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Effects of heat and mass transfer on MHD free convection and chemically reacting fluid flow over an inclined plate

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Abstract

The present investigation is combined heat and mass transfer effects on the MHD free convection flow of an electrically conducting and chemically reacting incompressible viscous fluid over an inclined plate embedded in a porous medium in impulsively started plate with variable temperature and mass diffusion is considered. The dimensionless momentum equation coupled with the energy and mass diffusion equations are analytically solved using the perturbation method. The effects of pertinent parameters on velocity, temperature and concentration profiles are graphically displayed whereas the variations in skin friction, Nusselt number and Sherwood number are shown through tables.

Keywords: chemical reaction, inclined plate, heat and mass transfer, MHD

1. Introduction

Chemical reaction 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 many practical situations such as condensation, evaporation and chemical reactions the heat transfer process is always accompanied by the mass transfer process. Perhaps, it is due to the fact that the study of combined heat and mass transfer is helpful in better understanding of a number of technical transfer processes. Besides, free convection flows with conjugate effects of heat and mass transfer past a vertical plate have been studied extensively in the literature due to its engineering and industrial applications in food processing and polymer production and granular insulation and geothermal systems [1-12].

In daily life applications convection of heat-mass transfer analysis play a very important role. In the last few years natural convection flow theory highly developed and became the most rapidly established research field. A lot of phenomena's relatable to convection flow over infinite vertical plate are studied in literature. In practical life heat and mass transfer procedure appears too much, such as chemical reaction evaporation, and also in condensation. Heat and mass transfer have also industrialized applications like the buoyancy effects of diffusion of chemical reactions and thermal diffusion; this is generated by thermal conduction and mass transfer analysis. Many researchers have been working in this field and eradicate many physical problems related to heat and mass transfer and investigated those problems analytically as well as graphically. The conjugate phenomenon of heat and mass transfer occurs as a result of combined buoyancy effects of thermal diffusion and diffusion through chemical species, which plays an important role in geophysics, aeronautics and chemical engineering. Some industrial applications are found in food drying, food processing and polymer production. Hence a considerable amount of attention has been focused in recent years by various scientists and engineers to study problems involving the conjugate phenomenon of heat and mass transfer either analytically or numerically. In view of the above some of the researchers studied [13-24].

Theoretical and Experimental investigation of problems within porous and non-porous medium of MHD unfastened convective drift of dissipative and radiative liquids or gases attracted many researchers at some stage in past few decades because of its critical applications in lots of fields of technology and engineering. Some programs in one-of-a-kind branches of technological know-how and era are in MHD power producers, industry making chemical substances, producing electric powers, processing meals, petroleum engineering, flow in a wasteland cooler and so on. The temperature differences occur due to atmospheric flow in natural circumstances like geothermal extraction, ground water flows and thermal insulation engineering. Magnetic fields are commonly applied in industry to pump, heat, levitate and stir liquid metals. There is the terrestrial magnetic field, which is maintained by fluid flow in the earth's core, the solar magnetic field, which originates sunspots and solar flares, and the galactic magnetic field, which is thought to control the configuration of stars from interstellar clouds. Recently, considerable attention has been focused on applications of MHD and heat transfer such as metallurgical processing, MHD generators and geothermal energy extraction. The phenomenon concerning heat and mass transfer with MHD flow is important due to its numerous applications in science and technology. The particular applications are found in buoyancy induced flows in the atmosphere, in bodies of water and quasi-solid bodies such as earth [25-39].

Hence, the present investigation is combined heat and mass transfer effects on the MHD free convection flow of an electrically conducting and chemically reacting incompressible viscous fluid over an inclined plate embedded in a porous medium in impulsively started plate with variable temperature and mass diffusion is considered. The dimensionless momentum equation coupled with the energy and mass diffusion equations are analytically solved using the perturbation method. The effects of pertinent parameters on velocity, temperature and concentration profiles are graphically displayed whereas the variations in skin friction, Nusselt number and Sherwood number are shown through tables.

2. Formulation of the problem

Let us consider the unsteady flow of an incompressible viscous fluid past an infinite inclined plate with variable heat and mass transfer. The $x^* -$axis is taken along the plate with the angle inclination α to the vertical and $y^* -$axis is normal to the plate. The viscous fluid is taken to be electrically conducting and fills the porous half space $y^* > 0$. A uniform magnetic field B_0 is applied in the $y^* -$direction transversely to the plate. The applied magnetic field is assumed to be strong enough so that the induced magnetic field due to the fluid motion is weak and can be neglected. According to Cramer and Pai [40], this assumption is physically justified for partially ionized fluids and metallic liquid because of their small magnetic Reynolds number. Since there is no applied or polarization of charges is zero. Initially, both the fluid and the plate are at rest with constant temperature $T_\infty{}^*$ and the constant concentration $C_\infty{}^*$. At time $t^* = 0^+$ plate is given a sudden jerk, and the motion is induced in the direction of flow against the gravity with uniform velocity u_0. The temperature and concentration of the plate are raised linearly with respect to time. Also, it is considered that the viscous dissipation is negligible and the fluid is thick gray absorbing – emitting radiation but non-scattering medium. Since the plate is infinite in the $\left(x^*, z^*\right)$ plane, all physical variables are functions of y^* and t^* only. The physical model and coordinates system is shown in figure (1).

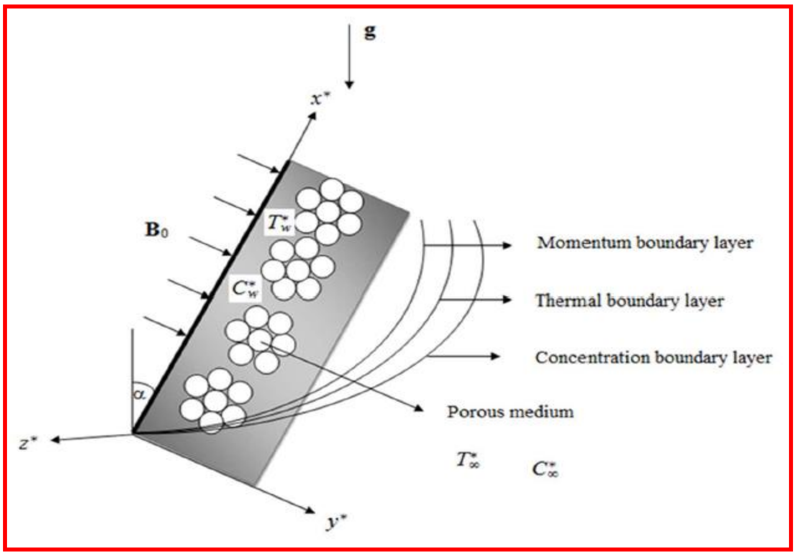

Figure (1): Physical model and coordinates system

In view of the above assumptions, as well as of the usual Boussinesq approximation, the governing equations reduce

