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Radiation Effects on Mass Transfer Flow through A Highly Porous Medium with Heat Generation and Soret Effect

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Abstract

The present paper is concerned to analyze the influence of the unsteady free convection flow of a viscous incompressible fluid through a porous medium with high porosity bounded by a vertical infinite moving plate in the presence of thermal radiation, heat generation, and chemical reaction. The fluid is considered to be gray, absorbing, and emitting but nonscattering medium, and Rosseland approximation is considered to describe the radiative heat flux in the energy equation. The dimensionless governing equations for this investigation are solved analytically using perturbation technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are shown in figures and tables and analyzed in detail.

Keywords: Radiation, heat generation, heat transfer, MHD, vertical plate, Soret effect.

Introduction

The heat and mass transfer from different geomeries embedded in porous media has many engineering and geophysical applications suah as drying of porous solids , thermal insulations, cooling of nuclear reactors, crude oil extraction, undergroud energy transport, etc. The effect of radiation on MHD flow and heat transfer problem have become more important industrially. At high operating temperature, radiation effect can be quite significant. Many processes in engineering areas occur at high temperature and a knowledge of radiation heat transfer becomes very important for the design of the pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering areas. Bestman [1] examined the natural convection boundary layer with suction and mass transfer in a porous medium. His results confirmed the hypothesis that suction stabilises the boundary layer and affords the most efficient method in boundary layer control yet known. Abdus Sattar and Hamid Kalim [2] investigated the unsteady free convection interaction with thermal radiation in a boundary layer flow past a vertical porous plate.

Transport of momentum and energy in fluid-saturated porous media with low porosities are commonly described by Darcy's model for conservation of momentum and by an energy equation based on the velocity field found from this model by Kaviany [3]. In contrast to rocks, soil, sand, and other media that do fall in this category, certain porous materials, such as foam metals and fibrous media, usually have high porosity. Vajravelu [4] examined the steady flow of heat transfer in a porous medium with high porosity. Raptis [5] studied mathematically the case of time varying two-dimensional natural convection heat transfer of an incompressible electrically conducting viscous fluid through a high porous medium bounded by an infinite vertical porous plate. Hong et al. [6], Chen and Lin [7], and Jaiswal and Soundalgekar [8] studied the natural convection in a porous medium with high porosity. Hiremath and Patil [9]studied the effect of free convection currents on the oscillatory flow of the polar fluid through a porous medium, which is bounded by the vertical plane surface with constant temperature.

The study of heat generation or absorption effects in moving fluids is important in the view of several physical problems, such as fluids undergoing exothermic or endothermic chemical reactions. Vajravelu and Hadjinicolaou[10] studied the heat transfer characteristics in the laminar boundary layer of a viscous fluid over a stretching sheet with viscous dissipation or frictional heating and internal heat generation. Hossain *et al.*[11] studied problem of the natural convection flow along a vertical wavy surface with uniform surface temperature in the presence of heat generation/absorption. Alam *et al.*[12] studied the problem of the free convection heat and mass transfer flow past an inclined semi-infinite heated surface of an electrically conducting and steady viscous incompressible fluid in the presence of magnetic field and heat generation.

Due to the importance of Soret (thermal-diffusion) effects for the fluids with very light molecular weight as well as medium molecular weight. The Soret effect arises when the mass flux contains a term that depends on the temperature gradient. Bhavana et al [13] proposed the Soret effect on unsteady MHD free convective flow over a vertical plate in presence of the heat source. Anand Rao et al. [14] explained the Soret and Radiation effects on unsteady MHD free convective flow past a vertical porous plate. Soret effect on MHD flow of heat and mass transfer over a vertical stretching plate in a porous medium in presences of heat source was proposed by Mohammad Ali and Mohammad Shah Alam [15]. Dufour and Soret effects on unsteady MHD free convective flow past a vertical porous plate embedded in a porous medium with mass transfer was studied by Alam et al [16].

In view of the above studies, an unsteady free convective at and mass transfer flow of a viscous incompressible radiating fluid through a porous medium with high porosity unded by an infinite vertical moving plate is considered the presence of heat generation and soret effect. It is assumed that the plate is embedded in porous medium and moves with constant velocity in the flow direction. The equations of continuity, linear momentum, energy, and diffusion, which govern the flow field, are solved by using regular perturbation method. The behavior of the velocity, temperature, concentration, skin friction, Nusselt number, and Sherwood number has been discussed for variations in governing parameters.

