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Unsteady radiative flow of a viscous incompressible fluid past an accelerated heat transfer isothermal infinite vertical plate with chemical reaction

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Abstract

This is study of the unsteady first order chemical reaction effects on radiative flow past a uniformly accelerated isothermal infinite vertical plate with radiation and uniform mass diffusion with 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 on the flow velocity, temperature and concentration discussed through graphs in detailed. This model finds applications in solar energy collection systems, geophysics and astrophysics, aero space and also in the design of high temperature chemical process systems.

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

1. Introduction

Materials of nonlinear liquids have been studied in the technological and engineering processes. Examples of non-Newtonian fluids are ketchup, paints, clay coating, toothpaste, cosmetic products, shampoos, sugar solutions, colloidal suspension solutions, silly putty, exotic lubrications detergents, condensed milk etc. Such fluids are used as a base liquid in numerous applications including plasma, lubrications of gases, food mixing, lubrications of oils, cooling of nuclear reactors and pseudoplastic liquids. Non-Newtonian liquids have gained considerable attention in physiology, pharmaceutical products, industry, biosciences, engineering and many others. Various models are developed to deliberate different characteristics of nonlinear liquid. Most of the studies dealing with transport phenomena are based on presuming that the fluid is incompressible and viscous, where the mass density is a constant quantity, and the velocity does not depend on the mass density. Pressure in the incompressible fluid flow model is not a thermodynamic state variable, but simply a force in the linear momentum balance equation. Such an easy rheological model for the fluid is suitable for modelling of slow flows [1-12].

In light of the previously conducted studies, a mathematical model is presented here to better understand the effects of a chemical reaction an optically thin radiating viscous incompressible non-Grey fluid flows naturally through an impulsively begun infinite vertical plate encased in a porous medium with ramped wall temperature, with ramped plate velocity and chemical reaction. The plate is accelerated for a limited period and then travels with uniform velocity. 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 [13-24].

The study of flow problems, which involve the interaction of several phenomena, has a wide range of applications in the field of science and technology. One such study is related to the effects of MHD free convection flow, which plays an important role in agriculture, engineering and petroleum industries. The problem of free convection under the influence of magnetic field has attracted the interest of many researchers in view of its application in geophysics and astrophysics. In many situations there may be an appreciable temperature difference between the surface and ambient fluid. These necessities the consideration of temperature dependent heat sources or sinks which may exert strong influence on the heat transfer characteristics. The study of heat generation or absorption in moving fluids is important in view of several physical problems, such as fluids undergoing exothermic or endothermic chemical reactions [25-42].

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 dimensionless governing equations are solved using the perturbation technique. The solutions are in terms of exponential and complementary error function. Such a study found useful in chemical process industries such as wire drawing, fibre drawing and food processing and polymer production.

2. 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_∞ and concentration C_∞. The x-axis is taken along the plate in the vertically upward direction and the yaxis is taken normal to the plate. At time $t' \le 0$, the plate and fluid are at the same temperature T_∞. 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:

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

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, β is the coefficient of volume expansion, β^* is the coefficient of thermal expansion with concentration, T_∞ is the temperature of the fluid near the plate, C' is the species concentration in the fluid near the plate, C'_∞ is the species concentration in the fluid far away from the plate, ν is the kinematic viscosity, σ is the electrical conductivity of the fluid, B_0 is the strength of applied magnetic field, ρ is the density of the fluid, C_p is the specific heat at constant pressure, K is the thermal conductivity of the fluid, μ 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 expressed as a linear function of the temperature. This is accomplished by expanding T^4 in a Taylor series about T_∞ and neglecting higher-order terms, thus

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \qquad (6)$$

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

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

On introducing the following non-dimensional quantities:

$$U = \frac{u}{u_0},\ \eta = \frac{u_0 y'}{\nu}, t = \frac{t' u_0^{\ 2}}{\nu}, \theta = \frac{T - T_\infty}{T_w - T_\infty}, C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \Pr = \frac{\mu C_p}{k}$$

$$M = \frac{\sigma B_0^{\ 2} \nu}{\rho u_0^{\ 2}}, Gr = \frac{\nu \beta g \left(T_w - T_\infty\right)}{u_0^{\ 3}}, \quad R = \frac{16 a^* \nu^2 \sigma T_\infty^3}{k u_0^2},\ \phi = \frac{\nu^2 Q_0}{k u_0^{\ 2}} \tag{8}$$

$$Ec = \frac{u_0^2}{k\left(T_w - T_\infty\right)},\ Gc = \frac{\nu \beta^* g\left(C'_w - C'_\infty\right)}{u_0^{\ 3}}, Kr = \frac{Kr'\nu}{u_0^{\ 2}}, \quad Sc = \frac{\nu}{D}$$

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, ϕ is Heat source parameter respectively.

