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# Radiation effect on Unsteady Flow Past an Accelerated Isothermal Infinite Vertical Plate with Chemical reaction and Heat Source

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## ABSTRACT

**The present study is the theoretical solution of unsteady radiative flow past a uniformly accelerated isothermal infinite vertical plate with radiation and uniform mass diffusion taking in to account the homogeneous chemical reaction in the presence of heat source and surface temperature are investigated. The governing nonlinear partial differential equations have been reduced to the coupled nonlinear ordinary differential equations by using perturbation technique. The influence of the various interesting parameters like thermal Grashof number, mass Grashof number, Schmidt number, Prandtl number, heat source, magnetic parameter, radiation parameter, chemical reaction parameter and time on the flow velocity, temperature, concentration, Skin friction and Nusselt number discussed through graphs in detail.**

***Keywords:*** Accelerated, Chemical reaction, Heat source, Isothermal, Mass transfer, Radiation and Vertical plate,

## INTRODUCTION

When technological processes take place at higher temperatures thermal radiation heat transfer has become very important and its effects cannot be neglected. The effect of radiation on MHD flow, heat and mass transfer become more important industrially. Many processes in engineering areas occur at high temperature and knowledge of radiation heat transfer becomes a very important for the design of the pertinent equipment. The quality of the final product depends to a great extent on the heat controlling factors, and the knowledge of radiative heat transfer in the system can lead to a desired product with sought qualities. Hossain and Takhar [12] studied the effect of radiation on mixed convection along a vertical plate with uniform surface temperature. Bakier [2] reported the effect of radiation on the mixed convection flow on an isothermal vertical surface in a saturated porous medium.

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Bakier and Gorla [3] studied thermal radiation effect on mixed convection from horizontal surfaces in porous media. Different researches have been forwarded to analyze the effects of thermal radiation on different flows. Aliakbar et al [1] and Cortell [5] among other researchers. Gupta et al [10] studied free convection on flow past a linearly accelerated vertical plate in the presence of viscous dissipative heat using perturbation method. Kafousias and Raptis [13] extended the above problem to include mass transfer effects subjected to variable suction or injection. Free convection effects on flow past an exponentially accelerated vertical plate was studied by Singh and Naveen Kumar [22]. The skin friction for accelerated vertical plate has been studied analytically by Hossain and Shayo [11]. Mass transfer effects on flow past a uniformly accelerated vertical plate was studied by Soundalgekar [24]. Again, mass transfer effects on flow past an accelerated vertical plate with uniform heat flux was analyzed by Singh and Singh [23]. Basant Kumar Jha and Ravindra Prasad [4] analyzed mass transfer effects on the flow past an accelerated infinite vertical plate with heat sources.

Chemical reactions usually accompany a large amount of exothermic and endothermic reactions. These characteristics can be easily seen in a lot of industrial processes. Chemical reactions can be codified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. In well-mixed systems, the reaction is heterogeneous, if it takes place at an interface and homogeneous, if it takes place in solution. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. A reaction is said to be of first order, if the rate of reaction is directly proportional to the concentration itself. It has been realized that it is not always permissible to neglect the convection effects in porous constructed chemical reactors Nield and Bejan [18]. Das et al. [6] investigated the effect of the first order homogeneous chemical reaction on the process of an unsteady flow past a vertical plate with a constant heat and mass transfer. Muthucumaraswamy [15] presented heat and mass transfer effects on a continuously moving isothermal vertical surface with uniform suction by taking into account the homogeneous chemical reaction of first order. Muthucumaraswamy and Meenakshisundaram [16] investigated theoretical study of chemical reaction effects on vertical oscillating plate with variable temperature and mass diffusion. Kesavaiah et.al [14] Radiation and mass transfer effects on moving vertical plate with variable temperature and viscous dissipation. Muthucumaraswamy and Ravi Shankar [17] first order chemical reaction and thermal radiation effects on unsteady flow past an accelerated isothermal infinite vertical plate. Saleh et.al [21] Heat and mass transfer in MHD visco-elastic fluid flow through a porous medium over a stretching sheet with chemical reaction. Mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction studied by Das et al. [7]