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

$$\rho c_p \frac{\partial T^*}{\partial t^*} = \kappa \frac{\partial^2 T^*}{\partial y^{*2}} - Q_0\left(T^* - T_\infty^*\right) \tag{2}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - k_1\left(C^* - C_\infty^*\right) \tag{3}$$

where u^* is the axial velocity of the fluid along the plate in the x' - direction, T^* is the temperature of the fluid, C^* is the species concentration in the fluid near the plate, u^* are the dimensional distance along and perpendicular to the plate, t^* is the time, σ is the electrical conductivity, $\nu = \frac{\mu}{\rho}$ (μ is the viscosity and ρ the constant density of the fluid) is the kinematic viscosity, $k > 0$ is the permeability of the porous medium, g is the acceleration due to gravity, β_T is the coefficient of volume expansion, β_C is the coefficient of thermal expansion with concentration, c_p is the specific heat at constant pressure, k_1 is the thermal diffusivity, D is the mass diffusibility and k_2 is the chemical reaction constant.

The initial and boundary conditions are:

$$\begin{aligned} &u^*\left(y^*,0\right)=0, T\left(y^*,0\right)=T_\infty^*, C\left(y^*,0\right)=C_\infty^*, \quad y^*>0 \\ &u^*\left(\infty,t^*\right)=0, T^*\left(\infty,t^*\right)=T_\infty{}^*, C^*\left(\infty,t^*\right)=C_\infty{}^*, t^*>0 \end{aligned} \tag{4}$$

where $A = \frac{u_0^2}{\nu}$

$$\begin{aligned} u^*\left(0,t^*\right)&=u_0 \\ T\left(0,t^*\right)&=T_\infty^*+\left(T_w^*+T_\infty^*\right)At^*, \\ C\left(0,t^*\right)&=C_\infty^*+\left(C_w^*+C_\infty^*\right)At^*, \quad t^*>0 \end{aligned} \tag{5}$$

On introducing the following non – dimensional quantities

$$y=\frac{u_0 y^*}{\nu}, u=\frac{u^*}{u_0}, \; t=\frac{t^* u_0{}^2}{\nu}, \; \theta=\frac{T^*-T_\infty{}^*}{T_w^*-T_\infty{}^*}, \; \phi=\frac{C^*-C_\infty{}^*}{C_w^*-C_\infty{}^*} \tag{6}$$

Equations (1), (2) and (3) reduces

$$\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial y^2}-\left(M+\frac{1}{K}\right)u+Gr\,\theta\cos\alpha+Gc\,\phi\cos\alpha \tag{9}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2}-Q\theta \tag{10}$$

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

where

$$M = \frac{\sigma B_0^{\ 2}\nu}{\rho u_0^{\ 2}}, \frac{1}{K} = \frac{\nu^2}{u_0^{\ 2}k}, Gr = \frac{g\beta_T \nu\left(T_w^* - T_\infty^*\right)}{u_0^{\ 3}}, Kr = \frac{k_1\nu}{u_0^{\ 2}}$$
$$Gc = \frac{g\beta_C \nu\left(C_w^* - C_\infty^*\right)}{u_0^{\ 3}}, \Pr = \frac{\mu c_p}{\kappa}, Q = \frac{Q_0\nu}{\rho c_p u_0^2},\ Sc = \frac{\nu}{D}$$

Here, M is the magnetic parameter called Hartmann number, K is the permeability parameter, Gr is the thermal Grashof number, Gc is the mass Grashof number, $\Pr$ is the Prandtl number, Q is the heat source parameter, Kr is the dimensionless chemical reaction parameter and Sc is the Schmidt number.

The corresponding initial and boundary conditions (4) become

$$\begin{aligned} &t \le 0 : u(y,t) = 0, \theta(y,t) = 0, \phi(y,t) = 0, \quad y > 0 \\ &t > 0 : u(0,t) = 1, \theta(0,t) = t, \phi(0,t) = t \\ &\quad u(y,t) \to 0, \theta(y,t) \to 0, \phi(y,t) \to 0, \quad y \to \infty \end{aligned} \tag{12}$$

3. 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

$$\begin{aligned} u &= u_0(y) + \varepsilon e^{at} u_1(y) \\ \theta &= \theta_0(y) + \varepsilon e^{at} \theta_1(y) \\ \phi &= \phi_0(y) + \varepsilon e^{at} \phi_1(y) \end{aligned} \tag{13}$$

Substituting (13) in Equation (9) – (11) and equating the harmonic and non – harmonic terms, we obtain

$$u_0'' + \beta_3^2 u_0 = -Gr\,\theta_0 \cos\alpha - Gc\,\phi_0 \cos\alpha \tag{14}$$

$$u_1'' - \beta_4^2 u_1 = -Gr\,\theta_1 \cos\alpha - Gc\,\phi_1 \cos\alpha \tag{15}$$

$$\theta_0'' - Q\Pr\theta_0 = 0 \tag{16}$$

$$\theta_1'' - \beta_1^2\,\theta_1 = 0 \tag{17}$$

$$\phi_0'' - Sc\,\gamma\,\phi_0 = 0 \tag{18}$$

$$\phi_1'' - \beta_2^2\phi_1 = 0 \tag{19}$$

The corresponding boundary conditions can be written as

$$\begin{aligned} &u_0 = 0, u_1 = 1,\ \theta_0 = t, \theta_1 = 0, \phi_0 = t, \phi_1 = 0 \qquad at\quad y = 0 \\ &u_0 = 0, u_1 = 0,\ \theta_0 = 0, \theta_1 = 0, \phi_0 = 0, \phi_1 = 0 \qquad as\ \ y \to \infty \end{aligned} \tag{20}$$

Solving Equations (14) – (19) under the boundary conditions (20) and we obtain the velocity, temperature and concentration distributions in the boundary layer as

$$u_0 = L_1 e^{m2y} + L_2 e^{m6y} + L_3 e^{m12y}; u_1 = 0$$

$$\phi_0 = e^{m6y}; \phi_1 = 0$$

$$\theta_0 = te^{m2y}; \theta_1 = 0$$

In view of the equation (13) becomes

$$u = L_1 e^{m2y} + L_2 e^{m6y} + L_3 e^{m12y}$$

$$\theta = te^{m2y}$$

$$\phi = e^{m6y}$$

Coefficient of Skin-Friction

The coefficient of skin-friction at the vertical porous surface is given by

$$C_f = \left(\frac{\partial u}{\partial y}\right)_{y=0} = L_1 m_2 + L_2 m_6 + L_3 m_{12}$$