Mathematical Analysis

An unsteady two-dimensional laminar free convective mass transfer flow of a viscous incompressible fluid through a highly porous medium past an infinite vertical moving porous plate in the presence of thermal radiation, heat generation, and chemical reaction is considered. The fluid and the porous structure are assumed to be in local thermal equilibrium. It is also assumed that there is radiation only from the fluid. The fluid is a gray, emitting, and absorbing, but non-scattering medium, and the Rosseland approximation is used to describe the radiative heat flux in the energy equation.

A homogeneous first order chemical reaction between fluid and the species concentration is considered, in which the rate of chemical reaction is directly proportional to the species concentration. All the fluid properties are assumed to be constant except that the influence of the density variation with temperature is considered only in the body force term (Boussinesq's approximation). The x' -axis is chosen along the plate in the direction opposite to the direction of gravity and the y' -axis is taken normal to it. Since the flow field is of extreme size, all the variables are functions of y' only. Hence, under the usual Boussinesq's approximation, the equations of mass, linear momentum, energy, and diffusion are

Continuity equation:

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

Momentum equation:

$$\frac{\partial u'}{\partial t'} + v' \frac{\partial u'}{\partial y'} = -\frac{1}{\rho}\frac{\partial p'}{\partial x'} + \nu \frac{\partial u'}{\partial y'^2} + g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) - \frac{\nu}{k'}\varphi u' \tag{2}$$

Energy Equation:

$$\sigma \frac{\partial T'}{\partial t'} + \varphi v' \frac{\partial T'}{\partial y'} = -\frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{\varphi}{\rho c_p}\frac{\partial q_r}{\partial y'} + \frac{q_0}{\rho c_p}(T' - T'_\infty) \tag{3}$$

Diffusion Equation:

$$\frac{\partial C'}{\partial t'} + v' \frac{\partial C'}{\partial y'} = -D\frac{\partial^2 C'}{\partial y'^2} + D_T \frac{\partial^2 T'}{\partial y'^2} \tag{4}$$

Where x', y' and t' are the distances along and perpendicular to the plate and dimensional time, respectively u' and v' are the components of dimensional velocities along x' and y' directions respectively C' and T' are the dimensional and concentration and temperature of the fluid respectively ρ fluid density ; v the kinematic viscosity; c_p the specific heat at constant pressure ; σ the heat capacity ratio; g the acceleration due to gravity; β and β^* the volumetric coefficient of thermal and concentration expansion; k' the permeability of the porous medium ; φ the porosity; D the molecular diffusivity; s_0 the soret effect parameter; and k the fluid thermal conductivity; the third and fourth terms on the right hand side of the momentum equation (2) denote the thermal and concentration buoyancy effects respectively, and the fifth term represents the bulk matrix linera resistance, that is, darcy term. also, the second term on the right hand side of the energy equation (3) represents thermal radiation. The radiative heat flux term by using the Rosseland approximation(Brewster[17]) is given by

$$q_r = \frac{4\sigma_s \partial T'^4}{3k_e \partial y'} \tag{5}$$

Where σ_s is the Stefan-Boltzmann constant and k_e is the mean absorption coefficient, it should be noted that by using the Rosseland approximation, the present analysis is limited to optically thick fluids. if temperature differences within the flow are sufficiently small, then (6) can be linearised by expanding T'^4 in to the Taylors series about T_∞, which after neglecting higher order terms take the form

$$T'^4 \approx 4T_\infty^3 T - 3T_\infty^4 \tag{6}$$

It is assumed that the permeable plate moves with constant velocity in the direction of fluid flow. it is also assumed that the plate temperature and concentration are exponentially varying with time. Under these assumptions, the appropriate boundary conditions for the velocity, temperature and concentration fields are

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

$$u' \to U'_\infty, \qquad T' \to T'_\infty, \quad C' \to C'_\infty, \qquad \text{as} \qquad y' \to \infty, \tag{7}$$

Where U'_p is the wall dimensional velocity; C'_w and T'_w are the wall dimensional concentration and temperature, respectively; U'_∞, C'_∞ and T'_∞ are the free stream dimensional velocity, concentration and temperature respectively; n' is the constant.
It is clear from (1) that the suction velocity normal to the plate is either a constant or a function of time. Hence the suction velocity normal to the plate is taken as

$$v'' = -v_0 \tag{8}$$

Where v_0 is the scale of suction velocity which is a nonzero positive constant?
The negative sign indicates that the suction is towards the plate.