In the processes involving high temperatures, the radiation heat transfer in combination with conduction, convection and also mass transfer plays very important role in the design of pertinent equipments in the areas such as nuclear power plants, gas turbines and the various propulsion devices for air crafts, missiles, satellites and space vehicles. Radiative heat and mass transfer play an important role in manufacturing industries for the design of fins, steel rolling, nuclear power plants, gas turbines and various propulsion device for aircraft, combustion and furnace design, materials processing, energy utilization, temperature measurements, remote sensing for astronomy and space exploration, food processing and cryogenic engineering, as well as numerous agricultural, health and military applications. England and Emery [9] have studied the thermal radiation effects of an optically thin gray gas bounded by a stationary vertical plate. Raptis and Perdikis [20] studied the effects of thermal radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically. Das et al. [8] have analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate. The dimensionless governing equations were solved by the usual Laplace transform technique. Rajesh and Varma [19] Radiation effects on MHD flow through a porous medium with variable temperature or variable mass diffusion**.**

Hence, it is proposed to study the first order chemical reaction on unsteady flow past a uniformly accelerated isothermal infinite vertical plate with heat and mass transfer in the presence of thermal radiation. The solutions are in terms of exponential function. Such a study found useful in chemical process industries such as wire drawing, fibre drawing, food processing and polymer production.

## FORMULATION OF THE PROBLEM

We consider unsteady radiative flow of a viscous incompressible fluid past a uniformly accelerated isothermal infinite vertical plate with uniform mass diffusion in the presence of chemical reaction with heat source has been considered. Here the unsteady flow of a viscous incompressible fluid which is initially at rest and surrounds an infinite vertical plate with temperature $T_\infty$ and concentration $C_\infty$ . The x-axis is taken along the plate in the vertically upward direction and the y-axis is taken normal to the plate. At time $t' \le 0$, the plate and fluid are at the same temperature $T_\infty$ . At time $t' > 0$, the plate is accelerated with a velocity $u = \frac{u_0^3 t'}{\nu}$ in its own plane and the temperature from the plate is raised to $T_w$ w and the concentration levels near the plate are also raised to $C_w$ . It is assumed that the effect of viscous dissipation is negligible in the energy equation and there is a first order chemical reaction between the diffusing species and the fluid. The fluid considered here is a gray, absorbing emitting radiation but a non-scattering medium. Then under usual Boussinesq's approximation the unsteady low is governed by the following equations:

$$\frac{\partial u}{\partial t'} = g\beta\left(T - T_\infty\right) + g\beta^*\left(C' - C'_\infty\right) + \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0{}^2}{\rho}u \qquad (1)$$

$$\rho C_p\frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2 - \frac{\partial q_r}{\partial y} - Q_0\left(T - T_\infty\right) \qquad (2)$$

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

The initial and boundary conditions for the velocity, temperature and concentration fields are

$$\begin{aligned} &u = 0, T = T_\infty, C' = C'_\infty \quad for \ \ all \ \ y \ t' > 0 \\ &t' > 0 : u = \frac{u_0{}^3 t'}{\nu}, T = T_w, C' = C'_w \ at \ y = 0 \\ &u \to 0, \ \ T \to T_\infty, \ \ C' \to C'_\infty \quad as \ \ y \to \infty \end{aligned} \qquad (4)$$

Where $u'$ is the velocity of the fluid along the plate in the $x'$ - direction, $t'$ is the time, g is the acceleration due to gravity, $\beta$ is the coefficient of volume expansion, $\beta^*$ is the coefficient of thermal expansion with concentration, $T_\infty$ is the temperature of the fluid near the plate, $C'$ is the species concentration in the fluid near the plate, $C'_\infty$ is the species concentration in the fluid far away from the plate, $\nu$ is the kinematic viscosity, $\sigma$ is the electrical conductivity of the fluid, $B_0$ is the strength of applied magnetic field, $\rho$ is the density of the fluid, $C_p$ is the specific heat at constant pressure, K is the thermal conductivity of the fluid, $\mu$ is the viscosity of the fluid, $D$ is the molecular diffusivity.
The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y} = -4a^*\sigma\left(T_\infty^4 - T^4\right) \qquad (5)$$

It is assume that the temperature differences within the flow are sufficiently small such that $T^4$ may be

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expressed as a linear function of the temperature. This is accomplished by expanding $T^4$ in a Taylor series about $T_\infty$ and neglecting higher-order terms, thus

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

By using equations (5) and (6), equation (2) reduces to

$$\rho C_p \frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2 + 16a^*\sigma T_\infty^3 \left(T - T_\infty\right) - Q_0\left(T - T_\infty\right) \tag{7}$$

