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Radiation and Joul Dissipation Effects on Chemically Reacting Unsteady MHD Convective Heat and Mass Transfer Flow past a Semi-infinite Vertical Permeable Plate Embedded in a Porous Medium

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ABSTRACT

Aim of the paper is to investigate effect of thermal radiation on the unsteady, two-dimensional, laminar, boundary layer, heat and mass transfer flow of a viscous, incompressible, electrically conducting fluid past a semi-infinite vertical permeable plate in the presence of a uniform transverse magnetic field with Joul and viscous dissipation effects, taking into account of the homogeneous chemical reaction of first order. The governing equations are solved analytically using successive perturbation technique. Numerical evaluation of the results for velocity, temperature and concentration profiles for various values of physical parameter are shown through graphs and numerical values of the skin-friction coefficient, Nusselt number and Sherwood number are presented through table and discussed numerically.

Keywords : Unsteady; MHD; thermal radiation; chemical reaction; mass transfer; porous medium

INTRODUCTION

The interaction of heat and mass transfer with magnetic field has attracted the interest of many researches in view of its applications in MHD generators, plasma studies, nuclear reactors, geophysics and astrophysics. Gribben studied boundary layer flow over a semi-infinite plate with an aligned magnetic field in the presence of a pressure gradient [9]. He obtained solutions for large and small magnetic Prandtl numbers using the method of matched asymptotic expansion. Soundalgekar obtained approximate solution for two dimensional flow of an incompressible, viscous fluid past an infinite porous vertical plate with constant suction velocity, the difference between the temperature of the plate and the free stream is moderately large causing free convection currents [23]. Bejan and Khair treated one of the most fundamental cases, namely buoyancy induced heat and mass transfer from a vertical plate embedded in a saturated porous medium [3]. Raptis studied time varying two dimensional natural convective flow of an incompressible electrically conducting fluid along an infinite vertical porous plate embedded in a porous medium [17]. Elbashbeshy studied heat and mass transfer along a vertical plate under the combined buoyancy effects of thermal and species diffusion, in the presence of magnetic field [7]. Helmy discussed MHD unsteady free convection flow past a vertical porous plate embedded in a porous plate [10]. Kim considered unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction by assuming that the free stream velocity follows the exponentially increasing small perturbation law [13]. Chamkha analyzed the chemical reaction effects on heat and mass transfer laminar boundary layer flow in presence of heat generation/absorption [4]. The combined heat and mass transfer of an electrically conducting fluid in MHD natural convection adjacent to a vertical surface was presented by Chen [5] . Effects of radiation on free convective flow and mass transfer past a vertical isothermal cone surface with chemical reaction in the presence of a transverse magnetic field was discussed by Afify [1].

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Muthucumaraswamy and Chandra Kala studied effects of radiation on moving isothermal vertical plate in presence of chemical reaction[14]. Ogulu et al. considered the effects of magnetic field on heat transfer flow past an infinite moving vertical plate with variable suction[15]. Jordan discussed the effects of viscous dissipation and radiation on unsteady MHD free convection flow past a vertical plate[12]. Alom et al. considered steady MHD heat and mass transfer by mixed convection flow from a moving vertical porous plate with induced magnetic, thermal diffusion, constant heat and mass fluxes[2]. Sharma and Sharma investigated the effects of mass transfer on three- dimensional unsteady mixed convective flow past an infinite vertical moving porous plate with periodic suction [22]. Sharma and Mehta discussed radiative and free convective effects on MHD flow through porous medium between infinite porous plates with periodic cross flow velocity [21]. Ibrahim and Mikinde discussed the radiation effect on chemically reacting MHD boundary layer flow of heat and mass transfer through a porous vertical flat plate [11]. Sharma et al. analyzed the effect of thermally stratified ambient fluid on MHD convective flow along a moving non-isothermal vertical plate [20]. Effects of radiation and viscous dissipation on MHD flow of a chemically reacting fluid past a vertical plate have been presented by Suneetha and Reddy [25]. Sharma and Katta discussed mass transfer effect on unsteady mixed convective flow and heat transfer along an infinite vertical plate bounded with porous medium [19]. Gangadhar considered radiation and viscous dissipation effects on chemically reacting MHD boundary layer flow of heat and mass transfer through a porous vertical flat plate [8]. Sharma et al. presented mass transfer with chemical reaction in MHD mixed convection flow along a vertical stretching sheet[18] .Olajuwon and Oahimire studied the effects of thermo-diffusion and thermal radiation on unsteady heat and mass transfer of free convective MHD micropolar fluid flow bounded by a semi-infinite porous plate in a rotating frame under the action of transverse magnetic field with suction[16].

Unsteady two-dimensional, laminar, mixed convective boundary layer flow of a viscous, incompressible and electrically conducting fluid past a semi-infinite vertical permeable plate, embedded in a uniform porous medium and subjected to a uniform transverse magnetic field in presence of radiation and Joul effect with mass transfer and thermal and concentration buoyancy effects is investigated taking in account of the homogenous chemical reaction of first order.

Formulation of the Problem

The x*-axis is taken along the vertical plate and the y*-axis normal to the plate. It is assumed that there is no applied voltage, which implies the absence of an electric field. The transverse applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and the Hall effect are negligible [Soundalgekar (23)]. The concentration for the diffusing species in the binary mixture is assumed to be very small in comparison with the other present chemical species present , and hence the Soret and Dufor effects are negligible. It is assumed that the permeable plate is stationary with periodic temperature, periodic mass concentration and free stream velocity oscillates with time.

Further due to the semi-infinite plane surface assumption, the flow variables are functions of y* and t* only. Now, under the usual Bousssinesq approximation, the governing boundary layer equations for mass, momentum, energy and species conservation are

$$\frac{\partial v^*}{\partial y^*} = 0, \qquad ...(1)$$

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \upsilon\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta T^* + g\beta^* C^* - \upsilon\frac{u^*}{K^*} - \frac{\sigma}{\rho}B_0^2 u^*, \qquad ...(2)$$

$$\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho C_p}\left[\frac{\partial^2 T^*}{\partial y^*} - \frac{1}{\kappa}\frac{\partial q^*}{\partial y^*}\right] + \frac{\mu}{\rho C_p}\left(\frac{\partial u^*}{\partial y^*}\right)^2 + \frac{\sigma B_0^2}{\rho C_p}[u^* - U_\infty(t^*)]^2, \qquad ...(3)$$

$$\frac{\partial C^*}{\partial t^*}+v^*\frac{\partial C^*}{\partial y^*}=D\frac{\partial^2 C^*}{\partial y^{*2}}-K_r(C^*-C_\infty), \quad \text{....(4)}$$

where u^*, v^* are the velocity components in x*, y* directions respectively, t* the time, p* the pressure, ρ^* the fluid density, g the acceleration due to gravity, β *and* β^* the thermal and concentration expansion coefficients respectively, K* the permeability of the porous medium, T* the temperature of the fluid, υ the kinematics viscosity, σ the electrical conductivity of the fluid, T_∞ the temperature of the fluid far away from the plate, C* the species concentration in the boundary layer, C_∞ the species concentration in the fluid far away from the plate, B_0 the magnetic induction, κ the thermal conductivity, C_p the specific heat at constant pressure, q* the radiative heat flux, μ the coefficient of viscosity, D the mass diffusion coefficient, and K_r chemical reaction parameter. The last three terms on the right hand side of the energy equation (3) represents the radiative heat flux, viscous and Joul dissipations respectively.

