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Research Article

Heat and Mass Transfer Effects on MHD Free Convection Flow over an Inclined Plate Embedded in a Porous Medium

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ABSTRACT:

The aim of this study is to present an exact analysis of combined effects of radiation and chemical reaction on the magnetohydrodynamic (MHD) free convection flow of an electrically conducting incompressible viscous fluid over an inclined plate embedded in a porous medium. The 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 closed analytical method. Expressions for velocity, temperature and concentration fields are obtained. They satisfy all imposed initial and boundary conditions and can be reduced, as special cases, to some known solutions from the literature. Expressions for skin friction, Nusselt number and Sherwood number are also obtained. Finally, the effects of pertinent parameters on velocity, temperature and concentration profiles are graphically discussed.

1. INTRODUCTION

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, fiber and granular insulation and geothermal systems [1–3]. Some recent attempts in this area of research are given in [4–7]. On the other hand, considerable interest has been developed in the study of interaction between magnetic field and the flow of electrically conducting fluids in a porous medium due to its applications in modern technology [8]. Toki et al. [9] have studied the unsteady free convection flows of incompressible viscous fluid near a porous infinite plate with arbitrary time dependent heating plate. The effects of chemical reaction in two dimensional steady free convection flow of an electrically conducting viscous fluid through a porous medium bounded by vertical surface with slip flow region has been studied by Senapati1 et al. [10]. Khan et al. [11] analyzed the effects of radiation and thermal diffusion on MHD free convection flow of an incompressible viscous fluid near an oscillating plate embedded in a porous medium. The influence of magnetic field on the other hand is observed in several natural and human-made flows. 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. Recently, Turkyilmazoglu and Pop [12] extended the work of Ahmad [13] by introducing a heat source term and by taking two different types of thermal boundary conditions namely prescribed wall temperature and prescribed heat flux. In their exact analysis, they found that the solutions of

Ahmad [13] are not error free, therefore, they used a better approach in the formulation and used a proper radiation term. Furthermore, the free convection flow over vertical surfaces immersed in porous media has paramount importance because of its potential applications in soil physics, geo-hydrology, and filtration of solids from liquids, chemical engineering and biological systems [14].

Osman et al. [15] studied analytically the thermal radiation and chemical reaction effects on unsteady MHD free convection flow in a porous medium with heat source/sink. By taking the porous medium effect, Sami et al. [16] provided an exact analysis to the study of the magnetohydrodynamic free convection flow of an incompressible viscous fluid past an infinite vertical oscillating plate with uniform heat flux. Makinde [17] have discussed the chemically reacting hydromagnetic unsteady flow of a radiating fluid past a vertical plate with constant heat flux. Olanrewaju et al [18] were investigated an unsteady mixed convection with Soret and Dufour effects past a porous plate moving through a binary mixture of chemically reacting fluid. Khan et al [19] studied the Magnetohydrodynamic free convection flow past an oscillating plate embedded in a porous medium. Pal and Mondal [20] investigated the MHD non-Darcian mixed convection heat and mass transfer over a non-linear stretching sheet with Soret-Dufour effects and chemical reaction. Chemical reaction and radiation effects on the transient MHD free convection flow of dissipative fluid past an infinite vertical porous plate with ramped wall temperature has presented by Rajesh [21].

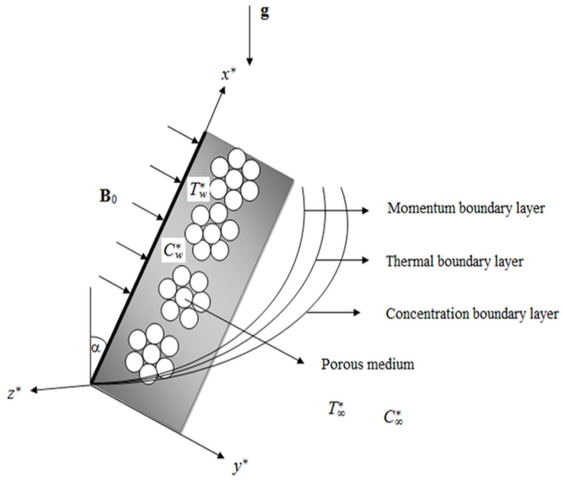
Rama Chandra Prasad et al [22] studied the thermal radiation effects on magnetohydrodynamic free convection heat and mass transfer from a sphere in a variable porosity regime. Magyari and Pantokratoras [23] have analysed the effect of thermal radiation in the linearized Rosseland approximation on the heat transfer characteristics of various boundary layer flows. Analytic heat and transfer of the mixed hydrodynamic/ thermal slip MHD viscous flow over a stretching sheet has presented by Turkyilmazoglu [24]. Chandrakala [25] have investigated the radiation effects on flow past an impulsively started vertical oscillating plate with uniform heat flux.

