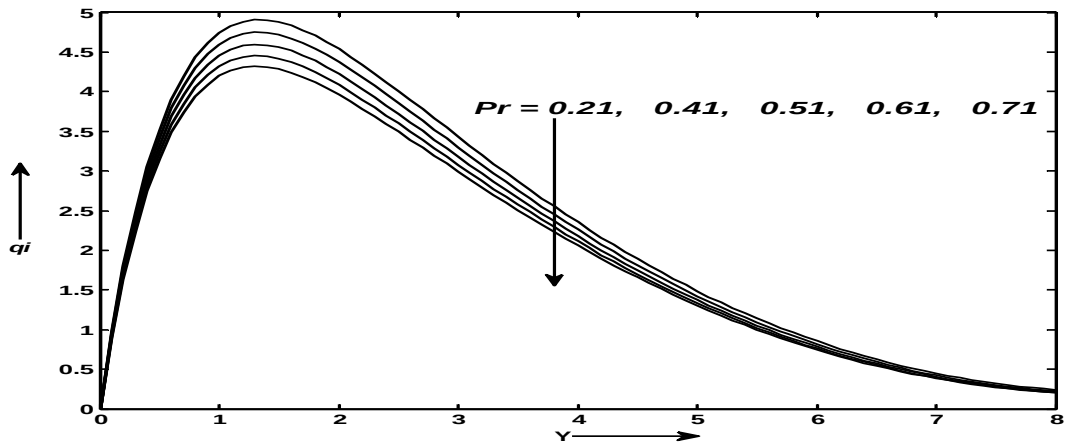



**Figure 6.** Effect of *Pr* on secondary velocity *qi*

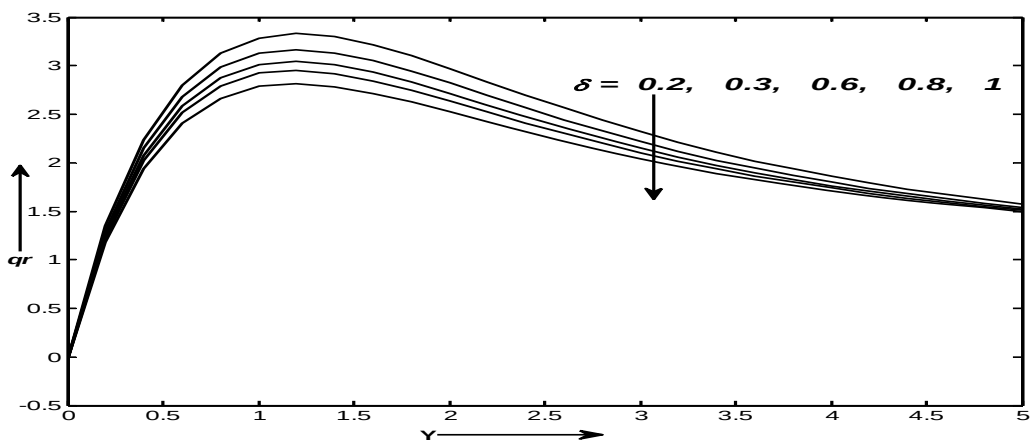



**Figure 7.** Effect of $\delta$ on primary velocity *qr*

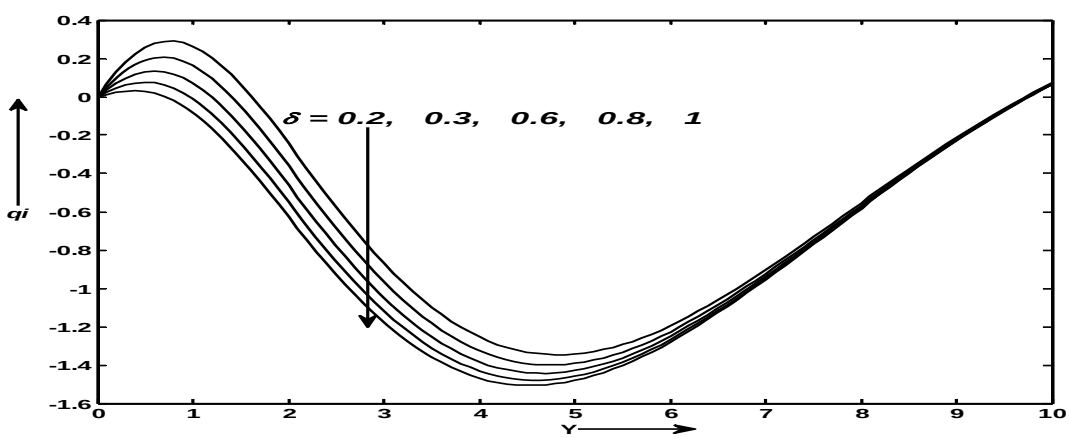



**Figure 8.** Effect of $\delta$ on secondary velocity *qi*

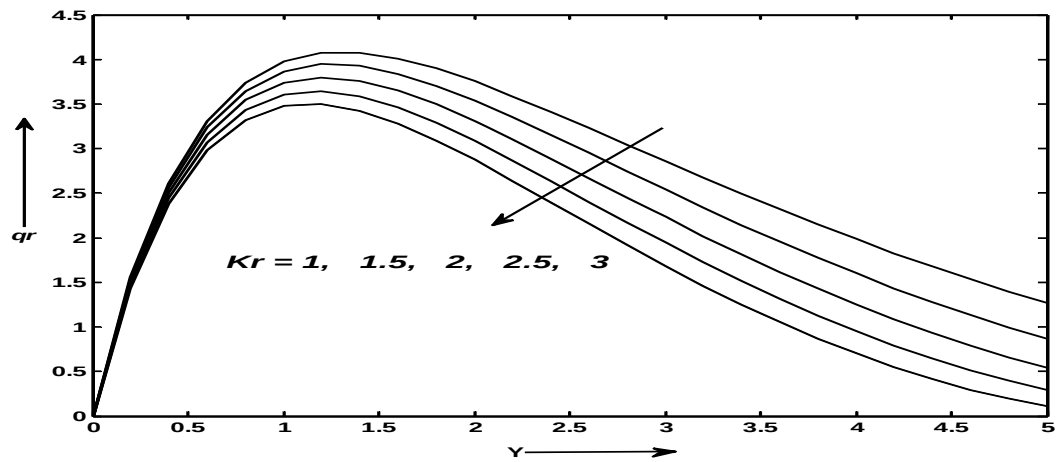



**Figure 9.** Effect of *Kr* on primary velocity *qr*

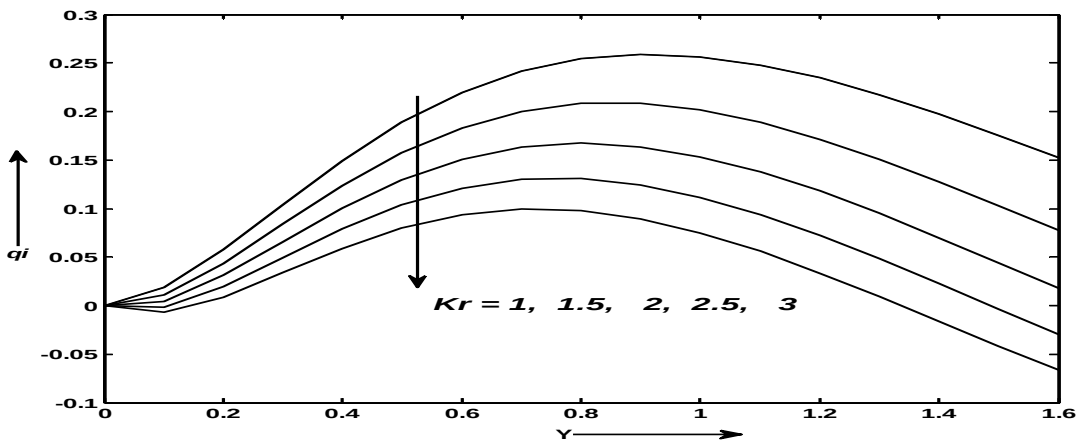



**Figure 10.** Effect of *Kr* on secondary velocity *qi*

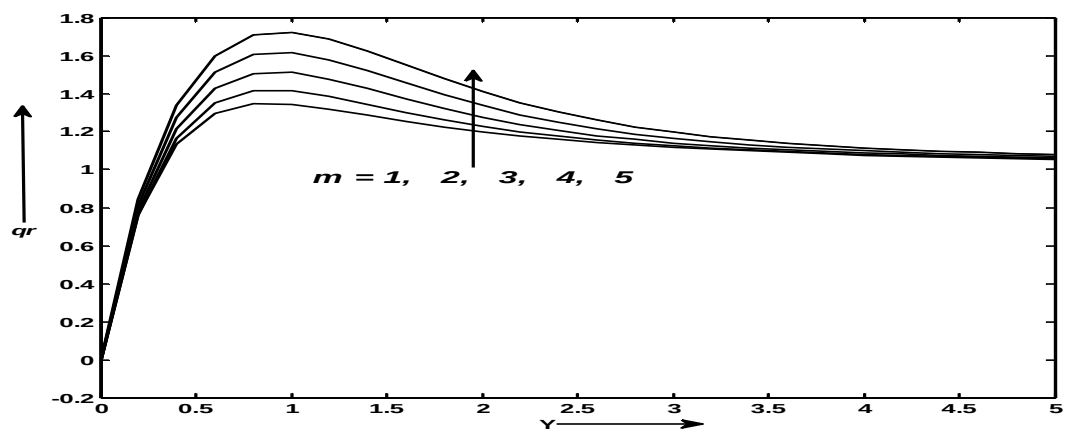



**Figure 11**. Effect of *m* on primary velocity *qr*

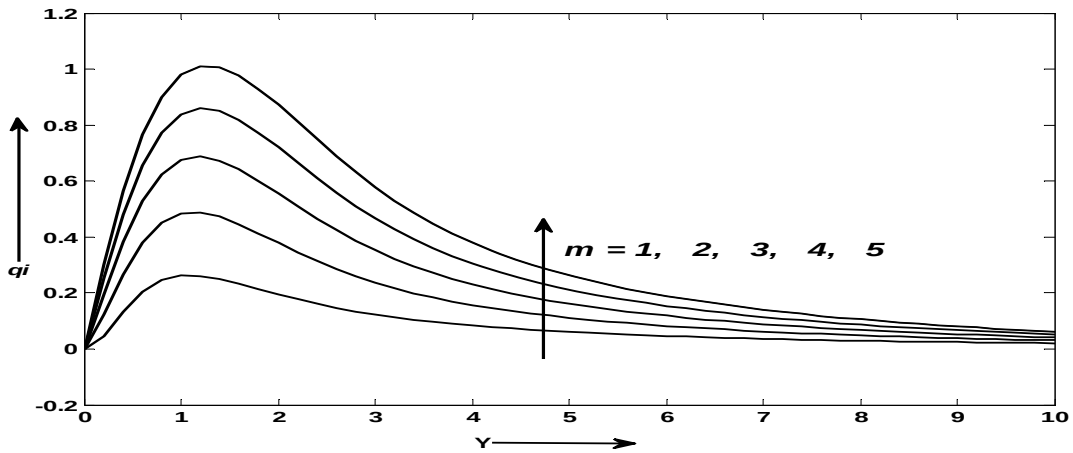



**Figure 12.** Effect of *m* on secondary velocity *qi*

## 4.2. Temperature Profiles

Figures 13 to 18 show the effects of material parameters such as *Pr* and $\delta$ on temperature distribution. The effect of Prandtl number is very important in temperature profiles. There is a decrease in primary and secondary temperatures due to increasing values of the Prandtl number as shown in Figures 13 and 14. From the Figures 15 and 16, it is noticed that the primary temperature decreases and secondary temperature increases with an increase in Heat absorption parameter. Figures 17 and 18 show the effect of Heat generation parameter ($\delta < 0$) on temperature distribution. It is found that the primary temperature increases and the secondary temperature decreases with decrease in $\delta$.