Outside the boundary layer, (2) gives

$$\frac{1}{\rho}\frac{dp^{'}}{dx^{'}} = -\frac{\varphi v}{K^{'}}U_{\infty}^{'} \tag{9}$$

in order to write the governing equations and the boundary conditions in dimensionless form, the following nondimensional quantities are introduced.

$$u = \frac{u^{'}}{U_{\infty}^{'}}, \quad y = \frac{v_0 y^{'}}{v}, \quad U_p = \frac{U_p^{'}}{U_{\infty}^{'}}, \quad n = \frac{n^{'}v}{v_0^2}, \quad t = \frac{v_0^2 t^{'}}{v}, \quad \lambda = \frac{\sigma}{\varphi}, \quad \theta = \frac{T^{'} - T_{\infty}^{'}}{T_w^{'} - T_{\infty}^{'}},$$

$$C = \frac{C^{'} - C_{\infty}^{'}}{C_w^{'} - C_{\infty}^{'}}, \qquad Gr = \frac{vg\beta(T_w^{'} - T_{\infty}^{'})}{U_{\infty}^{'}v_0^2}, \qquad Gc = \frac{vg\beta^{*}(C_w^{'} - C_{\infty}^{'})}{U_{\infty}^{'}v_0^2}, \qquad k = \frac{k^{'}v_0^2}{\varphi v^2},$$

$$pr = \frac{\rho c_p \varphi v}{k}, \quad R = \frac{K_e k}{4\varphi\sigma_s T_{\infty}^3}, \quad Sc = \frac{v}{D}, \; So = D_T \frac{T_w^{'} - T_{\infty}^{'}}{C_w^{'} - C_{\infty}^{'}}\frac{1}{v}, \; Q = \frac{Q_0 v}{\varphi\rho C_p v_0^2} \tag{10}$$

in view of (5)-(10), (2)-(4) reduce to the following non dimensional form:

$$\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + GcC + \frac{1}{k}(1-u)$$

$$\lambda\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{\Gamma}\frac{\partial^2 \theta}{\partial y^2} + Q\theta$$

$$\frac{\partial C}{\partial t} - \frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} + S_0\frac{\partial^2 \theta}{\partial y^2} \tag{11}$$

Where $\Gamma = \frac{1-4}{3R+4}p_r$ and Gr, Gc, Pr, R, Sc, Q, K and Kr are the thermal grashof number, solutal Grashof number, Pr and tl number, Radiation parameter, Schmidt number, heat generation parameter, permeability of the porous medium, and chemical reaction parameter respectively.

The corresponding dimensionless boundary conditions are

$$u = U_P, \quad \theta = 1 + \varepsilon e^{nt}, \quad = 1 + \varepsilon e^{nt} \quad \text{at} \quad y=0$$

$$u \to 1, \quad \theta \to 0, \quad C \to 0, \quad \text{as} \quad y \to \infty, \tag{12}$$

Solution of the problem:

Equations (11) are coupled, nonlinear partial differential equations and these cannot be solved in closed form. However, these equations can be reduced to a set of ordinary differential equations, which can be solved analytically. this can be done by representing the velocity, temperature and concentration of the fluid in the neighborhood of the plate as

$$
\begin{aligned}
u(y,t) &= u_0(y) + \varepsilon e^{nt} u_1(y) + o(\varepsilon)^2 + \ldots\ldots\ldots\ldots, \\
\theta(y,t) &= \theta_0(y) + \varepsilon e^{nt} \theta_1(y) + o(\varepsilon)^2 + \ldots\ldots\ldots\ldots, \qquad (13) \\
C(y,t) &= C_0(y) + \varepsilon e^{nt} C_1(y) + o(\varepsilon)^2 + \ldots\ldots\ldots\ldots,
\end{aligned}
$$

substituting 13 in 11 equating the harmonic and no harmonic terms, and neglecting the higher order terms of $o(\in)^{2,}$ we obtain