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

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

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

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

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:

$$U = 0,\ \ \theta = 0,\ \ C = 0 \qquad \text{for all} \quad \eta,\ t \le 0$$

$$\left.\begin{array}{l} U = t, \quad \theta = 1, \quad C = 1 \quad \text{at} \quad \eta = 0 \\ U \to 0, \theta \to 0, C \to 0 \ \text{ as } \ \eta \to \infty \end{array}\right\} \quad t > 0 \tag{12}$$

3. Solution of the problem

Equations (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

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

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

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

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

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

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

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

$$C_1'' - \left(Kr + n\right)ScC_1 = 0 \tag{19}$$

The corresponding boundary conditions can be written as

$$\left.\begin{array}{l} U_0 = t, \quad U_1 = 0, \quad \theta_0 = 1 \\ \theta_1 = 1, \quad C_0 = 1, \quad C_1 = 0 \end{array}\right\} \quad at \;\; \eta = 0$$

$$\left.\begin{array}{l} U_0 \to 0, U_1 \to 0, \; \theta_0 \to 0 \\ \theta_1 \to 0, C_0 \to 0, C_1 \to 0 \end{array}\right\} \quad as \;\; \eta \to \infty \tag{20}$$

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.

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

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.

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

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

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

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

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

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

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

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

$$C_{01}'' - Sc\,Kr\,C_{01} = 0 \tag{30}$$

$$C_{02}'' - Sc\,Kr\,C_{02} = 0 \tag{31}$$

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

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

The respective boundary conditions are

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

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

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

$$\begin{aligned} U(\eta, t) = {} & A_1 e^{m_3\eta} + A_2 e^{m_1\eta} + A_3 e^{m_4\eta} + Ec\left\{A_4 \; e^{m_3\eta} + A_5 e^{2m_4\eta} + A_6 e^{2m_3\eta} + A_7 e^{2m_1\eta} + A_8 e^{(m_3+m_4)\eta} \right. \\ & \left. + A_9 e^{(m_1+m_3)\eta} + A_{10} e^{(m_1+m_4)\eta} \; + \; A_{11} e^{m_4\eta}\right\} \end{aligned}$$

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

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

Skin-friction:

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

$\tau = -\left(\dfrac{\partial u}{\partial \eta}\right)_{\eta=0}$, where $\tau = -\dfrac{\tau'}{\rho U_0^{\;2}}$

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

Rate of heat transfer:

The dimensionless rate of heat transfer is given by

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

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

Sherwood number:

The dimensionless Sherwood number is given by

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

4. Results and discussion

For physical interpretation of the problem, the numerical computations are carried out for different physical parameters thermal Grashof number, mass Grashof number, chemical reaction parameter, Prandtl number, radiation parameter, heat source parameter, Schmidt number and time upon the nature of the flow and transport. The values were considered for graphical representation as R = 1.0, M = 0.5, $Gc = 2.0$, $Gr = 2.0$, Ec = 0.001, Kr = 1.0, Sc = 0. 65. 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 thermal Grashof number, mass Grashof number, chemical reaction parameter, Prandtl number, radiation parameter, heat source parameter, Schmidt number and time are studied graphically. The velocity profiles for different values of t 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. The velocity profiles for different values of chemical reaction parameter (Kr) and heat source parameter (ϕ) 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. Figure (6) it can be concluded that velocity decreases due to an increase in the Schmidt number. For lower Schmidt number the thickness of the concentration layer increases and the region of flow extend farther away from the plate. The temperature profiles are calculated for different values of heat source parameter at time $t = 0.2$ and $\Pr = 0.71$ from equation (13) and these are shown in figure (7) in the presence of air. The effect of heat source parameter decreases with increasing values of heat source parameter. The concentration profiles for different values of the chemical reaction parameter and Schmidt number are presented in figures (8) and (9). 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.

Conclusions

The following conclusions were made after studies this paper.

- It is observed that the velocity increases with increasing values of Grashof number, mass Grashof number and time.

