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CHEMICAL REACTION EFFECT ON MHD FLOW WITH HEAT AND MASS TRANSFER IN THE PRESENCE OF THERMAL RADIATION AND HEAT SOURCE

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ABSTRACT

The present work is concerned with the analytical solutions of the unsteady MHD free convective heat and mass transfer flow past a semi-infinite vertical porous plate embedded in a porous medium with heat source. The influence of chemical reaction is taken into account. The governing equations are solved by perturbation technique. The effects of different pertinent parameters on velocity temperature, concentration are discussed with the help of graphs and tables. The results of the present study agree well with the previous solutions. Applications of the present study are shown in material processing systems and different chemical industries.

Keywords: *MHD, Chemical reaction, Thermal radiation, Porosity, Heat source, skin friction, Nusselt number, Sherwood number.*

Nomenclature:

C^* Species concentration ($kg\,m^{-3}$)
C_p Specific heat at constant pressure ($Jkg^{-1}K$)
C_∞^* Species concentration in the free stream ($kg\,m^{-3}$)
C_w^* Species concentration at the surface ($kg\,m^{-3}$)
D_M Chemical molecular diffusivity (m^2s^{-1})
g Acceleration due to gravity (ms^{-2})
Gr Thermal Grashof number
Gc Mass Grashof number
K Permeability parameter
M Hartmann number
Nu Nusselt number
Pr Prandtl number
q_r Radiative heat flux
Sh Sherwood number
Sc Schmidt number
T^* Temperature (K)
T_w^* Fluid temperature at the surface (K)
T_∞^* Fluid temperature in the free stream (K)
u Dimensionless velocity component (ms^{-1})

Greek symbols

β Coefficient of volume expansion for heat transfer (K^{-1})
β' Coefficient of volume expansion for mass transfer (K^{-1})
θ Dimensionless fluid temperature (K)
k Thermal conductivity ($Wm^{-1}K^{-1}$)
ν Kinematic viscosity (m^2s^{-1})
ρ Density (kgm^{-3})
σ Electrical conductivity
C Dimensionless species concentration (kgm^{-3})
τ Shearing stress (Nm^{-2})

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Subscripts

w Conditions on the wall
∞ Free stream condition

INTRODUCTION

Magnetohydrodynamics is the study of flow of electrically conducting fluids in electric and magnetic fields. This phenomenon is essentially one of the mutual interaction between the fluid velocity and electromagnetic field i.e. the motion of the fluid affects the magnetic field and the magnetic field affects the fluid motion. Basically, magnetohydrodynamics is a research area that involves the study of motion of electrically conducting fluids such as plasma and salt water. MHD flows are found to have influential applications in many natural and man madeflows.MHD flow with combined heat and mass transfer have several important applications in variety of engineering processes including heat exchanger devices, petroleum reservoirs, chemical catalytic reactors, ceramic materials, migration of moisture through air contained in fibrous insulations and grain storage installations and the dispersion of chemical contaminants through water saturated soil, super convecting geotheramic etc..

The literature on the study of MHD flow with heat and mass transfer is abundant. Some of these are given here. Lai and Kulachi [11] used the series expansion method to investigate coupled heat and mass transfer in natural convection from a sphere in a porous medium. The heat and mass transfer effects on a flow along a vertical plate in the presence of magentic field was investigated by Elbashbeshy [8].The influence of combined natural convection from a vertical wavy surface due to thermal and mass diffusion was studied by Hossain and Rees [9]. Chen [6] investigated the effects of heat and mass transfer in MHD free convection from a vertical surface. Soundalgekar [6] presented an exact solution to the flow of a viscous fluid past an impulsively started infinite isothermal vertical plate with mass transfer. Muthucumaraswamy and Ganesan [7] have studied numerical solution of flow past an impulsively started semi-infinite isothermal vertical plate with uniform mass diffusion. Toki [24] developed the analytical solutions for free convection and mass transfer flow near a moving vertical porous plate. Das [25] developed the closed form solutions for the unsteady MHD free convection flow with thermal radiation and mass transfer near a moving vertical plate. Recently Ahmmed *et al.* [15] studied the unsteady MHD free convection and mass transfer flow past a vertical porous plate.

The effect of chemical reaction on above discussed flow is very useful for improving a number of chemical technologies such as drying, distribution of temperature and moisture over agricultural fields and groves of fruit trees, damage of crops due to freezing, evaporation at the surface of a water body, energy transfer in a wet cooling tower and flow in a desert cooler. Many practical diffusive operations involve the molecular diffusion of a species in the presence of chemical reaction within or at the boundary. Therefore, the study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists. Raji Reddy and Srihari [1] studied numerical solution of unsteady flow of a radiating and chemically reacting fluid with time-dependent suction. Venkateswarlu and Satyanarayana [31] have studied the effects of chemical reaction and radiation absorption on the heat and mass transfer flow of nano fluid in a rotating system. Chamber and Young (1958) analyzed the effects of homogeneous 1st order chemical reactions in the neighbourhood of a flat plate for destructive and generative reactions. Muthucumaraswamy et al. (2008) have studied the mass transfer effect on isothermal vertical oscillating plate in presence of chemical reaction. Swain *et al.* (2014) investigated the effect of chemical reaction and thermal radiation on the hydromagnetic free convective rotating flow past an accelerated vertical plate in the presence variable heat and mass diffusion. Das *et al.* [8] have considered the effects of homogeneous first order chemical reaction on the flow past an impulsively started infinite vertical plate with constant heat flux and mass transfer. Venkateswarlu *et al.* [30] had presented chemical reaction and radiation absorption effects on the flow and heat transfer of a Nano fluid in a rotating system.