Narahari and Yunus [26] were presented the free convection flow past an impulsively started infinite vertical plate with Newtonian heating in the presence of thermal radiation and mass diffusion. Seth et al [27] studied the MHD natural convection flow with radiative heat transfer past an impulsively moving plate with ramped wall temperature. Mishra et al [28] were investigated the mass and heat transfer effect on MHD flow of a visco-elastic fluid through porous medium with oscillatory suction and heat source. Jingchun and Lining [29] have considered the coupled heat and mass transfer during moisture exchange across a membrane. Ramana Reddy et al [30] have investigated the Unsteady MHD free convection flow and mass transfer near a moving vertical plate in the presence of thermal radiation. Ziyauddin and Kumar [31] studied the radiation effects on unsteady MHD natural convection flow in a porous medium with conjugate heat and mass transfer past a moving inclined plate in the presence of chemical reaction, variable temperature and mass diffusion.

In this paper we have developed closed form analytical solutions for the unsteady MHD free convection flow of a viscous fluid over an inclined plate with variable heat and mass transfer in a porous medium. In fact, the present model is more general as it considers the fluid to be optically thick instead of optically thin and takes into account chemical reaction, porous medium, variable temperature at the wall and the plate is inclined at a certain angle with vertical axis.

Moreover, the results for skin friction, Nusselt number and Sherwood number are also evaluated and their computational results are shown in graphically.

2. Formulation of the Problem



Physical configuration 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 of inclination α to the vertical and the $y'-$axis is taken 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 of strength 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. This assumption is physically justified for partially ionized fluids and metallic liquids because of their small magnetic Reynolds number. Since there is no applied or polarization voltage imposed on the flow field, the electric field due to polarization of charges is zero. Initially, both the fluid and the plate are at rest with constant temperature T'_∞ and constant concentration C'_∞. At time $t' > 0$, the 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 (x', z') plane, all physical variables are functions of y' and t' only. The physical model and coordinates system is shown in Fig. 1.

In view of the above assumptions, as well as of the usual Boussinesq's approximation, the unsteady flow is governed by the following equations:

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

$$\frac{\partial T'}{\partial t'} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y'} \quad (2)$$

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

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

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

$$t' > 0 : \begin{cases} u' = U_0,\ T' = T'_\infty + \left(T'_w - T'_\infty\right)At', C' = C'_\infty + \left(C'_w - C'_\infty\right)At' & \text{at } y' = 0 \\ u' = 0,\ \ T' = T'_\infty, C' = C'_\infty & \text{as } y' \to \infty \end{cases} \quad (4)$$

where $A = \frac{U_0^2}{\nu}$, u' is the axial velocity, T' is the temperature of the fluid, C' is the species concentration, q_r is the radiation heat flux, x' and y' are the dimensional distances 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^* is the permeability of the porous medium, g is the acceleration due to gravity, β is the coefficient of thermal expansion, β^* is the coefficient of concentration expansion, C_p is the specific heat at constant pressure, κ is the thermal diffusivity, D is the mass diffusivity and K_r^* is the chemical reaction constant.

We adopt the Rosseland approximation for radiative heat flux q_r, namely

$$q_r = -\frac{4\sigma_0}{3k^*}\frac{\partial T^{*^4}}{\partial y^*} \quad (5)$$

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

$$T'^4 \cong 4T'^3_\infty T' - 3T'^3_\infty \quad (6)$$

From equations (5) and (6), equation (2) reduces to

$$\rho C_p \frac{\partial T'}{\partial y'} = \kappa\frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma_0 T'^3_\infty}{3k^*}\frac{\partial^2 T'}{\partial y'^2} \quad (7)$$

