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# MHD double diffusion flow by free convection past an infinite inclined plate with ramped wall temperature in a porous medium

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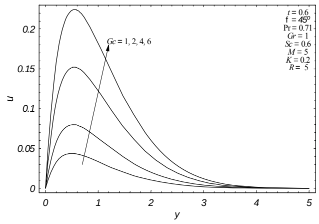
**GRAPHICAL ABSTRACT**




**ABSTRACT**

The combined effects of heat and mass transfer on unsteady magnetohydrodynamic (MHD) free convection flow in a porous medium past an infinite inclined plate with ramped wall temperature have been investigated. The closed form analytical solutions have been obtained for the velocity, temperature and concentration fields by using Laplace transforms method. The analytical expressions for non-dimensional skin-friction, Nusselt number and Sherwood number have been computed. The effects of the embedded flow parameters such as inclination angle, radiation parameter, magnetic field parameter, and Grashof number on flow fields are shown graphically. It is found that increasing the inclination angle and radiation parameters, the fluid velocity along an inclined plate will be decreased.

*Keywords: MHD, Thermal radiation, Porous medium, Inclined plate, Exact solution*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## 1. INTRODUCTION

The study of MHD natural convection flows in porous medium has been conducted extensively in recent years. Several solutions in this case were obtained by [1-9], where different initial boundary conditions have been considered as well as physical situation of flow formation. When free convection flows occur at high temperature, radiation and thermal source effects on the flow become significant. Many processes in engineering fields happens at high temperatures, such as cooling radioactive waste containers, energy efficient drying processes, food processing, grain storage, and solar power collectors, and understanding of radiative heat transfer become very essential for the design of the related equipment. Rajesh [10] used Laplace transforms to study the effects of thermal radiation on the unsteady MHD free convection flow of a viscous incompressible fluid past an infinite vertical plate containing a ramped type temperature profile. Seth et al. [11] studied the influence of radiation on unsteady hydromagnetic natural convection transient flow near an impulsively moving vertical flat plate with ramped wall temperature. Samiulhaq et al. [12] investigated the MHD free convection flow in a porous medium with thermal diffusion and ramped wall temperature. Phillips et al. [13] analytically solved the effects of heat source on MHD free convection flow past a vertical plate through porous medium. Recently, Jana et al. [14] reported the effect of radiation on the MHD flow past a vertical plate with oscillatory ramped plate temperature in a presence of a uniform transverse applied magnetic field.

However in real applications, the flows are not only occuring near vertical or horizontal plate, but also happen near to the inclined plates or surfaces. Ganesan and Palani [15] used finite different analysis to study the unsteady natural convection flow past an inclined plate with variable surface heat and mass flux. Thermal radiation effects on MHD flow past a semi-infinite inclined plate in the presence of mass diffusion was presented by [16]. Sharma and Singh [17] analysed the effects of variable thermal conductivity, viscous dissipation on steady MHD free convection flow of low Prandtl fluid on an inclined porous plate with Ohmic heating. They solved the problem numerically by using Runge-Kutta fourth order method and shooting technique. Narahari [18] took into account the effect of thermal radiation on unsteady MHD free convection flow of an optically thin gray gas past an infinite inclined plate with constant temperature.

The aim of this paper is to investigate the effects of mass diffusion and radiation on MHD free convection flow in a porous medium past an infinite inclined plate with ramped wall temperature.

## 2. PROBLEM FORMULATION

Consider the unsteady MHD of a viscous incompressible fluid with combined heat and mass transfer by natural convection flow, near an infinite inclined plate embedded in a saturated porous medium. The $x^*$-axis is along to the plate with the inclination angle $\phi$ to the vertical, the $y^*$- axis is taken normal to the plate. The plate is assumed to be electrically conducting with a uniform magnetic field **B** of strength $B_0$, applied in a direction perpendicular to the plate. The magnetic Reynolds number is assumed to be small to neglect the effect of applied magnetic field. The radiation effect is also taken into account. Initially, for time $t^* \leq 0$, both the fluid and the plate are at rest with the constant temperature $T_\infty^*$ and constant concentration $C_\infty^*$. At a time $t^* > 0$, the plate starts moving in $x^*$ direction with a constant velocity $u_o$. The temperature of the plate is raised or lowered to $T_\infty^* + \left(T_w^* - T_\infty^*\right)t^* / t_o$ when $t^* \leq t_o$. Thereafter, it is maintained at constant temperature $T_w^*$ when $t^* > t_o$. The concentration is raised to constant concentration $C_w^*$. The flow is assumed laminar, and the effects of the convective and pressure gradient terms in the momentum, energy and concentration equations are neglected. The physical variables become functions of the time $t^*$ and the space $y^*$ only, as a result of the boundary layer approximations.