The objective of this paper is to analyze the effect of chemical reaction on MHD flow studied by Ahmmed *et al.* [15].

MATHEMATICAL FORMULATION

A two dimensional unsteady, free convective laminar flow with heat and mass transfer past a semi-infinite vertical moving plate in a uniform porous medium is considered. It is taken that fluid is incompressible, viscous and electrically conducting. A uniform transverse magnetic field in the presence of pressure gradient is applied to the system. First order chemical reaction, heat generation effect, thermal diffusion and thermal radiation are taken into account. x^* axis is taken along the plate and y^*axis is taken normal to it. It is supposed that there is no applied voltage and induced magnetic field. Also viscous and Darcy resistance terms are assumed to be present. Due to the semi-infinite plate surface assumption, the flow variables are functions of y^* and t^*. Now under the usual Boussinesq approximation, the governing boundary layer equations are

$$\frac{\partial v'}{\partial y'}=0 \tag{1}$$

$$\rho\left(\frac{\partial u'}{\partial t'}+v'\,\frac{\partial u'}{\partial y'}\right)=\frac{\partial p'}{\partial x'}+\mu\,\frac{\partial^2 u'}{\partial y'^2}-\rho g-\frac{\mu}{k'}u'-\sigma B_0^2 u' \tag{2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} + \frac{1}{\rho C_p}\left(\frac{\partial q'}{\partial y'}\right) - \frac{Q_0}{\rho C_P}(T' - T'_\infty) \tag{3}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D_M\frac{\partial^2 C'}{\partial y'^2} + D_T\frac{\partial^2 T'}{\partial y'^2} - R'_C(C' - C'_\infty) \tag{4}$$

Boundary conditions are

$$u' = u'_p, T' = T'_w + \in (T'_w - T'_\infty)e^{n't'}, \quad C' = C'_w + \in (C'_w - C'_\infty)e^{n't'} \text{ at } y' = 0 \tag{5}$$

$$u' = U'_\infty, \ U'_\infty = U_0(1 + \in e^{n't'}), T' \to T'_\infty, C' \to C'_\infty, \text{ at } y' \to \infty \tag{6}$$

Now,

$$v' = -v_0(1 + \in Ae^{n't'}) \tag{7}$$

In free stream, we obtained

$$\frac{\partial p'}{\partial x'} = \rho\frac{dU'_\infty}{dt'} + \rho_\infty g + \frac{\mu}{k'}U'_\infty + \sigma B_0^2 U'_\infty \tag{8}$$

Eliminating $\frac{\partial p'}{\partial x'}$ using equation (2)and equation (4), we obtain

$$\rho\left(\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'}\right) = \rho\frac{dU'_\infty}{dt'} + \rho_\infty g + \frac{\mu}{k'}U'_\infty + \sigma B_0^2 U'_\infty + \mu\frac{\partial^2 u'}{\partial y'^2} - \rho g - \frac{\mu}{k'}u' - \sigma B_0^2 u'$$

$$= \rho\frac{dU'_\infty}{dt'} + (\rho_\infty - \rho) + \mu\frac{\partial^2 u'}{\partial y'^2} + \frac{\mu}{k'}(U'_\infty - u') + \sigma B_0^2(U'_\infty - u') \tag{9}$$

By using the equation state, we obtain

$$(\rho_\infty - \rho) = \beta(T' - T'_\infty) + \beta'(C' - C'_\infty) \tag{10}$$

Equation (9) becomes

$$\rho\left(\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'}\right) = (\rho_\infty - \rho)g + \rho\frac{dU'_\infty}{dt'} + \mu\frac{\partial^2 u'}{\partial y'^2} + \frac{\mu}{k'}(U'_\infty - u') + \sigma B_0^2(U'_\infty - u')$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \frac{dU'_\infty}{dt'} + \vartheta\frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_\infty) + g\beta'(C' - C'_\infty) + \frac{\vartheta}{k'}(U'_\infty - u') + \frac{\sigma B_0^2}{\rho}(U'_\infty - u') \tag{11}$$

The radioactive heat flux term by using the Roseland approximation is given by

$$q'_r = -\frac{4\sigma'}{3k'_1}\frac{\partial T'^4}{\partial y'} \tag{12}$$

T'^4 may be expressed as a linear combination of the temperature, this is accomplished by expanding in a Taylor series about T'_∞ and neglecting higher order terms.

