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Effect of Radiation Absorption and Chemical Reaction on Transient Hydromagnetic Convective Heat and Mass Transfer Flow in a Rotating Porous Medium with Heat Sources

Pavan Kumar Cintaginjala[1] R. Siva Prasad[2]
1.Research Scholar, Department of Mathematics, Sri Krishnadevaraya University, Anantapuramu – 515 003, A.P., India
2.Professor, Department of Mathematics, Sri Krishnadevaraya University, Anantapuramu – 515 003, A.P., India

Abstract
In this paper, we discussed the effect of radiation absorption and chemical reaction on transient hydromagnetic convective heat and mass transfer flow in a rotating porous medium with heat sources, when the temperature of the surface varies with time about a non-zero constant mean and the temperature at the free stream is constant. The non-linear coupled equations have been solved by perturbation technique. The velocity, temperature, concentration, skin friction, rate of heat and mass transfer have been discussed for different variations of the governing parameters G, R, γ, Q_1, α and Pr.
Keywords: Radiation Absorption, Chemical Reaction, Rotating Porous Medium, Heat Sources.

Introduction
The study of effects of magnetic field on free convection flow is important in liquid-metals, electrolytes and ionized gases. The thermal physics of hydromagnetic flow problems with mass transfer is of interest in power engineering and metallurgy. Free convection flows are of great interest in a number of industrial applications such as fiber and granular insulation, geothermal systems, *etc.* Buoyancy is also of importance in an environment where differences between land and air temperatures can give rise to complicated flow patterns. Magnetohydrodynamic (MHD) flows have attracted the attention of a large number of scholars due to their diverse applications. In astrophysics and geophysics, they are applied to study the stellar and solar structures, interstellar matter, radio propagation through the ionosphere, *etc.* In engineering, MHD flows find their application in MHD pumps, MHD bearings, etc. Convection in porous media has applications in geothermal energy recovery, oil extraction, thermal energy storage and flow through filtering devices. The phenomenon of mass transfer is also very common in the theory of stellar structure and observable effects are detectable, at least on the solar surface.

Malathy and Srinivas [2008] investigated the pulsating flow of a hydromagnetic fluid between two permeable beds. Singh [2004] analyzed the influence of a moving magnetic field on 3-D Couette flow. Das et al. [2009] discussed mass transfer effects on MHD flow and heat transfer past a vertical porous plate through a porous medium under oscillatory suction and heat source. Jain and Gupta [2006] discussed free convection effects on 3-D Couette flow with transpiration cooling. Singh and Rakesh [2001] analyzed the MHD effects on 3-D Couette flow with transpiration cooling. Singh et al. [2005] studied the effects of permeability and rotation parameters on oscillatory Couette flow through a porous medium in a rotating system. Raptis and Perdikis [1985] discussed the effect of permeability on oscillatory and free convection flow through a porous medium.

Ramana Reddy et al. [2012] have analyzed MHD oscillatory flow past a vertical porous plate embedded in rotating porous medium. Pawan Kumar Sharma et al. [2014] have discussed the MHD flow through rotating porous medium with radiating heat transfer in the presence of fluctuating thermal diffusion. Rahman et al. [2014] have analyzed numerical simulation on MHD free convection mass and heat transfer fluid flow over a vertical porous plate in a rotating system with induced magnetic field. Rabi Narayan et al. [2014] have discussed unsteady free convective MHD flow and mass transfer through porous medium in a rotating system with fluctuating heat source/sink and chemical reaction.

Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and the mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries, for example, in the power industry, among the methods of generating electric power is one in which electrical energy is extracted directly from a moving conducting fluid. Many practical diffusive operations involve the molecular diffusion of a species in the presence of chemical reaction within or at the boundary. There are two types of reactions. A homogeneous reaction is one that occurs uniformly throughout a give phase. The species generation in a homogeneous reaction is analogous to internal source of heat generation. In contrast a heterogeneous reaction takes place in a restricted region or within the boundary of a phase. It can therefore be treated as a boundary condition similar to the constant heat flux condition in heat transfer. The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Chamkha [2003] studied the MHD flow of a numerical of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and a chemical reaction. Muthucumaraswamy and Ganesan [2001] analyzed the effect of a chemical reaction on the unsteady flow past an impulsively started vertical plate which is subjected to uniform mass flux and in the presence of heat transfer.