Coefficient of Heat Transfer

The rate of heat transfer in terms of Nusselt number at the vertical porous surface is given by

$$N_u = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = t\,m_2$$

Sherwood number

$$Sh = \left(\frac{\partial \phi}{\partial y}\right)_{y=0} = t\ \ m_6$$

Table (1): Skin friction

K	Gc	Q	Kr	M	α	Pr	t	Sc	C_f
1.0	5.0	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	0.5641
2.0	5.0	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	0.9410
3.0	5.0	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	0.0900
4.0	5.0	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	1.1700
1.0	**1.0**	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 1.0190
1.0	**2.0**	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.6229
1.0	**3.0**	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.2272
1.0	**4.0**	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.1684
1.0	5.0	**1.0**	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.5657
1.0	5.0	**2.0**	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.8000
1.0	5.0	**3.0**	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.9798
1.0	5.0	**4.0**	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 1.1310
1.0	5.0	1.0	**1.0**	1.0	$\pi/6$	0.71	0.2	0.60	0.5641
1.0	5.0	1.0	**2.0**	1.0	$\pi/6$	0.71	0.2	0.60	0.3112
1.0	5.0	1.0	**3.0**	1.0	$\pi/6$	0.71	0.2	0.60	0.1570
1.0	5.0	1.0	**4.0**	1.0	$\pi/6$	0.71	0.2	0.60	0.0469
1.0	5.0	1.0	1.0	**1.0**	$\pi/6$	0.71	0.2	0.60	0.5641
1.0	5.0	1.0	1.0	**2.0**	$\pi/6$	0.71	0.2	0.60	- 0.0045
1.0	5.0	1.0	1.0	**3.0**	$\pi/6$	0.71	0.2	0.60	- 0.4394
1.0	5.0	1.0	1.0	**4.0**	$\pi/6$	0.71	0.2	0.60	- 0.7978
1.0	5.0	1.0	1.0	1.0	$\pi/6$	0.71	0.2	0.60	- 0.180
1.0	5.0	1.0	1.0	1.0	$\pi/4$	0.71	0.2	0.60	- 2.365
1.0	5.0	1.0	1.0	1.0	$\pi/2$	0.71	0.2	0.60	- 3.676
1.0	5.0	1.0	1.0	1.0	π	0.71	0.2	0.60	- 2.907
1.0	5.0	1.0	1.0	1.0	$\pi/6$	**0.71**	0.2	0.60	0.5641
1.0	5.0	1.0	1.0	1.0	$\pi/6$	**1.0**	0.2	0.60	0.5641
1.0	5.0	1.0	1.0	1.0	$\pi/6$	**7.0**	0.2	0.60	0.5641
1.0	5.0	1.0	1.0	1.0	$\pi/6$	**100.0**	0.2	0.60	0.5641

Table (2): Nusselt number	**Table (3):** Sherwood number

Q	Nu	Kr	Sh
1.0	- 0.5657	1.0	- 3.162
2.0	- 0.8000	2.0	- 4.472
3.0	- 0.9798	3.0	- 5.477
4.0	- 1.1310	4.0	- 6.325

4. Results and Discussions

The results are shown graphically for various parameters thermal Grashof number (Gr) modified Grashof number (Gc), heat source parameters (Q), magnetic parameter (M), permeability parameter (K), Chemical reaction parameter (Kr), Schmidt number (Sc), Prandtl number $(\Pr)$, rotation parameter (α) and time (t). In this observation the values of the Prandtl number are chosen to represents air $(\Pr = 0.71)$; Schmidt number are chosen to represents oxygen $(Sc = 0.60)$, The velocity profiles, concentration, skin friction and Sherwood number are shown from figures (2) – (15). For various values of thermal Grashof number $(Gr = 1, 2, 3, 4)$ and modified Grashof number $(Gm = 1, 2, 3, 4)$ are give an exhibition of the velocity profiles in figure (2) & (3), we noticed that the velocity increase with increasing values of modified thermal Grashof number and modified Grashof number. The velocity variations for different values of the magnetic parameter $(Q = 1, 2, 3, 4)$ are show in figure (4). Form this figure we observed that an increasing values of magnetic parameter the velocity decreases. The velocity variations for different values of the magnetic parameter $(M = 1, 2, 3, 4)$ are depicted in figure (5). Form this figure we observed that an increasing values of magnetic parameter the velocity decreases. The velocity variations for different values of the magnetic parameter $(K = 1, 2, 3, 4)$ are illustrated in figure (6). Form this figure we observed that an increasing values of magnetic parameter the velocity decreases. Figures (7) and (8) shown velocity profiles for different values of chemical reaction parameter $(Kr = 1, 2, 3, 4)$ and Schmidt number $(Sc = 0.16, 0, 22, 0.31, 0.60)$, it is observed that increasing values of chemical reaction parameter and Schmidt number the velocity decreases. The velocity profiles observed for different values of rotation parameter $\left(\alpha = \frac{\pi}{6}, \frac{\pi}{4}, \frac{\pi}{2}, \pi\right)$ are shown in figure (9), it is clear that the velocity decreases with increasing values of rotation parameter. The temperature profiles observed form figures (10) – (12) for various values of Prandtl number $\left(\Pr = 0.71, 1, 7, 100\right)$, heat source parameter $\left(Q = 1, 2, 3, 4\right)$ and time parameter $\left(t = 0.2, 0.4, 0.6, 0.8\right)$, it clear that an increasing values of Prandtl number, heat source parameter the temperature profiles decreases, but the reverse effects observed for time parameter. The concentration profiles are shown from figures (14) – (15). From these figures observed that the concentration profiles for different values of Schmidt number $\left(Sc = 0.16, 0, 22, 0.31, 0.60\right)$ and chemical reaction parameter $\left(Kr = 1, 2, 3, 4\right)$ and we observed that an increasing Schmidt number and chemical reaction parameter the concentration profiles decreases in both the parameters. The skin friction coefficient shown in table (1) for different values of permeability parameter $\left(K\right)$, modified Grashof number $\left(Gc\right)$, heat source parameters $\left(Q\right)$, Chemical reaction parameter $\left(Kr\right)$, magnetic parameter $\left(M\right)$, rotation parameter $\left(\alpha\right)$ and Prandtl number $\left(\Pr\right)$ versus thermal Grashof number, which is clear that an increasing values of permeability parameter the skin friction increasing, but the reverse effects observed for modified Grashof number, heat source parameters, Chemical reaction parameter, magnetic parameter, rotation parameter and there is no effects for Prandtl number. Table (2) and table (3) shows that the Nusselt number for different values of heat source parameter $\left(Q\right)$ and Sherwood number for various values of chemical reaction parameter $\left(Kr\right)$ it observed that an increasing values of heat source parameter and chemical reaction parameter the Nusselt number as well as Sherwood number are decreases.