$$T'^4 = 4T'T'^3_\infty - 3T'^4_\infty \tag{13}$$

By using equation (12)and equation (13)into the equation (3)

Equation (3)becomes

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_P}\frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma' T'^3_\infty}{3\rho c_p k'_1}\frac{\partial^2 T'}{\partial y'^2} - \frac{Q_0}{\rho C_P}(T' - T'_\infty) \tag{14}$$

To get the solution of equation(1) to equation (4) with boundary conditions (5) and (6), the following non dimensional parameters are used.

$$u = uU_0, v' = vV_0, T' = T'_\infty + \theta(T'_w - T'_\infty), C' = C'_\infty + C(C'_w - C'_\infty), U'_\infty = U_\infty U_0,$$

$$u'_p = U_P U_0, K' = \frac{K\nu^2}{{V_0}^2}, y' = \frac{y\nu}{V_0}, Gc = \frac{\nu g\beta'(C'_w - C'_\infty)}{{V_0}^2 U_0}, Gr = \frac{\nu g\beta(T'_w - T'_\infty)}{{V_0}^2 U_0},$$

$$Rc = \frac{Rc'\nu}{{V_0}^2}, Pr = \frac{\nu\rho C_p}{K}, M = \frac{\sigma B_0^2}{\rho {V_0}^2}, Q = \frac{Q_0\nu}{\rho {V_0}^2 C_p}, R = \frac{4\sigma T'^3_\infty}{K'_1 K}, Sc = \frac{\nu}{D_M}, t' = \frac{t\nu}{{V_0}^2}, n' = \frac{n{V_0}^2}{\nu}, So = \frac{D_T(T'_w - T'_\infty)}{\nu(C'_w - C'_\infty)} \tag{15}$$

Using the dimensionless parameters in equations (11), (14) and (4), we get

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + GcC + N(U_\infty - U), \tag{16}$$

$$\frac{\partial \theta}{\partial t} + v\frac{\partial \theta}{\partial y} = \frac{1}{Pr}\left(1 + \frac{4}{3}R\right)\frac{\partial^2 \theta}{\partial y^2} - Q\theta, \tag{17}$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} + So\frac{\partial^2 \theta}{\partial y^2} - RcC. \tag{18}$$

The reduced initial and boundary conditions are

$$u = U_p, \theta = 1 + \epsilon e^{nt}, C = 1 + \epsilon e^{nt} \quad at\ y = 0$$
$$u \to U_\infty = 1 + \epsilon e^{nt}, \theta \to 0, C \to 0 \quad as\ \ y \to \infty \tag{19}$$

Perturbation method is used to solve equations (16), (17) and (18). The following forms are considered.

$$u(y,t) = u_0(y) + \epsilon e^{nt} u_1(y) + O(\epsilon^2)$$
$$\theta(y,t) = \theta_0(y) + \epsilon e^{nt} \theta_1(y) + O(\epsilon^2) \tag{20}$$
$$C(y,t) = C_0(y) + \epsilon e^{nt} C_1(y) + O(\epsilon^2)$$

From equations (15), (16) and (17), we obtained

$$u_0'' + u_0' + Nu_0 = -N - Gr\theta_0 - GcC_0\ , \tag{21}$$
$$u_1'' + u_1' - (N+n)u_1 = -N - Au_0' - Gr\theta_1 - GcC_1\ \ , \tag{22}$$
$$(3+4R)\theta_0'' + 3Pr\theta_0' - 3PrQ\theta_0 = 0 \tag{23}$$
$$(3+4R)\theta_1'' + 3Pr\theta_1' - 3\,\mathrm{Pr}(n+Q)\,\theta_1 = -3APr\theta_0' \tag{24}$$
$$C_0'' + ScC_0' - RcScC_0 = -SoSc\theta_0''\ , \tag{25}$$
$$C_1'' + ScC_1' - (Rc+n)ScC_1 = -SoSc\theta_1'' - AScC_0', \tag{26}$$

Corresponding boundary conditions are

$$u_0 = U_p, u_1 = 0, \theta_0 = 1, \theta_1 = 1, C_0 = 1, C_1 = 1\ \ at\ \ y = 0\ , \tag{27}$$
$$u_0 \to 1, u_1 \to 1, \theta_0 \to 0, \theta_1 \to 0, C_0 \to 0, C_1 \to 0\ \ as\ \ y \to \infty \quad .$$

Solving equations (23) and (24) we find

$$\theta_0 = e^{m_2 y}, \tag{28}$$
$$\theta_1 = D_1 e^{m_2 y} + D_2 e^{m_4 y} \quad , \tag{29}$$

Solving equations (25) and (26) we find

$$C_0 = B_1 e^{m_2 y} + B_2 e^{m_6 y} \tag{30}$$
$$C_1 = B_3 e^{m_6 y} + B_4 e^{m_2 y} + B_5 e^{m_8 y} + D_3 e^{m_2 y} + D_4 e^{m_4 y} \quad . \tag{31}$$

