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# MASS TRANSFER AND RADIATION EFFECT ON MHD FLOW PAST AN INCLINED POROUS PLATE WITH VARIABLE TEMPERATURE IN THE PRESENCE OF HEAT SOURCE AND CHEMICAL REACTION

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***ABSTRACT***

*An attempt is made to investigate the mass transfer and radiation effects on unsteady MHD flow of an electrically conducting radiating, viscous incompressible fluid past an inclined porous plate with variable temperature in the presence of heat source and chemical reaction. The fluid is considered is gray, absorbing/emitting radiation but a non-scattering medium. The dimensionless governing equations involved in the present analysis are solved using the Laplace transform technique. The velocity, temperature, concentration and skin friction are studied graphically for different physical parameters. It has been observed that the concentration decrease with the increase in the chemical reaction parameter and there is a decrease in temperature with an increase in the value of radiation parameter.*

***Keywords:*** *MHD flow, thermal radiation, heat source, chemical reaction, mass transfer.*

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## 1. INTRODUCTION

Study of MHD flow with heat and mass transfer play an important role in various industrial applications. Some important applications are cooling of nuclear reactors, liquid metals fluid, power generation system and aerodynamics. It is of importance in connection with many engineering problems, such as sustained plasma confinement for controlled thermo nuclear fusion and electromagnetic casting of metals.MHD finds applications in electromagnetic pumps, crystals growing, MHD couples and bearing, plasma jets and chemical synthesis. Radiative heat and mass transfer play an important role in manufacturing industries for the design reliable equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering applications.

Hydromagnetic incompressible viscous flow has many important engineering applications such as magnetohydrodynamic power generators and the cooling of reactors also its applications to problems in geophysics, astrophysics etc. On the other hand, the study of heat generation or absorption in moving fluids is important in problems dealing with chemical reactions dissociating fluids. Since some fluids can emit or absorb thermal radiation, it is of interest to study the effects of magnetic field on the temperature distribution and heat transfer when the fluid is not only an electrical conductor but also when it is capable of emitting and absorbing radiation, Hence, heat transfer by thermal radiation is becoming of greater importance in space applications and higher operating temperatures.

In several problems related to demanding of efficient transfer of mass over inclined beds related to geophysical, petroleum, chemical, bio-mechanical, chemical technology and in situations the viscous drainage over an inclined porous plane is a subject of considerable interest to both theoretical and experimental investigators. Especially, in the flow of oil through porous rock, the extraction of geo-thermal energy from the deep interior of the earth to the shallow layers, the evaluation of the capability of heat removal from particulate nuclear fuel debris that may result from hypothetical accident in a nuclear reactor, the filtration of solids from liquids, flow of liquids through ion exchange beds, drug permeation through human glands, chemical reactor for economical separation or purification of mixtures flow through porous medium has been the subject of considerable research activity in recent years due to its notable applications. An important application in the petroleum industry where crude oil is trapped from natural underground reservoirs in which oil is entrapped since the flow behavior of fluids in petroleum reservoir rock depends to a large extent on the properties of the rock, techniques that yield new or additional information on the characteristics of the rock would enhance the performance of petroleum reservoirs. An important bio medical application is the flow of fluids in lungs, blood vessels, arteries and so on, where the fluid is bounded by two layers which are held together by a set of fairly regularly spaced tissues. Slurry adheres to the reactor vessel and gets consolidated in many chemical processing industries, as a result of which chemical compounds within the reactor vessels percolates through the boundaries. Thus adhered substance within the reactor vessel acts as a porous boundary. The problem assumes greater importance in all such situations. The thin film adhering to the surfaces of the container must be taken into account for the purpose of

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precise chemical calculations in all such situations wherein hear and mass transfer occurs. Failure to do so leads to severe experimental errors. Hence, there is a need for such an analysis in detail. A mathematical model related to such a situation has been studied in detail.

Kumar and Verma [1] studied the radiation effects on MHD flow past an impulsively started exponentially accelerated vertical plate with variable temperature in the presence of heat generation. They [2] have also studied the thermal radiation and mass transfer effects on MHD flow past a vertical oscillating plate with variable temperature and variable mass diffusion. The forced convection flow in a horizontal channel permeated by uniform vertical magnetic fluid in the presence of radiation was studied by Viskanta [3]. Takhar *et al.* [4] investigated the effects of radiation on the MHD free convection flow past a semi-infinite vertical plate. The thermal diffusion effects on moving infinite vertical plate in the presence of variable temperature and mass diffusion were studied by Muthucumaraswamy and Kumar [5]. England and Emery [6] have studied the thermal radiation effects of an optically thin gray gas bounded by a stationary vertical plate. Radiation effects on mixed convection along isothermal vertical plate were studied by Hossain and Takhar [7]. Das *et al.* [8] have analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate.

Sobha and Ramakrishna [9] presented the effects of magnetic field on heat transfer characteristics in porous medium under natural convection. Effects of the chemical reaction and radiation absorption on free convection flow through porous medium with variable suction in the presence of uniform magnetic field were studied by Sudheer Babu and Satyanarayana [10]. Dulal Pal *et al.* [11] studied perturbation analysis of unsteady magnetohydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction.