The boundary conditions are

$$y^*=0 \quad : \quad u^*=0, \quad T^*=T_w+\in(T_w-T_\infty)e^{i\omega^* t^*},$$
$$C^*=C_w+\in(C_w-C_\infty)e^{i\omega^* t^*};$$

$$y^*\to\infty \quad : \quad u^*=U_\infty^*(t^*)=U_\infty(1+\in e^{i\omega^* t^*}),$$
$$T^*\to T_\infty, \quad C^*\to C_\infty. \quad \text{....(5)}$$

where T_w is the mean temperature of the wall, C_w is mean concentration near the wall, U_∞ is the mean free stream velocity and $\in$ (<<1) is a positive parameter.

From equation (1), it is clear that the suction velocity at the plate is independent of y*, hence the suction velocity normal to the plate is assumed of the form given below

$$v^*=-V_0(1+\in Ae^{i\omega^* t^*}), \quad \text{....(6)}$$

where A is a real positive constant and V_0 (>0) is mean cross-flow velocity. The negative sign indicates the suction through the wall.

Outside the boundary layer, equation (2) gives

$$-\frac{1}{\rho}\frac{\partial p^*}{\partial x^*}=\frac{dU_\infty^*}{dt^*}-g\beta T_\infty-g\beta^* C_\infty+\frac{\upsilon}{K^*}U_\infty^*+\frac{\sigma}{\rho}B_0^2U_\infty^* \quad \text{....(7)}$$

The fluid considered is a gray, emitting and absorbing radiation, but non-scattering medium and to be optically thick, hence the radiative heat flux term is simplified by using Rosseland approximation [Sparrow and Cess [24]] as given below

$$q^*=-\frac{4\sigma_s}{3K_e}\frac{\partial T^{*4}}{\partial y^*} \quad \text{...(8)}$$

where σ_s is Stefan-Boltzman constant and K_e is the mean absorption coefficient. Following Rosseland approximation, the present analysis is limited to optically thick fluid. If temperature difference within the flow are sufficiently small, then equation (8) can be linearized by expanding T^{*4} into the Taylor series about T_∞ which after neglecting higher order terms takes the form

$$T^{*4}\cong 4T_\infty^3T^*-3T_\infty^4. \quad \text{...(9)}$$

Method of Solution

Introducing the following dimensionless quantities

$$u=\frac{u^*}{U_\infty}, v=\frac{v^*}{V_0},\ y=\frac{V_0y^*}{\upsilon},\ t=\frac{t^*V_0^2}{\upsilon}, \theta=\frac{T^*-T_\infty}{T_w-T_\infty},$$
$$C=\frac{C^*-C_\infty}{C_w-C_\infty},\ K=\frac{K^*V_0^2}{\upsilon^2}, U_\infty=\frac{U_\infty^*}{U_\infty}, \Pr=\frac{\upsilon\rho C_p}{K},$$
$$Sc=\frac{\upsilon}{D}, M=\frac{\sigma B_0^2\upsilon}{\rho V_0^2}, Gr=\frac{\upsilon g\beta(T_w-T_\infty)}{U_\infty V_0^2}, \omega=\frac{\omega^*\upsilon}{V_0^2},$$

$$Gm=\frac{\upsilon g\beta^*(C_w-C_\infty)}{U_\infty V_0^2}, h=\frac{\Pr}{(1+R)}, R=\frac{16}{3}\frac{\sigma_sT_\infty^3}{\kappa K_e},$$
$$M+\frac{1}{K}=N, Ec=\frac{U_\infty^2}{C_p(T_w-T_\infty)}, K_r=\frac{K_r^*\upsilon}{V_0^2}, \quad \text{.....(10)}$$

into the equations (2) to (4) with equation (7) to (9), we get

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=\frac{dU_\infty}{dt}+\frac{\partial^2 u}{\partial y^2}+Gr\theta + GmC+N(U_\infty-u), \quad ...(11)$$

$$\frac{\partial \theta}{\partial t}+v\frac{\partial \theta}{\partial y}=\frac{(1+R)}{\Pr}\frac{\partial^2 \theta}{\partial y^2}+Ec\left(\frac{\partial u}{\partial y}\right)^2 + M.Ec[u-U_\infty]^2, \quad ...(12)$$

$$\frac{\partial C}{\partial t}+v\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-K_rC, \quad ....(13)$$

where $N=M+\frac{1}{K}$ and Gr is the thermal Grashof number, Gm is modified Grashof number, Pr is Prandtl number, Ec is Eckert number, R is radiation parameter, Sc is Schmidt number, K is permeability parameter, M is Hartmann number and K_r is chemical reaction parameter.

The corresponding dimensionless boundary conditions are

$$y=0 \quad : \quad u=0, v=-(1+\in Ae^{i\omega t}),\ \theta=1+\in e^{i\omega t},\ C=1+\in e^{i\omega t};$$
$$y\to\infty : \quad u=U_\infty(t)=1+\in e^{i\omega t},\ \theta\to 0,\ C\to 0. \quad ...(14)$$

