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IMPACT OF CHEMICAL REACTION AND HEAT ABSORPTION IN RADIATING FLUID THROUGH A POROUS MEDIUM

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Abstract

The present paper analyses two dimensional motions of incompressible electrically conducting and radiating fluid through a porous medium occupying a semi-infinite region of space bounded a vertical infinite surface with heat source/heat sink in the presence of chemical reaction taking into an account. An analytical solution for this flow is utilized by means of perturbation technique. The expressions are obtained for velocity, temperature and concentration fields are derived and results for various parameters shown graphically and the skin friction coefficient, the rate of heat transfer are also derived.

Key Words: Magnetic field, Free convection, MHD, Porous medium, Chemical reaction

1. Introduction

Rotating flows of fluids with the effect of magnetic fields through a porous media have the significant role in the study of Cosmic and oceanic fluids eddies, rotating food machinery, processing industry, and filtration plants. A porous medium is a material or substance that contains interconnected void spaces or pores through which fluids, such as gases or liquids, can flow. Porous media are commonly found in various natural and engineered systems, including soils, rocks, ceramics, foams, and filters. The physical properties of porous media, such as pore size, shape, and connectivity, play a crucial role in determining their overall behaviors, including flow of fluid, heat and mass fluxes. Flow through a porous medium have numerous engineering and geophysical applications, for example, in chemical engineering for filtration and purification process; in agriculture engineering to study the underground water resources; in petroleum technology to study the movement of natural gas, oil and water through the oil reservoirs. In view of these applications, many researchers have studied MHD free convective heat and mass transfer flow in a porous medium [1-15].

Multiple material processing and chemical flow techniques include the boundary layer flow caused by extending the surface. A numerous examples include drawing wire, making glass fiber, making paper, and making polymer sheets and liquid metal. It is clear that the classical theory of Newtonian fluid flows does not provide an appropriate description of the flow and heat transfer behavior of these fluids. Considerable attention has been focused in recent years by various scientists and engineers the study problem involving the phenomena of heat and mass transfer with radiation effect. This is due to the fact that radiation effects on convection is quite important in the context of many practical applications such as in cooling and heating of channels, nuclear power plant, fire research, electrical power generation, nuclear reactors, gas turbines and nuclear waste disposal [16-30].

The convective heat and mass transfer rates for external interface layer can alter in response to changes in the surface mass flow, often known as blowing. Evaporation can occasionally cause a significant transfer of species. The blowing effect is brought on by Stefan, an issue for species transmission. 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. In particular, the study of chemical reaction, heat and mass transfer with heat radiation is of considerable importance in chemical and hydrometallurgical industries. A reaction is said to be first-order if the rate of reaction is directly proportional to the concentration itself. In many chemical processes, a chemical reaction occurs between a foreign mass and a fluid in which a plate is moving. These processes take place in numerous industrial applications, e.g., polymer production, manufacturing of ceramics or glassware [31-46].

The aim of the present paper concentrates to investigate the effect of chemical reaction on steady two -dimensional free convection heat and mass transfer flow of a viscous incompressible electrically conducting and radiating fluid through a porous medium bounded by an inclined surface with constant suction velocity, constant heat and mass flux under the influence of uniform magnetic field applied normal to the direction of flow.

2. Mathematical Formulation

Consider steady two dimensional motion of incompressible electrically conducting and radiating fluid through a porous medium occupying semi-infinite region of space bounded by a vertical infinite surface with heat source or absorption in the presence of chemical reaction under the action of uniform magnetic field applied normal to the direction of the flow. The x-axis is taken along the surface in the upward direction and y-axis is taken normal to it. The fluid properties are assumed constant except for the influence of density in the body force term. As the bounding surface is infinite in length, all the variables are function of η only. Hence, by usual boundary layer approximation the basic equations for steady flow highly porous medium are

$$\frac{\partial v}{\partial \eta} = 0 \tag{1}$$

$$v\frac{\partial u}{\partial \eta} = \nu\frac{\partial^2 u}{\partial \eta^2} + g\ \beta(T - T_\infty) + g\ \beta^*(C - C_\infty) - \left(\frac{\sigma B_0^2}{\rho}\right)u + \left(\frac{\nu}{k}\right)u \tag{2}$$

$$v\frac{\partial T}{\partial \eta}=\frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial \eta^2}-\frac{1}{\rho C_p}\frac{\partial q}{\partial \eta}-\frac{Q_0}{\rho C_p}\left(T-T_\infty\right)+Q_l'\left(C-C_\infty\right) \quad (3)$$

$$v\frac{\partial C}{\partial \eta}=D\frac{\partial^2 C}{\partial \eta^2}-Kr'\left(C-C_\infty\right) \quad (4)$$

Where u and v are the velocity components along and perpendicular to the surface, g is the acceleration due to gravity, T the temperature of the fluid near the plate, T_∞ the free stream temperature, C concentration, β the coefficient of thermal expansion, β^* is the volumetric coefficient of expansion of the spices concentration, k the thermal conductivity, C_p the specific heat of constant pressure, B_0 the magnetic field coefficient, μ viscosity of the fluid, ρ the density, σ the magnetic permeability of fluid V_0 constant suction velocity, ν the kinematic viscosity and D chemical molecular diffusivity.