Recently, Ramana Reddy *et al.* [12] have studied the mass transfer and radiation effects of unsteady MHD free convective fluid flow embedded in porous medium with heat generation/absorption. Radiation effects on MHD free convection flow over a vertical plate with heat and mass flux was studied by Sivaiah *et al.* [13]. Recently, radiation and mass transfer effects on MHD free convection flow through porous medium past an exponentially accelerated vertical plate with variable temperature has been studied by Pattnaik *et al.* [14]. Reddy *et al.* [15] have studied the radiation and chemical reaction effects on MHD heat and mass transfer flow inclined porous heated plate.

The objective of the present study is to analyze the effects of thermal radiation and chemical reaction of an unsteady MHD flow past an inclined porous plate with variable temperature in the presence of heat generation under the action of a constant magnetic field of constant pressure gradient is subjected to an external magnetic field of constant strength in the direction to the plate and to the direction to the flow. The mass transfer aspect with chemical reaction is incorporated to the work of Kumar and Varma [1].

## 2. MATHEMATICAL FORMULATION

Consider a two dimensional unsteady MHD free convection flow of a viscous, incompressible, electrically conducting fluid past a semi-infinite tilted porous plate with an angle $\alpha$ to the vertical. With the x-axis measured along the plate, a uniform magnetic field of strength $B_0$ is applied in y-direction which is perpendicular to the plate. It is assumed that there is no applied voltage which implies the absence of an electric field. The fluid has constant kinematic viscosity and constant thermal conductivity, and the Boussinesq approximation have been adopted for the flow. Also it is considered that the viscous dissipation is negligible, the fluid is considered to be gray absorbing-emitting radiation but non-scattering medium. The concentration of the species far from the plate $C_\infty$ is very small. The chemical reactions are taking place in the flow and all the thermo-physical properties are assumed to be constant. Initially the fluid and the plate are at same temperature and same concentration in a stationary condition. At time $t' > 0$, the plate is given an impulsive motion in the direction of flow i.e. along x-axis against the gravity with constant velocity $u_0 t'$, it is assumed that the plate temperature and concentration at the plate are varying linearly with time. Under these assumptions the equations governing the flow are:

$$\frac{\partial u'}{\partial t'} = g\beta\left(T' - T'_\infty\right)\cos\gamma + \nu\frac{\partial^2 u}{\partial y'^2} - \frac{\sigma B_0^2 u'}{\rho} + g\beta\left(C' - C'_\infty\right)\cos\gamma - \frac{\nu}{K'_p}u' \tag{1}$$

$$\rho C_p \frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} + S'\left(T' - T'_\infty\right) \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} - K'_c\left(C' - C'_\infty\right) \tag{3}$$

With boundary conditions

$t' \le 0: \quad u' = 0, T' = T'_\infty, C' = C'_\infty$ for all $y'$

$t' > 0: \quad u' = u_0 t', T' = T'_\infty + \left(T'_w - T'_\infty\right), C' = C'_\infty + \left(C'_w - C'_\infty\right)$ at $y' = 0$

and $u' \to 0, T' \to T'_\infty, C' \to C'_\infty$ as $y' \to \infty$ (4)

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y'} = -4a^* \sigma \left(T'^4_\infty - T'^4\right) \tag{5}$$

It is assumed that the temperature differences within the flow are sufficiently small and that $T'^4$ may be expressed as a linear function of the temperature. This is obtained by expanding $T'^4$ in a Taylor series about $T'_\infty$ and neglecting the higher order terms, thus we get

$$T'^4 = 4T'^3_\infty T' - 3T'^4_\infty \tag{6}$$

Now, Introducing the following non-dimensional quantities into equations (1)—(3)

$$u = \frac{u'}{u_0}, y = \frac{y' u_0}{\nu}, T = \frac{T' - T'_\infty}{T'_w - T'_\infty}, P_r = \frac{\mu C_p}{k}, K_p = \frac{K'_p u_0^2}{\nu^2}, K_c = \frac{\nu K'_c}{u_0^2}$$

$$R = \frac{16\nu^2 \sigma T_\infty^3}{k u_0^2}, S = \frac{S' \nu}{\rho C_p u_0^2}, C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, M = \frac{\sigma B_0^2 \nu}{\rho u_0^2}$$

$$G_c = \frac{g\beta\nu\left(C'_w - C'_\infty\right)}{u_0^3}, G_r = \frac{g\beta\nu\left(T'_w - T'_\infty\right)}{u_0^3}, S_c = \frac{\nu}{D} \tag{7}$$

Using the above non-dimensional quantities equations (1)—(3) reduce to

$$\frac{\partial u}{\partial t} = G_r T \cos\gamma + G_c C \cos\gamma + \frac{\partial^2 u}{\partial y^2} - \left(M + \frac{1}{K_p}\right) u \tag{8}$$

$$\frac{\partial T}{\partial t} = \frac{1}{P_r} \frac{\partial^2 T}{\partial y^2} - \left(\frac{R}{P_r} - S\right) T \tag{9}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c} \frac{\partial^2 u}{\partial y^2} - K_c C \tag{10}$$

Where $M, K_p, G_r, G_c, P_r, R, S, S_c$ and $K_c$ denote the magnetic parameter, permeability parameter, Grashof number, modified Grashof number, Prandtl number, radiation parameter, heat source parameter, Schmidt number and chemical reaction parameter respectively.