$$u_0'' + u_0' - \frac{1}{k} u_0 = -\frac{1}{k} - Gr\theta_0 - GcC_0$$

$$u_1'' + u_1' - (n + \frac{1}{k}) u_1 = -Gr\theta_1 - GcC_1$$

$$\theta_0'' + \Gamma\theta_0' + \Gamma Q\theta_0 = 0$$

$$\theta_1'' + \Gamma\theta_1' - n\lambda\Gamma\theta_1 + \Gamma Q\theta_1 = 0$$

$$C_0'' + ScSoC_0' = ScSo\theta_0''$$

$$C_1'' + ScC_1' + ScC_1 = ScSo\theta_1'' \qquad (14)$$

Where the prime denotes ordinary differentiation with respect to y. the corresponding boundary conditions can be written as

$$u_0 = U_p, \quad u_1 = 0, \quad \theta_0 = 1, \quad \theta_1 = 1, \quad C_0 = 1, \quad C_1 = 1, \quad \text{at} \quad y = 0,$$

$$u_0 \to 1, \quad u_1 \to 0, \quad \theta_0 \to 1, \quad \theta_1 \to 0, \quad C_0 \to 1, \quad C_1 \to 0, \quad \text{as} \quad y \to \infty, \qquad (15)$$

solving (14) subject to boundary conditions (15) we obtain the velocity, temperature and concentration distributions in the boundary layer as

$$u(y,t) = 1 + B_1 e^{-m_3 y} - A_2 e^{-m1y} + A_3 + A_4 e^{-m2y} - A_5 e^{-m1y} + A_3 e^{-m3y}$$
$$+ \varepsilon e^{nt} (B_2 e^{-m6y} + A_7 e^{-m4y} + A_8 e^{-m5y} + A_9 e^{-m4y})$$

$$\theta(y,t) = e^{-m1y} + + \varepsilon e^{nt} e^{-m4y})$$

$$C(y,t) = 1 - A_1 e^{-m_2 y} + A_1 e^{-m1y} + \varepsilon e^{nt} (-A_6 e^{-m5y} + A_6 e^{-m4y}) \qquad (16 - 17 - 18)$$

Where the expressions for the constants are given in the appendix.

The skin-friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. These parameters can be defined and determined as follows.

Knowing the velocity field, the skin friction at the plate can be obtained, which in non-dimensional form is given by

$$C_f = \frac{\tau'_w}{\rho U_0 v_0} = \left(\frac{\partial u}{\partial y}\right)_{y=0} = \left(\frac{\partial u_0}{\partial y} + \varepsilon e^{nt}\frac{\partial u_1}{\partial y}\right)_{y=0}$$
$$= -B_1 m_3 + m_1 A_2 - m_2 A_4 + m_1 A_5 - m_3 A_3 + \varepsilon e^{nt}(B_2 m_6 - m_4 A_7 - m_5 A_8 - m_4 A_9)$$

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which in the non-dimensional form, in terms of the Nusselt number, is given by

$$Nu = -x\frac{(\partial T / \partial y')_{y'=0}}{(T'_w - T'_\infty)} \Rightarrow Nu\,\mathrm{Re}_x^{-1} = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -\left(\frac{\partial \theta_0}{\partial y} + \varepsilon e^{nt}\frac{\partial \vartheta_1}{\partial y}\right)_{y=0}$$
$$= -(m_1 + \varepsilon e^{nt} m_4)$$

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which in the nono-dimensional form, in terms of the sherwood number is given by

$$Sh = -x\frac{(\partial C / \partial y')_{y'=0}}{(C'_w - C'_\infty)} \Rightarrow Sh\,\mathrm{Re}_x^{-1} = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = -\left(\frac{\partial C_0}{\partial y} + \varepsilon e^{nt}\frac{\partial C_1}{\partial y}\right)_{y=0}$$
$$= -m_2 A_1 - m_1 A_1 + \varepsilon e^{nt}(A_6 m_5 - m_4 A_6)$$

where $\mathrm{Re}_x = \dfrac{v_0 x}{v}$ is the local Rreynolds number.