Equations (11) to (13) are coupled, non-linear partial differential equation and these cannot be solved in a closed form. Assuming velocity, temperature and concentration of the fluid in the neighbourhood of the plate as given below

$$\left.\begin{aligned} u(y,t)&=u_0(y)+\in e^{i\omega t}u_1(y)+0(\in^2)\\ \theta(y,t)&=\theta_0(y)+\in e^{i\omega t}\theta_1(y)+0(\in^2)\\ C(y,t)&=C_0(y)+\in e^{i\omega t}C_1(y)+0(\in^2)\end{aligned}\right] \quad ...(15)$$

where u_0,θ_0 *and* C_0 denote steady part and u_1,θ_1 *and* C_1 show unsteady part. Substituting (15) into equations (11) to (13), in view of (14), equating the harmonic and non-harmonic terms and neglecting the higher order terms of $0(\in^2)$, we obtain

$$u_0''+u_0'-Nu_0=-Gr\theta_0-GmC_0-N, \quad ...(16)$$

$$u_1''+u_1'-(N+i\omega)u_1=-Gr\theta_1-GmC_1-Au_0'-(N+i\omega), \quad ...(17)$$

$$\theta_0''+h\theta_0'=-Ec\,hu_0'^2-M\ Ec\,h(u_0-1)^2, \quad ...(18)$$

$$\theta_1''+h\theta_1'-i\omega h\theta_1=-Ah\theta_0'-2Ec\,hu_0'u_1'-2M\ Ec\,h(u_0-1)(u_1-1), \quad ...(19)$$

$$C_0''+ScC_0'-K\,ScC_0=0, \quad ...(20)$$

$$C_1''+ScC_1'-(K+i\omega)ScC_1=-A\,ScC_0', \quad ...(21)$$

where prime denotes ordinary differentiation with respect to y. he corresponding boundary conditions are given by

$$y=0 \quad : \quad u_0=0,\ u_1=0,\ \theta_0=1,\ \theta_1=1,\ C_0=1,\ C_1=1;$$
$$y\to\infty : \quad u_0=1,\ u_1=1,\ \theta_0\to 0,\ \theta_1\to 0,\ C_0\to 0,\ C_1\to 0. \quad ...(22)$$

Equations (20) and (21) are ordinary second order differential equations and solved under the boundary conditions (22). Through straight forward calculations, the expressions of C_0 and C_1 are known and given by

$$C_0(y)=e^{-F_1y} \quad ...(23)$$

$$C_1(y)=(1-J_1)e^{-F_2y}+J_1e^{-F_1y} \quad ...(24)$$

The equations (16)-(19) are still coupled and non-linear second order differential equations whose solutions cannot be determined. Further, for incompressible fluid flows, the Eckert number is very small, therefore, u_0,u_1,θ_0 *and* θ_1 can be expanded in the power of Ec as follows

$$F(y)=F_0(y)+Ec\,F_1(y)+0(Ec^2), \quad ...(25)$$

where F stands for u_0,u_1,θ_0 *or* θ_1.

Substituting (25) into the equations (16)-(19), equating the terms free from Ec and coefficients of Ec, to zero and neglecting the terms in Ec^2 and higher order, we get the following system of ordinary differential equations

$$u_{00}''+u_{00}'-Nu_{00}=-Gr\theta_{00}-GmC_0-N, \quad ..(26)$$

$$u_{01}''+u_{01}'-Nu_{01}=-Gr\theta_{01}, \quad ...(27)$$

$$u_{10}''+u_{10}'-(N+i\omega)u_{10}=-Gr\theta_{10}-GmC_1-Au_{00}'-(N+i\omega), \quad ...(28)$$

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$$u''_{11} + u'_{11} - (N + i\omega)u_{11} = -Gr\theta_{11} - Au'_{01}, \quad ...(29)$$

$$\theta''_{00} + h\theta'_{00} = 0, \quad ...(30)$$

$$\theta''_{01} + h\theta'_{01} = -hu'^{2}_{00} - M\,h(u_{00} - 1)^2. \quad ...(31)$$

$$\theta''_{10} + h\theta'_{10} - i\omega h\theta_{10} = -Ah\,\theta'_{00}, \quad ...(32)$$

$$\theta''_{11} + h\theta'_{11} - i\omega\,h\theta_{11} = -A\,h\,\theta'_{01} - 2hu'_{00}u'_{10} - 2M\,h(u_{00} - 1)(u_{10} - 1). \quad ...(33)$$

The corresponding boundary conditions are

$$y = 0: \quad u_{00} = 0, u_{01} = 0, u_{10} = 0, u_{11} = 0, \quad \theta_{00} = 1, \theta_{01} = 0, \theta_{10} = 1, \theta_{11} = 0\ ;$$

$$y \to \infty : u_{00} \to 1, u_{01} \to 0, u_{10} \to 1, u_{11} \to 0, \quad \theta_{00} \to 0, \theta_{01} \to 0,\ \theta_{10} \to 0,\ \theta_{11} \to 0. \quad ...(34)$$

Equations (26) to (33) are ordinary second order coupled differential equations and solved under the boundary conditions (34).

Through straight forward calculations, the solutions of $u_{00}, u_{01}, u_{10}, u_{11}, \theta_{00},\ \theta_{01}, \theta_{10}$, $and\ \theta_{11}$ are known. Finally the expressions of $u(y,t), \theta(y,t)$ and $C(y,t)$ are known and given by

$$\begin{aligned} u(y,t) = {} & [(1 + J_2 e^{-F_3 y} + J_3 e^{-hy} + J_4 e^{-F_1 y}) \\ & + Ec(J_{12} e^{-F_3 y} + J_{13} e^{-hy} + J_{14} e^{-2F_3 y} + J_{15} e^{-2hy} \\ & + J_{16} e^{-2F_1 y} + J_{17} e^{-E_1 y} + J_{18} e^{-E_2 y} + J_{19} e^{-E_3 y})] \\ & + \in e^{i\omega t}[(1 + J_{21} e^{-F_5 y} + J_{22} e^{-F_4 y} + J_{23} e^{-hy} \\ & + J_{24} e^{-F_2 y} + J_{25} e^{-F_1 y} + J_{26} e^{-F_3 y}) + Ec(J_{44} e^{-F_5 y} \\ & + J_{45} e^{-F_4 y} + J_{46} e^{-hy} + J_{47} e^{-2F_3 y} + J_{48} e^{-2hy} \\ & + J_{49} e^{-2F_1 y} + J_{50} e^{-E_1 y} + J_{51} e^{-E_2 y} + J_{52} e^{-E_3 y} \\ & + J_{53} e^{-E_4 y} + J_{54} e^{-E_5 y} + J_{55} e^{-E_6 y} + J_{56} e^{-E_7 y} \\ & + J_{57} e^{-E_8 y} + J_{58} e^{-E_9 y} + J_{59} e^{-E_{10} y} + J_{60} e^{-E_{11} y} \\ & + J_{61} e^{-E_{12} y} + J_{62} e^{-F_3 y})], \quad ...(35) \end{aligned}$$