Under the Boussinesq approximation, the unsteady MHD natural convection boundary layer flow past an inclined plate flow in a porous medium with effects of thermal diffusion and heat absorption, is governed by the equations

$$\frac{\partial u^*}{\partial t^*} = \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma B_0^2}{\rho} u^* - \frac{\nu}{K^*} u^* + g\beta_T \cos\phi\left(T^* - T_\infty^*\right) + g\beta_C \cos\phi\left(C^* - C_\infty^*\right) \tag{1}$$

$$\frac{\partial T^*}{\partial t^*} = \frac{k}{\rho c_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \tag{2}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} \tag{3}$$

with the following initial and boundary conditions

$$\begin{aligned} &u^* = 0,\quad T^* = T_\infty^*,\quad C^* = C_\infty^* \quad \text{for } y^* \geq 0 \text{ and } t^* \leq 0 \\ &u^* = 0,\quad C^* = C_w^*,\quad \text{for } y^* = 0 \text{ and } t^* > 0 \\ &T^* = T_\infty^* + \left(T_w^* - T_\infty^*\right)\frac{t^*}{t_0} \quad \text{for } y^* = 0 \text{ and } 0 < t^* \leq t_0 \\ &T^* = T_w^* \quad \text{for } y^* = 0 \text{ and } t^* > t_0 \\ &u^*, C^*, T^* \to 0, \quad \text{as } y^* \to \infty \text{ for } t^* > 0 \end{aligned} \tag{4}$$

where $T^*$ and $C^*$ denote the temperature and concentration respectively, υ is the kinematic viscosity, $\sigma$ is the electrical conductivity of the fluid, $\rho$ is the fluid density, $K^* > 0$ is the permeability of the porous medium, $g$ is the acceleration due to gravity, $\beta_T$ and $\beta_c$ are the thermal expansion and concentration expansion, $k$ is the fluid thermal diffusivity, $c_p$ is the specific heat, $q_r$ is the radiative heat flux and $D$ is the mass diffusion. It is assumed that the radiative heat flux term is produced by plates temperature $T_\infty^*$ and $T_w^*$ and simplified by using Rosseland approximation is given by

$$\frac{\partial q_r}{dy} = 4\alpha\sigma^*\left(T^{*4} - T_\infty^{*4}\right) \tag{5}$$

where $\alpha$ is the mean radiation absorption coefficient and $\sigma^*$ is the Stefan-Boltzmann constant. 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. Using Taylor series by expanding $T^{*4}$ about $T_\infty^*$ and neglecting higher-order terms, thus

$$T^{*4} \cong 4T_\infty^3 T - 3T_\infty^4 \tag{6}$$

Using (5) and (6), (2) now becomes

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial y^2} - \frac{16\alpha\sigma^* T_\infty^{*3} L^2}{k} T\right) \tag{7}$$

Introducing the following dimensionless variables:

$$\begin{aligned} &y = \frac{y^*}{L},\ t = \frac{t^*(\upsilon g)^{1/3}}{L},\ L = \frac{\upsilon^{2/3}}{g^{1/3}},\ u = \frac{u^*}{(\upsilon g)^{1/3}}, \\ &Gc = \frac{g^{1/3}\beta_C \upsilon\left(C_w^* - C_\infty^*\right)}{\upsilon^{2/3}},\ \Pr = \frac{\mu c_p}{k},\ R = \frac{16\alpha\sigma^* T_\infty^{*3} L^2}{k}, \\ &M = \frac{\sigma B_o^2 L^2}{\rho u_o^2},\ K = \frac{K^*}{L^2},\ Gr = \frac{g^{1/3}\beta_T \upsilon\left(T_w^* - T_\infty^*\right)L}{\nu^{2/3}}, \\ &T = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},\ C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*},\ Sc = \frac{\upsilon}{D}, \end{aligned} \tag{8}$$

Here, $T$, $C$, $M$, $K$, $Gr$, $Gc$, Pr, $R$ and $Sc$ are nondimensional fluid temperature, nondimensional fluid concentration, magnetic parameter known as Hartmann number, porosity parameter, thermal Grashof number and the mass Grashof number, Prandtl number, radiation parameter and Schmidt number, respectively.