Results and Discussion

In this problem of an unsteady free convective flow of a viscous incompressible, thermally radiating, and chemically reacting fluid past a semi-infinite plate in the presence of heat generation was formulated and solved by means of a perturbation method. The expressions for the velocity, temperature, and concentration were obtained. To illustrate the behavior of these physical quantities, numerical values of these quantities were computed with respect to the variations in the governing parameters, namely, the thermal Grashof number Gr, the solutal Grashof number Gc,Prandtl number Pr, Schmidt numberSc, the radiation parameter R, the permeability of the porous medium K, the heat generation parameter Q,and thesoret parameter S0 . In the present study the following default parametric values are adopted: Gr = 2.0, Gc= 2.0, K = 5.0, λ = 1.4,Sc = 0.2, R = 5.0, So= 1.0, Q = 0.1 , Pr = 0.71, U_p= 0.4, A = 0.5, t = 1.0, n= 0.1,andε = 0.01.All the graphs and tables therefore correspond to these values unless specifically indicated on the appropriate graph.

Figure 1 presents the typical velocity profiles in the boundary layer for various values of the thermal Grashof number Gr. The thermal Grashof number Gr signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. It is observed that an increase in Gr leads to a rise in the values of velocity due to enhancement of thermal buoyancy force. Here the positive values of Gr correspond to cooling of the surface. It is observed that velocity increases rapidly near the wall of the porous plate as Gr increases and then decays to the free stream velocity. For the case of different values of the solutal Grahof number Gc, the velocity profiles in the boundary layer are shown in Figure 2. The solutal Grashof number Gc defines the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, as Gc increases, the fluid velocity increases and the peak value is more distinctive maximum value in the vicinity of the plate and then decreases properly to approach the free stream value. Figure 3 shows the velocity profiles for different values of the permeability of the porous medium K. Clearly, as K increases the velocity tends to increase.

For different values of the radiation parameter R the velocity and temperature profiles are plotted in Figures 4 and 5. The radiation parameter R defines the relative contribution of conduction heat transfer to thermal radiation ransfer. It is obvious that an increase in the radiation param- eter R results in a decrease in the velocity and temperature within the boundary layer, as well as decreased thickness of he velocity and temperature boundary layers.

Figures 6 and 7 illustrate the velocity and temperature profiles for different values of Prandtl number Pr. The numerical results show that the effect of increasing values of Prandtl number results in a decreasing velocity. From Figure 7 as expected, the numerical results show that an increase in the Prandtl number results in a decrease of the thermal boundary layer and in general lower average temperature with in 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 numbers the thermal boundary layer is thicker and the rate of heat transfer is reduced.

Figures 8 and 9 display the effects of the Schmidt number Sc on velocity and concentration, respectively. The Schmidt number Sc embodies the ratio of the momentum to the mass diffusivity. The Schmidt number therefore quantifies the relative effectiveness of momentum and mass transport by diffusion in the hydrodynamic (velocity) and concentration (species) boundary layers. As the Schmidt number increases the concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. The reductions in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layers. These behavior are evident from Figures 8 and 9.

Figure 10 and 11depict the effect of heat generation parameter Q on velocity and temperature it is noticed that velocity as well as temprature across the boundary layer increases with the increase in the heat generation parameter Q.

Fig.12 illustrates the concentration profiles for different values of soret. It is observed that concentration decreases as the increase in soret.

Tables 1–7 show the effects of the thermal Grashof number Gr, solutal Grashof number Gc, radiation parameter R, Prandtl number Pr, Schmidt number Sc, soret effect parameter So , and heat generation parameter Q on the skin friction coefficient Cf ,Nusselt number Nu, and the Sherwood number Sh. From Tables 1 and 2,itisobservedthat as Gr or Gc increases, the skin-friction coefficient increases. From Table 3, it can be seen that as the radiation parameter increases, the skin-friction decreases and the Nusselt number increases. From Table 4, it is found that an increase in Pr leads to a decrease in the skin-friction and an increase in the Nusselt number. From Table 5, it is observed that, as the Schmidt number increases, the skin-friction decreases and the Sherwood number increases. From Table 6, it is observed that, as the heat generation parameter Qincreases, the skin-friction increases and the Nusselt number decreases. From Table 7, it is seen that, Effects of soret effect shows the decrease in skin friction and Nusselt number.