Solving equations (22) and (23) we find

$$u_0 = 1 + J_1 e^{m_2 y} + J_2 e^{m_6 y} + J_3 e^{m_2 y} + J_4 e^{m_{10} y} \tag{32}$$

$$u_1 = 1 + J_6 e^{m_{10} y} + J_7 e^{m_2 y} + J_8 e^{m_6 y} + (J_9 + J_{10}) e^{m_2 y} + (J_{11} + J_{16}) e^{m_4 y} + J_{12} e^{m_6 y} + J_{13} e^{m_2 y} + J_{14} e^{m_8 y} + J_{15} e^{m_2 y} + J_{17} e^{m_{12} y} \quad . \tag{33}$$

$$u(y,t) = 1 + J_1 e^{m_2 y} + J_2 e^{m_6 y} + J_3 e^{m_2 y} + J_4 e^{m_{10} y} + \epsilon e^{n\,t} \begin{pmatrix} 1 + J_6 e^{m_{10} y} + J_7 e^{m_2 y} + J_8 e^{m_6 y} + (J_9 + J_{10}) e^{m_2 y} + (J_{11} + J_{16}) e^{m_4 y} + J_{12} e^{m_6 y} + J_{13} e^{m_2 y} + J_{14} e^{m_8 y} \\ + J_{15} e^{m_2 y} + J_{17} e^{m_{12} y} \end{pmatrix}$$

$$\theta(y,t) = e^{m_2 y} + \epsilon e^{n\,t}(D_1 e^{m_2 y} + D_2 e^{m_4 y}) \quad .$$

$$c(y,t) = B_1 e^{m_2 y} + B_2 e^{m_6 y} + \epsilon e^{nt}(B_3 e^{m_6 y} + B_4 e^{m_2 y} + B_5 e^{m_8 y} + D_3 e^{m_2 y} + D_4 e^{m_4 y}) \quad .$$

$$C_f = \left(\frac{\partial u}{\partial y}\right)_{y=0} = m_2 J_1 + m_6 J_2 + m_2 J_3 + m_{10} J_4 + \epsilon e^{n\,t}\left(m_{10} J_6 + m_2 J_7 + m_6 J_8 + m_2(J_9 + J_{10}) + m_4(J_{11} + J_{16}) + m_6 J_{12} + m_2 J_{13} + m_8 J_{14} + m_2 J_{15} + m_{12} J_{17}\right)$$

The dimensionless local surface heat flux i.e

Nusselt number (Nu) can be written as

$$\mathrm{Nu} = \frac{q_w'}{k(T_w' - T_\infty')}, NuRe_x = -\left(1 + \frac{4}{3}R\right)\left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$
$$= -\left(1 + \frac{4}{3}R\right)[m_2 + \epsilon e^{nt}(m_2 D_1 + m_4 D_2)]$$

Where $q_w' = \frac{k(T_w' - T_\infty')V_0}{\nu}\left(1 + \frac{4}{3}R\right)\left(\frac{\partial \theta}{\partial y}\right)_{y=0}$ and Re_x *is the Reynolds number.*

The Sherwood number is given by

$$\mathrm{Sh} = -\left(\frac{\partial c}{\partial y}\right)_{y=0} = -[m_2 B_1 + m_6 B_2 + \epsilon e^{nt}(m_6 B_3 + m_2 B_4 + m_8 B_5 + m_2 D_3 + m_4 D_4)]$$

RESULTS AND DISCUSSION

To discuss the physical significance of various parameters involved in the results, the numerical calculations have been carried out. The effects of the various parameters entering in the governing equations on the velocity, temperature, skin friction, Nusselt number and Sherwood number are shown through graphs.

Fig.1: Solutal Grashoff number Gc is defined by the ratio of the species buoyancy force to viscous hydrodynamic force. The fluid velocity increases to a peak value and decreases. The peak value is more distinctive due to increase in species buoyancy force. Velocity distribution attains maximum value in the vicinity of the plate. It is observed that velocity increases with increasing values of solutal Grashoff number.

Fig.2: illustrates the influence of Prandtl number Pr on the flow field. It is observed that velocity increases with increase in Pr. Again the thickness of momentum boundary layer is more for fluid with low Prandtl number. The reason underlying this behavior arises from the fact that the increase in the Prandtl number is due to the increase in the viscosity of the fluid, which makes the fluid thick and hence the fluid moves slowly.

Fig.3 and **Fig.8** show the behavior of velocity for different values of chemical reaction parameter Rc. It is seen that the velocity and concentration profiles decrease with increases in the chemical reaction parameter. This shows that the diffusion rates can be tremendously altered by chemical reactions. It is also important to note that increasing the chemical reaction parameter significantly alters the concentration boundary layer thickness without any significant effect on the momentum and thermal boundary layers.