- But the trend is just reversed with respect to the chemical reaction parameter.

Appendix

$$m_1 = -\sqrt{Kr\,Sc},\ m_2 = -\sqrt{Sc\left(Kr+n\right)},\ m_3 = -\sqrt{\phi + R},\ m_4 = -\sqrt{M}$$

$$m_5 = -\sqrt{\phi + R + n\Pr},\ m_6 = -\sqrt{M+n}\ A_1 = -\frac{Gr}{m_3^{\ 2} - M}\ A_2 = -\frac{Gc}{m_1^{\ 2} - M},\ A_3 = \left(t - A_1 - A_2\right)$$

$$A_4 = -\frac{GrB_7}{m_3^{\ 2} - M}\ A_5 = -\frac{GrB_1}{4m_4^{\ 2} - M}\ A_6 = -\frac{GrB_2}{4m_3^{\ 2} - M}\ A_7 = -\frac{GrB_3}{4m_1^{\ 2} - M}\ A_8 = -\frac{GrB_4}{\left(m_3 + m_4\right)^2 - M}$$

$$A_9 = -\frac{GrB_5}{\left(m_1 + m_3\right)^2 - M}\ A_{10} = -\frac{GrB_6}{\left(m_1 + m_4\right)^2 - M}\ A_{11} = -\left(A_4 + A_5 + A_6 + A_7 + A_8 + A_9 + A_{10}\right)$$

$$B_1 = -\frac{m_4^{\ 2} A_3^{\ 2}}{4m_4^{\ 2} - \left(R+\phi\right)},\ B_2 = -\frac{m_3^{\ 2} A_1^{\ 2}}{4m_3^{\ 2} - \left(R+\phi\right)}\ B_3 = -\frac{m_1^{\ 2} A_2^{\ 2}}{4m_1^{\ 2} - \left(R+\phi\right)}\ B_4 = -\frac{2m_4 m_3 A_1 A_3}{\left(m_3 + m_4\right)^2 - \left(R+\phi\right)}$$

$$B_5 = -\frac{2m_1 m_3 A_1 A_2}{\left(m_1 + m_3\right)^2 - \left(R+\phi\right)}\ B_6 = -\frac{2m_1 m_4 A_3 A_2}{\left(m_1 + m_4\right)^2 - \left(R+\phi\right)},\ B_7 = -\left(B_1 + B_2 + B_3 + B_4 + B_5 + B_6\right)$$

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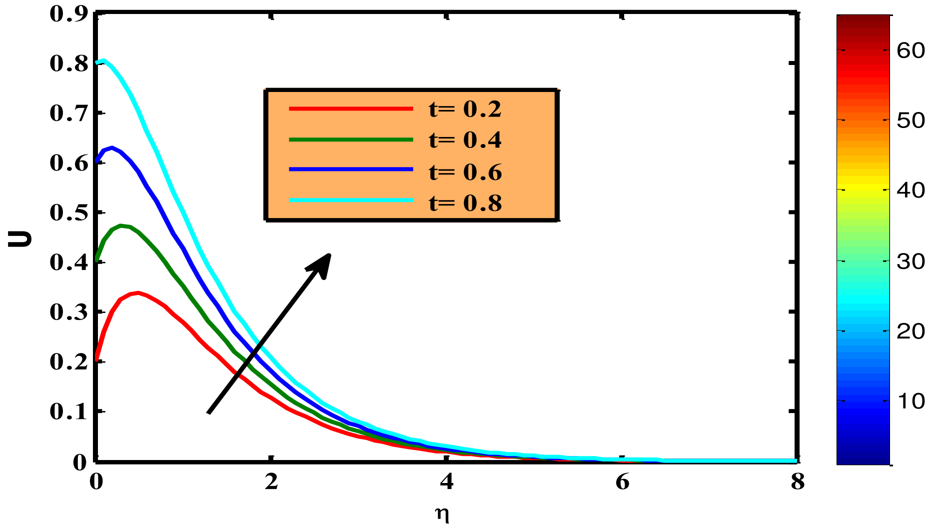