On introducing the following non-dimensional quantities

$$u=\frac{u'}{U_0},t=\frac{t'U_0^2}{\nu},y=\frac{y'U_0}{\nu},\theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},\quad \phi=\frac{C'-C'_\infty}{C'_w-C'_\infty}, \tag{8}$$

we get the following governing equations which are dimensionless

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

$$\frac{\partial \theta}{\partial t}=\left(\frac{1+N}{\Pr}\right)\frac{\partial^2\theta}{\partial y^2} \tag{10}$$

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

The initial and boundary conditions in dimensionless form are as follows:

$$t\le 0:\quad u=0,\quad \theta=0,\quad \phi=0 \quad \text{forall} \quad y>0$$

$$t>0,\ \begin{cases} u=1, & \theta=t, & \phi=t & \text{at } y=0 \\ u\to 0, & \theta\to 0 & \phi\to 0 & \text{as } y\to\infty \end{cases} \tag{12}$$

$$Gr=\frac{g\beta\nu(T'_w-T'_\infty)}{U_0^3},Gm=\frac{g\beta^*\nu(C'_w-C'_\infty)}{U_0^3},\Pr=\frac{\mu C_p}{k},$$

$$K=\frac{U_0^2K^*}{\nu^2},Sc=\frac{\nu}{D},M=\frac{\sigma B_0^2\nu}{\rho U_0^2},N=\frac{16\sigma T'^3_\infty}{3\kappa k^*},\gamma=\frac{K'_r\nu}{U_0^2},$$

where $M, K, Gr, Gm, N, \Pr, Sc$ and γ denote the magnetic parameter (Hartmann number), permeability parameter, thermal Grashof number, mass Grashof number, radiation parameter, Prandtl number, Schmidt number and chemical reaction parameter respectively.

3. Solution of the Problem

In order to reduce the above system of partial differential equations to a system of ordinary equations in dimensionless form, we may represent the velocity, temperature and concentration as

$$u(y,t)=u_0(y)e^{\omega t} \tag{13}$$

$$\theta(y,t)=\theta_0(y)e^{\omega t} \tag{14}$$

$$\phi(y,t)=\phi_0(y)e^{\omega t} \tag{15}$$

Substituting Eqns (13), (14) and (15) in Eqns (9), (10) and (11), we obtain:

$$u_0''-k_1^2u_0=-\left[Gr\theta_0+Gm\phi_0\right]\cos\alpha \tag{16}$$

$$\theta_0''-k_2^2\theta_0=0 \tag{17}$$

$$C_0''-k_3^2C_0=0 \tag{18}$$

Here the primes denote the differentiation with respect to y.
The corresponding boundary conditions can be written as

$$\begin{aligned} &u_0 = e^{-\omega t} \quad \theta_0 = te^{-\omega t}, \ \phi_0 = te^{-\omega t} \qquad \text{at} \quad y = 0 \\ &u_0 \to 0, \quad \theta_0 \to 0, \quad \phi_0 \to 0 \qquad \text{as} \quad y \to \infty \end{aligned} \tag{19}$$

The analytical solutions of equations (16) – (18) with satisfying the boundary conditions (19) are given by

$$u_0(y) = A_3 e^{-N_3 y} e^{-i\omega t} + \left(A_1 e^{-N_2 y} + A_4 e^{-N_1 y}\right) t e^{-i\omega t} \tag{20}$$

$$\theta_0(y) = \left(te^{-N_2 y}\right) e^{-i\omega t} \tag{21}$$

$$\phi_0(y) = \left(t\,\mathrm{e}^{-N_1 y}\right) e^{-i\omega t} \tag{22}$$

In view of the above solutions, the velocity, temperature and concentration distributions in the boundary layer become

$$u(y,t) = k_6 e^{-k_1 y} + k_4 e^{-k_2 y} + k_5 e^{-k_3 y} \tag{23}$$

$$\theta(y,t) = te^{-k_2 y} \tag{24}$$

$$\phi(y,t) = t\,\mathrm{e}^{-k_3 y} \tag{25}$$

It is now important to calculate the physical quantities of primary interest, which are the local wall shear stress, the local surface heat, and mass flux. Given the velocity field in the boundary layer, we can now calculate the local wall shear stress (i.e., skin- friction) is given by

$$C_f = -\left(\frac{\partial u}{\partial y}\right)_{y=0} = k_6 k_1 + k_4 k_2 + k_5 k_3$$

From temperature field, now we study the rate of heat transfer which is given in non -dimensional form as:

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = tk_2$$

From concentration field, now we study the rate of mass transfer which is given in non -dimensional form as:

$$Sh = -\left(\frac{\partial \phi}{\partial y}\right)_{y=0} = tk_3$$

Here constants are not given due shake of brevity.