On introducing the following non-dimensional quantities:

$$U = \frac{u}{u_0},\ Y = \frac{u_0 y}{\nu}, t = \frac{t' u_0^{\ 2}}{\nu},\ \theta = \frac{T - T_\infty}{T_w - T_\infty}$$
$$C = \frac{C' - C'_\infty}{C'_w - C'_\infty},\quad \Pr = \frac{\mu C_p}{k}, M = \frac{\sigma B_0^{\ 2}\nu}{\rho u_0^{\ 2}}$$
$$Gr = \frac{\nu\beta g\left(T_w - T_\infty\right)}{u_0^{\ 3}},\quad R = \frac{16a^*\nu^2\sigma T_\infty^3}{k u_0^2} \tag{8}$$
$$Ec = \frac{u_0^2}{k\left(T_w - T_\infty\right)}, Gc = \frac{\nu\beta^* g\left(C'_w - C'_\infty\right)}{u_0^{\ 3}}$$
$$Kr = \frac{Kr'\nu}{u_0^{\ 2}},\quad \phi = \frac{\nu^2 Q_0}{k u_0^{\ 2}},\quad Sc = \frac{\nu}{D}$$

where $Gr$ is the thermal Grashof number, $Gc$ is modified Grashof Number, $\Pr$ is Prandtl Number, $M$ is the magnetic field, $Sc$ is Schmdit number, $Kr$ is Chemical Reaction, $\phi$ is Heat source parameter respectively.

Introducing the above non dimensional quantities in equations (1) - (3) and using equation (7) reduces to

$$\frac{\partial U}{\partial t} = Gr\,\theta + Gc\,C + \frac{\partial^2 U}{\partial Y^2} - M\,U \tag{9}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2\theta}{\partial Y^2} + \frac{Ec}{\Pr}\left(\frac{\partial U}{\partial Y}\right)^2 - \frac{1}{\Pr}\left(R + \phi\right)\theta \tag{10}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial Y^2} - Kr\,C \tag{11}$$

The negative sign of $Kr$ in the last term of the equation (11) indicates that the chemical reaction takes place from higher level of concentration to lower level of concentration.

The initial and boundary conditions in non-dimensional quantities are

$$\begin{aligned} &U = 0,\ \ \theta = 0,\ \ C = 0 \quad for\ all\ \ Y, t \le 0 \\ &t > 0 : U = t,\ \ \theta = 1,\ \ C = 1 \quad at\ \ Y = 0 \\ &\qquad U \to 0, \theta \to 0, C \to 0 \ \ as\ \ Y \to \infty \end{aligned} \tag{12}$$

## SOLUTION OF THE PROBLEM

Equation (9) – (11) are coupled, non – linear partial differential equations and these cannot be solved in closed – form using the initial and boundary conditions (12). However, these equations can be reduced to a set of ordinary differential equations, which can be solved analytically. This can be done by representing the velocity, temperature and concentration of the fluid in the neighbourhood of the fluid in the neighbourhood of the plate as

$$\begin{aligned} U &= U_0\left(y\right) + \varepsilon e^{nt} U_1\left(y\right) + o\left(\varepsilon^2\right) \\ \theta &= \theta_0\left(y\right) + \varepsilon e^{nt}\theta_1\left(y\right) + o\left(\varepsilon^2\right) \\ C &= C_0\left(y\right) + \varepsilon e^{nt} C_1\left(y\right) + o\left(\varepsilon^2\right) \end{aligned} \tag{13}$$

Substituting (13) in Equation (9) – (11) and equating the harmonic and non – harmonic terms, and neglecting the higher order terms of $0\left(\varepsilon^2\right)$, we obtain

$$U_0'' - MU_0 = -Gr\,\theta_0 - Gc\,C_0 \tag{14}$$

$$U_1'' - \left(M + n\right)U_1 = -Gr\,\theta_1 - Gc\,C \tag{15}$$

$$\theta_0'' - \left(R + \phi\right)\theta_0 = -Ec\,U_0'^2 \tag{16}$$

$$\theta_1'' - \left(\phi + R + n\Pr\right)\theta_1 = -2Ec\,U_0 U_1 \tag{17}$$

$$C_0'' - Sc\,Kr\,C_0 = 0 \tag{18}$$

$$C_1'' - \left(Kr + n\right)Sc C_1 = 0 \tag{19}$$

The corresponding boundary conditions can be written as

$$\left.\begin{aligned} &U_0 = t,\quad U_1 = 0,\quad \theta_0 = 1 \\ &\theta_1 = 1,\quad C_0 = 1,\quad C_1 = 0 \end{aligned}\right\} \quad at\ \ y = 0$$
$$\left.\begin{aligned} &U_0 \to 0, U_1 \to 0,\ \theta_0 \to 0 \\ &\theta_1 \to 0, C_0 \to 0, C_1 \to 0 \end{aligned}\right\} \quad as\ \ y \to \infty \tag{20}$$