Fig.4: This figure displays the effects of Schmidt number Sc on the velocity field. It is inferred that the velocity decreases with increasing Schmidt number. An increasing Schmidt number implies that viscous forces dominate over the diffusion effects. Schmidt number in free convection flow regimes represents the relative effectiveness of momentum and mass transport by diffusion in the velocity (momentum) and concentration (species) boundary layers. Smaller Sc values correspond to lower molecular weight species diffusing in air (eg Helium (Sc = 0.3), water vapour (Sc = 0. 6), ammonia (Sc = 0.78),) and higher values to denser hydrocarbons diffusing in air. Therefore an increase in Sc will counteract momentum diffusion since viscosity effects will increase and molecular diffusivity will be reduced. The flow will therefore be decelerated with a rise in Sc.

Fig.5: It shows the behaviour of temperature for different values of Prandtl number. It is observed that an increase in the Prandtl number results a decrease of the thermal boundary layer thickness and in general lower average temperature within the boundary layer. The reason is that smaller values of Pr are equivalent to increase in the thermal conductivity of the fluid and therefore, heat is able to diffuse away from the heated surface more rapidly for higher values of Pr. Hence, in the case of smaller Prandtl number as the thermal boundary layer is thicker and the rate of heat transfer is reduced.

Fig.6: Here temperature profiles inside the boundary layer, against span wise coordinate y for different values of Boltzmann-Rosseland radiation parameter R is shown. It is noticed that an increase in radiation parameter leads to an increase in the temperature which implies that radiation tends to enhance fluid temperature.

Fig.7: In this figure concentration profiles are depicted for various values of Soret number (So). It is observed that when So increases concentration also increases. It yields a maximum value near the plate and then decreases.

Table-1: Variations of Nusselt number Nu are illustrated in this table. It is noticed that increase in Q, R and Pr result an increase in the Nusselt number.

Table-2: Variations of Sherwood number Sh are illustrated in this table. It is noticed that increase in Q and Sc result and decrease in the Sherwood number. On the other hand when Rc results an increase in Sherwood number.

Table-3: It presents the numerical values of skin friction (τ) at the plate due to variations in Gr, Gc, Pr, Rc, Sc. It is noticed that skin friction decreases as Rc, Sc and Pr increase. But Gr and Gc enhance the skin friction.

CONCLUSION

A two dimensional unsteady, free convective laminar flow with heat and mass transfer along with chemical reaction past a semi-infinite vertical moving plate in a uniform porous medium is considered. The governing system of equations was solved analytically with the help of Perturbation method. The effects of the parameters on the velocity, concentration, temperature skin friction, Sherwood number were studied in details. Some important conclusions are summarized as follows.

- Velocity decreases with increase in Rc, Sc and Pr.
- Concentration decreases when we increase Rc.
- Temperature and Prandtl number are inversely proportional to each other.
- Nusselt number increases with increase in Pr.
- Chemical reaction parameter Rc results an increase in Sherwood number.

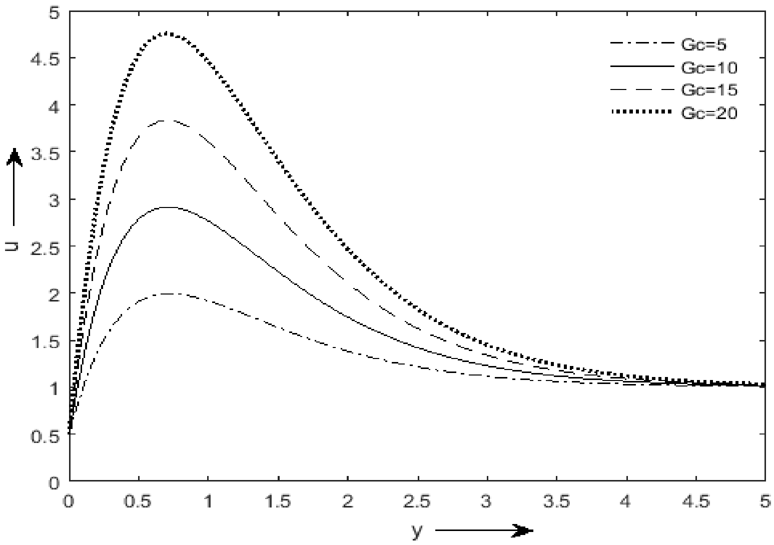

Figure-1: Velocity profiles for different values of Gc (R=2, Rc=2, Pr=7, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