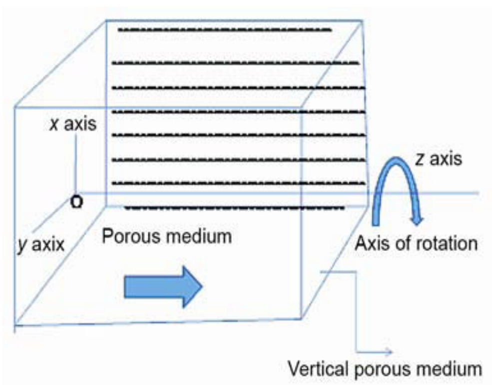
Chaudhary and Jain [2007] analyzed combined heat and mass transfer effects on MHD free convection flow past an oscillating plate embedded in porous medium. Dinarvand and Rashidi [2010] studied a reliable treatment of homotopy analysis method for 2-D viscous flow in a rectangular domain bounded by two moving porous walls. Muthuraj and Srinivas [2010] discussed heat transfer effects on MHD oscillatory flow in an asymmetric wavy channel. Rashidi and Sadri [2010] analyzed the solution of the laminar viscous flow in a semi-porous channel in the presence of a uniform magnetic field by using the differential transform method. Rashidi and Erfani [2011] discussed a new analytical study of MHD stagnation-point flow in porous media with heat transfer. Zueco et al. [2010] have analyzed combined heat and mass transfer by mixed convection MHD flow along a porous plate with chemical reaction in presence of heat source. Das et al. [2010] have discussed heat and mass transfer effects on unsteady MHD free convection flow near a moving vertical plate in porous medium. Magodora et al. [2013] have discussed double diffusive heat and mass transfer over a vertical plate in the presence wall suction and chemical reaction. Saeid [2013] has analyzed magnetic field effects on entropy generation in heat and mass transfer in porous cavity. Poornima et al. [2013] have discussed mixed convection heat and mass transfer flow along a stretching cylinder in a thermally stratified medium with thermal radiation effects.

Raptis and Perdikis [2006] analyzed the effect of a chemical reaction of an electrically conducting viscous fluid on the flow over a non-linearly (quadratic) semi-infinite stretching sheet in the presence of a constant magnetic field which is normal to the sheet. Seddeek et al. [2007] analyzed the effects of chemical reaction, radiation and variable viscosity of hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media. Ibrahim et al. [2008] analyzed the effects of the chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Recently Arunachalam Govindarajan et al. [2014] have studied chemical reaction effects on unsteady magnetohydrodynamic free convective flow in a rotating porous medium with mass transfer.

In this paper, we discussed the effect of radiation absorption and chemical reaction on transient hydromagnetic convective heat and mass transfer flow in a rotating porous medium with heat sources, when the temperature of the surface varies with time about a non-zero constant mean and the temperature at the free stream is constant. The non-linear coupled equations have been solved by perturbation technique. The velocity, temperature, concentration, skin friction, rate of heat and mass transfer have been discussed for different variations of the governing parameters G, R, γ, Q_1, α and Pr.

Formulation of the Problem :

We consider an unsteady flow of a viscous, electrically conducting incompressible fluid through a porous medium occupying a semi-infinite region of the space bounded by a vertical infinite porous plate in a rotating system under the action of a uniform magnetic field of strength H_o applied normal to the direction of the flow. The temperature of the surface varies with time about a non-zero constant mean and the temperature of the free surface is constant. The porous medium is, in fact, a non-homogeneous medium which may be replaced by a homogeneous fluid having dynamical properties equal to those of a non-homogeneous continuum. Also, we assume that the fluid properties are not affected by the temperature and concentration differences except by the density ρ in the body force term the influence of the density variations in the momentum and energy equations is negligible. 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. Initially the plate and the fluid are of same temperature T_∞ and the species concentration C_∞.The plate temperature is raised to T_w and the species concentration level near the plate is made raise to C_w.



We consider that the vertical infinite porous plate rotates in unison with a viscous fluid occupying the porous region with the constant angular velocity Ω about an axis which is perpendicular to the vertical plate surface. The Cartesian co-ordinate system is chosen such that x, y axes ,respectively, are in the vertical upward and perpendicular directions on the plane of the vertical porous surface z=0 while z-axis is normal to it as shown in diagram with the above frame of reference and assumptions, the physical variables, except the pressure p, are functions of t only. Consequently, the equations expressing the conservation of mass, momentum, and energy and the equation of mass transfer, neglecting the heat due to viscous dissipation which is valid for small velocities, are given by

$$\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+w\frac{\partial u}{\partial z}-2\Omega v=\beta g(T-T_\infty)+\beta^\bullet g(C-C_\infty)+\nu\frac{\partial^2 u}{\partial z^2}-(\frac{\nu}{k})u-\frac{\sigma\mu_e^2H_o^2}{\rho}u \tag{2}$$