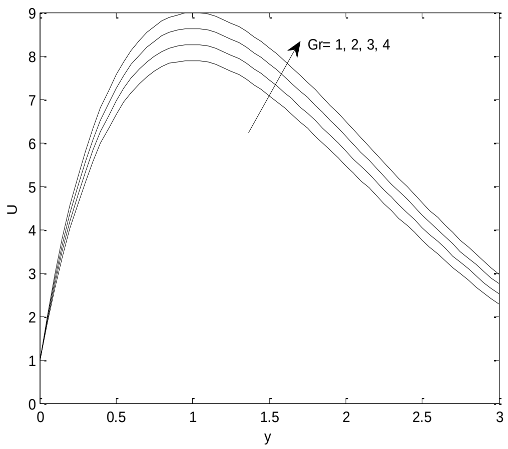

Fig 1: Velocity profle for different values of Gr

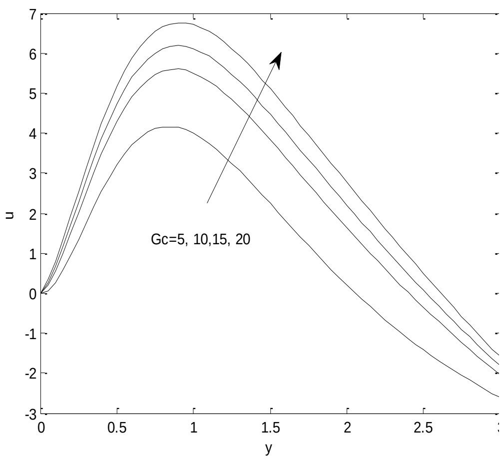

Fig 2: Velocity profle for different values of Gc

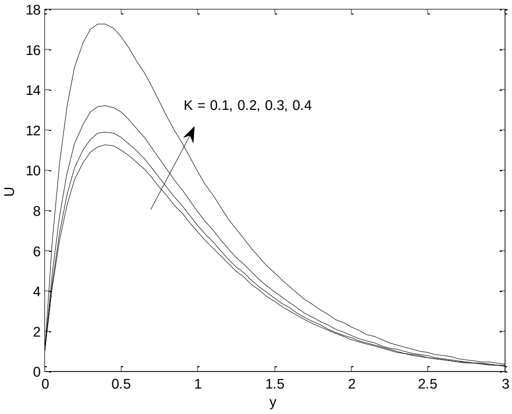

Fig 3: Velocity profle for different values of K

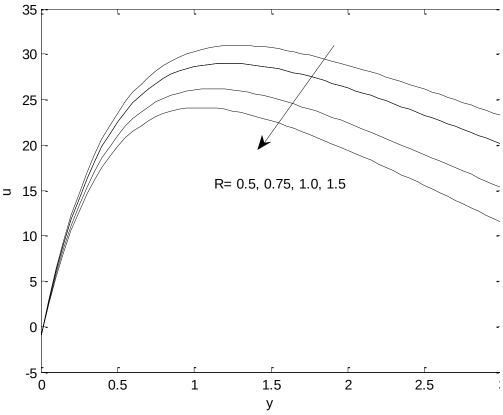

Fig 4: Velocity profle for different values of R

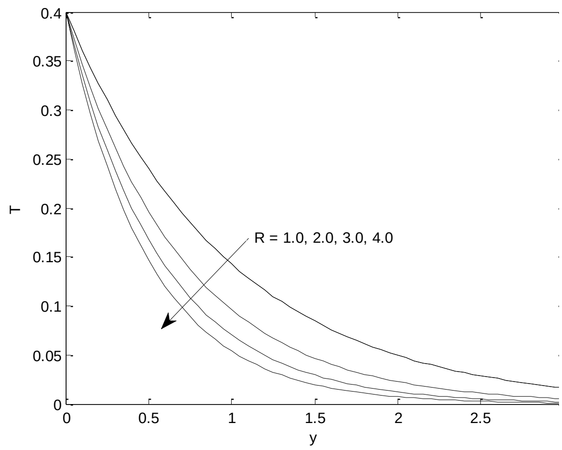

Fig 5: Temperature profle for different values of R

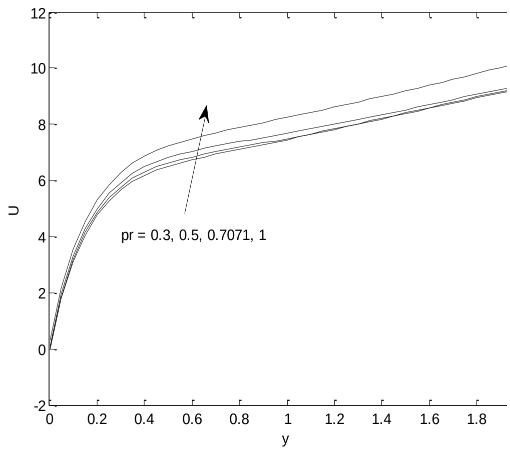