Fig. (1): Velocity profiles for different values of t

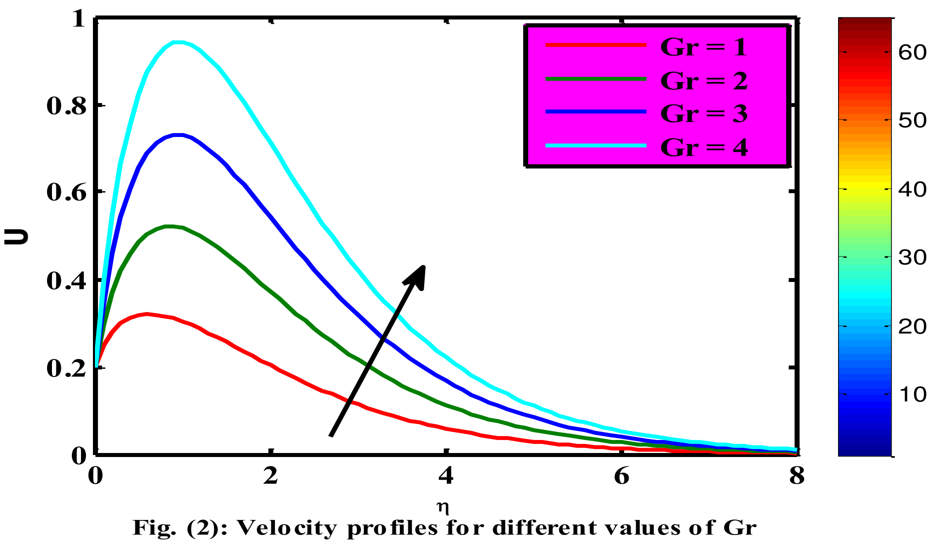
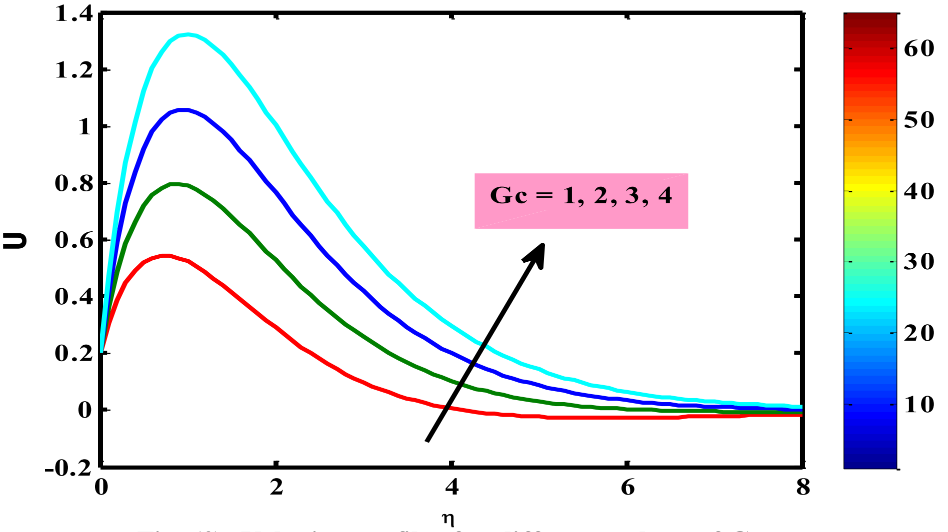


Fig. (2): Velocity profiles for different values of Gr



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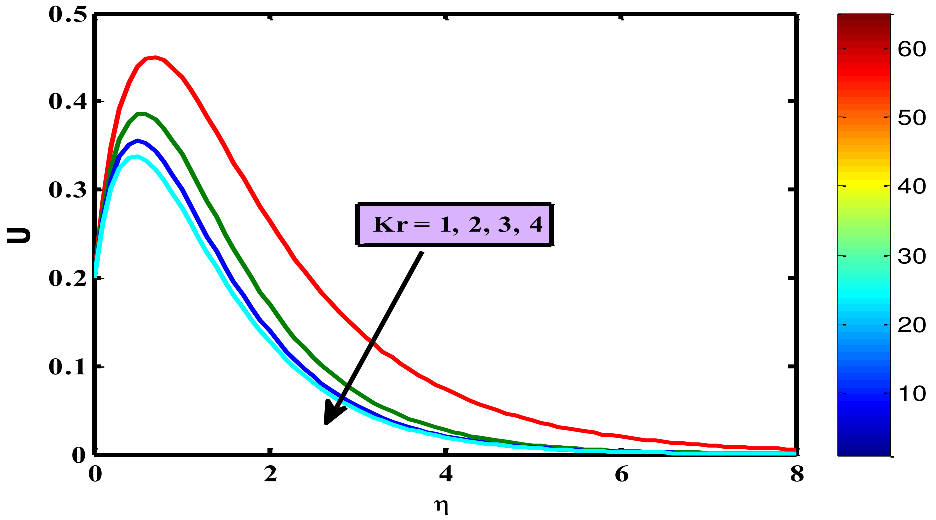