4. RESULTS AND DISCUSSION

In order to reveal the effects of various parameters on the dimensionless velocity field, temperature field, concentration field, skin friction, Nusselt number and Sherwood number. The effects of material parameters such as Magnetic Parameter (Hartmann number M), Prandtl number (Pr), permeability parameter (K), Grashof number (Gr), modified Grashof number (Gm), radiation parameter (N), Schmidt number (Sc), chemical reaction parameter (γ), inclination angle (α) and dimensionless time (t) on velocity profiles, Prandtl number (Pr) and radiation parameter (N) on temperature profiles, Schmidt number (Sc), chemical reaction parameter (γ) and time (t) on concentration profiles, inclination angle (α) and time (t) on skin friction, Nusselt number and Sherwood number are examined in Figs. 2–20. The influence of these parameters on skin friction, Nusselt number and Sherwood number are also shown in Tables 1–3. The graphical results are plotted using some built-in functions in the computational software MatLab. During the numerical computation of velocity and temperature fields, the values of the Prandtl number are chosen as Pr =0.71 (air) and Pr = 7.0 (water), which are the most encountered fluids in nature and frequently used in engineering and industry. Figure 2 reveals the effect of magnetic parameter (M) on velocity profiles in the case of cooling of the plate (Gr > 0). It is evident from the figure that the velocity decreases with an increasing of the magnetic parameter (M). Physically, it is justified because the application of transverse magnetic field always results in a resistive type force called Lorentz force which is similar to drag force and tends to resist the fluid motion, finally reducing its velocity. Figure 3 shows the velocity distribution against for different values of permeability parameter *K*. It is observed that the velocity increases with an increasing permeability parameter due to which the drag force decreases and hence velocity increases.

Figure 4 shows that the effect of velocity profile for different values of thermal Grashof number (Gr). It is observed that an increase in thermal Grashof number Gr leads to an increase in the velocity due to the enhancement in buoyancy forces. Actually, the thermal Grashof number signifies the relative importance of buoyancy force to the viscous hydrodynamic force. Increase of Grashof number (Gr) indicates small viscous effects in the momentum equation and consequently, causes increase in the velocity profiles.

Figure 5 shows the variation of velocity distribution with different values of modified Grashof number. The modified Grashof number Gm defines the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a maximum value in the neighborhood of the plate and then decreases properly to approach the free stream value. Figure 6 illustrates the influence of inclination angle (α) on velocity profiles. It is observed that the velocity profiles decreases with an increasing inclination angle (α).

The influence of Schmidt number (Sc) on the velocity and concentration profiles is shown figures 7 and 8 respectively. Graphical results of velocity and concentration profiles for different values of Schmidt number Sc shows that an increase in Sc, decreases the velocity and concentration profiles. Physically this is true because of the fact that the water vapors can be used for maintaining normal concentration field whereas Hydrogen can be used for maintaining effective concentration field.

Figure 9 and 10 are illustrates the effect of velocity and temperature profiles for different values of Prandtl number ***Pr***. It is observed that the velocity and temperature increases with an increasing the Prandtl number due increasing viscous nature of the fluid. For smaller values of Pr fluids possess high thermal conductivity and heat diffuses away from the surface faster than at higher values of Pr.

The velocity and temperature profiles for different values of radiation parameter (N) are as shown in figures 11 and 12 respectively. It can be observed that the fluid pressure decreases as the radiation parameter increases on the velocity profiles. Also, it is noticed that the radiation parameter (N) increases the temperature profiles decreases.

Figure 13 and 14 displays the effects of the chemical reaction parameter (γ) on the velocity and concentration profiles. It is observed that the velocity and concentration profiles are decreases with increasing of the chemical reaction parameter. Figure 15 shows that the effect of concentration profiles for different values of time (t). It is observed that the concentration profiles are increases when time is increased. Moreover, this figure provides a check of our analytical solution for concentration field. It is found that to be in good agreement with boundary condition given in equation (12).

The influence of time on Skin friction with respect to the magnetic parameter is shown graphically in Figure 15. It is observed that the skin-friction decrease whereas time increases. The consolidated contribution of the inclination angle and magnetic parameter on the skin friction is illustrated graphically in Figure 16. In general, it is seen that as the inclination parameter is increased, the skin friction also increases.