With the boundary conditions

$t \le 0: \quad u = 0, T = 0, C = 0$ for all $y$

$t > 0: \quad u = t, T = 1, C = 1$ at $y = 0$

and $u \to 0, T \to 0, C \to 0$ at $y \to \infty$ (11)

Using Laplace transform we get

$\bar{u} = \frac{1}{s^2}, \bar{T} = \frac{1}{s}, \bar{C} = \frac{1}{s}$ at $y = 0$

$\bar{u} \to 0, \bar{T} \to 0, \bar{C} \to 0$ as $y \to \infty$ (12)

## 3. SOLUTION OF THE PROBLEM

The solutions of equations (8)—(10) subject to the boundary conditions (12) are obtained by Laplace transform technique.

Hence, the solutions of equations (8), (9) and (10) satisfying the boundary conditions (12) are:

$$\bar{C} = \frac{1}{s} e^{-y\sqrt{S_c(s+K_c)}} \tag{13}$$

$$\bar{T} = \frac{1}{s} e^{-y\sqrt{d+sP_r}} \tag{14}$$

$$\bar{u} = \left( \frac{1}{s^2} + \frac{G_r \cos\gamma}{(P_r-1)s(s+\alpha_1)} + \frac{G_c \cos\gamma}{(S_c-1)s(s+\alpha_2)} \right) e^{-y\sqrt{s+\lambda}} - \frac{G_r \cos\gamma}{(P_r-1)s(s+\alpha_1)} e^{-y\sqrt{d+sP_r}} - \frac{G_c \cos\gamma}{(S_c-1)s(s+\alpha_2)} e^{-y\sqrt{S_c(s+K_c)}} \tag{15}$$

Inverse Laplace transform of (13), (14) and (15) yields:

$$C = \frac{1}{2}\left\{ e^{-y\sqrt{S_cK_c}} erfc\left( \frac{y}{2}\sqrt{\frac{S_c}{t}} - \sqrt{K_c t} \right) + e^{y\sqrt{S_cK_c}} erfc\left( \frac{y}{2}\sqrt{\frac{S_c}{t}} + \sqrt{K_c t} \right) \right\} \tag{16}$$

$$T = \frac{1}{2}\left\{ e^{-y\sqrt{d}} erfc\left( \frac{y}{2}\sqrt{\frac{P_r}{t}} - \sqrt{\frac{dt}{P_r}} \right) + e^{y\sqrt{d}} erfc\left( \frac{y}{2}\sqrt{\frac{P_r}{t}} + \sqrt{\frac{dt}{P_r}} \right) \right\} \tag{17}$$

$$\begin{aligned}
u = &\left(\frac{t}{2} - \frac{y}{2}\right)\left\{ e^{-y\sqrt{\lambda}} erfc\left( \frac{y}{2\sqrt{t}} - \sqrt{\lambda t} \right) \right\} + \left(\frac{t}{2} + \frac{y}{2}\right)\left\{ e^{y\sqrt{\lambda}} erfc\left( \frac{y}{2\sqrt{t}} + \sqrt{\lambda t} \right) \right\} \\
&-\frac{\alpha_3}{2} e^{-\alpha_1 t}\left\{ e^{-y\sqrt{-\alpha_1+\lambda}} erfc\left( \frac{y}{2\sqrt{t}} - \sqrt{(-\alpha_1+\lambda)t} \right) + e^{y\sqrt{-\alpha_1+\lambda}} erfc\left( \frac{y}{2\sqrt{t}} + \sqrt{(-\alpha_1+\lambda)t} \right) \right\} \\
&+\frac{\alpha_3}{2}\left\{ e^{-y\sqrt{\lambda}} erfc\left( \frac{y}{2\sqrt{t}} - \sqrt{\lambda t} \right) \right\} + \left\{ e^{y\sqrt{\lambda}} erfc\left( \frac{y}{2\sqrt{t}} + \sqrt{\lambda t} \right) \right\} \\
&-\frac{\alpha_4}{2} e^{-\alpha_2 t}\left\{ e^{-y\sqrt{-\alpha_2+\lambda}} erfc\left( \frac{y}{2\sqrt{t}} - \sqrt{(-\alpha_2+\lambda)t} \right) + e^{y\sqrt{-\alpha_2+\lambda}} erfc\left( \frac{y}{2\sqrt{t}} + \sqrt{(-\alpha_2+\lambda)t} \right) \right\} \\
&+\frac{\alpha_4}{2}\left\{ e^{-y\sqrt{\lambda}} erfc\left( \frac{y}{2\sqrt{t}} - \sqrt{\lambda t} \right) \right\} + \left\{ e^{y\sqrt{\lambda}} erfc\left( \frac{y}{2\sqrt{t}} + \sqrt{\lambda t} \right) \right\} \\
&+\frac{\alpha_3}{2} e^{-\alpha_1 t}\left\{ e^{-y\sqrt{-\alpha_2P_r+d}} erfc\left( \frac{y}{2}\sqrt{\frac{P_r}{t}} - \sqrt{\left(-\alpha_2+\frac{d}{P_r}\right)t} \right) + e^{y\sqrt{-\alpha_2P_r+d}} erfc\left( \frac{y}{2}\sqrt{\frac{P_r}{t}} + \sqrt{\left(-\alpha_2+\frac{d}{P_r}\right)t} \right) \right\} \\
&-\frac{\alpha_3}{2}\left\{ e^{-y\sqrt{d}} erfc\left( \frac{y}{2}\sqrt{\frac{P_r}{t}} - \sqrt{\frac{dt}{P_r}} \right) + e^{y\sqrt{d}} erfc\left( \frac{y}{2}\sqrt{\frac{P_r}{t}} + \sqrt{\frac{dt}{P_r}} \right) \right\} \\
&+\frac{\alpha_4}{2} e^{-\alpha_2 t}\left\{ e^{-y\sqrt{-\alpha_2S_c+S_cK_c}} erfc\left( \frac{y}{2}\sqrt{\frac{S_c}{t}} - \sqrt{(-\alpha_2+K_c)t} \right) + e^{y\sqrt{-\alpha_2S_c+S_cK_c}} erfc\left( \frac{y}{2}\sqrt{\frac{S_c}{t}} + \sqrt{(-\alpha_2+K_c)t} \right) \right\} \\
&-\frac{\alpha_4}{2}\left\{ e^{-y\sqrt{S_cK_c}} erfc\left( \frac{y}{2}\sqrt{\frac{S_c}{t}} - \sqrt{K_c t} \right) + e^{y\sqrt{S_cK_c}} erfc\left( \frac{y}{2}\sqrt{\frac{S_c}{t}} + \sqrt{K_c t} \right) \right\}
\end{aligned} \tag{18}$$