$$\frac{\partial v}{\partial t}+w\frac{\partial v}{\partial z}+2\Omega u=\nu\frac{\partial^2 v}{\partial z^2}-(\frac{\nu}{k})v-\frac{\sigma\mu_e^2H_o^2}{\rho}v \tag{3}$$

$$0=-\frac{1}{\rho}\frac{\partial p}{\partial z}-(\frac{\nu}{k})w \tag{4}$$

$$\frac{\partial T}{\partial t}+w\frac{\partial T}{\partial z}=\frac{k_f}{\rho C_p}\frac{\partial^2 T}{\partial z^2}+\frac{Q_h}{\rho C_p}(T-T_\infty)+Q_1^{'}(C-C_\infty) \tag{5}$$

$$\frac{\partial C}{\partial t}+w\frac{\partial C}{\partial z}=D_B\frac{\partial^2 C}{\partial z^2}-k_r^{'}(C-C_\infty) \tag{6}$$

The relevant boundary conditions are

$$\begin{aligned}&u=0,v=0,T=T_w+\varepsilon(T_w-T_\infty)e^{i\omega t},C=C_w=0 \text{ at } z=0\\&u,v\to 0,T\to T_\infty,C\to C_\infty \text{ as } z\to\infty\end{aligned} \tag{7}$$

In a physical realistic situation, we cannot ensure perfect insulation in any experiment setup. There will always be some fluctuations in the temperature. The plate temperature is assumed to vary harmonically with time. It varies from $T_w\pm\varepsilon(T_w-T_\infty)$ as t varies from 0 to $2\pi/\omega$.since ε is small, the plate temperature varies on y slightly from the mean value T_w.
For constant suction, we have from equation (1) in view of (7):

$$w = -w_0 \tag{10}$$

Considering V=u+iv and taking into account equation (10), the equations (2) & (3) can be written as

$$\frac{\partial V}{\partial t}-w_0\frac{\partial V}{\partial z}+2i\Omega V=\beta g(T-T_\infty)+\beta^\bullet g(C-C_\infty)+\nu\frac{\partial^2 V}{\partial z^2}-(\frac{\nu}{k})V-\frac{\sigma\mu_e^2H_o^2}{\rho}V \tag{11}$$

We introduce the following non-dimensional quantities:

$$z'=\frac{zw_0}{\nu},V'=\frac{V}{w_0},t'=\frac{tw_0^2}{\nu},\omega'=\frac{\omega\nu}{w_0^2},\theta=\frac{T-T_\infty}{T_w-T_\infty},\phi=\frac{C-C_\infty}{C_w-C_\infty},Sc=\frac{\nu}{D_B},\Pr=\frac{\rho\nu C_p}{k_f}$$

$$D^{-1}=\frac{\nu^2}{w_0^2k},G=\frac{\beta g\nu(T_w-T_\infty)}{w_0^3},N=\frac{\beta^\bullet(C_w-C_\infty)}{\beta(T_w-T_\infty)},R=\frac{\Omega\nu}{w_0^2},\gamma=\frac{k_r^{'}\nu}{w_0},\alpha=\frac{Q_H\nu^2}{w_0^2\rho C_p},Q_1=\frac{Q_1^{'}(C_w-C_\infty)\nu^2}{C_p(T_w-T_\infty)w_o^2}$$

By introducing the non-dimensional quantities, equations (5),(6) and (11) reduce to

$$\frac{\partial V}{\partial t}-\frac{\partial V}{\partial z}+2iRV=Gr(\theta+N\phi)+\frac{\partial^2 V}{\partial z^2}-(D^{-1}+M^2)V \tag{12}$$

$$\frac{\partial\theta}{\partial t}-\frac{\partial\theta}{\partial z}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial z^2}+\alpha\theta+Q_1\phi \tag{13}$$

$$\frac{\partial\phi}{\partial t}-\frac{\partial\phi}{\partial z}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial z^2}-\gamma\phi \tag{14}$$

The corresponding boundary conditions are

$$V = 0, \quad \theta = 1 + \varepsilon e^{i\omega t}, \quad \phi = 1 \ at \ z = 0,$$
$$V \to 0, \theta \to 0, \phi \to 0 \qquad as \ z \to \infty \tag{15}$$

Method of Solution

In order to reduce the system of partial differential equations (12)-(14) under their boundary conditions(15), to a system of ordinary differential equations in the non-dimensional form, we assume the following for velocity, temperature and concentration of the flow field as the amplitude ε (<<1) of the permeability variations is very small.