$$\begin{aligned} \theta(y,t) = {} & [e^{-hy} + Ec(J_5 e^{-hy} + J_6 e^{-2F_3 y} + J_7 e^{-2hy} \\ & + J_8 e^{-2F_1 y} + J_9 e^{-E_1 y} + J_{10} e^{-E_2 y} + J_{11} e^{-E_3 y})] \\ & + \in e^{i\omega t}[[(1 - J_{20}) e^{-F_4 y} + J_{20} e^{-hy}] + Ec[J_{27} e^{-F_4 y} \\ & + J_{28} e^{-hy} + J_{29} e^{-2F_3 y} + J_{30} e^{-2hy} + J_{31} e^{-2F_1 y} \\ & + J_{32} e^{-E_1 y} + J_{33} e^{-E_2 y} + J_{34} e^{-E_3 y} + J_{35} e^{-E_4 y} \\ & + J_{36} e^{-E_5 y} + J_{37} e^{-E_6 y} + J_{38} e^{-E_7 y} + J_{39} e^{-E_8 y} \\ & + J_{40} e^{-E_9 y} + J_{41} e^{-E_{10} y} + J_{42} e^{-E_{11} y} + J_{43} e^{-E_{12} y}]], \quad ...(36) \end{aligned}$$

$$C(y,t) = e^{-F_1 y} + \in e^{i\omega t}[(1 - J_1) e^{-F_2 y} + J_1 e^{-F_1 y}]. \quad ...(37)$$

SKIN FRICTION COEFFICIENT

The skin-friction coefficient, at the plate, is given by

$$C_f = \frac{\tau_w}{\rho U_\infty V_0} = \left(\frac{\partial u}{\partial y}\right)_{y=0} ; \tau_w = \mu\left(\frac{\partial u^*}{\partial y^*}\right)_{y^*=0},$$

$$= [J_{63} + EcJ_{64}] + \varepsilon e^{i\omega t}[J_{65} + EcJ_{66}]. \quad ...(38)$$

NUSSELT NUMBER

The rate of heat transfer in terms of Nusselt number at the plate is given by

$$Nu = \frac{q_w \upsilon}{\kappa V_0 (T_w - T_\infty)} = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} ; q_w = -\kappa\left(\frac{\partial T^*}{\partial y^*}\right)_{y^*=0},$$

$$= \left[h + EcJ_{67}\right] + \in e^{i\omega t}\left[J_{68} + EcJ_{69}\right]. \quad ...(39)$$

SHERWOOD NUMBER

The rate of mass transfer coefficient in terms of Sherwood number is given by

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$$Sh = \frac{m_w \upsilon}{D V_0 (C_w - C_\infty)}; \quad m_w = -D\left(\frac{\partial C^*}{\partial y^*}\right)_{y^*=0},$$

$$= -\left(\frac{\partial C}{\partial y}\right)_{y=0} = F_1 + \in e^{i\omega t} J_{70}. \qquad \ldots(40)$$

Here where $J_1\, to\, J_{70},\ F_1\, to\, F_5\ \ and\ \ E_1\, to\, E_{12}$ are constants and their expressions are not given here for sake of brevity.

RESULTS AND DISCUSSION

Numerical results are obtained to illustrate the influence of different values of the physical parameters on the velocity profiles, temperature profiles, concentration profiles, skin-friction coefficient, rate of heat transfer in terms of Nusselt number and rate of mass transfer in terms of Sherwood number. For numerical calculations, parameter $\in$ is valued as 0.02, ω is values as 5, ωt is valued as $\pi/6$ and A is valued as 0.5.

It is observed from figure 1 that fluid velocity increases due to increase of Grashof number for heat transfer or modified Grashof number for mass transfer or permeability parameter. Figure 2 represents that the velocity profiles increases due to increase of Eckert number or radiation parameter whereas velocity decreases due to increase in Hartmann number. It is noted from figure 3 that velocity decreases due to increase in Prandtl number, Schmidt number or chemical reaction parameter. Figure 4 illustrates that the temperature profiles increase due to increase in radiation parameter or Eckert number. It is seen from figure 5 that fluid temperature increases due to increase in Prandtl number upto Pr=5.0 whereas it decreases due to increase in Hartmann number or when Pr=7.0. Figure 6 shows that concentration profiles decrease due to increase in Schmidt number or chemical reaction parameter.

It is observed from Table1 that the skin-friction at the plate increases with the increase in Grashof number, modified Grashof number, permeability parameter, radiation parameter or Eckert number, while it decreases due to increase in Hartmann number, Prandtl number, Schmidt number or chemical reaction parameter. Nusselt number at the plate increases due to increase in Hartmann number, Schmidt number, chemical reaction parameter or Prandtl number, while it decreases due to increase in Grashof number, modified Grashof number, permeability parameter, Radiation parameter or Eckert number. Sherwood number at the plate increases due to increase in Schmidt number or chemical reaction parameter.

CONCLUSION

In view of the graphs and tables, the following conclusions are made :

- Fluid velocity increases with an increase in Grashof number, modified Grashof number, permeability parameter, Eckert number or radiation parameter whereas it decreases due to increase in Hartmann number, Prandtl number, Schmidt number or chemical reaction parameter.
- An increase in radiation parameter or Eckert number leads to increase in fluid temperature.
- It is observed that fluid temperature increases due to increase in Prandtl number upto Pr=5.0 whereas it decreases when Pr=7.0.
- An increase in Hartmann number leads to decrease in fluid temperature.
- Concentration profiles decrease due to increase in Schmidt number or chemical reaction parameter.
- Grashof number, modified Grashof number, permeability parameter, radiation parameter or Eckert number enhance the coefficient of skin-friction, whereas the reverse effect is observed for Hartmann number, chemical reaction parameter, Schmidt number or Prandtl number.
- Nusselt number increases due to increase in Hartmann number, Schmidt number, chemical reaction parameter or Prandtl number, while it decreases due to increase in Grashof number, modified Grashof number, permeability parameter, radiation parameter or Eckert number.

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- An increase in Schmidt number or chemical reaction parameter leads to increase in Sherwood number.