Using equations (8), equations (1), (3), and (7) can be expressed as

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - Mu - \frac{u}{K} + GrT\cos\phi + GcC\cos\phi \tag{9}$$

$$\frac{\partial T}{\partial t} = \frac{1}{\Pr}\left(\frac{\partial^2 T}{\partial y^2} - RT\right) \tag{10}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \tag{11}$$

The initial and boundary conditions given by equation (4) now become

$$\begin{aligned}
&u = T = C = 0 \quad \text{for } y \ge 0 \text{ and } t \le 0\\
&u = 0, C = 1 \quad \text{for } y = 0 \text{ and } t > 0\\
&T = t, \quad \text{for } y = 0 \text{ and } 0 < t \le 1\\
&T = 1, \quad \text{for } y = 0 \text{ and } t > 1\\
&u, T, C \to 0 \quad \text{for } y \to \infty \text{ and } t > 0
\end{aligned} \tag{12}$$

## 3. PROBLEM SOLUTION

We can see that the energy equation (10) and concentration equation (11) is uncoupled from the momentum equation (9). Therefore, we can solve for the temperature variable $T(y,t)$ and concentration variable $C(y,t)$ whereupon the solution of $u(y,t)$ can also be gained. In order to solve these equations, taking Laplace transforms of equations (11), (10) and (9) with respect to $t$, in concurrence with equation (12), and solving the result from differential equations, we obtain

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

$$\bar{T} = \left(\frac{1 - e^{-s}}{s^2}\right) e^{-y\sqrt{\Pr(\Phi + s)}} \tag{14}$$

$$\begin{aligned}
\bar{u} = &\left(\frac{a_1}{s - a_2}\right)\left(\frac{1 - e^{-s}}{s^2}\right) e^{-y\sqrt{\Pr(\Phi+s)}} + \\
&\left(\frac{a_3}{s - a_4}\frac{1}{s}\right) e^{-y\sqrt{Scs}} - \left[\frac{a_1}{s - a_2}\left(\frac{1 - e^{-s}}{s^2}\right) + \right.\\
&\left.\frac{a_3}{s - a_4}\frac{1}{s}\right]\left(e^{-y\sqrt{\lambda + s}}\right)
\end{aligned} \tag{15}$$

where

$$\lambda = \frac{1}{K_1} + M,\ \Phi = \frac{R}{\Pr},\ a_1 = \frac{Gr\cos\phi}{1 - \Pr},$$

$$a_2 = \frac{R - \lambda}{1 - \Pr},\ a_3 = -\frac{Gc\cos\phi}{Sc - 1},\ a_4 = \frac{\lambda}{Sc - 1}$$

The exact solutions for the concentration, temperature and complex velocity fields can be obtained from equations (12), (13) and (14) by using inverse Laplace transforms. These solutions are

$$C(y,t) = erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}}\right) \tag{16}$$

$$T(y,t) = T_1(y,t) - T_1(y,t-1)H(t-1) \tag{17}$$

$$\begin{aligned}
u(y,t) = &U_1(y,t) + U_2(y,t) + U_3(y,t) - \\
&H(t-1)[U_1(y,t-1) + U_3(y,t-1)]
\end{aligned} \tag{18}$$

where

$$\begin{aligned}
U_1(y,t) = &\frac{a_1}{a_2^2}\left[u_1\left(t, a_2, \Phi, y\sqrt{\Pr}\right) - u_1(t, a_2, \lambda, y)\right]\\
&-\frac{a_1}{a_2^2}\left[u_2\left(t, \Phi, y\sqrt{\Pr}\right) - u_2(t, \lambda, y)\right]
\end{aligned}$$

$$\begin{aligned}
U_2(y,t) = &\frac{a_3}{a_4}\left[u_1\left(t, a_4, 0, y\sqrt{Sc}\right) + u_2(t, \lambda, y)\right]\\
&-\frac{a_3}{a_4}\left[u_1(t, a_4, \lambda, y) - erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}}\right)\right]
\end{aligned}$$

$$U_3(y,t) = \frac{a_1}{a_2}\left[T_2(y,t) - T_1(y,t)\right]$$

$$\begin{aligned}
u_1(t, a, b, c) = \frac{e^{a_2 t}}{2}&\left[e^{c\sqrt{b}} erfc\left(\frac{c}{2\sqrt{t}} + \sqrt{(a+b)t}\right)\right.\\
&\left.+ e^{-c\sqrt{b}} erfc\left(\frac{c}{2\sqrt{t}} - \sqrt{(a+b)t}\right)\right]
\end{aligned}$$