where

$$d = R - SP_r,\ \lambda = M + \frac{1}{K_p},\ \alpha_1 = \frac{d-\lambda}{P_r - 1},\ \alpha_2 = \frac{S_c K_c - \lambda}{S_c - 1},\ \alpha_3 = \frac{G_r \cos\gamma}{\alpha_1 (P_r - 1)},\ \alpha_4 = \frac{G_c \cos\gamma}{\alpha_2 (S_c - 1)}$$

**Skin friction:**

From velocity field, the skin friction (rate of change of velocity in flow with respect to y) in non-dimensional form is given by

$$\tau = -\left[\frac{du}{dy}\right]_{y=0} \tag{19}$$

From equations (18) and (19) we get the skin friction as follows

$$\begin{aligned}\tau = {} & t\sqrt{\lambda}\, erf\sqrt{\lambda t} + \sqrt{\frac{t}{\pi}} e^{-\lambda t} + erf\sqrt{\lambda t} + \alpha_3 e^{-\alpha_1 t}\left\{\sqrt{\lambda - \alpha_1}\, erf\sqrt{(\lambda - \alpha_1)t} + \frac{1}{\sqrt{\pi t}} e^{-(\lambda - \alpha_1)t}\right\} \\ & + (\alpha_3 + \alpha_4)\left(\sqrt{\lambda}\, erf\sqrt{\lambda t} + \frac{1}{\sqrt{\pi t}} e^{-\lambda t}\right) + \alpha_4 e^{-\alpha_2 t}\left\{\sqrt{\lambda - \alpha_2}\, erf\sqrt{(\lambda - \alpha_2)t} + \frac{1}{\sqrt{\pi t}} e^{-(\lambda - \alpha_2)t}\right\} \\ & + \alpha_3 e^{-\alpha_1 t}\left\{\sqrt{d - \alpha_1 P_r}\, erf\sqrt{\left(\frac{d}{P_r} - \alpha_1\right)t} + \sqrt{\frac{P_r}{\pi t}} e^{-\left(\frac{d}{P_r} - \alpha_1\right)t}\right\} + \alpha_3\left(\sqrt{d}\, erf\sqrt{\frac{dt}{P_r}} + \sqrt{\frac{P_r}{\pi t}} e^{-\frac{dt}{P_r}}\right) \\ & + \alpha_4 e^{-\alpha_2 t}\left\{\sqrt{S_c K_c - \alpha_2 S_c}\, erf\sqrt{(K_c - \alpha_2)t} + \sqrt{\frac{S_c}{\pi t}} e^{-(K_c - \alpha_2)t}\right\} + \alpha_4\left(\sqrt{S_c K_c}\, erf\sqrt{K_c t} + \sqrt{\frac{S_c}{\pi t}} e^{-K_c t}\right)\end{aligned} \tag{20}$$

**Rate of heat transfer (Nusselt number):**

From temperature field, the Nusselt number (rate of change of heat transfer in flow with respect to y) in non-dimensional form is given by

$$Nu = -\left[\frac{dT}{dy}\right]_{y=0} \tag{21}$$

From equations (17) and (21) we get the skin friction as follows

$$Nu = \sqrt{d}\, erf\sqrt{\frac{dt}{P_r}} - \sqrt{\frac{P_r}{\pi t}} e^{-\frac{dt}{P_r}} \tag{22}$$

**Rate of mass transfer (Sherwood number):**

From concentration field, the Sherwood number (rate of change of mass transfer in flow with respect to y) in non-dimensional form is given by

$$Sh = -\left[\frac{dC}{dy}\right]_{y=0} \tag{23}$$

From equations (16) and (23) we get the skin friction as follows

$$Sh = \sqrt{S_c K_c}\, erf\sqrt{K_c t} - \sqrt{\frac{S_c}{\pi t}} e^{-K_c t} \tag{24}$$

## 4. RESULT AND DISCUSSIONS

In order to get the physical insight into the problem the velocity, temperature, concentration, skin-friction, the rate of heat transfer and the rate of mass transfer are shown in graphs and tables. Some numerical computations are also performed for different pertinent parameters.

Fig.1 (a) displays the effects of thermal Grashof number, mass Grashof number, magnetic parameter and porosity parameter on the velocity profiles. It is observed that mass Grashof number has no significant effect on velocity profiles. Further, it is observed that the velocity profiles increase due to an increase in either of the thermal Grashof number or the Hartmann number or the permeability of the medium.