The Equations (14) - (19) are still coupled and non-linear, whose exact solutions are not possible. So we expand $U_0, U_1, \theta_0, \theta_1, C_0, C_1$ in terms $\left(f_0, f_1\right)$ of $Ec$ in the following form, as the Eckert number is very small for incompressible flows.

$$\begin{aligned} f_0(y) &= f_{01}(y) + Ec\ \ f_{02}(y) \\ f_1(y) &= f_{11}(y) + Ec\ \ f_{12}(y) \end{aligned} \tag{21}$$

Substituting (21) in Equations (14) - (19), equating the coefficients of $Ec$ to zero and neglecting the terms in $Ec^2$ and higher order, we get the following equations.

$$U_{01}'' - MU_{01} = -Gr\,\theta_{01} - Gc\,C_{01} \tag{22}$$

$$U_{02}'' - MU_{02} = -Gr\,\theta_{02} - Gc\,C_{02} \tag{23}$$

$$U_{11}'' - (M+n)U_{11} = -Gr\,\theta_{11} - Gc\,C_{11} \quad (24)$$

$$U_{12}'' - (M+n)U_{12} = -Gr\,\theta_{12} - Gc\,C_{12} \quad (25)$$

$$\theta_{01}'' - (R+\phi)\theta_{01} = 0 \quad (26)$$

$$\theta_{02}'' - (R+\phi)\theta_{02} = -U_{01}'^{2} \quad (27)$$

$$\theta_{11}'' - (\phi + R + n\Pr)\theta_{11} = 0 \quad (28)$$

$$\theta_{12}'' - (R+\phi+n\Pr)\theta_{12} = -2U_{01}U_{11} \quad (29)$$

$$C_{01}'' - Sc\,Kr\,C_{01} = 0 \quad (30)$$

$$C_{02}'' - Sc\,Kr\,C_{02} = 0 \quad (31)$$

$$C_{11}'' - (Kr+n)ScC_{11} = 0 \quad (32)$$

$$C_{12}'' - (Kr+n)ScC_{12} = 0 \quad (33)$$

The respective boundary conditions are

$$\left.\begin{array}{lll} U_{01}=t, & U_{02}=0, & \theta_{01}=1 \\ \theta_{02}=0, & C_{01}=1, & C_{02}=0 \\ U_{11}=0, & U_{12}=0, & \theta_{11}=0 \\ \theta_{12}=0, & C_{11}=0, & C_{12}=0 \end{array}\right\} at \;\; y=0$$

$$\left.\begin{array}{l} U_{01}\to 0, U_{02}\to 0, \theta_{01}\to 0 \\ \theta_{02}\to 0, C_{01}\to 0, C_{02}\to 0 \\ U_{11}\to 0, U_{12}\to 0, \theta_{11}\to 0 \\ \theta_{12}\to 0, C_{11}\to 0, C_{12}\to 0 \end{array}\right\} as \;\; y\to\infty \quad (34)$$

Solving Equations (22) - (33) under the boundary conditions (34) we obtain the velocity, temperature and concentration distributions in the boundary layer as

$$U(y,t) = A_1 e^{m_3 y} + A_2 e^{m_1 y} + A_3 e^{m_4 y} + Ec\{A_4\, e^{m_3 y} + A_5 e^{2m_4 y} + A_6 e^{2m_3 y} + A_7 e^{2m_1 y} + A_8 e^{(m_3+m_4)y} + A_9 e^{(m_1+m_3)y} + A_{10} e^{(m_1+m_4)y} + A_{11} e^{m_4 y}\}$$

$$\theta(y,t) = e^{m_3 y} + Ec\{B_1 e^{2m_4 y} + B_2 e^{2m_3 y} + B_3 e^{2m_1 y} + B_4 e^{(m_3+m_4)y} + B_5 e^{(m_1+m_3)y} + B_6 e^{(m_1+m_4)y} + B_7 e^{m_3 y}\}$$

$$C(y,t) = e^{m_1 y}$$

**Skin-friction:**

We now calculate Skin-friction from the velocity field. It is given in non-dimensional form as:

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0}, \text{ where } \tau = -\frac{\tau'}{\rho U_0^{\,2}}$$

$$= m_3 A_1 + m_1 A_2 + m_4 A_3 + Ec\{m_4 A_{11} + m_3 A_4 + 2m_4 A_5 + 2m_3 A_6 + 2m_1 A_7 + (m_3+m_4)A_8 + (m_1+m_3)A_9 + (m_1+m_4)A_{10}\}$$

**Rate of heat transfer:**

The dimensionless rate of heat transfer is given by

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

$$= m_3 + Ec\{m_3 B_7 + 2m_4 B_1 + 2m_3 B_2 + 2m_1 B_3 + (m_3+m_4)B_4 + (m_1+m_3)B_5 + (m_1+m_4)B_6\}$$