$$V(z,t) = V_0(z) + \varepsilon e^{i\omega t} V_1(z)$$
$$\theta(z,t) = \theta_0(z) + \varepsilon e^{i\omega t} \theta_1(z)$$
$$\phi(z,t) = \phi_0(z) + \varepsilon e^{i\omega t} \phi_1(z) \tag{16}$$

Substituting system (16) into the system(12)-(14) and equating harmonic and non-harmonic terms we get

$$\frac{d^2V_0}{dz^2} + \frac{dV_0}{dz} - 2i\Omega V_0 - M_1^2 V_0 = -Gr(\theta_0 + N\phi_0) \tag{17}$$

$$\frac{d^2V_1}{dz^2} + \frac{dV_1}{dz} - 2i\Omega V_1 - M_1^2 V_1 = -Gr(\theta_1 + N\phi_1) \tag{18}$$

$$\frac{d^2\theta_0}{dz^2} + \Pr\frac{d\theta_0}{dz} - Q\theta_0 = -Q_1\phi_0 \tag{19}$$

$$\frac{d^2\theta_1}{dz^2} + \Pr\frac{d\theta_{10}}{dz} - (i\omega + Q)\theta_1 = -Q_1\phi_1 \tag{20}$$

$$\frac{d^2\phi_0}{dz^2} + Sc\frac{d\phi_0}{dz} - \gamma Sc\phi_0 = 0 \tag{21}$$

$$\frac{d^2\phi_1}{dz^2} + Sc\frac{d\phi_1}{dz} - (i\omega + \gamma)Sc\phi_1 = 0 \tag{22}$$

The corresponding boundary conditions are

$$V_0(0) = 0, \theta_0(0) = 1, \phi_0(0) = 1; V_1(0) = 0, \theta_1(0) = 1, \phi_1(0) = 0$$
$$V_0(\infty) \to 0, \theta_0(\infty) \to 0, \phi_0(\infty) \to 0 : V_1(\infty) \to 0, \theta_1(\infty) \to 0, \phi_1(\infty) \to 0 : \tag{23}$$

Solving the equations (15)-(20) subject to the boundary conditions (23) we obtain

$$V(z,t) = V_0(z) + \varepsilon e^{i\omega t} V_1(z) \tag{23}$$

$$\theta(z,t) = \theta_0(z) + \varepsilon e^{i\omega t} \theta_1(z) \tag{24}$$

$$\phi(z,t) = \phi_0(z) \tag{25}$$

$$\phi_0(z) = \exp(-m_1 z), \theta_0(z) = (1 + a_1)\exp(-m_2 z) - a_1 \exp(-m_1 z)$$
$$V_0(z) = a_4 \exp(-_4 z) + a_2 \exp(-m_1 z) + a_3 \exp(-m_2 z)$$
$$\theta_1(z) = \exp(-m_3 z), \phi_1(z) = 0, V_1(z) = a_5(\exp(-m_3 z) - \exp(-m_5 z))$$

It is convenient to write the primary and secondary velocity fields, in terms of the fluctuating parts, separating the real and imaginary part from equations (23) & (24) and taking only the real parts as they have physical significance, the velocity and temperature distribution of the flow field can be expressed in fluctuating parts as:

$$\frac{u}{w_0} = u_0 + \varepsilon\{N_r Cos(\omega t) - N_i Sin(\omega t)\} \tag{26}$$

$$\frac{v}{w_0} = v_0 + \varepsilon\{N_r Sin(\omega t) + N_i Cos(\omega t)\} \tag{27}$$

Where $u_0 + iv_0 = V_0$ and $N_r + i N_i = V_1$

Hence the expressions for the transient velocity profiles for $\omega t = \pi / 2$ are given by

$$\frac{u}{w_0}(z, \frac{\pi}{2\omega}) = u_0(z) - \varepsilon N_i(z) \quad and \quad \frac{v}{w_0}(z, \frac{\pi}{2\omega}) = v_0(z) - \varepsilon N_r(z)$$

Skin Friction

The skin friction at the plate z=0 in terms of amplitude and phase is given by

$$(\frac{dV}{dz})_{z=0} = (\frac{dV_0}{dz})_{z=0} + \varepsilon\, e^{i\omega t} (\frac{dV_1}{dz})_{z=0} = (-a_4 m_4 - a_2 m_1 - a_3 m_3) + \varepsilon\, e^{i\omega t} (a_5(m_5 - m_3)) \tag{28}$$