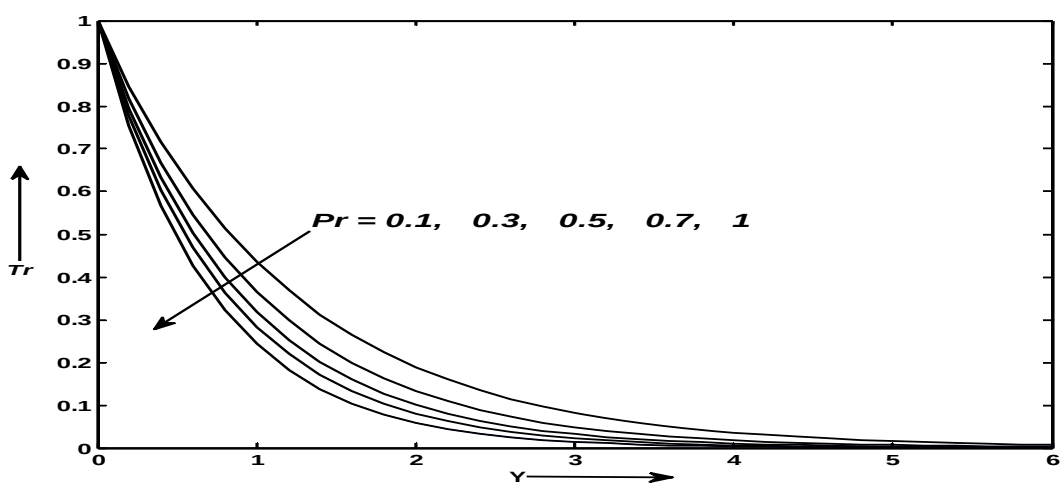



**Figure 13**. Effect of *Pr* on primary temperature *Tr*

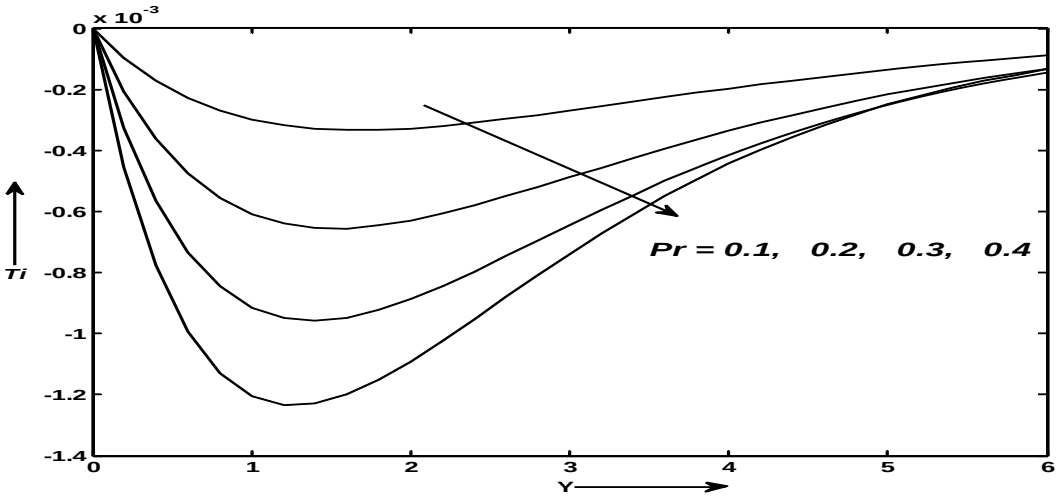



**Figure 14.** Effect of *Pr* on secondary temperature *Ti*

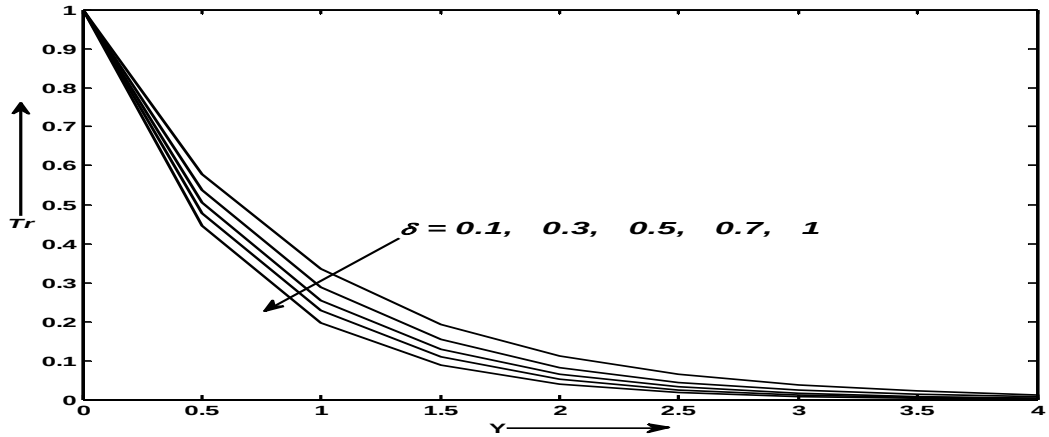



**Figure 15.** Effect of $\delta$ on primary temperature *Tr*

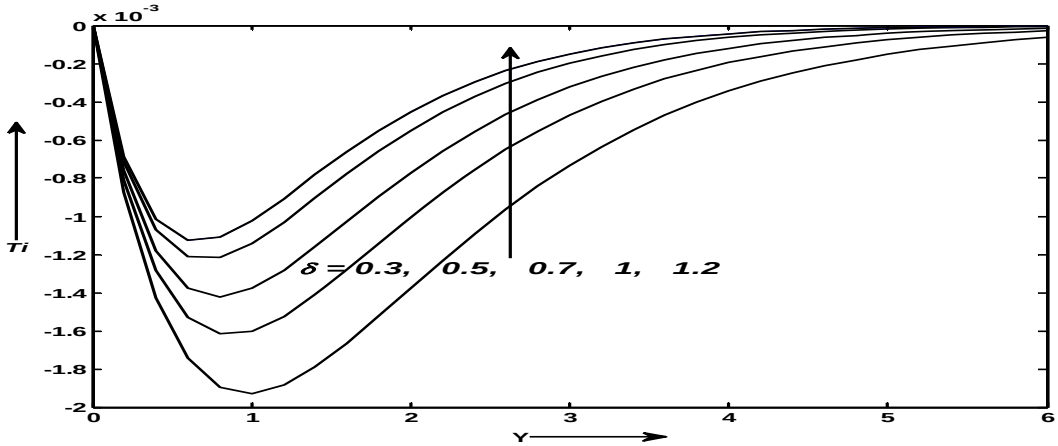



**Figure 16.** Effect of $\delta$ on secondary temperature *Ti*

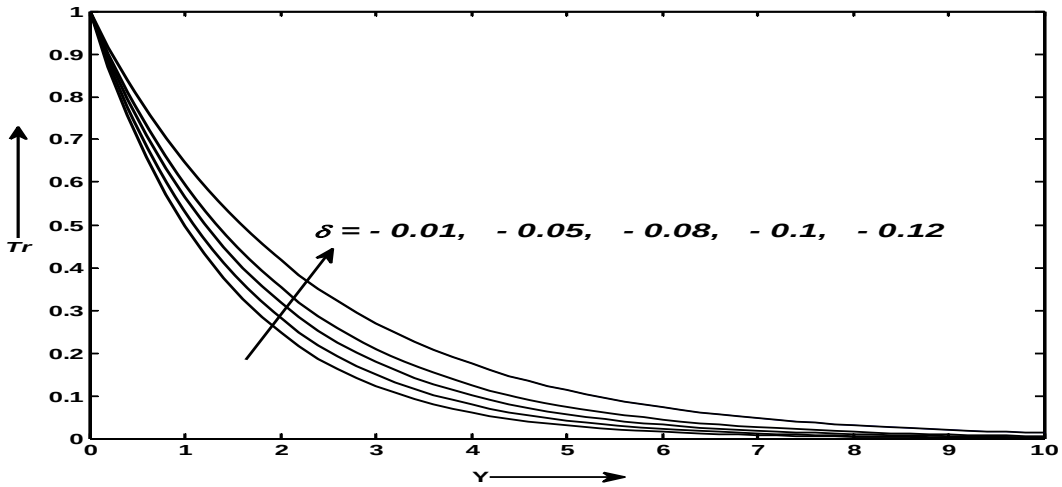



**Figure 17**. Effect of $\delta < 0$ on primary temperature *Tr*

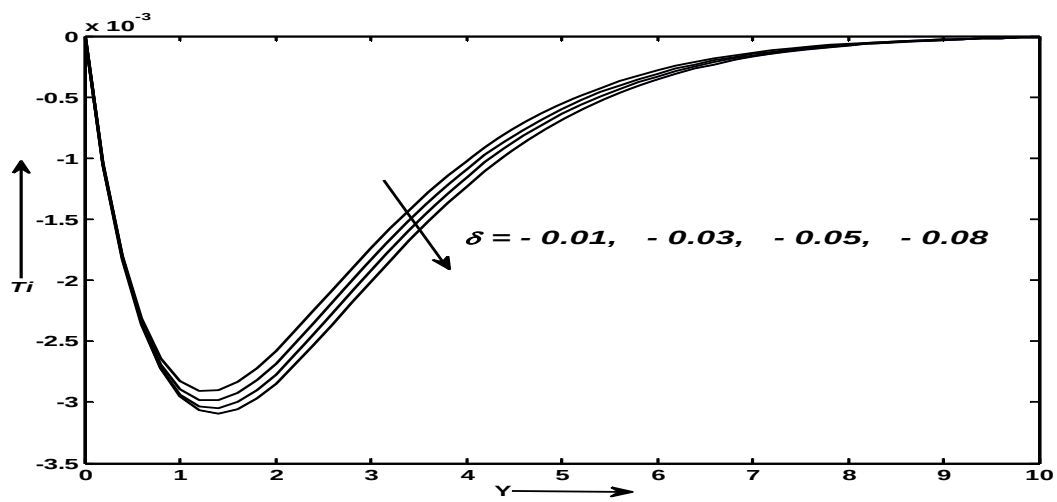



**Figure 18**. Effect of $\delta < 0$ on secondary temperature *Ti*

### 4.3. Concentration Profiles

Figures 19 to 22 show the profiles of primary and secondary concentrations. Figure 19 shows the effect of Schmidt number on the primary concentration. It is found that the primary concentration decreases with increase in *Sc*. As the Schmidt number increases, the mass transfer rate increases and hence the concentration profiles decreases. From figure 20, it is found that the secondary concentration increases in the region $0 \leq y \leq 2.8$. For $y > 2.8$ a complete reverse phenomenon is observed. From Figure 21, it is found that the primary concentration increases as the Chemical reaction parameter increases. As shown in figure 22, an increase in the Chemical reaction parameter leads to decrease in the secondary concentration in the region approximately given by $y \in (0, 2)$, but this trend reverses completely for $y > 2$.

In the absence of a chemical reaction effect these results are in good agreement with the results of Takharet al (1992). Also these graphs are shown in Figures 23 to 25.