**Sherwood number:**

The dimensionless Sherwood number is given by

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

**RESULTS AND DISCUSSION**

For physical interpretation of the problem, the numerical computations are carried out for different physical parameters $Gr, Gc, Sc, R, \Pr, \phi, Kr$ and $t$ upon the nature of the flow and transport. The value of Prandtl number $(\Pr)$ are chosen such that they represent air $(\Pr = 0.71)$. The numerical values of the velocity, temperature and concentration are computed for different physical parameters like Prandtl number, thermal Grashof number, mass Grashof number, chemical reaction parameter, radiation parameter, heat source parameter, Schmidt number and time are studied graphically.

The velocity profiles for different values of $(t = 0.2, 0.4, 0.6, 0.8)$ is studied and presented in Figure (1). It is observed that the velocity increases with increasing values of the time $(t)$. In Figure (2) and (3) velocity profiles for different values of $Gr$ and $Gc$ for fluid Prandtl number, $\Pr = 0.71$ are shown. From Figure (2) and (3) it can be concluded that velocity increases with increasing values of $Gr$ and $Gc$. In these Figures (2) and (3) for $Sc = 0.65$ is lower than $\Pr = 0.71$ and hence concentration layer is thinner than thermal layer. This confirms the downward flow to a thin region near the surface. For lower Schmidt number $(Sc)$ the thickness of the concentration layer increases and the region of flow extend farther away from the plate. The velocity profiles for different values of chemical reaction parameter $(Kr)$ and heat source parameter $(\phi)$ shown in figures (4) and (5). It is observed that the velocity decreases with increasing values of chemical reaction parameter $(Kr)$ and heat source parameter $(\phi)$. The effect of velocity for different values of the radiation parameter $(R = 1.0, 2.0, 3.0, 4.0)$ and t = 0.2 are shown in Figure (6). The trend shows that the velocity decreases with increasing radiation parameter. It is observed that there is a fall in velocity in the presence of high thermal radiation. Figure (7) it can be concluded that velocity decreases due to an increase in the Schmidt number $(Sc)$. For lower $Sc$ the thickness of the concentration layer increases and the region of flow extend farther away from the plate. Figure (8) illustrate the influence of the magnetic parameter $(M)$ on the velocity profiles in the boundary layer respectively. Application of a transverse magnetic field to an electrically conducting gives rise to a resistive type of force called Lorenz force. This force has the tendency to slowdown the motion of the fluid in the boundary layer and to increase its temperature also, the effects on the flow and thermal fields become more so as the strength of the magnetic field increases. This is obvious from the decrease in the velocity profiles presented in figure (8).

The temperature profiles are calculated for different values of heat source parameter $(\phi = 1.0, 2.0, 3.0, 4.0)$ and thermal radiation parameter $(R = 1.0, 2.0, 3.0, 4.0)$ at time $t = 0.2$ and $\Pr = 0.71$ from Equation (13) and these are shown in figures (9) and (10) in the presence of air. The effect of heat source parameter $(\phi)$ decreases with increasing values of $\phi$, and thermal radiation parameter is important in temperature profiles. It is observed that the temperature decreases with increasing radiation parameter.

The concentration profiles for different values of the chemical reaction parameter $(Kr = 1.0, 2.0, 3.0, 4.0)$ and Schmidt number $(Sc = 0.60, 0.65, 0.70, 0.75)$ are presented in figures (11) and (12). The effect of the chemical reaction parameter is dominant in concentration field. The profiles have the common feature that the concentration decreases in a monotone fashion from the surface to a zero value far away in the free stream. It is observed that the wall concentration increases with decreasing values of the chemical reaction parameter. The effect of the Schmidt number is dominant in concentration field. It is observed that the wall concentration decreases with increasing values of the Schmidt number.

Figure (13) and (14) show the effect of the radiation parameter $(R = 1.0, 2.0, 3.0, 4.0)$ on the skin-friction $(\tau)$ and the Nusselt number $(Nu)$ versus the thermal Grashof number $(Gr)$ at $\Pr = 0.71$. From these figures, it is observed that as radiation parameter $(R)$ increases, the skin-friction coefficient and Nusselt number decreases.

## CONCLUSION

The theoretical solution of radiative flow past a uniformly accelerated isothermal infinite vertical plate with uniform mass diffusion, in the presence of homogeneous chemical reaction of first order has been studied. The dimensionless governing equations were solved by the usual perturbation technique. The effect of different physical parameters like chemical reaction parameter, radiation parameter, thermal Grashof number, mass Grashof number and time are studied graphically. It is observed that the velocity increases with increasing values of $Gr, Gc$ and $t$. But the trend is just reversed with respect to the chemical reaction parameter or radiation parameter.