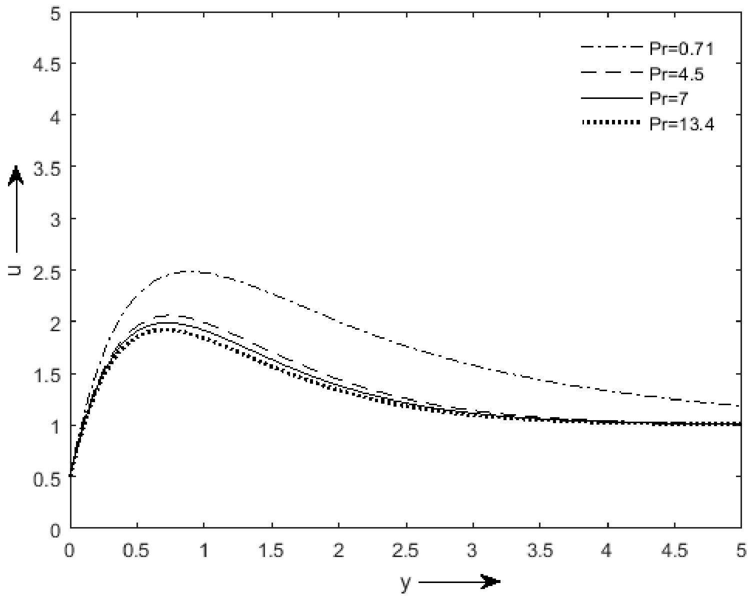

Figure-2: Velocity profiles for different values of Pr (R=2, Rc=2, Gc=5, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

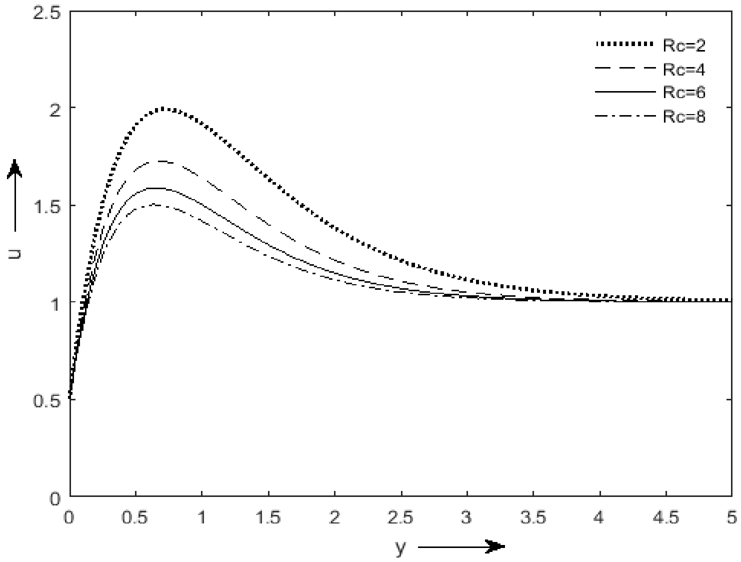

Figure-3: Velocity profiles for different values of Rc (R=2, Pr=7, Gc=5, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

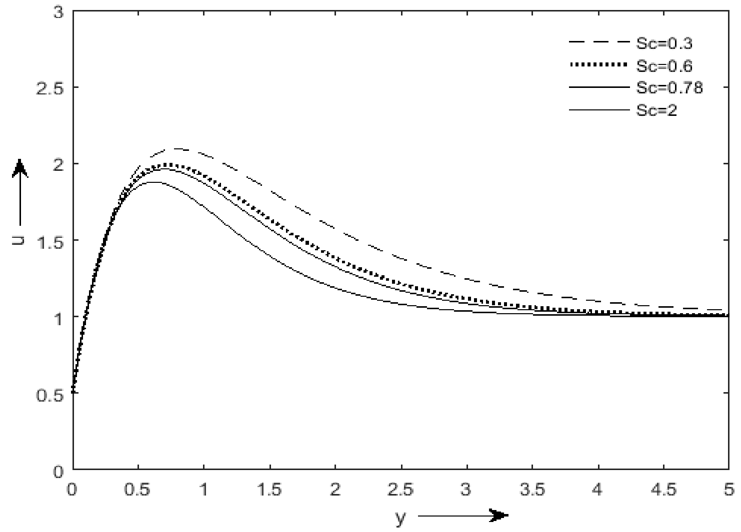

Figure-4: Velocity profiles for different values of Sc (R=2, Rc=2, Gc=5, So=2, Q=1, n=0.5, ϵ=0.001, Pr=7, N=2, A=0.5, Gr=5, t=1, Up=0.5)

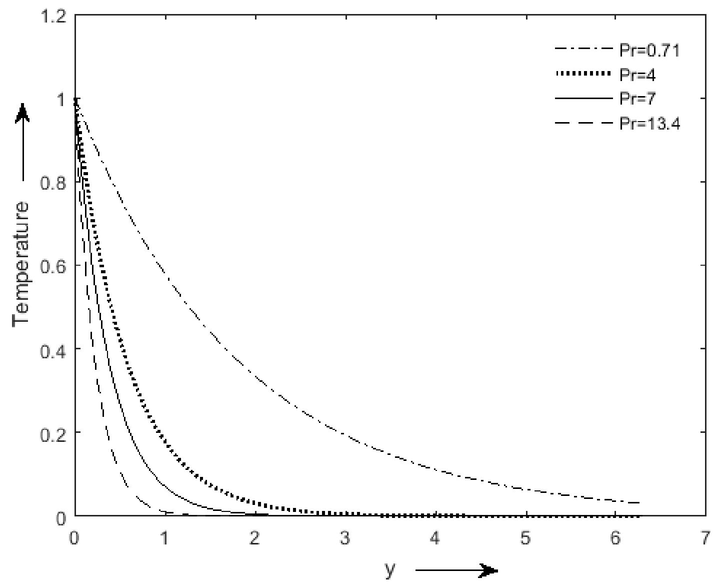

Figure-5: Temperature profiles for different values of Pr (R=2, Rc=2, Gc=5, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