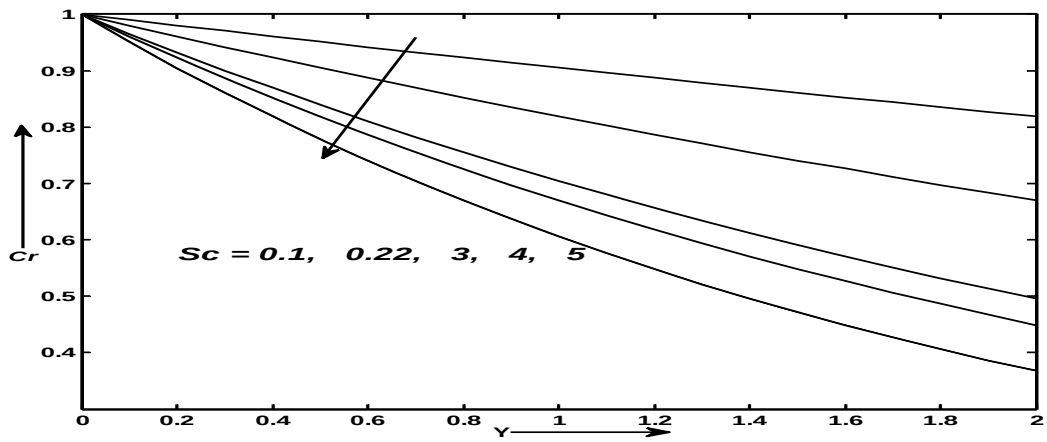



**Figure 19.** Effect of *Sc* on primary concentration *Cr*

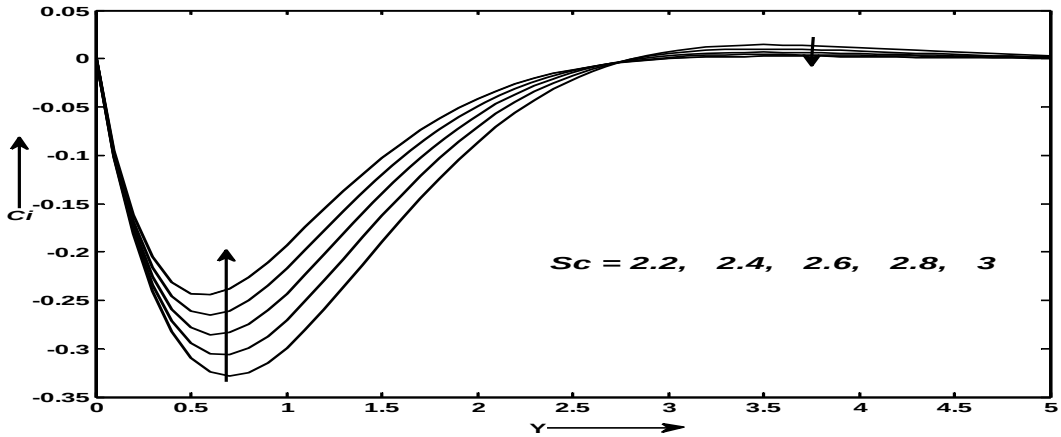



**Figure 20.** Effect of *Sc* on secondary concentration *Ci*

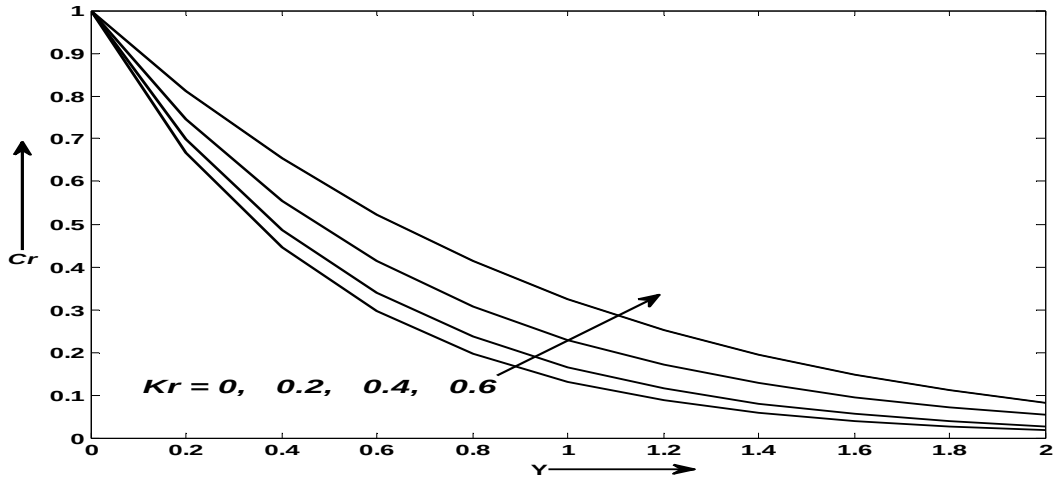



**Figure 21.** Effect of *Kr* on primary concentration *Cr*

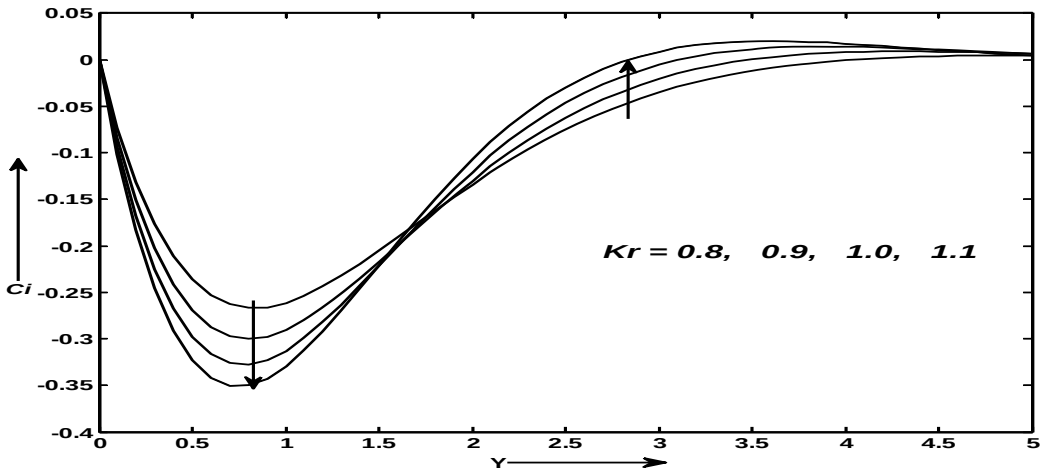



**Figure 22.** Effect of *Kr* on secondary concentration *Ci*

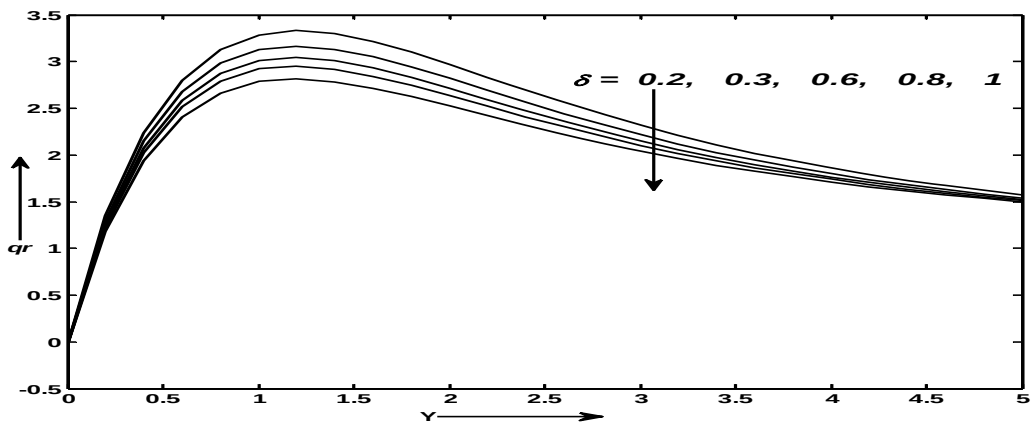



**Figure 23.** Effect of $\delta$ on primary velocity *qr* when $Kr = 0$

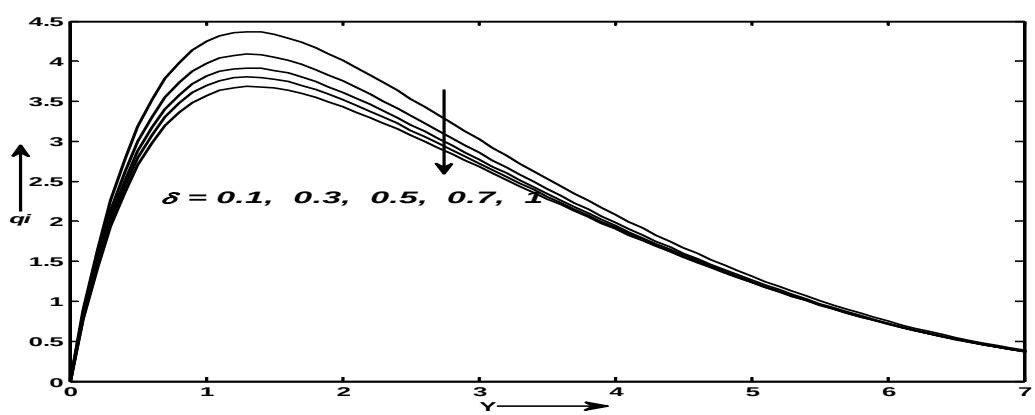