## APPENDIX

$$m_1 = -\sqrt{Kr\,Sc},\; m_2 = -\sqrt{Sc(Kr+n)}$$

$$m_3 = -\sqrt{\phi + R},\; m_4 = -\sqrt{M}$$

$$m_5 = -\sqrt{\phi + R + n\Pr},\; m_6 = -\sqrt{M+n}$$

$$A_1 = -\frac{Gr}{m_3^2 - M}$$

$$A_2 = -\frac{Gc}{m_1^2 - M},\; A_3 = (t - A_1 - A_2)$$

$$A_4 = -\frac{GrB_7}{m_3^2 - M} \quad A_5 = -\frac{GrB_1}{4m_4^2 - M}$$

$$A_6 = -\frac{GrB_2}{4m_3^2 - M} \quad A_7 = -\frac{GrB_3}{4m_1^2 - M}$$

$$A_8 = -\frac{GrB_4}{(m_3 + m_4)^2 - M} \quad A_9 = -\frac{GrB_5}{(m_1 + m_3)^2 - M}$$

$$A_{10} = -\frac{GrB_6}{(m_1 + m_4)^2 - M}$$

$$A_{11} = -(A_4 + A_5 + A_6 + A_7 + A_8 + A_9 + A_{10})$$

$$B_1 = -\frac{m_4^2 A_3^2}{4m_4^2 - (R+\phi)},\; B_2 = -\frac{m_3^2 A_1^2}{4m_3^2 - (R+\phi)}$$

$$B_3 = -\frac{m_1^2 A_2^2}{4m_1^2 - (R+\phi)}$$

$$B_4 = -\frac{2m_4 m_3 A_1 A_3}{(m_3 + m_4)^2 - (R+\phi)}$$

$$B_5 = -\frac{2m_1 m_3 A_1 A_2}{(m_1 + m_3)^2 - (R+\phi)}$$

$$B_6 = -\frac{2m_1 m_4 A_3 A_2}{(m_1 + m_4)^2 - (R+\phi)}$$

$$B_7 = -(B_1 + B_2 + B_3 + B_4 + B_5 + B_6)$$

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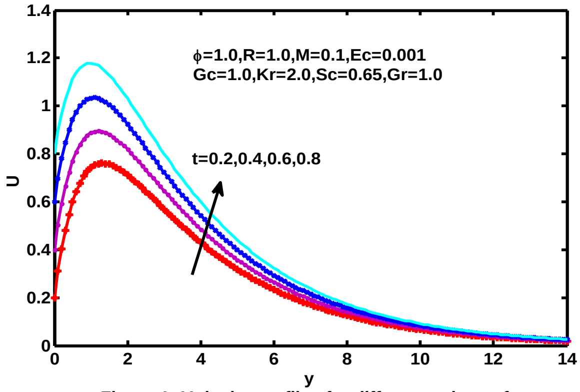