$$\begin{aligned}
u_2(t, b, c) = \frac{1}{2}&\left[e^{c\sqrt{b}} erfc\left(\frac{c}{2\sqrt{t}} + \sqrt{bt}\right)\right.\\
&\left.+ e^{-c\sqrt{b}} erfc\left(\frac{c}{2\sqrt{t}} - \sqrt{bt}\right)\right]
\end{aligned}$$

$$\begin{aligned}
T_1(y,t) = &\left(\frac{t}{2} + \frac{y}{4}\sqrt{\frac{\Pr}{\Phi}}\right) e^{y\sqrt{\Phi\Pr}} erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}} + \sqrt{\Phi t}\right) + \\
&\left(\frac{t}{2} - \frac{y}{4}\sqrt{\frac{\Pr}{\Phi}}\right) e^{-y\sqrt{\Phi\Pr}} erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}} - \sqrt{\Phi t}\right)
\end{aligned}$$

$$\begin{aligned}
T_2(y,t) = &\left(\frac{t}{2} + \frac{y}{4\sqrt{\lambda}}\right) e^{y\sqrt{\lambda}} erfc\left(\frac{y}{2\sqrt{t}} + \sqrt{\lambda t}\right) + \\
&\left(\frac{t}{2} - \frac{y}{4\sqrt{\lambda}}\right) e^{-y\sqrt{\lambda}} erfc\left(\frac{y}{2\sqrt{t}} - \sqrt{\lambda t}\right)
\end{aligned}$$

*erfc(x)* being the complimentary error function defined by

$$erfc(x) = 1 - erf(x), \quad erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\eta^2} d\eta$$

and $H(\bullet)$ is Heaviside unit step function.

### 3.1 Skin friction, Nusselt number and Sherwood number

The expression of skin friction is given by

$$\tau = -\left.\frac{\partial u}{\partial y}\right|_{y=0}$$

$$= \sqrt{\frac{\Pr}{(t-1)\pi}} \left( \frac{a_1 e^{-\Phi t}(1 + a_2 t)}{a_2^2} - \frac{e^{-\Phi t} Gr K^2 (\Pr - 1)\cos\phi}{A^2} \right) -$$

$$\frac{e^{-\frac{At}{(\Pr-1)K}}}{A^2} \left( Gr K^2 (\Pr - 1) \sqrt{\frac{B}{(\Pr-1)K}} \cos\phi \, erf \sqrt{\frac{Bt}{(\Pr-1)K \Pr}} \right)$$

$$- \frac{a_1}{2a_2^2} \left( a_2 \sqrt{\frac{\Pr}{\Phi}} + 2\sqrt{\Pr \Phi} + 2a_2 t \sqrt{\Pr \Phi} \right) erf \sqrt{\Phi t} +$$

$$\left[ \begin{array}{l} \sqrt{\frac{\Pr}{(t-1)\pi}} \left( \begin{array}{l} \frac{a_1 e^{(t-1)\Phi}(1 + a_2)(t-1)}{a_2^2} + \\ \frac{e^{-\Phi(t-1)} Gr K^2 (\Pr - 1)\cos\phi}{A^2} \end{array} \right) \\ + \frac{e^{\frac{A(t-1)}{(\Pr-1)K}}}{A^2} \left( \begin{array}{l} Gr K^2 (\Pr-1) \sqrt{\frac{B}{(\Pr-1)K}} \cos\phi \\ erf \sqrt{\frac{B(t-1)}{(\Pr-1)K \Pr}} \end{array} \right) + \\ \frac{a_1}{2a_2^2 \sqrt{\Phi}} \left( 2\Phi\sqrt{\Pr} + a_2\sqrt{\Pr} + 2a_2(t-1)\Phi\sqrt{\Pr} \right) \\ erf \sqrt{(t-1)\Phi} \end{array} \right] H(t-1)$$

$$+ \frac{a_3}{\sqrt{a_4 Sc}} e^{a_4 t} Sc \, erf \sqrt{a_4 t} -$$

$$\left[ - \frac{a_1 e^{-\lambda t}\left(2a_2^2 \sqrt{\lambda t}\right) + e^{\lambda t}\sqrt{\pi}}{2a_2^2 \sqrt{\lambda t}} \left( \begin{array}{l} (a_2 + 2\lambda + 2a_2 \lambda t) erf \sqrt{\lambda t} \\ - 2e^{a_2 t} \lambda \sqrt{a_2} \, erf \sqrt{(a_2 + \lambda)t} \end{array} \right) \right] +$$