**Figure 24**. Effect of $\delta$ on secondary velocity *qi* when $Kr = 0$.

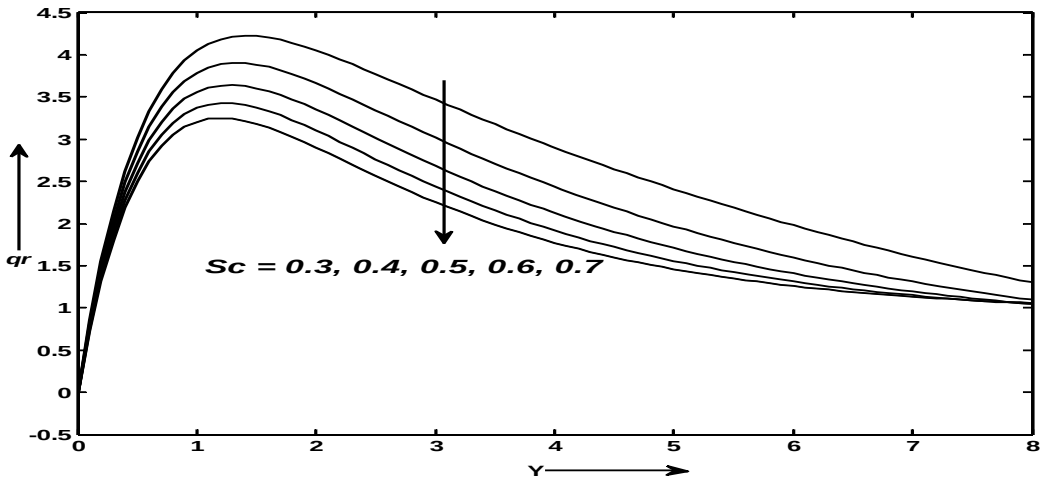



**Figure 25**. Effect of *Sc* on primary velocity *qr* when *Kr* = 0.

Table 1 presents numerical values of the magnitude of Skin-friction coefficient $|\tau|$ for variation in *Pr, δ, Kr, Sc* and M. It is observed that, an increase in *Pr* or *δ* or *Sc* or *M* leads to decrease in the value of magnitude of Skin-friction coefficient. It is noticed that $|\tau|$ increases with increasing *Kr* up to 0.5 and then decreases for further increase in *Kr*.

**Table 1.** Effects of various parameters on $|\tau|$ for $\omega t = \frac{\pi}{2}, \omega = 5$

| ***Pr*** | $\delta$ | ***Kr*** | ***Sc*** | ***M*** | ***ω*** | $\lvert\tau\rvert$ |
|---|---|---|---|---|---|---|
| 0.01 | 0.1 | 0.1 | 0.4 | 1 | 5 | 10.7011 |
| 0.31 | 0.1 | 0.1 | 0.4 | 1 | 5 | 9.5320 |
| 0.71 | 0.1 | 0.1 | 0.4 | 1 | 5 | 8.6150 |
| 0.71 | 0.3 | 0.1 | 0.4 | 1 | 5 | 8.1441 |
| 0.71 | 0.6 | 0.1 | 0.4 | 1 | 5 | 7.7315 |
| 0.71 | 1.0 | 0.1 | 0.4 | 1 | 5 | 7.3914 |
| 0.71 | 1.0 | 0.5 | 0.4 | 1 | 5 | 7.4325 |
| 0.71 | 1.0 | 0.7 | 0.5 | 1 | 5 | 6.7559 |
| 0.71 | 1.0 | 0.7 | 0.6 | 1 | 5 | 6.5237 |
| 0.71 | 1.0 | 0.7 | 0.4 | 1 | 5 | 6.3379 |
| 0.71 | 1.0 | 0.7 | 0.4 | 3 | 5 | 6.3315 |
| 0.71 | 1.0 | 0.7 | 0.4 | 4 | 5 | 5.5716 |