Rate of Heat Transfer

The heat transfer coefficient in terms of the Nusselt Number at the plate z=0 in terms of amplitude and phase is given by

$$(\frac{d\theta}{dz})_{z=0} = (\frac{d\theta_0}{dz})_{z=0} + \varepsilon e^{i\omega t} (\frac{d\theta_1}{dz})_{z=0}$$
$$= a_1 m_1 - (1 + a_1) m_2 - \varepsilon e^{i\omega t} m_3$$

Rate of Mass Transfer

The rate of mass transfer coefficient in terms of Sherwood number at the plate z=0 is given by

$$(\frac{d\phi}{dz})_{z=0} = (\frac{d\phi_0}{dz})_{z=0} + \varepsilon e^{i\omega t} (\frac{d\phi_1}{dz})_{z=0}$$
$$= -m_1$$

RESULTS AND DISCUSSION

In this analysis we investigate the influence of the heat source and radiation absorption on the convective heat and mass transfer flow of a rotating fluid past a plate at z=0.

The solutions for primary and secondary velocities, temperature and concentration profiles have solved by using perturbation technique. The effects of flow parameters such as heat source parameter α, rotation parameter R, radiation absorption parameter Q_1, and chemical reaction parameter γ on the velocity, temperature and concentration fields have been studied analytically and presented with the help of the figures 1-10. The effects of flow parameter on the stress components and rate of heat and mass transfer have been discussed with the help of the tables 1-4.

Fig.1-3 represents primary velocity (u) for different values of G, R, α, Q_1, γ and Pr. It is clear from fig.1 that the primary velocity increases with increase in |G| and an increase in the rotation parameter R reduces u. This shows that the rotation, permeability of the porous medium exert retarding influence on the primary flow. From fig.1 it is noted that all the velocity profiles increased steadily near the lower plate and thereafter they show a constant decrease and reach the value zero far away from the plate. Figure.2 represents u with heat source parameter α and radiation absorption parameter Q_1. It can be seen from the profiles that u enhances with increase in the radiation absorption parameter Q_1 and reduces with the strength of the heat source parameter α. Figure.3 represents u with chemical reaction parameter γ and Prandtl number Pr. We observed from the velocity profiles that the primary velocity u enhances in the degenerating chemical reaction case (γ>0) also the velocity u enhances with increase in Pr.

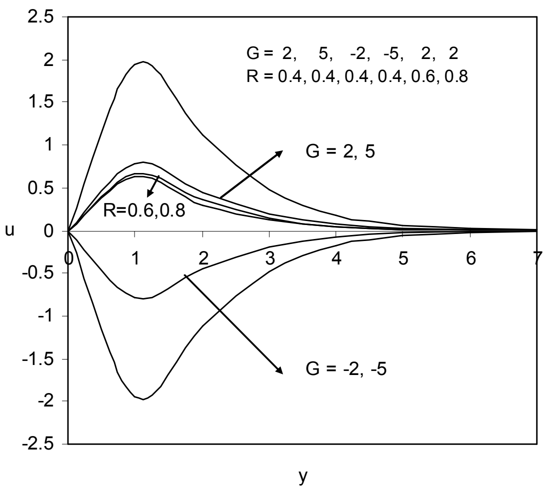


Fig. 1 : Variation of u with G & R
N=0.5, Sc=1.3, α=2, Q_1=0.5, γ=0.5, Pr=0.71, M=2,D^{-1}=2

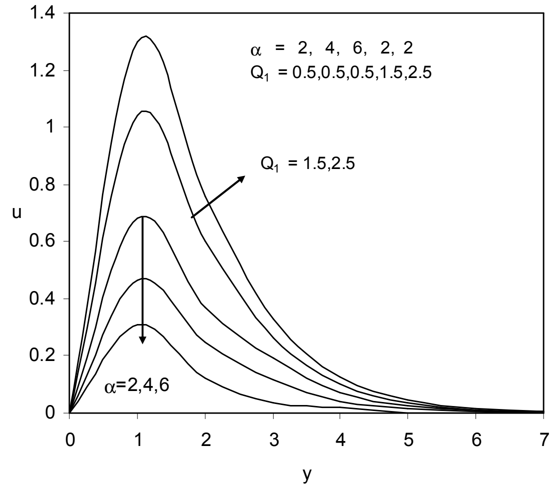


Fig. 2 : Variation of u with α & Q_1
G=2, R=0.4, N=0.5, Sc=1.3, γ=0.5, Pr=0.71, M=2,D^{-1}=2