$$\left[ -2a_2^2 e^{\lambda} \sqrt{(t-1)\lambda} + e^{\lambda t}\sqrt{\pi} \left( \begin{array}{l} 2e^{a_2(t-1)} \sqrt{a_2} \lambda \\ erf \sqrt{(a_2 + \lambda)(t-1)} \\ - (a_2 + 2 + 2a_2(t-1)) \\ \lambda \, erf \sqrt{(t-1)\lambda} \end{array} \right) \right] H(t-1)$$

$$- \frac{a_3}{a_4} \left( e^{a_4 t} \sqrt{a_4 \lambda} \, erf \sqrt{(a_4 \lambda)t} \right) - \sqrt{\lambda} \, erf \sqrt{\lambda t}$$

With

$$A = 1 + K(M - R), \; B = \Pr + KM\Pr - KR$$

Nusselt number, the rate of heat transfer is given by

$$Nu = -\left.\frac{\partial T}{\partial y}\right|_{y=0}$$

$$= \frac{1}{2\sqrt{\pi\Phi}} \left[ e^{-\Phi t} \sqrt{\pi} \left( \sqrt{\Pr} + 2\Phi t \sqrt{\Pr} \right) erf \sqrt{\Phi t} \right] -$$

$$\left[ \begin{array}{l} 2e^{\Phi} \sqrt{(t-1)\Pr\Phi} + e^{\Phi t} \sqrt{\pi} \left( \sqrt{\Pr} + 2(t-1)\sqrt{\Pr\Phi} \right) \\ erf \sqrt{(t-1)\Phi} \end{array} \right] H(t-1)$$

and Sherwood number, the rate of mass transfer is given by

$$Sh = \left.\frac{\partial C}{\partial y}\right|_{y=0} = -\frac{\sqrt{Sc}}{\sqrt{\pi t}}$$

## 4. GRAPHICAL RESULTS AND DISCUSSION

An exact solution to the problem of heat and mass transfer for MHD free convection flow with radiation effect passing through a porous medium near an inclined plate with wall ramped temperature is presented. In order to get into the physical insight of the problem, the effects of various parameters such as inclination angle $\phi$, radiation parameter $R$, Hartmann number $M$, thermal Grashof number $Gr$, and concentration Grashof number $Gc$ are analysed. The results for concentration $C$, temperature $T$, and velocity $u$ are presented graphically and discussed.

In Figure 1 shows the velocity profiles at various values of inclination angle $\phi$. It is noted that decreasing the inclination angle accelerates the fluid motion along the plate. This is towards the fact that as the plate is inclined from the vertical the buoyancy force effect due to the thermal and mass diffusion decreases as cos $\phi$ decreases. In this case, lower buoyancy for the same temperature difference occurs at $\phi = 90^o$, because cos $\phi$ increases as $\phi$ decreases from $90^o$ to $0^o$. Figure 2 depicts the effect of velocity profiles at various radiations $R$. It is observed that the fluid velocity increase as the radiation parameter decrease. The reason is the rate of transportation energy to the fluid increases as the radiation parameter decreases and thereby the fluid velocity increases.

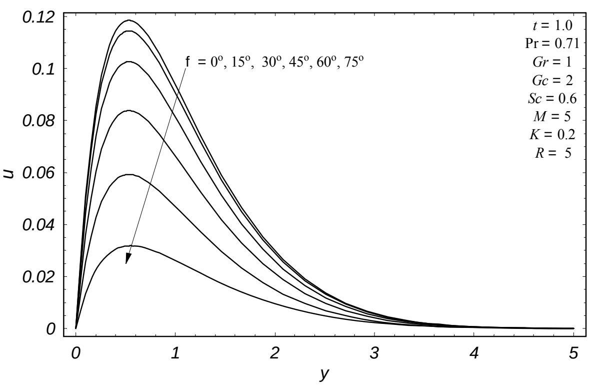


**Fig. 1** Velocity profiles for various angle

The variation of velocity for different values of Hartmann number $M$ is plotted in Figure 3. We can see that the application of transverse magnetic field will result a resistive type force namely the Lorentz force. This force tends to resist the fluid flow and thus reducing its velocity. It is appealing to note from all the graphs for the velocity profiles that velocity of the fluid is zero at $y = 0$, increases continuously with increasing distance from the plate vicinity, approaches a maximum value in the middle of the flow regime and then decreases continuously with increasing distance from the plate. Finally, when $y$ tends to infinity, velocity goes to zero.