CONCLUSIONS

In this paper we have studied an analytical solutions corresponding to the phenomenon of heat and mass transfer on MHD free convection flow of an electrically conducting incompressible viscous fluid over an inclined plate with variable heat and mass transfer passing through porous medium are obtained by closed analytical method. The effects of radiation and chemical reaction are also considered and required expressions for skin-friction, Nusselt number and Sherwood number are obtained. The accuracy of the obtained solutions is checked through imposed conditions and graphs. Furthermore, some well known established results from the literature are obtained as limiting cases from the present solutions. Numerical results for the velocity field, temperature field and concentration field are graphically displayed. The comparison for the present numerical results of skin-friction and Nusselt number are shown in graphically. The following main results are concluded from this study:

- The effects of the permeability and magnetic parameters on velocity are opposite.
- Velocity increases with increasing K, Gr, Gm, Pr and t.
- Velocity decreases with increasing M, Sc, N, γ and α.
- Temperature increases with increasing Pr and decreases if N increases.
- Concentration decreases with increasing γ and Sc.

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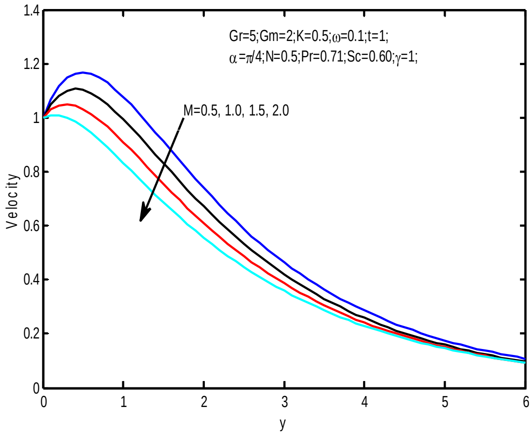

Fig.2. Velocity profiles for different values of Magnetic parameter (M)

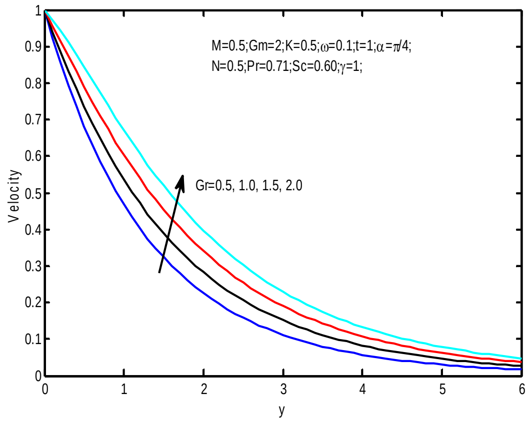

Fig.4. Velocity profiles for different values of Grashof number (Gr)

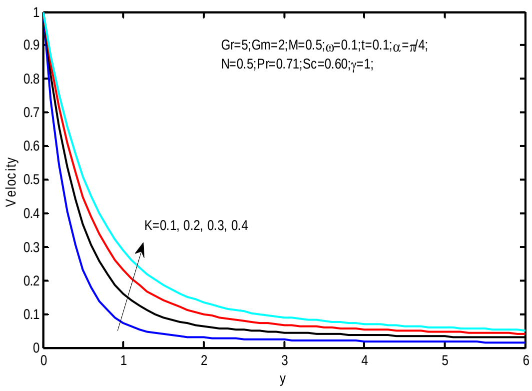

Fig.3. Velocity profiles for different values of Permeability parameter (K)

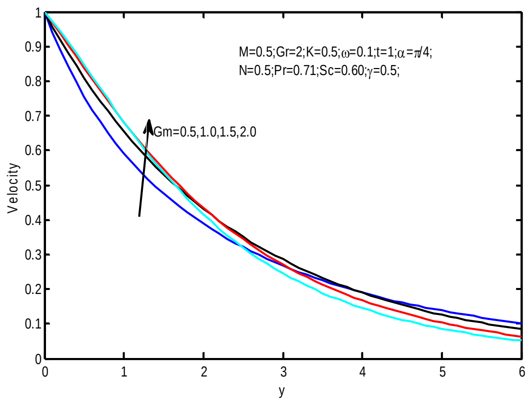

Fig.5. Velocity profiles for different values of modified Grashof number (Gm)