Table 1
Numerical values of skin-friction coefficient, Nusselt number and Sherwood number at the plate for various values of physical parameters

Gr	Gm	M	K	R	Pr	Ec	Sc	Kr	Cf	Nu	Sh
1	2	1	2	0.5	0.71	0.001	0.22	2	3.88918	0.48359	0.79491
5	2	1	2	0.5	0.71	0.001	0.22	2	6.99823	0.46872	0.79491
7	2	1	2	0.5	0.71	0.001	0.22	2	8.59007	0.45793	0.79491
5	1	1	2	0.5	0.71	0.001	0.22	2	6.36103	0.47255	0.79491
5	4	1	2	0.5	0.71	0.001	0.22	2	8.2731	0.46069	0.79491
5	2	0	2	0.5	0.71	0.001	0.22	2	9.2173	0.44881	0.79491
5	2	5	2	0.5	0.71	0.001	0.22	2	5.81532	0.48013	0.79491
5	2	10	2	0.5	0.71	0.001	0.22	2	5.8074	0.48212	0.79491
5	2	1	1	0.5	0.71	0.001	0.22	2	6.57175	0.47467	0.79491
5	2	1	4	0.5	0.71	0.001	0.22	2	7.31526	0.4634	0.79491
5	2	1	2	0	0.71	0.001	0.22	2	6.39191	0.69946	0.79491
5	2	1	2	1	0.71	0.001	0.22	2	7.39135	0.35226	0.79491
5	2	1	2	2	0.71	0.001	0.22	2	7.8715	0.23547	0.79491
5	2	1	2	0.5	1	0.001	0.22	2	6.48858	0.65759	0.79491
5	2	1	2	0.5	5	0.001	0.22	2	4.92353	3.40917	0.79491
5	2	1	2	0.5	7	0.001	0.22	2	4.08218	4.77032	0.79491
5	2	1	2	0.5	0.71	0.01	0.22	2	7.34198	0.30381	0.79491
5	2	1	2	0.5	0.71	0.02	0.22	2	7.72393	0.012058	0.79491
5	2	1	2	0.5	0.71	0.1	0.22	2	10.77952	-1.34524	0.79491
5	2	1	2	0.5	0.71	0.001	0.6	2	6.8865	0.46873	1.46019
5	2	1	2	0.5	0.71	0.001	0.78	2	6.58956	0.47718	1.7279
5	2	1	2	0.5	0.71	0.001	1.002	2	6.4207	0.49282	2.03806
5	2	1	2	0.5	0.71	0.001	0.22	1	7.16753	0.46824	0.60214

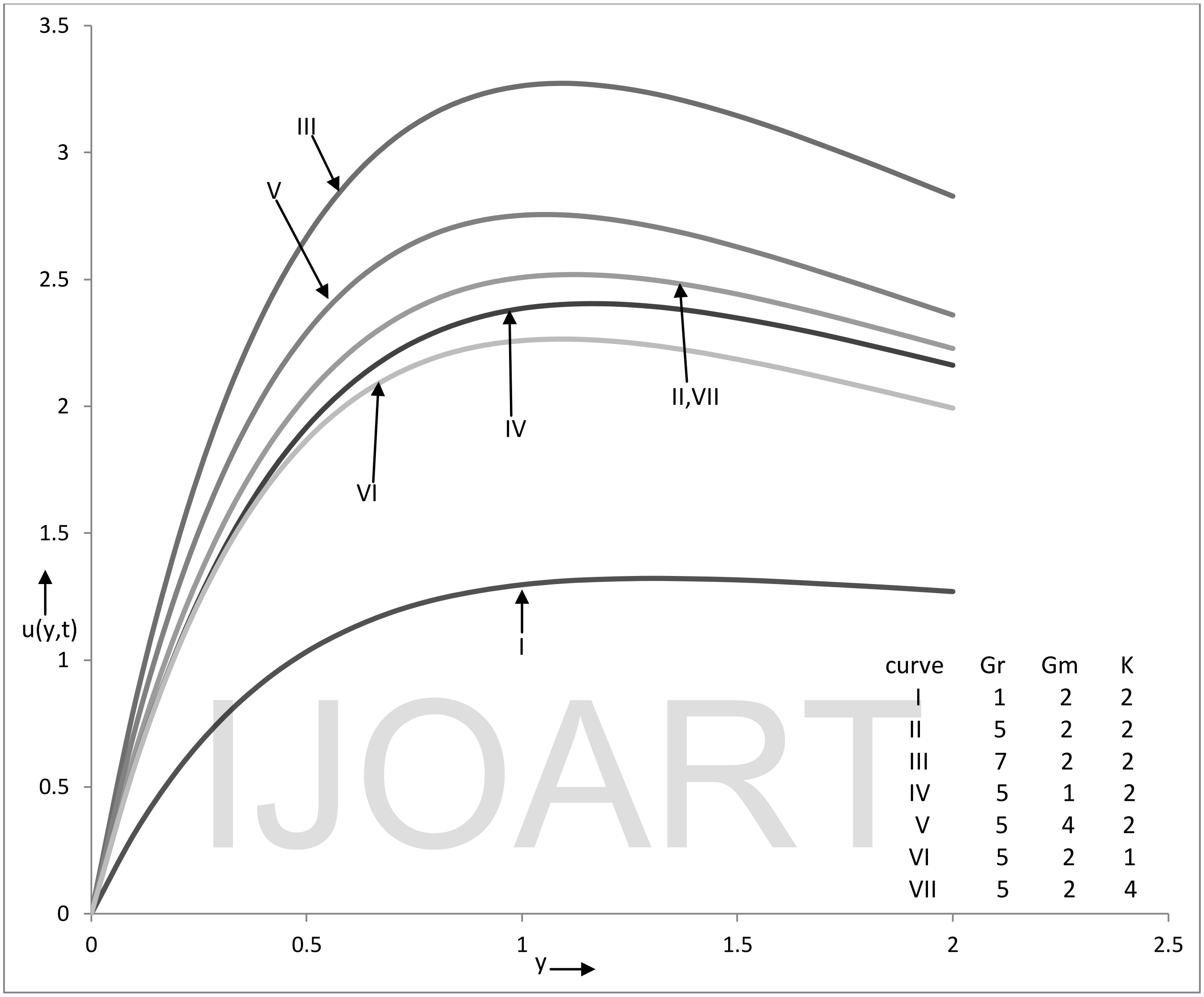

*Figure*1. *Velocity profiles for different values of* Gr, Gm, *and* K *when* $Sc=.6$, $\omega=5$, $A=.5$, $R=.5$, $\Pr=.71$, $M=51$, $Ec=.001$, $K_r=2$, $\varepsilon=.02$, $\omega t=\pi/6$