 

Fig.1(b) shows the effects of Prandtl number, heat source parameter and radiation parameter on velocity profile. It is found that the velocity increases due to an increase in either of the heat source parameter or Prandtl number whereas the profiles show the reverse trend whenever there is an increase in radiation parameter.

Fig.1(c) shows the effects of Schmidt number, chemical reaction parameter, time parameter and angle of inclination. It is found that all the parameters decrease the velocity.

It is concluded that the thermal Grashof number, the Hartmann number, the porosity parameter, the heat source parameter, Prandtl number increases the velocity but the reverse effect is observed in case of radiation parameter, Schmidt number, chemical reaction parameter, time parameter and angle of inclination.

Fig.2 exhibits the effects of Prandtl number, heat source parameter and radiation parameter on temperature profiles. It is observed that in the absence or presence of heat source parameter the temperature decreases with the increasing of radiation parameter. Further, the temperature increases with increasing heat source parameter and Prandtl number.

Fig.3 shows the effects of Schmidt number and chemical reaction parameter on concentration profiles. It is observed that in the absence or presence of chemical reaction parameter concentration decreases as the Schmidt number increases. Further, the concentration decreases with increasing chemical reaction parameter.

Table 1 exhibits the effects of thermal Grashof number, mass Grashof number, magnetic parameter and porosity parameter on skin friction. It is observed that mass Grashof number has no significant effect on skin friction. Further, it is observed that the skin friction increase due to an increase in either of the thermal Grashof number or the Hartmann number but the opposite effect is observed in case of porosity parameter.

Table 2 shows the effects of Prandtl number, heat source parameter and radiation parameter on skin friction. It is found that the skin friction increases due to an increase in either of the heat source parameter or Prandtl number or radiation parameter.

Table 3 shows the effects of Schmidt number, chemical reaction parameter, time parameter and angle of inclination on skin friction. It is found that skin friction decrease with increasing in either of the Schmidt number or chemical reaction parameter or angle of inclination but the reverse effect is observed in case of time span.

Table 4 shows the rate of heat transfer. It is seen that the rate of heat transfer decrease with increasing either in Prandtl number or heat source parameter or time parameter. The reverse effect is marked in case of rotation parameter.

Table 5 shows the rate of mass transfer. It is seen that Schmidt number, chemical reaction parameter and time parameter increase the rate mass transfer.

## 5. CONCLUSION

(i) Mass Grashof number has no significant effect on velocity profiles as well as skin friction.
(ii) The thermal Grashof number and the Hartmann number increase the velocity and also the skin friction.
(iii) The porosity parameter increases the velocity but decreases the skin friction.
(iv) The velocity and skin friction increases due to an increase in either of the heat source parameter or Prandtl number.
(v) The radiation parameter decreases the velocity as well as temperature profiles but increases the skin friction.
(vi) Velocity and skin friction decrease with increasing in either of the Schmidt number or chemical reaction parameter or angle of inclination.
(vii) The time parameter decreases the velocity but increases the skin friction and the rate of mass transfer.
(viii) The concentration profile and skin friction coefficient decreases with an increase in the chemical reaction parameter or Schmidt number.

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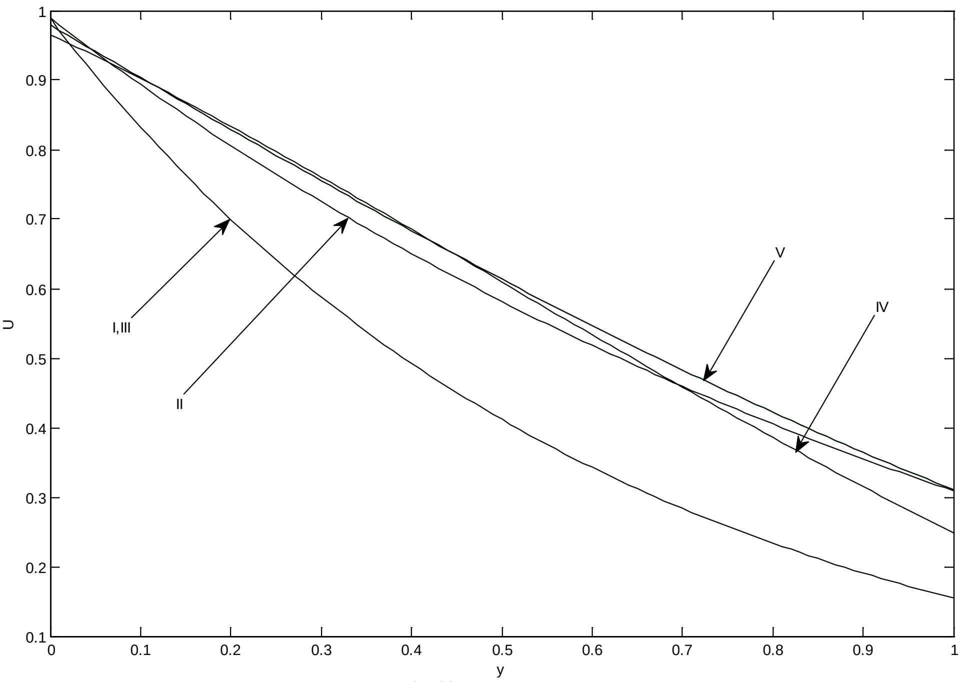