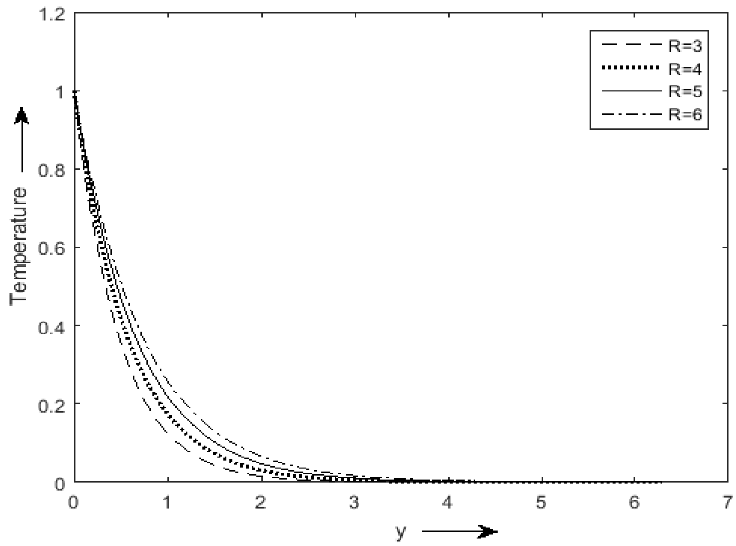

Figure-6: Temperature profiles for different values of R (Rc=2, Gc=5, Pr=7, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

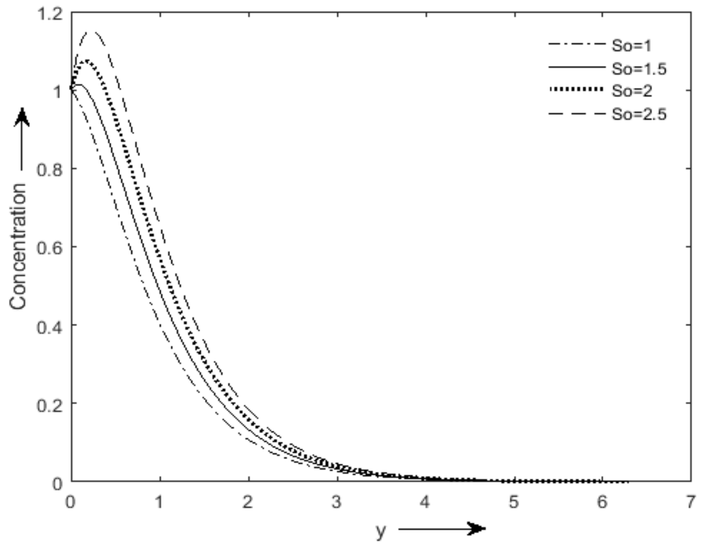

Figure-7: Concentration profiles for different values of So (Rc=2, R=2, Gc=5, Pr=7, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

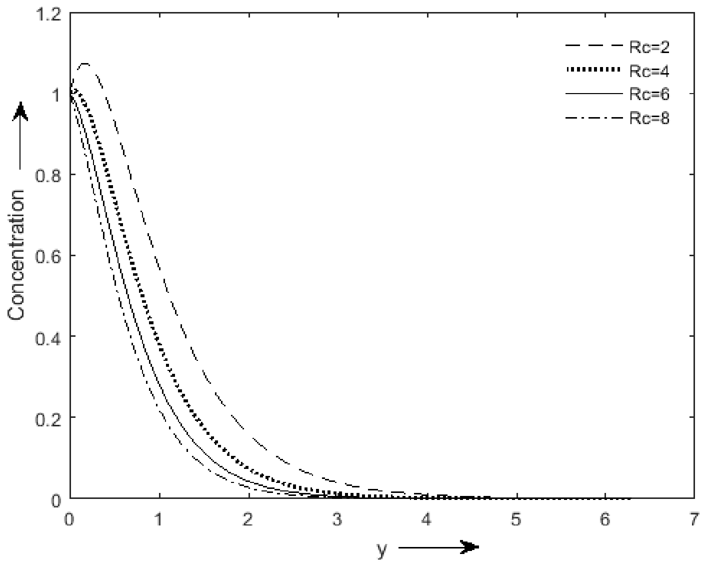

Figure-8: Concetration profiles for different values of Rc (Gc=5, Pr=7, So=2, Q=1, n=0.5, ϵ=0.001, Sc=0.6, N=2, A=0.5, Gr=5, t=1, Up=0.5)

Table-1

Sl. No.	Q	R	Pr	Nu
1	1	2	0.71	2.0113
2	2	2	0.71	2.6694
3	3	2	0.71	3.1780
4	1	3	0.71	2.2770
5	1	4	0.71	2.5103
6	1	2	4.5	6.9088
7	1	2	7	9.6794