Fig 6: Velocity profle for different values of Pr

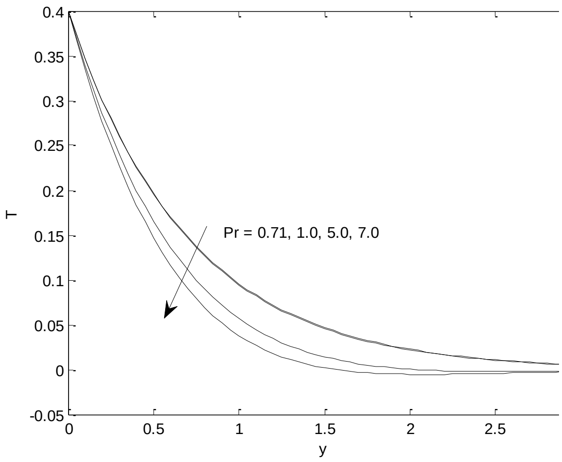

Fig 7: Temperature profle for different values of Pr

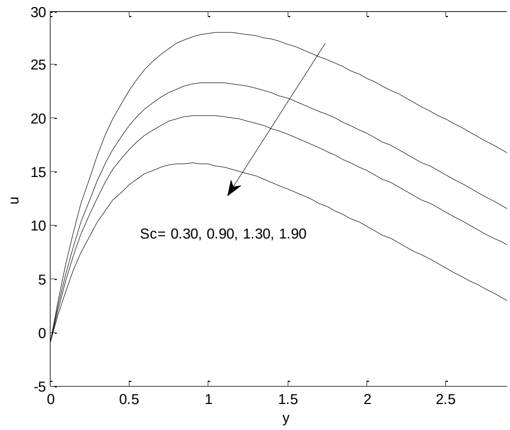

Fig 8: Velocity profle for different values of Sc

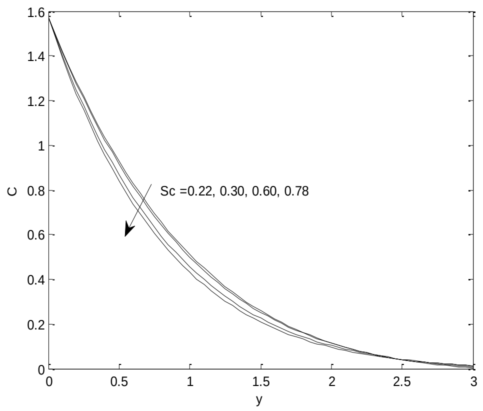

Fig 9: Concntration profle for different values of Sc

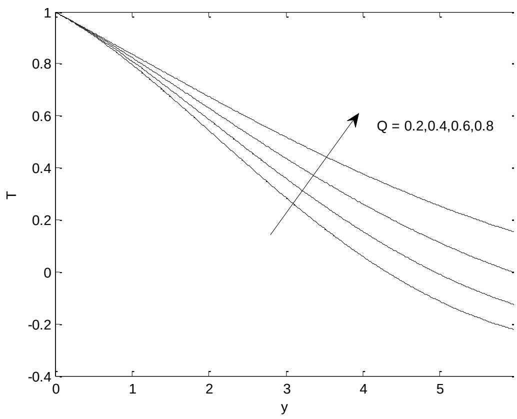

Fig10: Temperature Profile for different values of Q

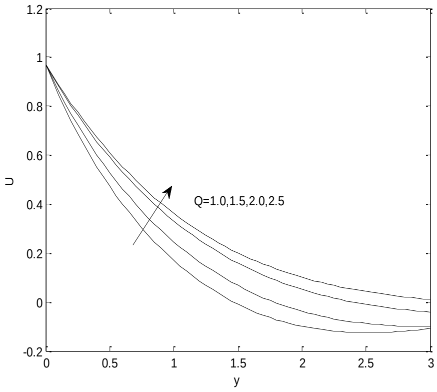

Fig 11: Velocity profiles for different values heat generation.