Fig. (4): Velocity profiles for different values of Kr

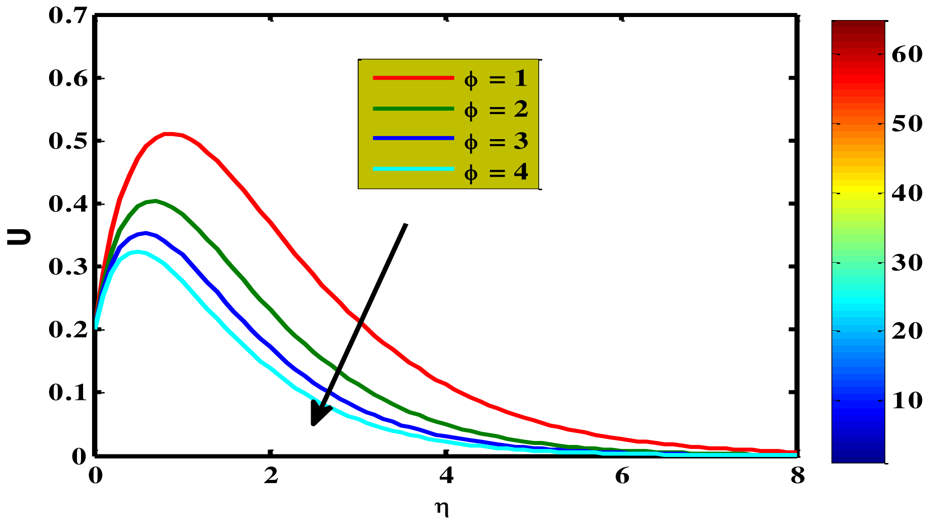

Fig. (5): Velocity profiles for different values of ϕ

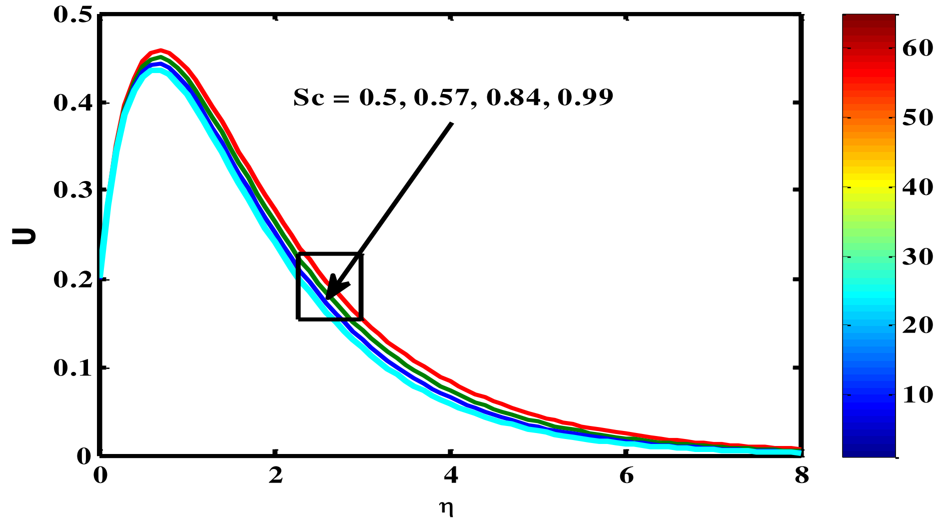

Fig. (6): Velocity profiles for different values of Sc

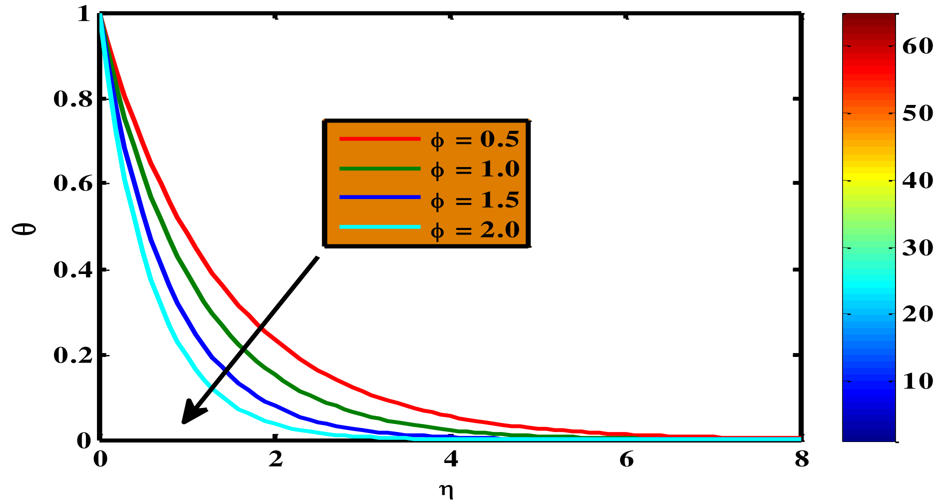