Fig.1(a) VELOCITY PROFILE

Effect of $G_r, G_c, M, K_p$ on velocity profile with $P_r = 0.71, S_c = 0.30, S = 3, R = 5, K_c = 2, t = 1, \gamma = \dfrac{\pi}{3}$.

| Curves | $G_r$ | $G_c$ | $M$ | $K_p$ |
|---|---|---|---|---|
| I | 2 | 2 | 1.0 | 1 |
| II | 4 | 2 | 1.0 | 1 |
| III | 2 | 8 | 1.0 | 1 |
| IV | 4 | 2 | 0.5 | 1 |
| V | 4 | 2 | 1.0 | 10 |

 

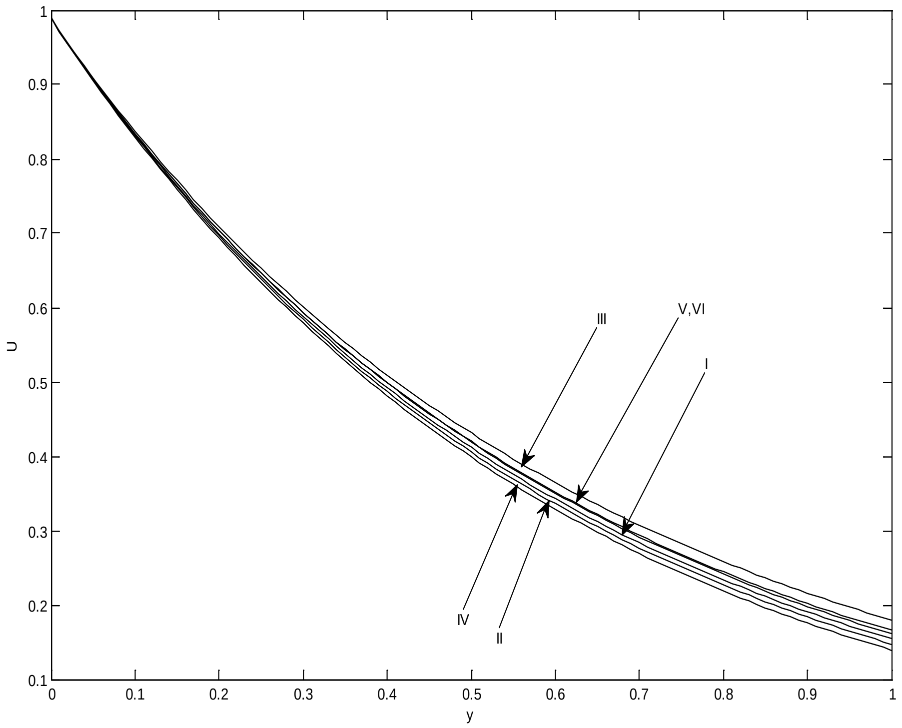


Fig.1(b) VELOCITY PROFILE

Effect of $P_r, S, R$ on velocity profile with $G_r = 2, G_c = 2, M = 1, K_p = 1, K_c = 2, S_c = 0.30, t = 1, \gamma = \dfrac{\pi}{3}$.

| Curves | $P_r$ | $S$ | $R$ |
|---|---|---|---|
| I | 0.71 | 3 | 5 |
| II | 0.50 | 3 | 5 |
| III | 0.71 | 5 | 5 |
| IV | 0.71 | 1 | 5 |
| V | 0.71 | 4 | 5 |
| VI | 0.71 | 3 | 4 |

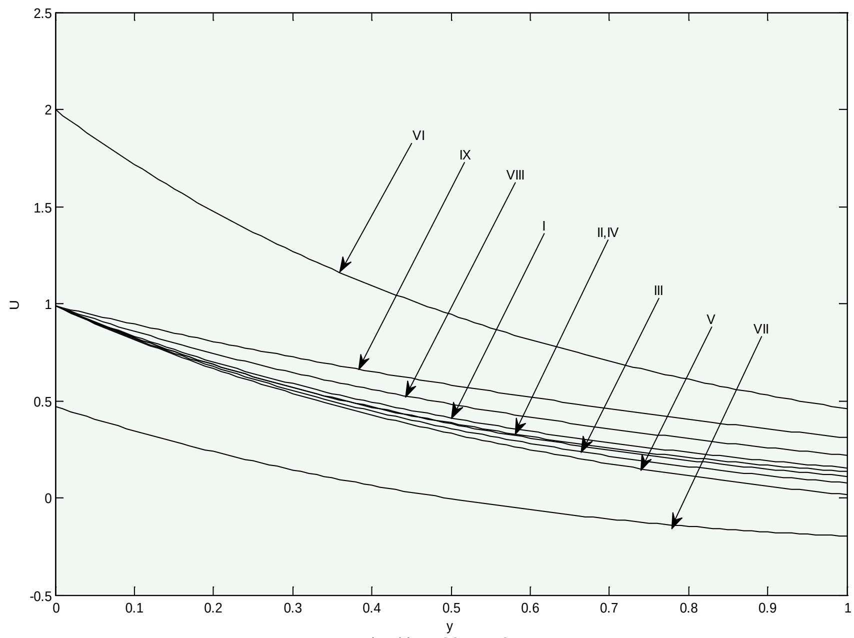


Fig.1 (c) VELOCITY PROFILE

 