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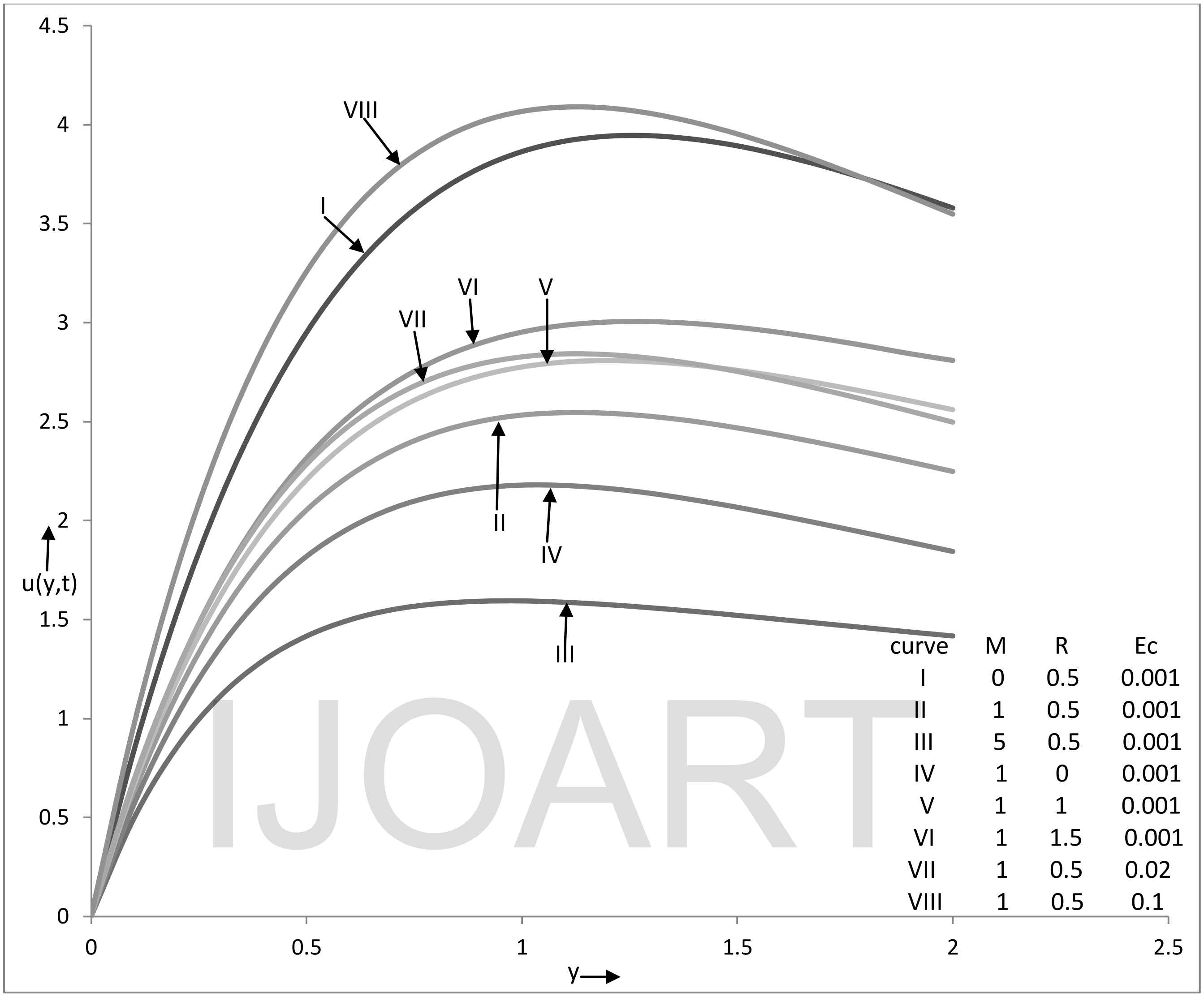

Figure 2. Velocity profiles for different values of M, R *and* Ec, *when* $Sc = .22$, $\omega = 5$, $K = 2$, $A = .5$, $Gr = 5$, $K = 2$, $Gm = 2$, $\Pr = .71$, $K_r = 2$, $\varepsilon = .02$, $\omega t = \pi / 6$

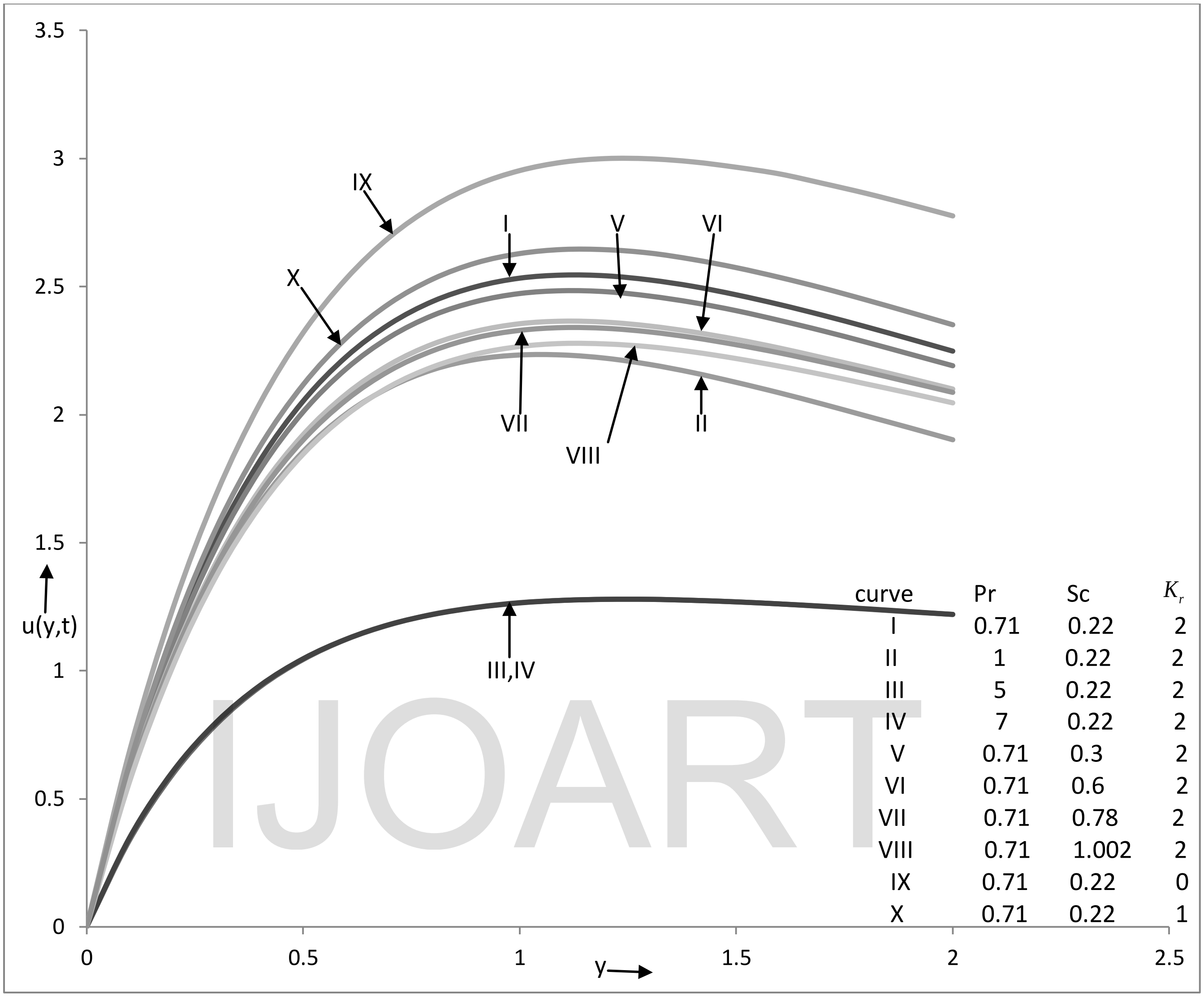

Figure 3. *Velocity profiles for different values of* Pr, Sc *and* K_r, *when* $\omega = 5$, $K = 2$, $A = .5$, $R = .5$, $Gr = 5$, $Gm = 2$, $Ec = .001$, $\varepsilon = .02$, $\omega t = \pi / 6$