Fig. (7): Temperature profiles for different values of ϕ

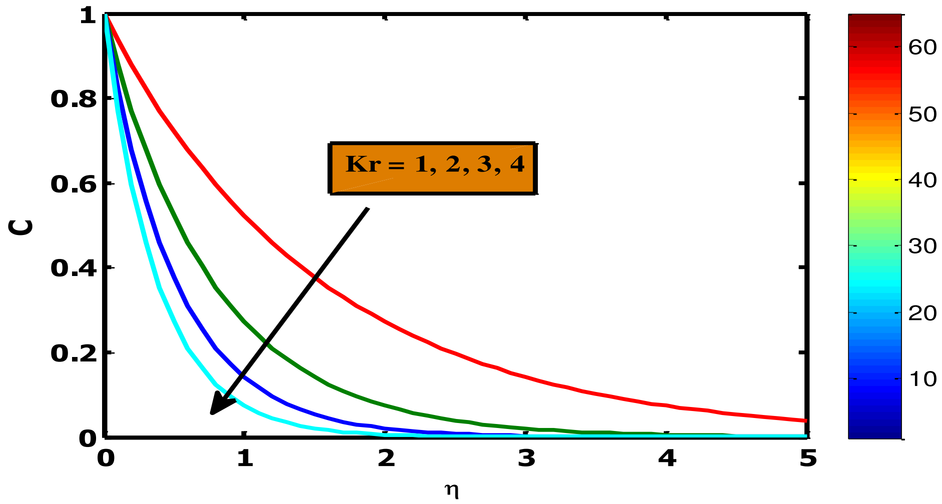

Fig. (8). Concentration profiles for different values of Kr

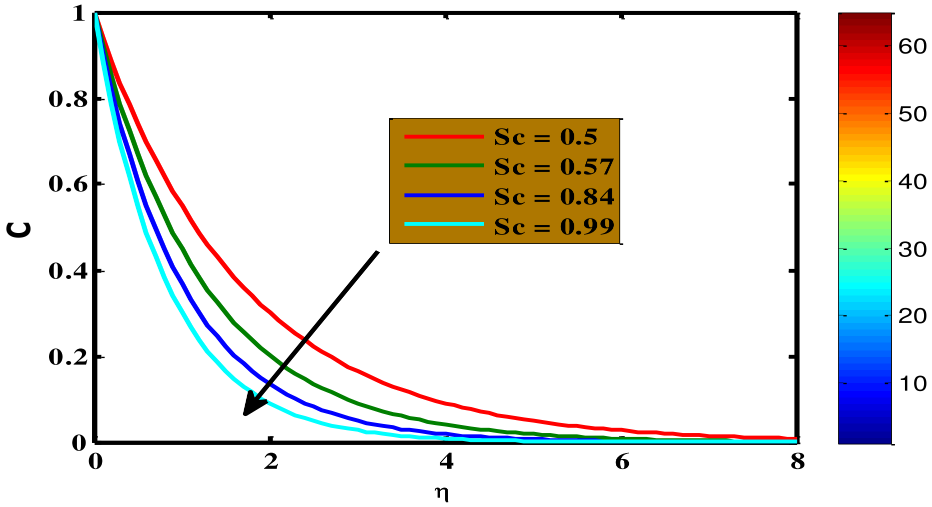

Fig. (9). Concentration profiles for different values of Sc