Figure 1: Velocity profiles for different values of t

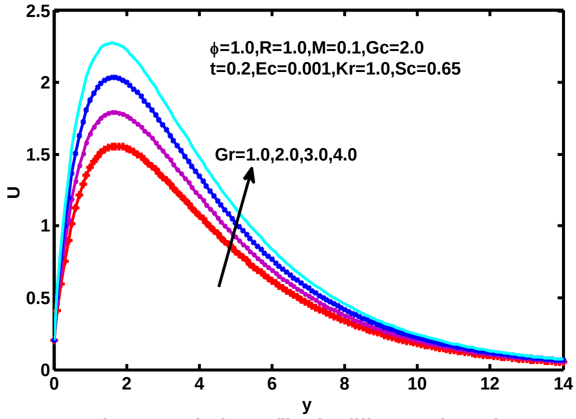

Figure 2: Velocity profiles for different values of Gr

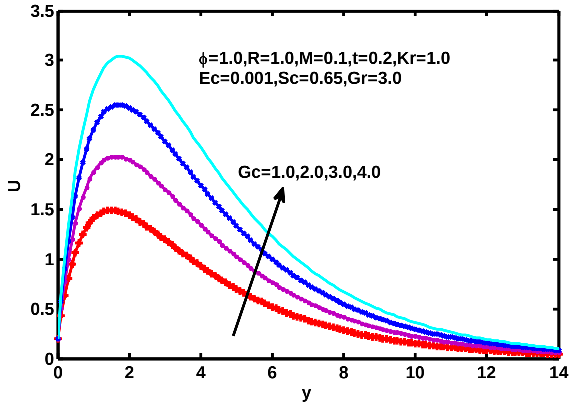

Figure 3: Velocity profiles for different values of Gc

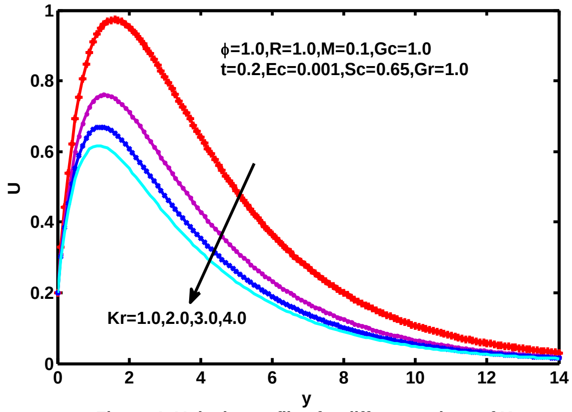

Figure 4: Velocity profiles for different values of Kr

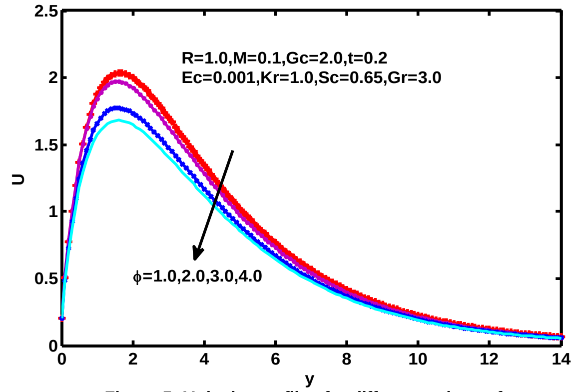

Figure 5: Velocity profiles for different values of $\phi$

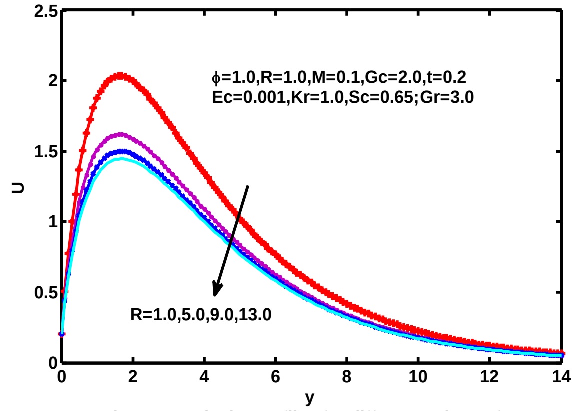

Figure 6: Velocity profiles for different values of R

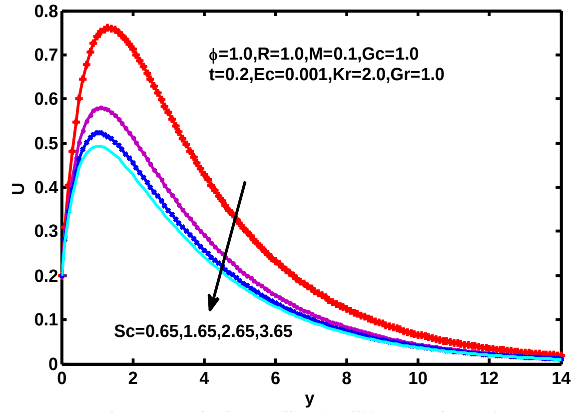

Figure 7: Velocity profiles for different values of Sc

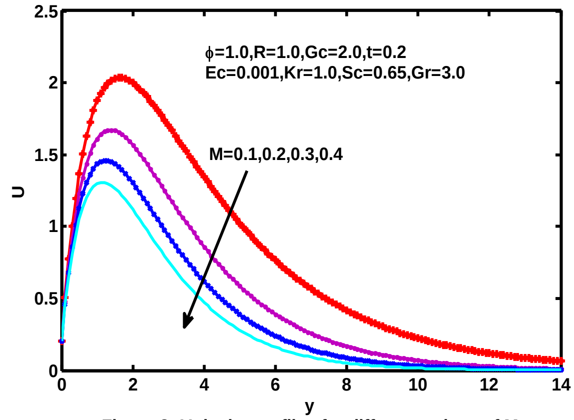