Appendix

$$m_2 = -\sqrt{Q\Pr}, \qquad m_4 = -\beta_1, \qquad m_6 = -\sqrt{Kr\,Sc}, \qquad m_{12} = -\beta_3$$

$$L_1 = -\frac{t\,Gr\cos\alpha}{m_2^2 - \beta_3^2}, \qquad L_2 = -\frac{Gc\cos\alpha}{m_6{}^2 - \beta_3^2}, \qquad L_3 = \left(1 - L_1 - L_2\right)$$

$$\beta_1{}^2 = \Pr\left(at + Q\right), \beta_2^2 = Sc\left(\gamma + at\right), \beta_3 = \left(M + \frac{1}{K}\right), \beta_4^2 = \left(\beta_3^2 + 1\right)at$$

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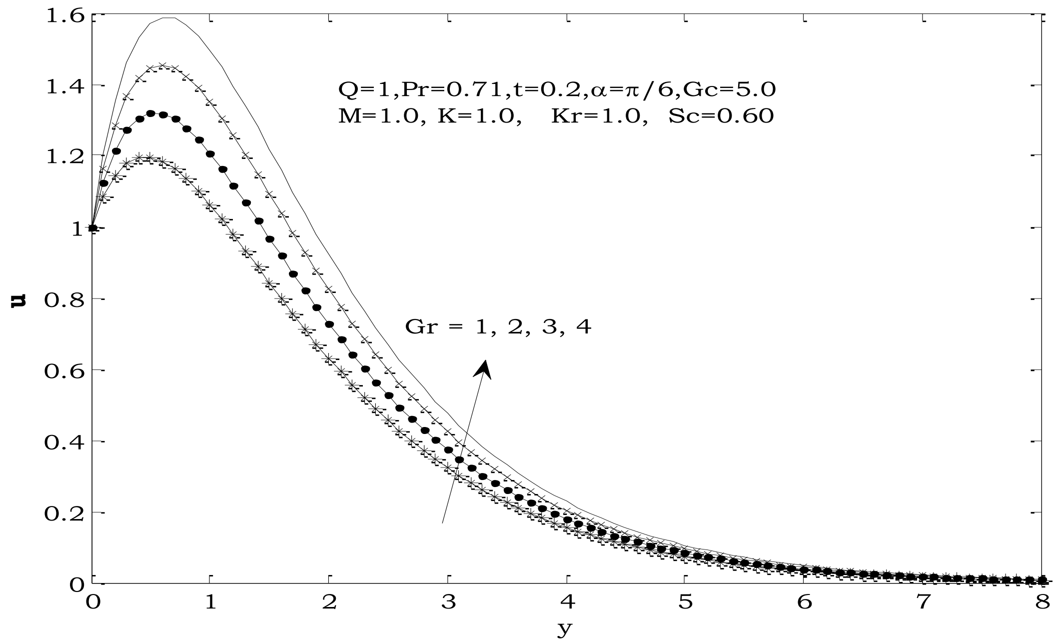