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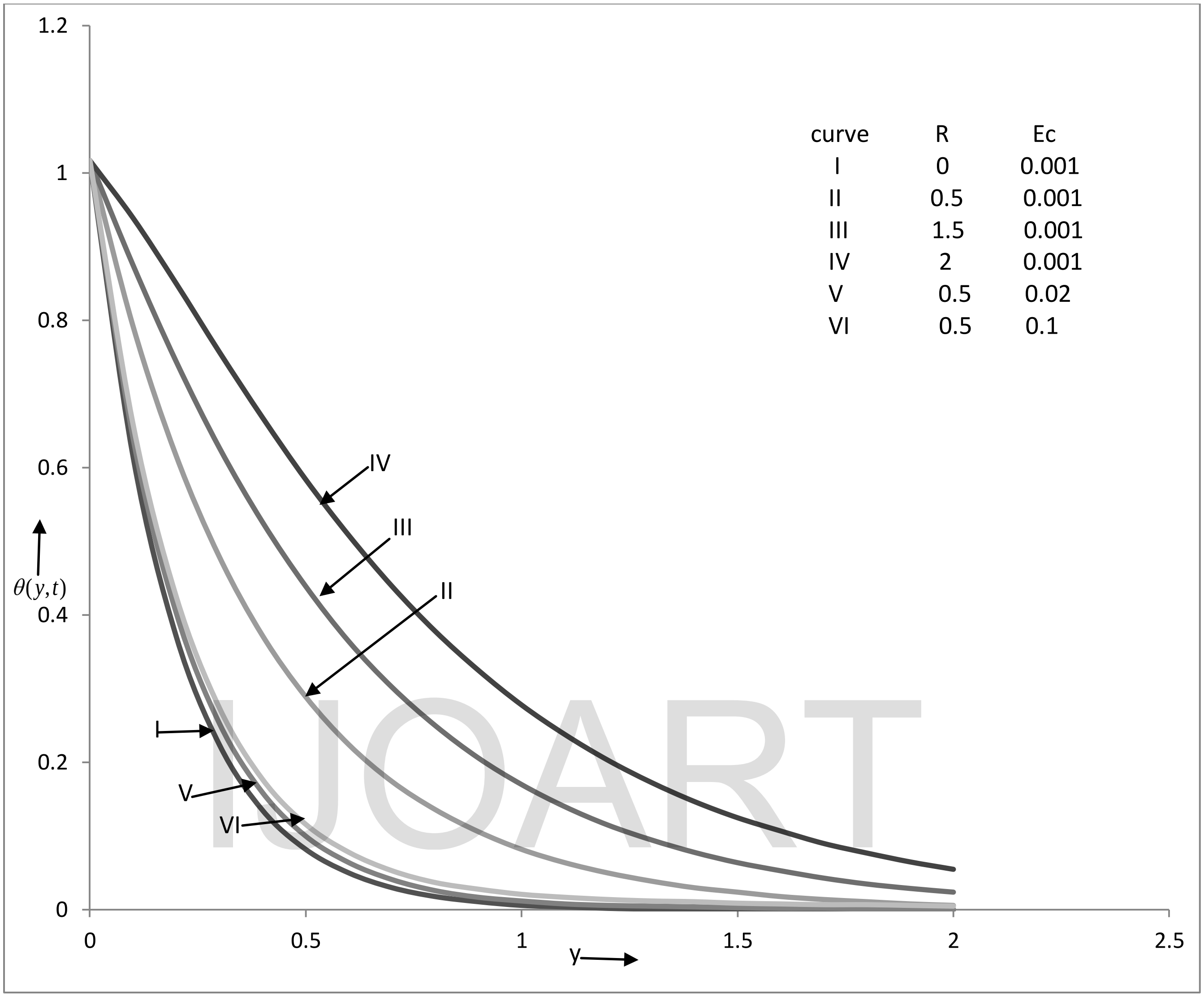


Figure 4. *Temperature profiles for different values of R and Ec, when* $Sc = .22,\ \omega = 5,\ K = 2,\ A = .5,\ Gr = 5,\ Gm = 2,\ \Pr = .71,\ \varepsilon = .02,\ \omega t = \pi/6,\ M = 1$