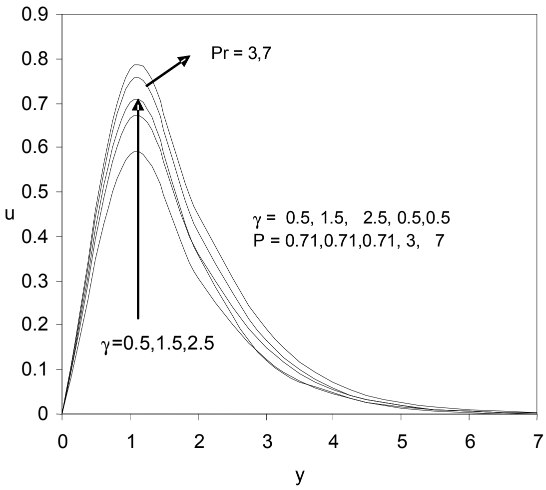


Fig. 3: Variation of u with γ & Pr
G=2, R=0.4, N=0.5, Sc=1.3, α=2, Q_1=0.5, M=2,D^{-1}=2

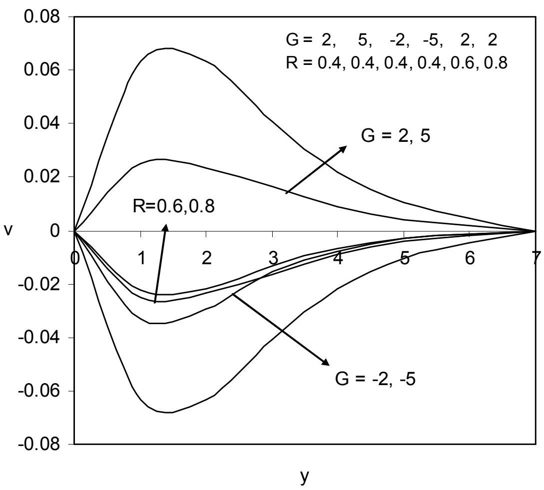


Fig. 4 : Variation of v with G & R
N=0.5, Sc=1.3, α=2, Q_1=0.5, γ=0.5, Pr=0.71, M=2,D^{-1}=2

The secondary velocity (v) which arises due to the rotation of the fluid is exhibited in figures 4-6 for various values of G, R, α, Q_1, γ and Pr. It is observed from fig.4 that the magnitude of the secondary velocity profile increases whenever there is an increase in either of Grashof number G or rotation parameter R. An increase in the strength of the heat source $\alpha>0$ reduces $|v|$ and it enhances with increase in Q_1 (Fig.5). An increase in chemical reaction parameter γ or Prandtl number Pr reduces $|v|$ in the flow region (Fig.6).

The non-dimensional temperature (θ) is shown in figures 7-9 for different values of R, α, Q_1, γ and Pr. It is found that the non-dimensional temperature enhances with increase in the rotation parameter R or radiation absorption parameter Q_1. While it reduces with the strength of the heat source α or the chemical reaction parameter γ. An increase in the Prandtl number Pr leads to an enhancement in θ.

The non-dimensional concentration (ϕ) is exhibited in figure 10. It is found from the profiles that the non-dimensional concentration reduces with increase in the chemical reaction parameter γ.

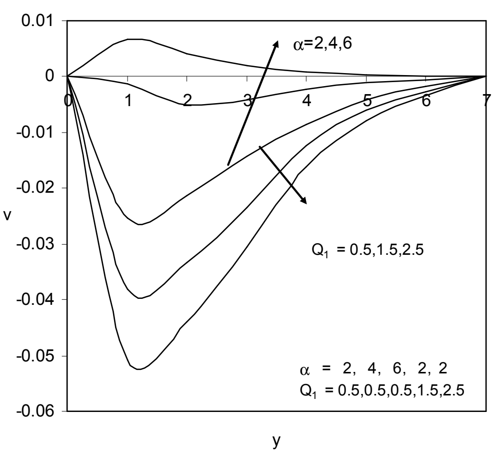


Fig. 5 : Variation of v with α & Q_1
G=2, R=0.4, N=0.5, Sc=1.3, γ=0.5, Pr=0.71, M=2,D^{-1}=2

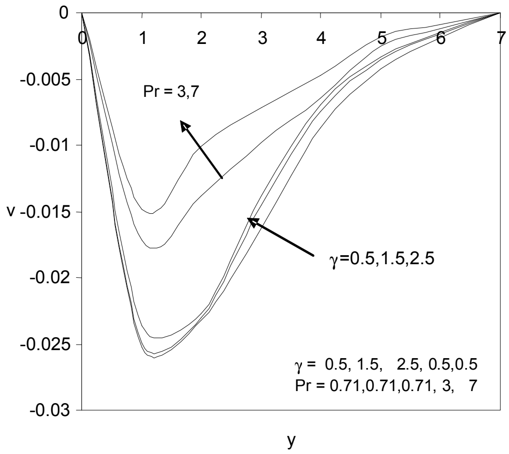


Fig. 6 : Variation of v with γ & Pr
G=2, R=0.4, N=0.5, Sc=1.3, α=2, Q_1=0.5, M=2,D^{-1}=2