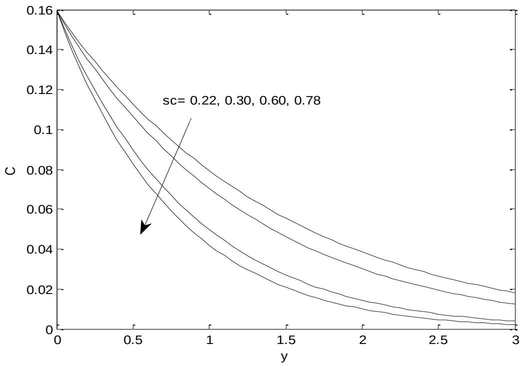

Fig 12: concentration profle for different values of So

Table 1: Effects of Gr on skin friction Cf.

Gr	Cf
1.0	2.3910
2.0	2.9137
3.0	3. 4365
4.0	3. 9592

Table 2: Effects of Gc on skin friction Cf.

Gr	Cf
1.0	17.0698
2.0	13. 0596
3.0	8.5094
4.0	3.9592

Table 3: Effects of R on skin friction Cf and Nusselt number NuRe_x^{-1}.

R	cf	NuRe_x^{-1}.
3.0	2.3910	0.2377
5.0	2.2201	0.3368
7.0	2.0693	0.3763
10.0	1.9186	0.4737

Table 4: Effects of Pr on skin friction Cf and Nusselt number NuR e_x^{-1}.

Pr	cf	NuR e_x^{-1}.
0.71	2.2735	0.4397
0.8	1.8946	0.4145
1.0	1.3134	0.6811
1.25	0.9186	0.8873

Table 5: Effects of Sc on skin friction Cf and sherhood number ShR e_x^{-1}

Sc	cf	ShR e_x^{-1}.
0.2	2.2733	0.6487
0.4	1.6259	1.1091
0.6	1.3134	1.3529
0.9	0.0489	0.8873

Table 6: Effects of Q on skin friction Cf and Nusselt number NuR e_x^{-1}

Q	cf	NuR e_x^{-1}.
0.01]	2.9040	0.6677
0.05	2.9259	0.6121
0.1	3.2735	0.5052
0.15	4.2681	0.4863

Table 7: Effects of So on skin friction Cf and sherhood number ShR e_x^{-1}

So	cf	ShR e_x^{-1}.
0.22	1.3532	0.8873
0.30	1.9040	1.1173
0.60	0.9141	1.3538
0.78	0.3532	1,5246

Appendix:

$$m_1 = \frac{-\Gamma + \sqrt{\Gamma^2 - 4\Gamma Q}}{2} \qquad m_2 = -Sc \qquad m_3 = \frac{1 + \sqrt{1 + 4/k}}{2}$$

$$m_4 = \frac{-\Gamma + \sqrt{\Gamma^2 - 4(n\lambda T - \Gamma Q}}{2} \qquad m_5 = \frac{-Sc + \sqrt{Sc^2 - 4Sc}}{2} \qquad A_1 = \frac{1}{m_1^2 - m_1} S_0 S_c m_1^2$$

$$A_2 = \frac{Gr}{m_1^2 - m_1 - (1/k)} \qquad A_3 = kGc \qquad A_4 = \frac{GcA_1}{m_2^2 - m_2 - (1/k)}$$

$$A_5 = \frac{GcA_1}{m_1^2 - m_1 - (1/k)} \qquad A_6 = \frac{ScS0}{m_4^2 - m_4 Sc + Sc} \qquad A_7 = \frac{-Gr}{m_4^2 - m_4 Sc - (n + (1/k))}$$

$$A_7 = \frac{-Gr}{m_4^2 - m_4 Sc - (n + (1/k))} \qquad A_8 = \frac{GcA_6}{m_5^2 - m_5 Sc - (n + (1/k))} \qquad A_9 = \frac{-GcA_6}{m_4^2 - m_4 - (n + (1/k))}$$

$$B_1 = Up + A_2 - A_4 + A_5 - 1 \qquad B_2 = -A_7 - A_8 - A_9$$

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