Figure (2): Velocity profiles for different values of Gr

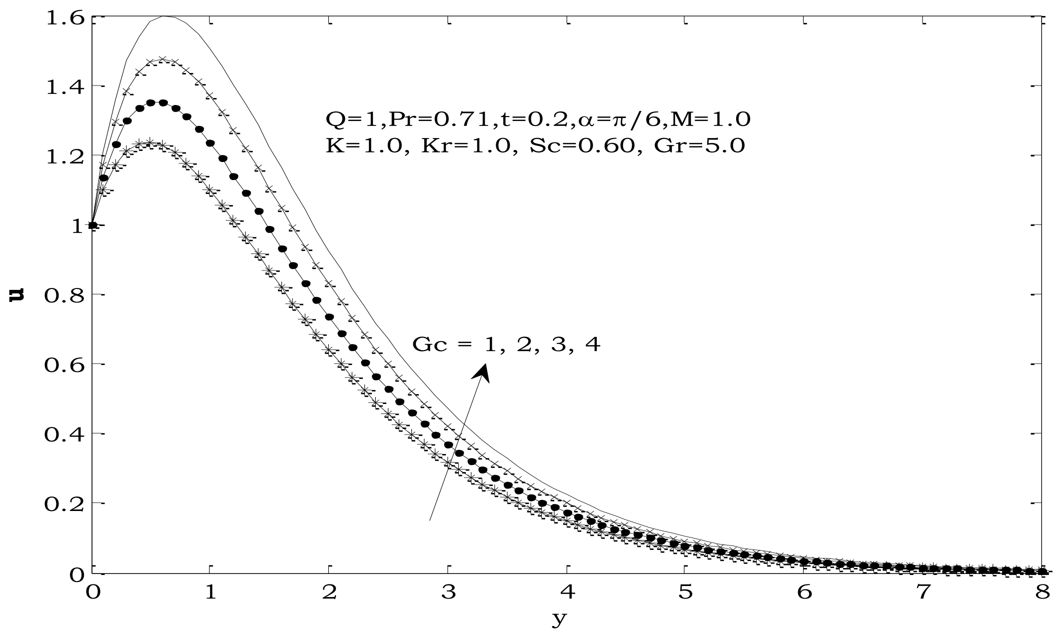

Figure (3): Velocity profiles for different values of Gc

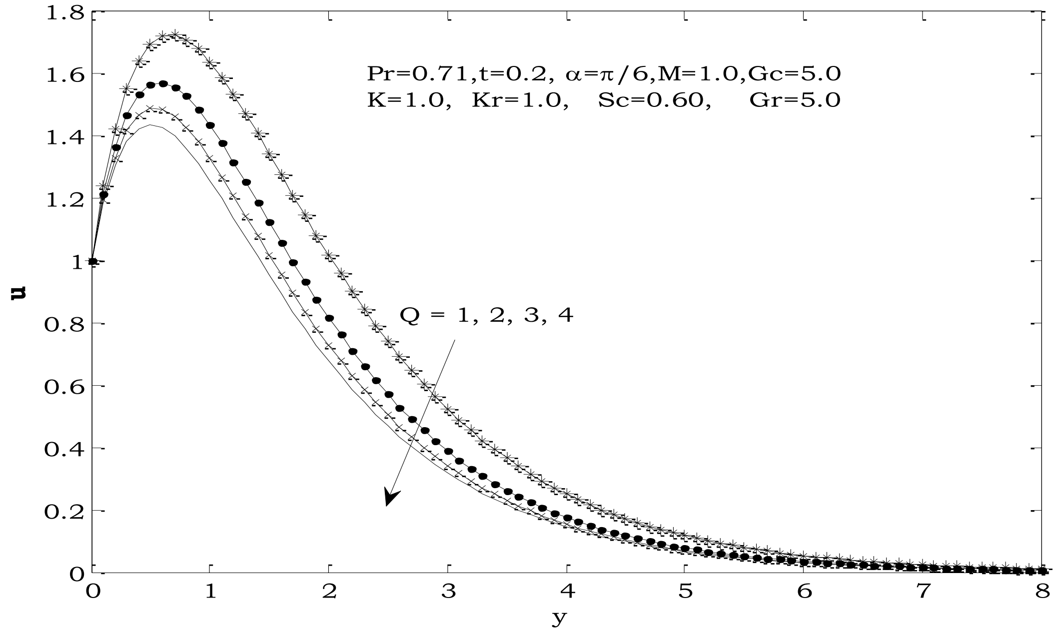

Figure (4): Velocity profiles for different values of Q

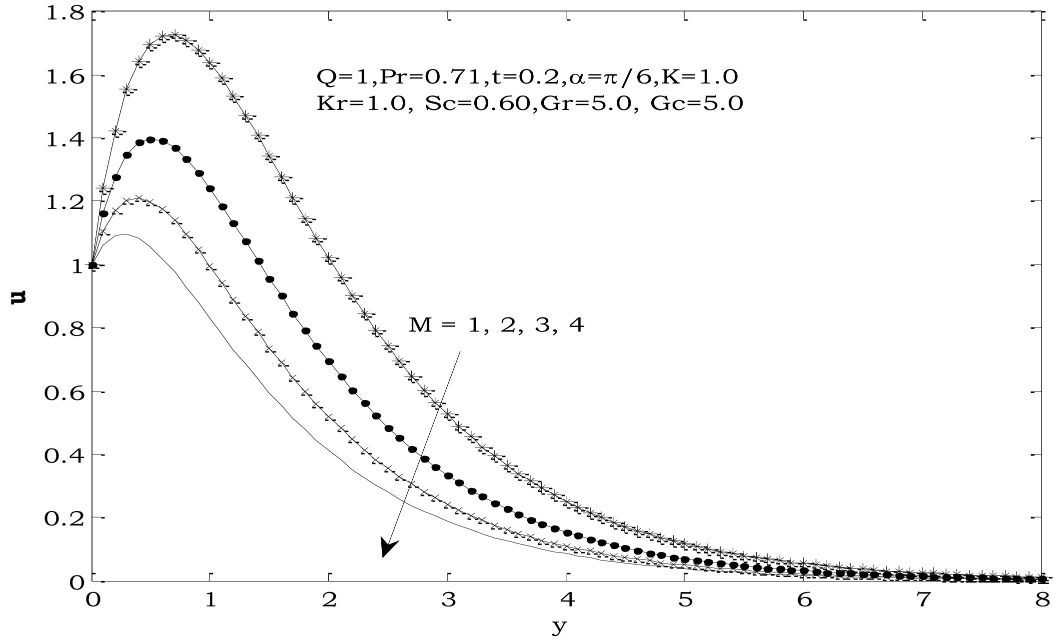

Figure (5): Velocity profiles for different values of M