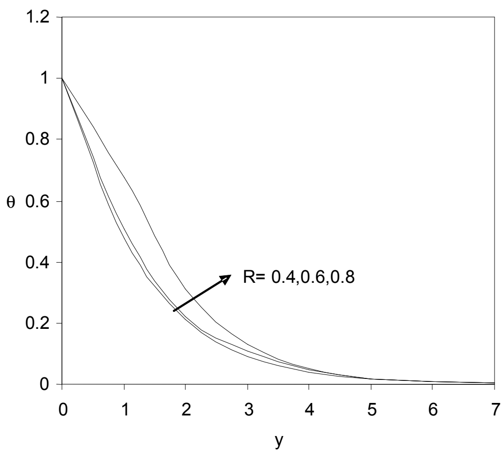


Fig. 7 : Variation of θ with R
Sc=1.3, α=2, Q_1=0.5, γ=0.5, Pr=0.71

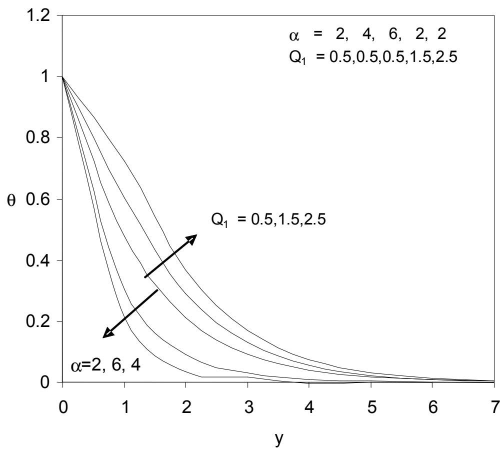


Fig. 8 : Variation of θ with α & Q_1
R=0.4, Sc=1.3, γ=0.5, Pr=0.71

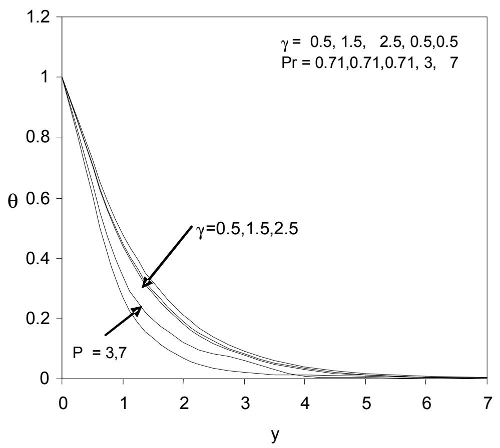


Fig. 9 : Variation of θ with γ & Pr
R=0.4, Sc=1.3, α=2, Q_1=0.5

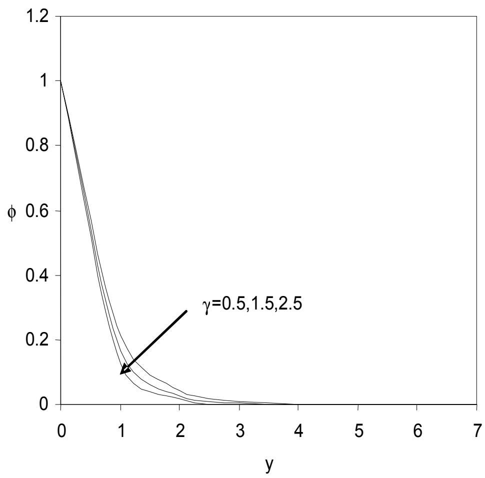


Fig. 10 : Variation of ϕ with γ

The stress components τ_x and τ_y at the boundary z=0 is shown in tables 1 & 2 for different variations of the parameters G, R, α, Q_1, γ and Pr. It is found that the stress components τ_x and τ_y enhances with increase in G or Q_1 and reduces with the strength of the heat source α. The variation of τ_x and τ_y with rotation parameter R shows that an increase in R≤0.6 reduces $|\tau_x|$ and $|\tau_y|$ and enhances for further higher R≥0.8. An increase in the chemical reaction parameter γ reduces $|\tau_x|$ and enhances $|\tau_y|$ at z=0 in the degenerating chemical reaction case. The variation of τ with Prandtl number Pr shows that lesser the thermal conductivity (Pr≤1.71) smaller the stress components and for further lowering of the thermal conductivity (Pr≥7) larger the stress components at z=0 (Tables 1 & 2).