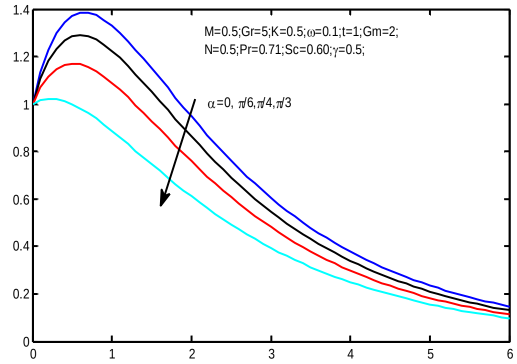

Fig.6. Velocity profiles for different values of Inclination parameter (α)

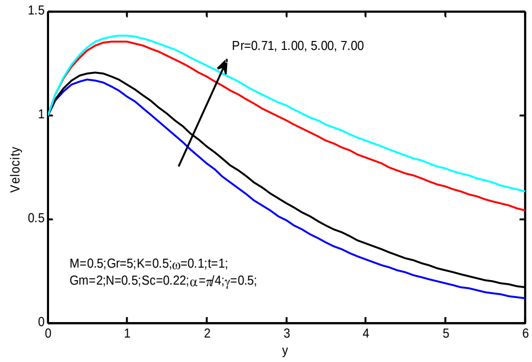

Fig.9. Velocity profiles for different values of Prandtl number (Pr)

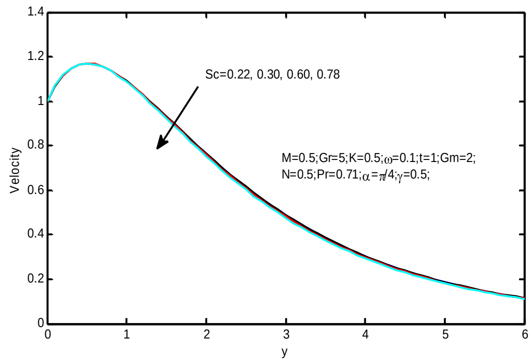

Fig.7. Velocity profiles for different values of Schmidt number (Sc)

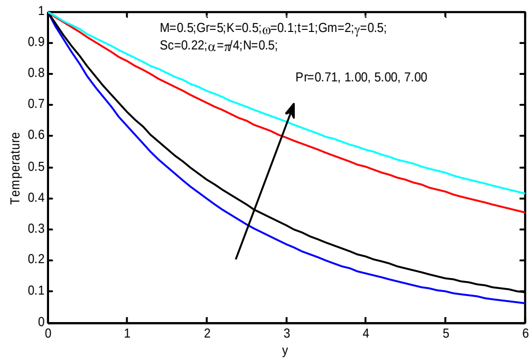

Fig.10. Temperature profiles for different values of Prandtl number (Pr)

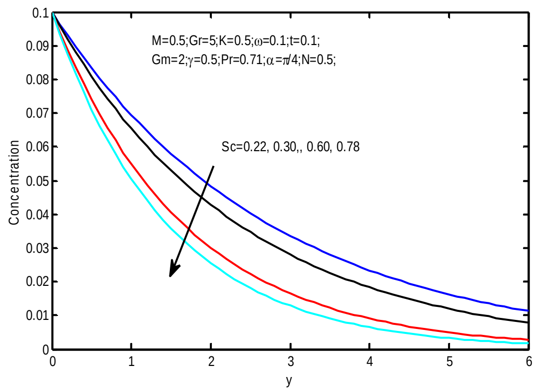

Fig.8. Concentration profiles for different values of Schmidt number (Sc)

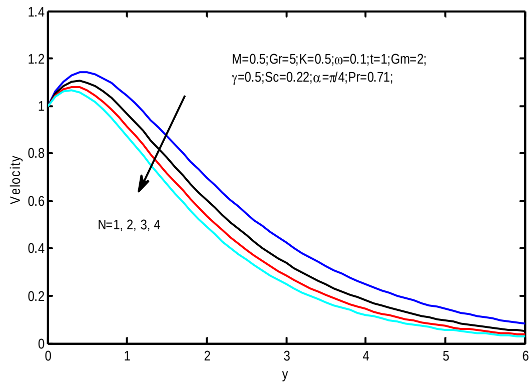

Fig.11. Velocity profiles for different values of Radiation parameter (N)