Effect of $S_c, K_c, t, \gamma$ on velocity profile with $G_r = 2, G_c = 2, M = 1, K_p = 1, P_r = 0.71$, $S = 3, R = 5$.

| Curves | $S_c$ | $K_c$ | $t$ | $\gamma$ |
|---|---|---|---|---|
| I | 0.30 | 2 | 1.0 | $\pi/3$ |
| II | 0.60 | 2 | 1.0 | $\pi/3$ |
| III | 0.78 | 2 | 1.0 | $\pi/3$ |
| IV | 0.60 | 5 | 1.0 | $\pi/3$ |
| V | 0.60 | 3 | 1.0 | $\pi/3$ |
| VI | 0.30 | 2 | 0.5 | $\pi/3$ |
| VII | 0.30 | 2 | 1.0 | $\pi/3$ |
| VIII | 0.30 | 2 | 1.0 | $\pi/4$ |
| IX | 0.30 | 2 | 1.0 | 0 |

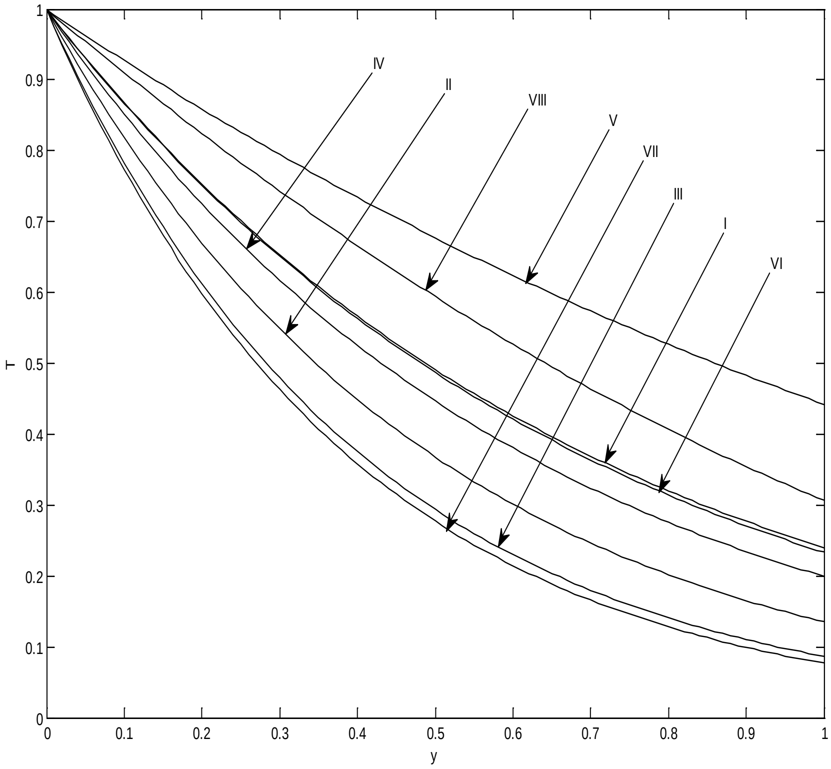


Fig.2 TEMPERATURE PROFILES

Effects of $P_r, S, R$ on temperature profile with $t = 1$.

| Curves | $P_r$ | $S$ | $R$ |
|---|---|---|---|
| I | 0.71 | 0 | 2 |
| II | 0.71 | 0 | 4 |
| III | 0.71 | 0 | 6 |
| IV | 0.71 | 2 | 4 |
| V | 0.71 | 5 | 4 |
| VI | 0.91 | 2 | 4 |
| VII | 0.71 | 2 | 8 |
| VIII | 1.80 | 2 | 4 |

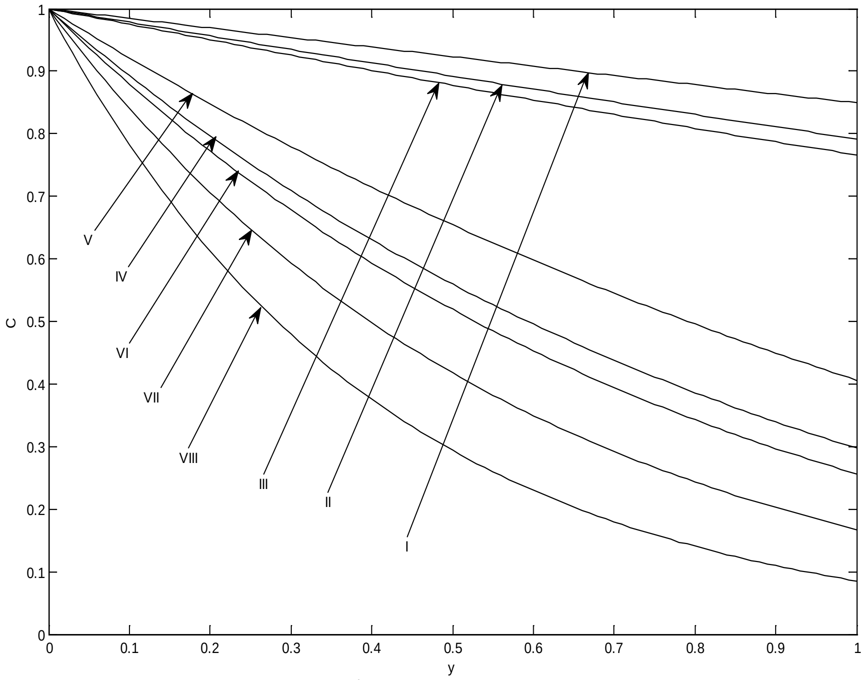


Fig.3 CONCENTRATION PROFILE

Effects $S_c, K_c$ on concentration profile with $t = 1$.