The local rate of heat transfer (Nusselt number) at z=0 is shown in table 3 for different parametric variations. It is found from the table values that the rate of heat transfer enhances with increase in γ and reduces with increase in α or Q_1. An increase in the Prandtl number Pr results an enhancement in |Nu| at z=0.

The rate of mass transfer (Sherwood number) is shown in table 4 for different values of Sc and γ. It is found that the rate of mass transfer enhances with increase in Sc or chemical reaction parameter γ.

Table-1: Shear stress (τ_x)

G	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
2	2.6985	3.5841	4.4697	2.1828	1.8648	2.4514	3.1356	2.5671	2.5021	2.6307	2.7132
5	6.7462	8.9603	11.1743	5.4570	4.6619	6.1286	7.8390	6.4178	6.2552	6.5768	6.7830
10	13.4922	17.9205	22.3485	12.9139	9.3238	12.2572	15.678	12.8357	12.5104	13.1536	13.5660
Q_1	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
α	2	2	2	4	6	2	2	2	2	2	2
R	0.4	0.4	0.4	0.4	0.4	0.6	0.8	0.4	0.4	0.4	0.4
γ	2	2	2	2	2	2	2	4	6	2	2
Pr	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	1.71	7

Table-2: Shear stress (τ_y)

G	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
2	-0.3075	-0.5366	-0.7657	0.2382	0.2251	-0.2533	-0.4895	-0.3164	-0.3691	-0.1332	0.6122
5	-0.7689	-1.3415	-1.9141	0.5954	0.5628	-0.6332	-1.2238	-0.7910	-0.9227	-0.3330	1.5306
10	-1.5379	-2.6830	-3.8283	1.1908	1.1256	-1.2663	-2.4475	-1.5821	-1.8454	-0.6659	3.0612
Q_1	0.5	1.5	2.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
α	2	2	2	4	6	2	2	2	2	2	2
R	0.4	0.4	0.4	0.4	0.4	0.6	0.8	0.4	0.4	0.4	0.4
γ	2	2	2	2	2	2	2	4	6	2	2
Pr	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	1.71	7

Table-3: Nussselt number (Nu)

γ	I	II	III	IV	V	VI	VII	VIII	IX
2	-0.6725	-0.2671	0.1383	0.5436	-0.5918	-0.4687	-0.7712	-0.9775	-1.3101
5	-0.7680	-0.5538	-0.3395	-0.1253	-0.6821	-0.5283	-0.8525	-1.0290	-1.3137
10	-0.7971	-0.6409	-0.4952	-0.3285	-0.7082	-0.5664	-0.8778	-1.0464	-1.3185
Q_1	0.5	1.5	2.5	3.5	0.5	0.5	0.5	0.5	0.5
α	2	2	2	2	4	6	2	2	2
Pr	0.71	0.71	0.71	0.71	0.71	0.71	1.71	3.71	7

Table-4: Sherwood number (Sh)

γ	I	II	III	IV
2	-0.9073	-1.2351	-1.5455	-1.8752
5	-1.1054	-1.4752	-1.8114	-2.0687
10	-1.2938	-1.7088	-2.0769	-2.4126
Sc	0.24	0.6	1.3	2.01

Conclusions

Some of the salient results for the velocity (primary, secondary), temperature and concentration profiles are listed below.

1. Grashof number (G) has the effect of accelerating the primary velocity profiles, the magnitude of the secondary velocity profile and the stress components τ_x and τ_y .
2. The rotation parameter (R) enhances the secondary velocity and temperature while it decreases the primary velocity of the flow field. An increase in R≤0.6 reduces $|\tau_x|$ and $|\tau_y|$ and enhances for further higher R≥0.8.
3. Increase in the radiation absorption parameter (Q_1) increases the primary velocity, temperature and stress components τ_x and τ_y while it decreases the secondary velocity and the rate of heat transfer.
4. Increasing values of chemical reaction parameter (γ) enhances the primary velocity and stress component $|\tau_y|$ while it reduces the magnitude of the secondary velocity, temperature, concentration and stress component $|\tau_x|$.
5. The heat source parameter (α) decreases the primary velocity, temperature, the rate of heat transfer, stress components τ_x and τ_y and enhances the secondary velocity.
6. Increase in the Prandtl number (Pr) enhances the primary velocity, temperature, the rate of heat transfer while it decreases the magnitude of the secondary velocity.

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