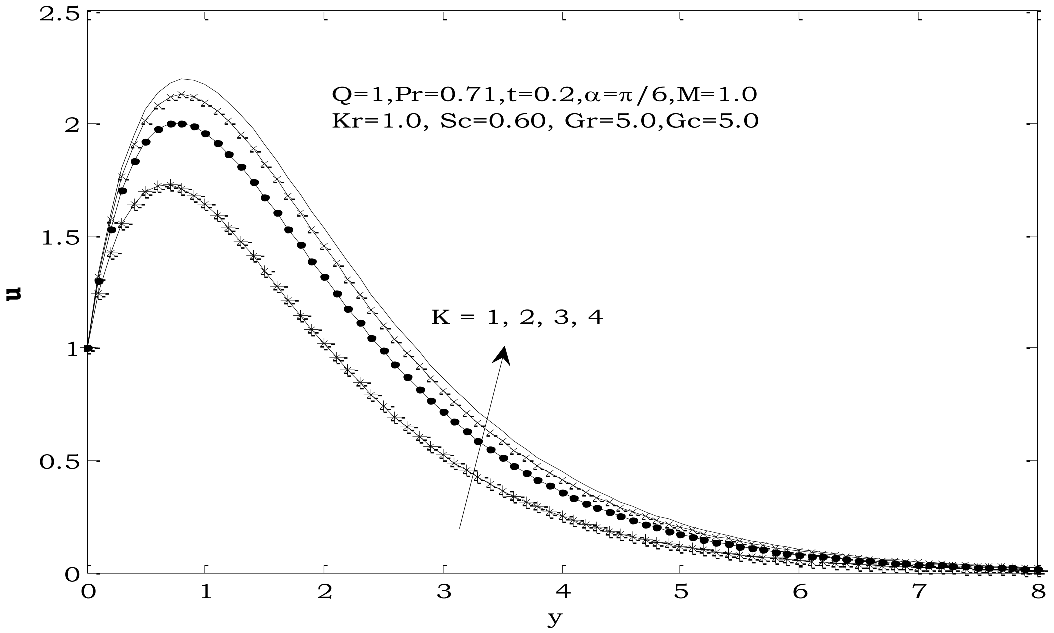

Figure (6): Velocity profiles for different values of K

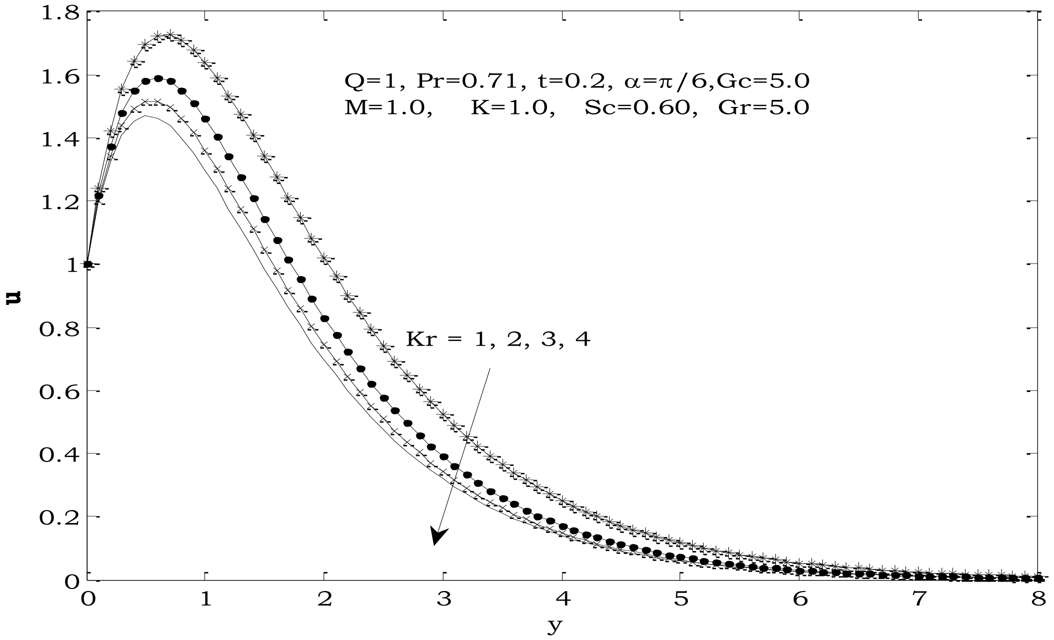

Figure (7): Velocity profiles for different values of Kr

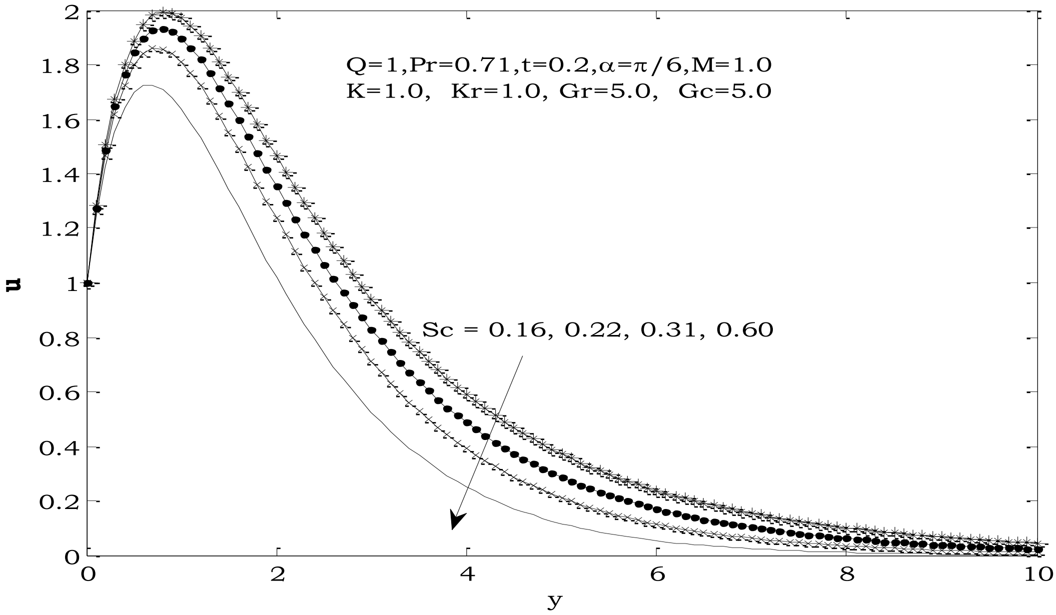

Figure (8): Velocity profiles for different values of Sc

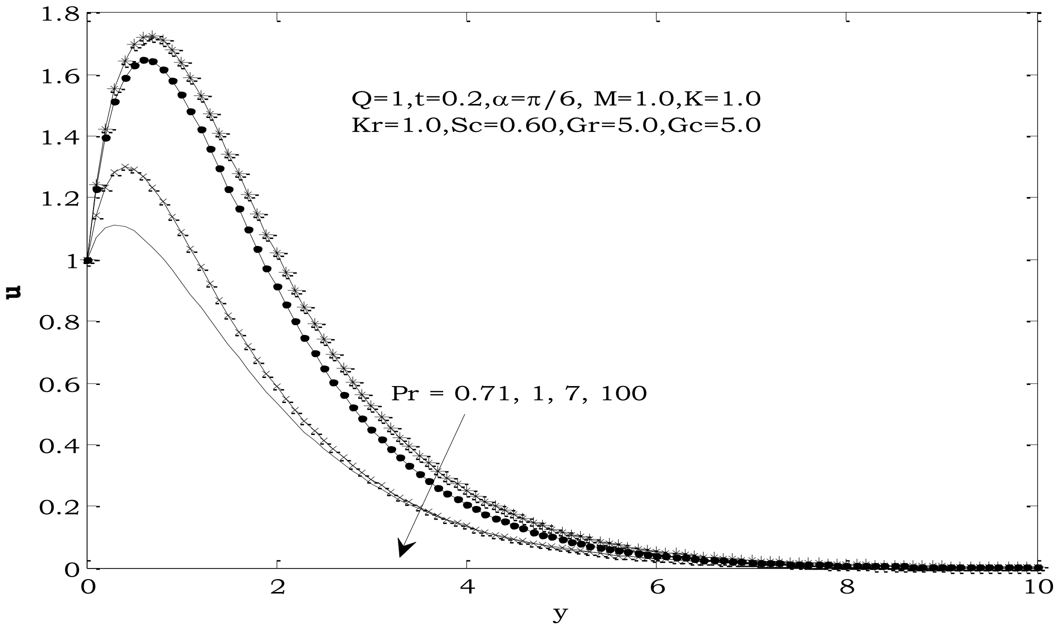