Table-2

Sl. No	Q	Rc	Sc	Sh
1	1	2	0.6	-0.9664
2	2	2	0.6	-1.5314
3	3	2	0.6	-1.9948
4	1	4	0.6	-0.2518
5	1	6	0.6	0.2635
6	1	2	0.78	-1.3519
7	1	2	2	-3.9453

Table-3

Sl.No.	Rc	Sc	Gr	Gm	Pr	τ
1	2	0.6	5	5	0.71	6.6414
2	4	0.6	5	5	0.71	6.2017
3	6	0.6	5	5	0.71	5.9614
4	2	0.3	5	5	0.71	7.075
5	2	0.78	5	5	0.71	6.4783
6	2	2	5	5	0.71	5.9356
7	2	0.6	10	5	0.71	9.8777
8	2	0.6	15	5	0.71	13.1139
9	2	0.6	5	10	0.71	9.0427
10	2	0.6	5	15	0.71	11.444
11	2	0.6	5	5	4.5	5.9132
12	2	0.6	5	5	7	5.7951

Appendix

$m_1 = \frac{-1+\sqrt{1+4Q\beta_1}}{2\beta_1}$

$\beta_1 = \frac{3+4R}{3Pr}$

$m_2 = \left(\frac{1+\sqrt{1+4Q\beta_1}}{2\beta_1}\right)$

$D_1 = \frac{-Am_2}{\beta_1 m_2^2 + m_2 - (n+Q)}$

$m_3 = \frac{-1+\sqrt{1+4(n+Q)\beta_1}}{2\beta_1}$

$D_2 = (1 - D_1)$

$m_4 = -\left(\frac{1+\sqrt{1+4(n+Q)\beta_1}}{2\beta_1}\right)$

$D_3 = \frac{-ScSom_2^2 D_1}{m_2^2+Scm_2-Sc(Rc+n)}$

$m_5 = \frac{-Sc+\sqrt{(Sc)^2 +4RcSc}}{2}$

$D_4 = \frac{-ScSom_4^2 D_2}{m_4^2+Scm_4-Sc(Rc+n)}$

$m_6 = -\left(\frac{Sc+\sqrt{(Sc)^2 +4RcSc}}{2}\right)$

$B_1 = \frac{-ScSom_2^2}{m_2^2+Scm_2-RcSc}$

$m_7 = \frac{-Sc+\sqrt{(Sc)^2 +4Sc(Rc+n)}}{2}$

$B_2 = (1 - B_1)$

$m_8 = -\left(\frac{Sc+\sqrt{(Sc)^2 +4Sc(Rc+n)}}{2}\right)$

$B_3 = \frac{-ASc\, m_6 B_2}{m_6^2+Scm_6-Sc(Rc+n)}$

$m_9 = \frac{-1+\sqrt{1+4N}}{2}$

$B_4 = \frac{-AScm_2 B_1}{m_2^2+Scm_2-Sc(Rc+n)}$

$m_{10} = -\left(\frac{1+\sqrt{1+4N}}{2}\right)$

$B_5 = (1 - D_3 - D_4 - B_3 - B_4)$

$m_{11} = \frac{-1+\sqrt{1+4(n+N)}}{2}$

$m_{12} = -\left(\frac{1+\sqrt{1+4(n+N)}}{2}\right)$

$J_1 = \frac{-Gr}{m_2^2+m_2-N}$

$J_2 = \frac{-GcB_2}{m_6^2+m_6-N}$

$J_3 = \frac{-GcB_1}{m_2^2+m_2-N}$

$J_4 = (U_P - 1 - J_1 - J_2 - J_3)$

$J_6 = -\frac{AJ_4\, m_{10}}{m_{10}^2+m_{10}-(N+n)}$

$J_7 = -\frac{AJ_1\, m_2}{m_2^2+m_2-(N+n)}$

$J_9 = -\frac{AJ_3\, m_2}{m_2^2+m_2-(N+n)}$

$J_8 = -\frac{AJ_2\, m_6}{m_6^2+m_6-(N+n)}$

$J_{10} = -\frac{Gr\, D_1}{m_2^2+m_2-(N+n)}$

$J_{11} = -\frac{GrD_2}{m_4^2+m_4-(N+n)}$

$J_{12} = -\frac{GcB_3}{m_6^2+m_6-(N+n)}$

$J_{13} = -\frac{GcB_4}{m_2^2+m_2-(N+n)}$

$J_{14} = -\frac{GcB_5}{m_8^2+m_8-(N+n)}$

$J_{15} = -\frac{GcD_3}{m_2^2+m_2-(N+n)}$

$J_{16} = -\frac{GcD_4}{m_4^2+m_4-(N+n)}$

$J_{17} = -(1 + J_6 + J_7 + J_8 + J_9 + J_{10} + J_{11} + J_{12} + J_{13} + J_{14} + J_{15} + J_{16})$.

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