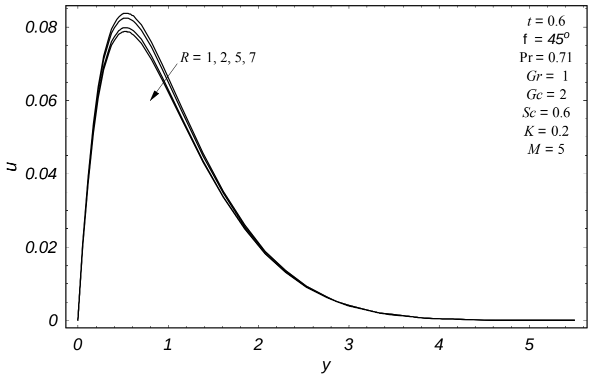


**Fig. 2** Velocity profiles for various $R$

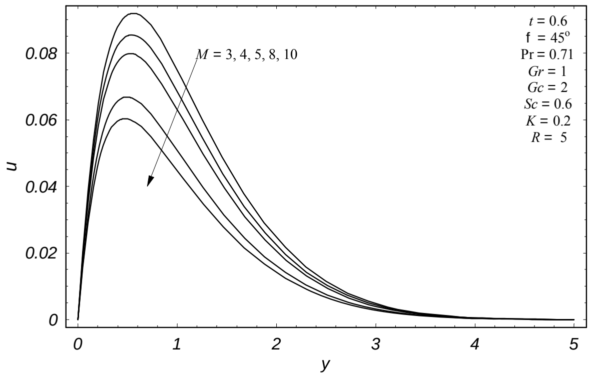


**Fig. 3** Velocity profiles for various $M$

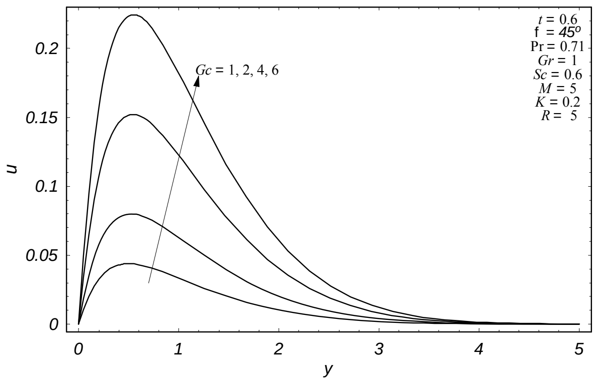


**Fig. 4** Velocity profiles for various $Gc$

The velocity profiles at various $Gc$ and $Gr$ is shown in Figure 4 and Figure 5. We analysed that the velocity decreases as the Grashof number decreases. Decreasing Grashof number means decreasing thermal buoyancy force and thereby velocity of the fluid decreases in the vicinity of the inclined plate. A similar behaviour of velocity was also expected in the presence of the imposed boundary conditions on velocity in equation (11). Hence, all these graphical results provide a useful mathematical cross checking to the calculation. Therefore, we are quite sure at the accuracy of the solution.

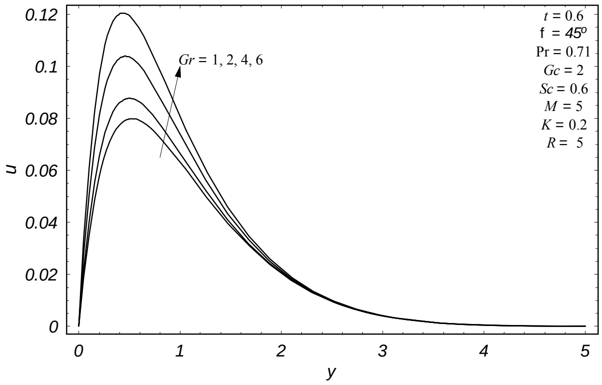


**Fig. 5** Velocity profiles for various $Gr$

## 5. CONCLUSION

In this paper, we have studied the governing equations for the double diffusion and radiation effects on unsteady MHD free convection flow passing through a porous channel past an infinite inclined plate with ramped wall temperature. Exact solution using Laplace transforms for the concentration, temperature and velocity profiles with the effects of embedded parameters are examined. It is reported that the velocity of a fluid is increases with the decreases of $\phi$, $R$ and $M$. However, the effects of $Gc$ and $Gr$ on the velocity are opposite to $\phi$, $R$ and $M$.

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