Figure (9): Velocity profiles for different values of Pr

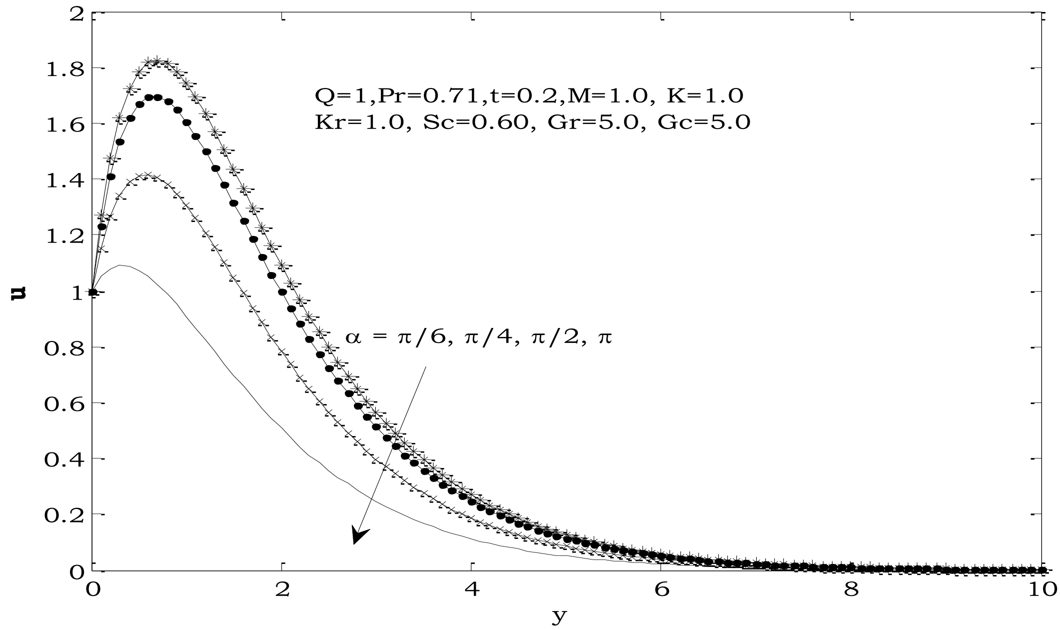

Figure (10): Velocity profiles for different values of α

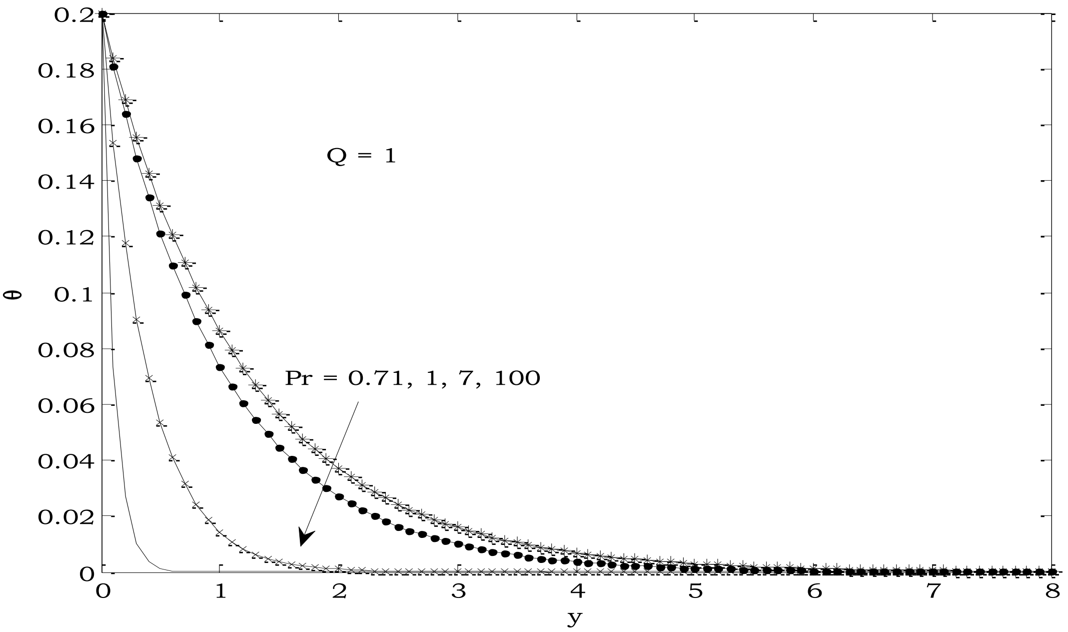

Figure (11): Temperature profiles for different values of Pr

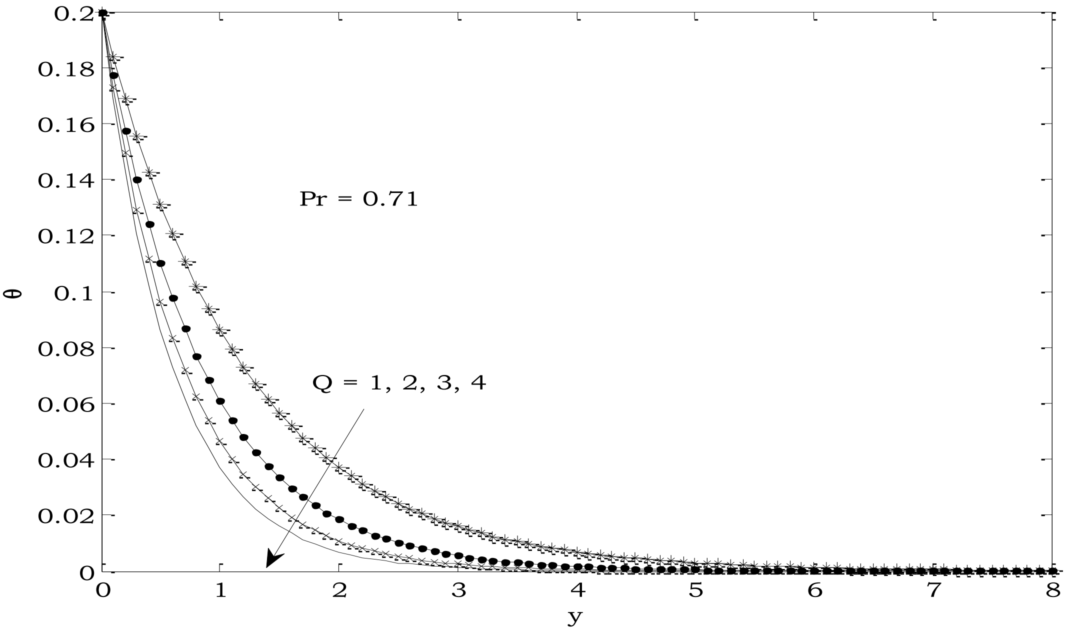