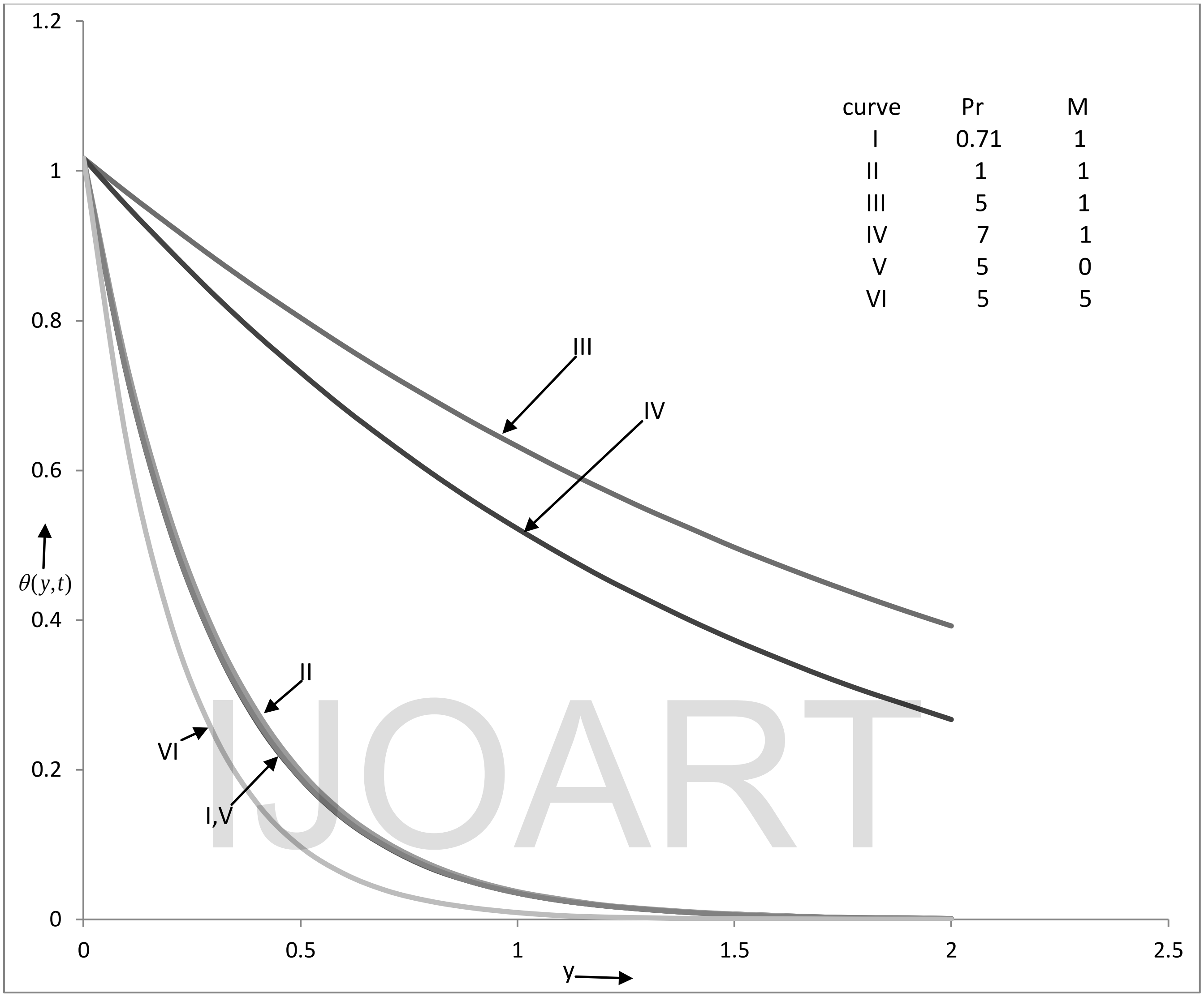
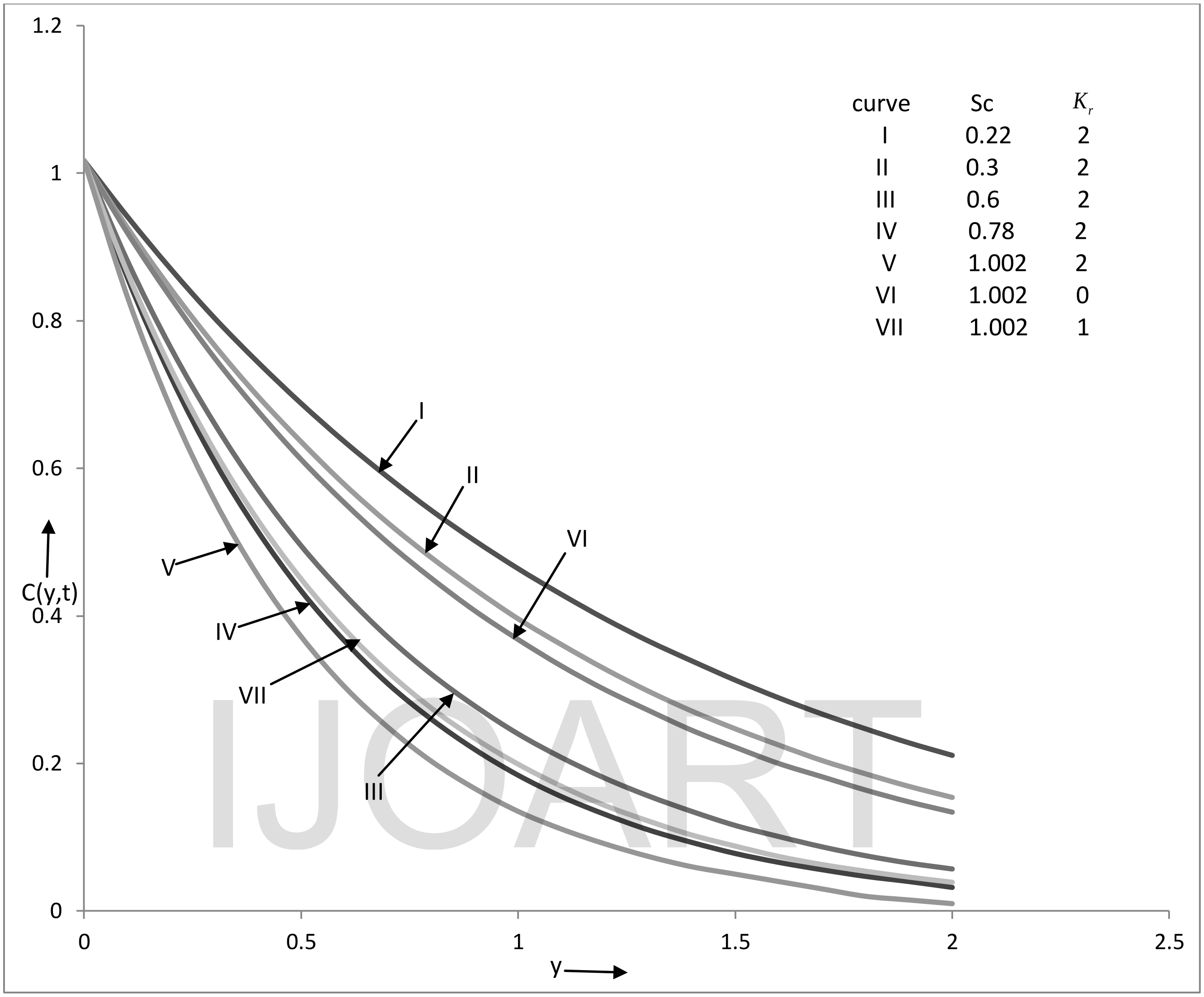


Figure 5. *Temperature profiles for different values of* Pr *and* M, *when* $Sc = .22,\ \omega = 5,$
$K = 2,\ A = .5,\ R = .5,\ Gr = 5,\ Gm = 2,\ Ec = .001,\ K_r = 2,\ \varepsilon = .02,\ \omega t = \pi / 6$



$Figure\,6.$ *Concentration profiles for different values of* Sc *and* K_r, when $K=2,\ \omega=5,\ Ec=.001,\ R=.5\ \ Gr=.5,\ Gm=.2,\ \Pr=.71,\ M=1,\ \varepsilon=.2,\ \omega t=\pi/6$

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