| Curves | $S_c$ | $K_c$ |
|---|---|---|
| I | 0.30 | 0 |
| II | 0.60 | 0 |
| III | 0.78 | 0 |
| IV | 0.30 | 2 |
| V | 0.60 | 2 |
| VI | 0.78 | 2 |
| VII | 0.60 | 5 |
| VIII | 0.60 | 10 |

**Skin friction:**

**Table 1**

Effect of $G_r, G_c, M, K_p$ on skin friction with $P_r = 0.71, S_c = 0.30, S = 3, R = 5, K_c = 2, t = 1, \gamma = \frac{\pi}{3}$.

| SL NO. | $G_r$ | $G_c$ | $M$ | $K_p$ | $\tau$ |
|---|---|---|---|---|---|
| 1 | 2 | 2 | 1.0 | 1 | 12.374694 |
| 2 | 4 | 2 | 1.0 | 1 | 23.6213573 |
| 3 | 8 | 2 | 1.0 | 1 | 45.6583447 |
| 4 | 2 | 4 | 1.0 | 1 | 12.3746945 |
| 5 | 2 | 8 | 1.0 | 1 | 12.3746945 |
| 6 | 2 | 2 | 0.5 | 1 | 9.6864073 |
| 7 | 2 | 2 | 0.3 | 1 | 8.77966356 |
| 8 | 2 | 2 | 1.0 | 5 | 8.17589723 |
| 9 | 2 | 2 | 1.0 | 10 | 7.33980766 |

**Table: 2:** Effect of $P_r, S, R$ on skin friction with $G_r = 2, G_c = 2, M = 1, K_p = 1, K_c = 2, S_c = 0.30, t = 1, \gamma = \frac{\pi}{3}$

| SL NO | $P_r$ | $S$ | $R$ | $\tau$ |
|---|---|---|---|---|
| 1 | 0.71 | 3 | 5 | 12.37469 |
| 2 | 0.50 | 3 | 5 | 7.177009 |
| 3 | 0.30 | 3 | 5 | 5.114649 |
| 4 | 0.71 | 4 | 5 | 39.65866 |
| 5 | 0.71 | 2 | 5 | 11.83646 |
| 6 | 0.71 | 3 | 6 | 12.57946 |
| 7 | 0.71 | 3 | 8 | 29.70837 |

**Table: 3:** Effect of $S_c, K_c, t, \gamma$ on skin friction with $G_r = 2, G_c = 2, M = 1, K_p = 1, P_r = 0.71$ , $S = 3, R = 5$ .

| SL NO | $S_c$ | $K_c$ | $t$ | $\gamma$ | $\tau$ |
|---|---|---|---|---|---|
| 1 | 0.30 | 2 | 0.2 | $\pi/3$ | 12.374694 |
| 2 | 0.60 | 2 | 0.2 | $\pi/3$ | 10.879313 |
| 3 | 0.78 | 2 | 0.2 | $\pi/3$ | 8.1029299 |
| 4 | 0.30 | 3 | 0.2 | $\pi/3$ | 11.117002 |
| 5 | 0.30 | 5 | 0.2 | $\pi/3$ | 5.0039166 |
| 6 | 0.30 | 2 | 0.4 | $\pi/3$ | 20.237972 |
| 7 | 0.30 | 2 | 0.6 | $\pi/3$ | 34.475466 |
| 8 | 0.60 | 2 | 0.2 | $\pi/4$ | 14.87117 |
| 9 | 0.60 | 2 | 0.2 | 0 | 20.406247 |

**Table: 4 Rate of heat transfer**

| SL NO. | $P_r$ | $S$ | $R$ | $t$ | $Nu$ |
|---|---|---|---|---|---|
| 1 | 0.71 | 3 | 5 | 0.2 | 1.82293 |
| 2 | 0.50 | 3 | 5 | 0.2 | 1.91446 |
| 3 | 1.00 | 3 | 5 | 0.2 | 1.73506 |
| 4 | 0.71 | 5 | 5 | 0.2 | 1.46989 |
| 5 | 0.71 | 2 | 5 | 0.2 | 1.98553 |
| 6 | 0.71 | 5 | 10 | 0.2 | 2.56867 |
| 7 | 0.71 | 5 | 15 | 0.2 | 3.38850 |
| 8 | 0.71 | 5 | 5 | 0.4 | 1.29399 |
| 9 | 0.71 | 5 | 5 | 0.6 | 1.24293 |

**Table: 5 Rate of mass transfer**

| SL NO. | $S_c$ | $K_c$ | $t$ | $Sh$ |
|---|---|---|---|---|
| 1 | 0.30 | 2 | 0.2 | 0.950332 |
| 2 | 0.60 | 2 | 0.2 | 1.343973 |
| 3 | 0.78 | 2 | 0.2 | 1.532365 |
| 4 | 0.60 | 4 | 0.2 | 1.669296 |
| 5 | 0.60 | 8 | 0.2 | 2.226851 |
| 6 | 0.30 | 2 | 0.4 | 0.834648 |
| 7 | 0.30 | 2 | 0.6 | 0.800770 |

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