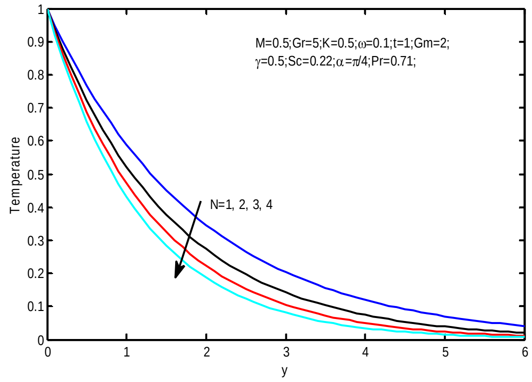

Fig.12. Temperature profiles for different values of Radiation parameter (N)

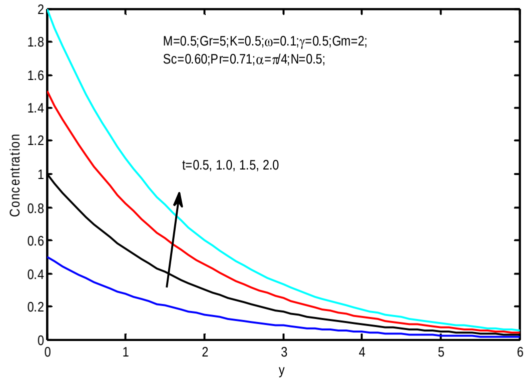

Fig.15. Concentration profiles for different values of time (t)

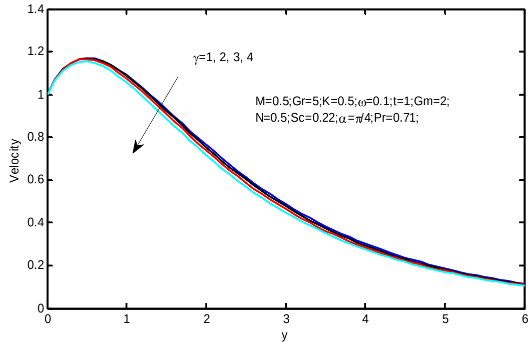

Fig.13. Velocity profiles for different values of Chemical reaction parameter (γ)

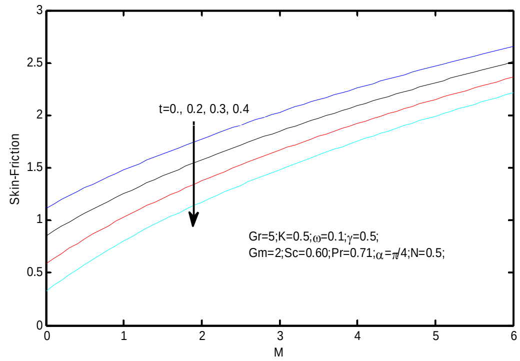

Fig.16. Skin-friction profiles for different values of time (t)

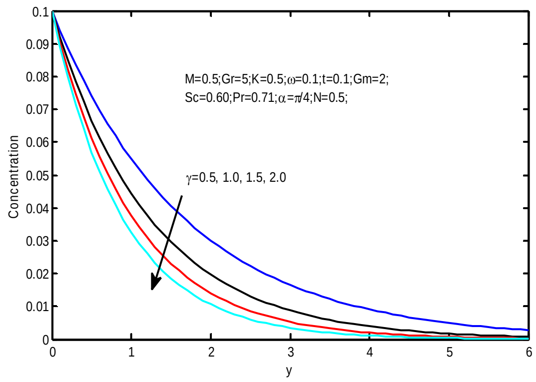

Fig.14. Concentration profiles for different values of Chemical reaction parameter (γ)

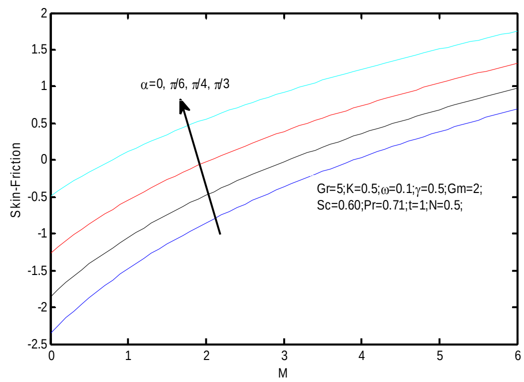

Fig.17. Skin-friction profiles for different values of inclination parameter (α)