Figure (12): Temperature profiles for different values of Q

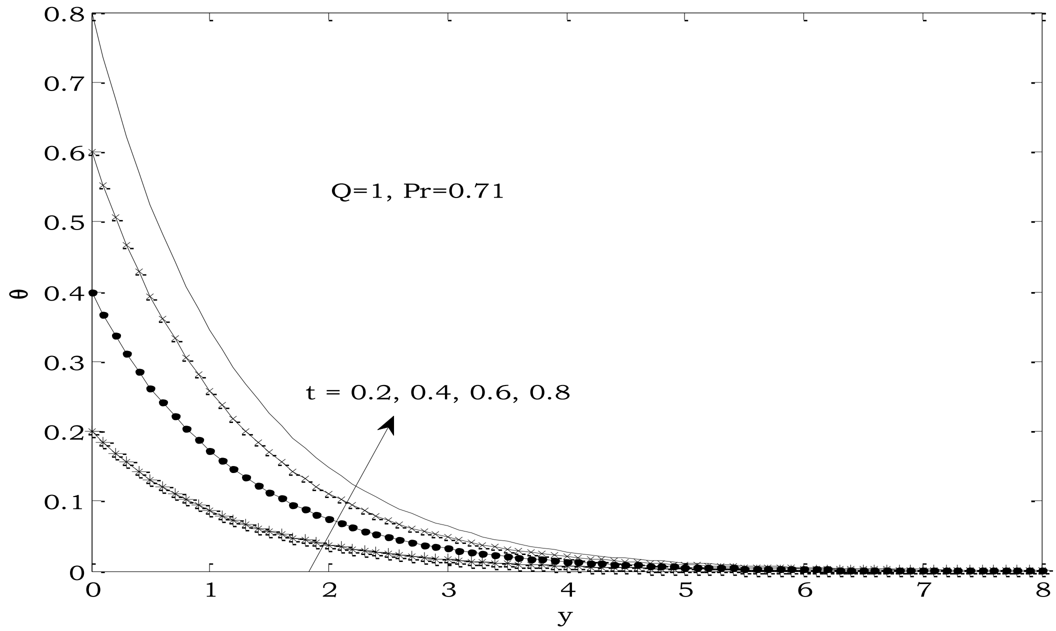

Figure (13): Temperature profiles for different values of t

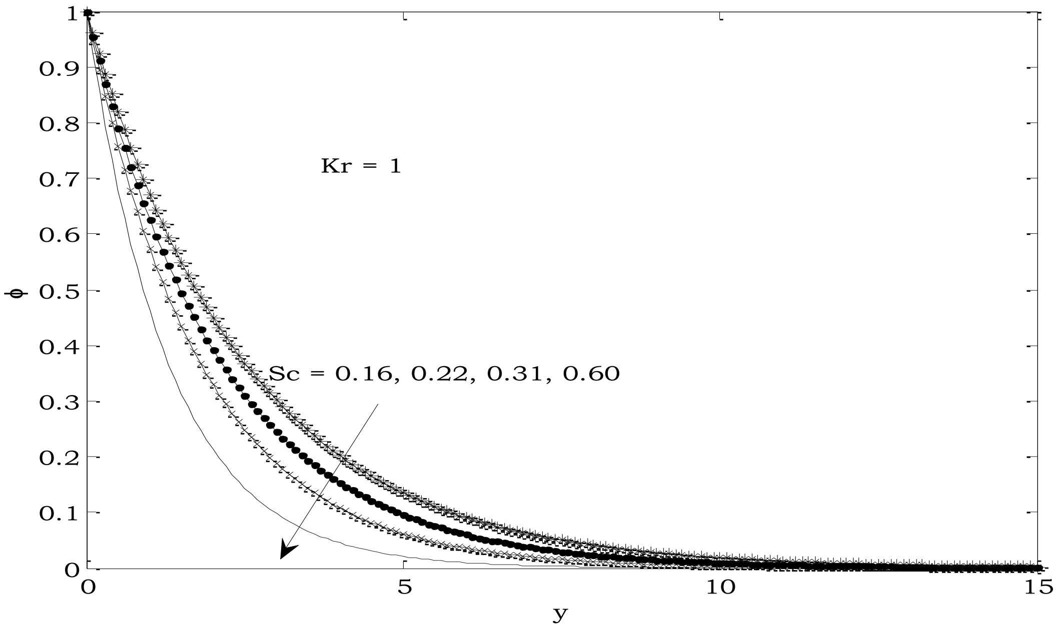

Figure (14): Concentration profiles for different values of Sc

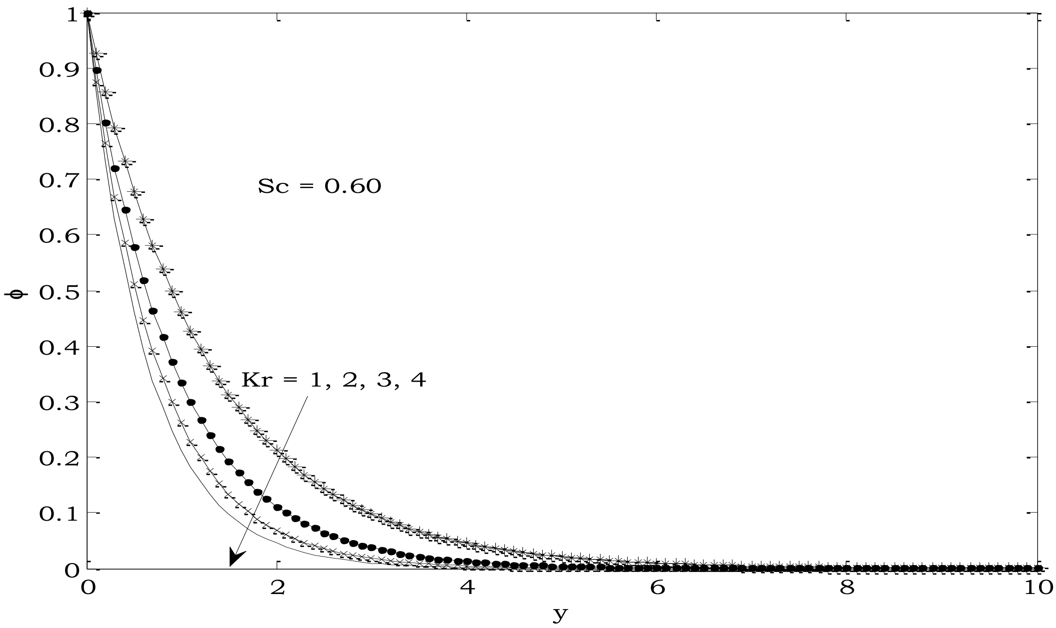

Figure (15): Concentration profiles for different values of γ