Figure 8: Velocity profiles for different values of M

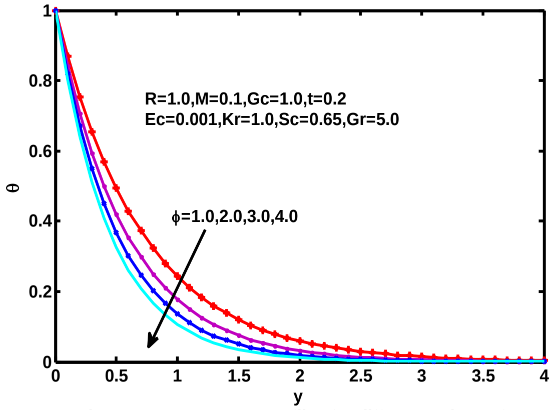


Figure 9: Temperature profiles for different values of ϕ

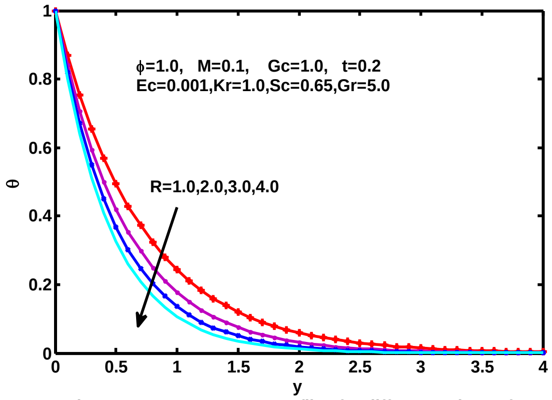


Figure 10: Temperpature profiles for different values of R

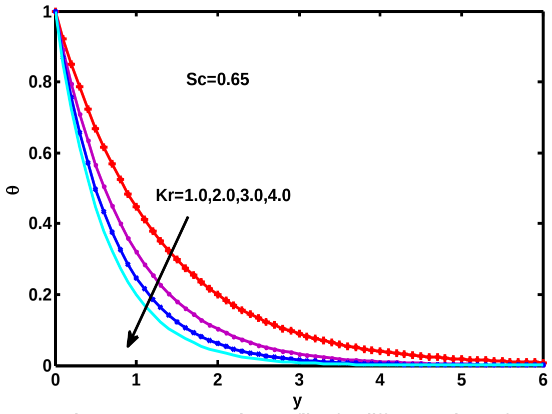


Figure 11: Concentration profiles for different values of Kr

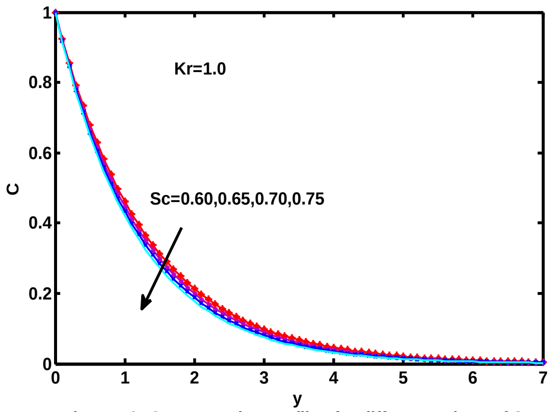


Figure 12: Concentration profiles for different values of Sc

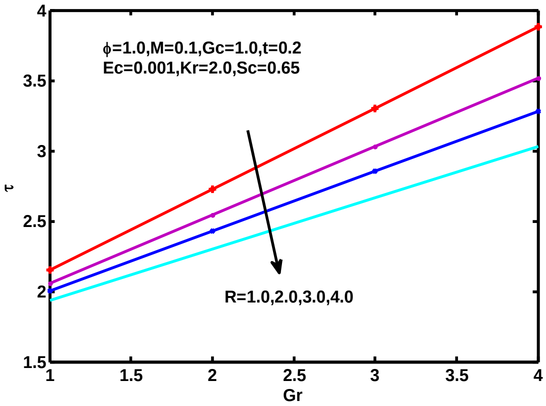


Figure 13: Skin friction for different values of R versus Gr

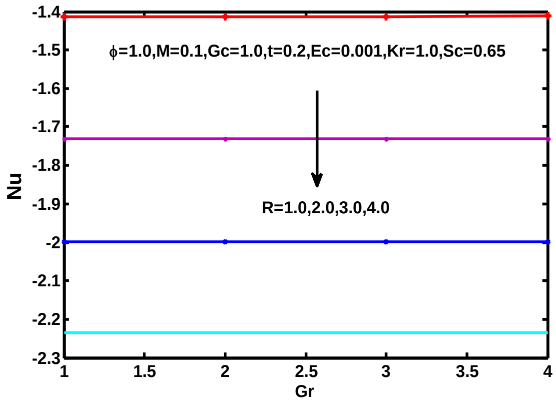


Figure 14: NUsselt number for different values of R versus Gr

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