**Table 2.** The variations of the $|N_u|$ for $\omega t = \frac{\pi}{2}, \omega = 5$ and $\varepsilon = 0.01$

| $Pr$ | $\delta$ | Nusselt number $\lvert N_u \rvert$ |
|---|---|---|
| 0.1 | 0.2 | 0.5001 |
| 0.5 | 0.2 | 0.7634 |
| 0.71 | 0.2 | 0.9277 |
| 0.71 | 0.5 | 1.1475 |
| 0.71 | 0.8 | 1.3182 |
| 0.71 | 1.0 | 1.4169 |

**Table 3.** The variations of the $|S_h|$ for $Pr = 0.71$, $\delta = 0.5$, $M = 1$ and $\varepsilon = 0.01$

| $Kr$ | $Sc$ | Sherwood number $\lvert S_h \rvert$ |
|---|---|---|
| 0.1 | 0.2 | 0.1415 |
| 0.5 | 0.2 | 0.3164 |
| 1.0 | 0.2 | 0.4475 |
| 1.5 | 0.2 | 0.5480 |
| 1.5 | 0.3 | 0.6714 |
| 1.5 | 0.4 | 0.7756 |
| 1.5 | 0.5 | 0.8676 |
| 1.5 | 0.6 | 0.9510 |

Table 2 presents numerical values of the magnitude of Nusselt number $|N_u|$ for different values of the Prandtl number *Pr,* heat absorption parameter $\delta$ respectively. It is observed that, an increase in the Prandtl number or heat absorption parameter leads to increase in the value of $|N_u|$.

Table 3 presents numerical values of the magnitude of Sherwood number $|S_h|$ for different values of Schmidt number *Sc* and Chemical reaction rate constant *Kr* respectively. It is noticed that, an increase in the Schmidt number or Chemical reaction rate constant leads to increase in the value of $|S_h|$.

## 5 Conclusions

The effects of chemical reaction and hall current on MHD convective flow along an infinite vertical porous plate subjected to variable suction velocity and heat absorption have been investigated. The equations governing the fluid flow are solved using the perturbation technique. The conclusions of the study are as follows:

1 An increase in the Prandtl number leads to a decrease in the primary velocity, secondary velocity, primary temperature and secondary temperature.
2 The primary and secondary velocities decrease with an increase in the Chemical reaction parameter or Magnetic field parameter.

3 The primary and secondary velocity at the plate is significantly increased by an increase in the Hall current parameter.
4 The Schmidt number reduces the primary velocity, secondary velocity, primary concentration and enhances the secondary concentration.

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## Appendix

$$M_1 = \frac{M^2(1-im)}{1+m^2}, M_2 = M_1 + \frac{i\omega}{4}, \quad M_3 = \frac{1}{2}\left[1+\sqrt{1+4M_1}\right], \quad M_4 = \frac{1}{2}\left[1+\sqrt{1+4M_2}\right]$$

$$\delta_1 = \delta + \frac{i\omega \Pr}{4}, \delta_2 = \frac{1}{2}\left[\Pr + \sqrt{\Pr^2 + 4\delta}\right], \quad \delta_3 = \frac{1}{2}\left[\Pr + \sqrt{\Pr^2 + 4\delta_1}\right],$$

$$\delta_4 = \frac{1}{2}\left[Sc + \sqrt{Sc^2 - 4ScKr}\right]$$

$$\delta_5 = \frac{1}{2}\left[Sc + \sqrt{Sc^2 - 4Sc\left(k_r - \frac{iw}{4}\right)}\right]$$

$$a_0 = \delta_4^2 - Sc\delta_4 + Sc\left(k_r - \frac{iw}{4}\right)$$

$$a_1 = \delta_2^2 - \delta_2 - M_1, \quad a_2 = \delta_4^2 - \delta_4 - M_1, \quad a_3 = \delta_2^2 - \Pr\delta_2 - \delta_1, \quad a_4 = \delta_2^2 - \delta_2 - M_2$$
$$a_5 = \delta_3^2 - \delta_3 - M_2, \quad a_6 = \delta_4^2 - \delta_4 - M_2, \quad a_7 = \delta_5^2 - \delta_5 - M_2, \quad a_8 = M_3^2 - M_3 - M_2$$

$$A_4 = \frac{G\delta_2}{a_4}\left[\frac{\Pr}{a_3} + \frac{1}{a_1}\right], \quad A_5 = \frac{G\Pr\delta_2}{a_5 a_3}, \quad A_6 = \frac{Gc\delta_4}{a_6}\left[\frac{1}{a_2} + \frac{Sc}{a_0}\right], \quad A_7 = \frac{Gc\delta_4 Sc}{a_2 a_7}$$

$$A_8 = \frac{M_3}{a_8}A_3, A_9 = 1 - A_4 + A_5 - A_6 + A_7 - A_8$$