3. Solution of the problem

$$v'=-v_0 \text{ (Constant)} \quad (5)$$

where $v_0>0$ corresponds to steady suction velocity (normal) at the surface. In view of equation (5), equations (2), (3) and (4) are reduced to

$$v_0\frac{\partial u'}{\partial \eta'}=\nu\frac{\partial^2 u'}{\partial \eta'^2}+g\ \beta(T-T_\infty)+g\ \beta^*(C-C_\infty)-\left(\frac{\sigma B_0^2}{\rho}\right)u'+\left(\frac{\nu}{k}\right)u' \quad (6)$$

$$v_0\frac{\partial T'}{\partial \eta'}=\frac{\lambda}{\rho C_p}\frac{\partial^2 T'}{\partial \eta'^2}-\frac{1}{\rho C_p}\frac{\partial q}{\partial \eta'}-\frac{Q_0}{\rho C_p}\left(T-T_\infty\right)+Q_l'\left(C-C_\infty\right) \quad (7)$$

$$v_0\frac{\partial C'}{\partial \eta'}=D\frac{\partial^2 C'}{\partial \eta'^2}-Kr'\left(C-C_\infty\right) \quad (8)$$

The relevant boundary conditions are

$$\begin{aligned}
&u'=0,\quad T=T_w,\ \ C=C_\infty && \text{for all}\quad \eta\ \ t\le 0\\
&u'=0,\quad T_y=-\frac{q}{\lambda},\quad C_y=\frac{m}{D} && \eta=0, t>0\\
&u'\to 0,\ T\to T_\infty,\ C\to C_\infty && \eta\to\infty, t>0
\end{aligned} \quad (9)$$

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial \eta'}=-4a^*\sigma\left(T_\infty^4-T^4\right) \quad (10)$$

It is assume that the temperature differences within the flow are sufficiently small such that T^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T^4 in a Taylor series about T_∞ and neglecting higher-order terms, thus

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \quad (11)$$

By using equations (10) and (11), equation (7) reduces to

$$v_0 \frac{\partial T'}{\partial \eta'} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T'}{\partial \eta'^2} + 16a^*\sigma T_\infty^3\left(T - T_\infty\right) - \frac{Q_0}{\rho C_p}\left(T - T_\infty\right) + Q_l'\left(C - C_\infty\right) \quad (12)$$

Introducing the following non-dimensional quantities in equations (6), (8) and (12) and asterisk

$$u' = \frac{u}{v_0}, v' = \frac{v_0\eta}{\nu}, M = \frac{\sigma B_0^2 \nu}{v_0^2 \rho}, \theta = \frac{\left(T - T_\infty\right)v_0\lambda}{q\nu}, Sc = \frac{\nu}{D}, \Pr = \frac{\mu C_p}{\lambda}$$
$$\phi = \frac{\left(C - C_\infty\right)v_0 D}{m\nu}, \alpha = \frac{V_0^2 K}{\nu^2}, Gr = \frac{\rho\beta g\nu^2(T_w - T_\infty)}{v_0^3\mu}, R = \frac{16a\nu^2\sigma T_\infty^3}{kv_0^2} \quad (13)$$
$$Gm = \frac{\rho\beta^* g(C - C_\infty)}{v_0^3}, Kr = \frac{Kr'm\nu}{DV_0^2}, Q_0 = \frac{QV_0^2\rho C_p}{\nu}, \quad Q_l' = \frac{QqV_0^2 D}{m\nu\lambda}$$

where Gr is Grashof number, $\Pr$ is Prandtl number, M is Magnetic number, Sc is Schmidt number, Kr is Chemical reaction parameter, Q_l is radiation absorption parameter, Q is heat source parameter, and R Radiation parameter where q is the heat flux term per unit area and m is the mass flux per unit area.
We get

$$u'' + u' - \left(\frac{1}{\alpha} + M\right)u = -Gr\theta - Gr\phi \quad (14)$$

$$\theta'' - \Pr\theta' - \Pr\left(R + Q\right)\theta = \Pr Q_l\phi \quad (15)$$

$$\phi'' + Sc\phi' - KrSc\,\phi = 0 \quad (16)$$

The corresponding boundary condition in dimensionless form are reduced to

$$\begin{aligned} &\eta = 0 \;:\; u = 0, \theta' = -1, \phi' = -1 \\ &\eta \to \infty :\; u \to 0,\; \theta \to 0,\; \phi \to 0 \end{aligned} \quad (17)$$

The physical variables u, θ *and* ϕ can be expanded in the power of $\left(\varepsilon\right)$. This can be possible physically as ε for the flow of an incompressible fluid is always less than unity. It can be interpreted physically as the flow due to the Joules dissipation is super imposed on the main flow. Hence we can assume

$$\begin{aligned} u\left(\eta\right) &= u_0(\eta) + \varepsilon u_1(\eta) + 0\left(\varepsilon^2\right) \\ \theta\left(\eta\right) &= \theta_0(\eta) + \varepsilon\theta_1(\eta) + 0\left(\varepsilon^2\right) \\ \phi\left(\eta\right) &= \phi_0(\eta) + \varepsilon\phi_1(\eta) + 0\left(\varepsilon^2\right) \end{aligned} \quad (18)$$

Using equation (18) in equations (14)–(16) and equating the coefficient of like powers of ε, we have

$$u_0'' + u_0' + \left(\alpha^{-1} + M\right)u_0 = -Gr\,\theta_0 - Gm\,\phi_0 \quad (19)$$

$$\theta_0'' - \Pr\ \theta_0' - \Pr\left(R+Q\right)\theta_0 = \Pr Q_l \phi_0 \qquad (20)$$

$$\phi_0'' + Sc\,\phi_0' - Kr\phi_0 = 0 \qquad (21)$$

$$u_1'' + u_1' - \left(\frac{1}{\alpha} + M\right)u_1 = -Gr\,\theta_1 - Gm\,\phi_1 \qquad (22)$$

$$\theta_1'' - \Pr\theta_1' - \Pr\left(R+Q\right)\theta_1 = \Pr Q_l \phi_1 \qquad (23)$$

$$\phi_1'' + Sc\,\phi_1' - Kr\phi_1 = 0 \qquad (24)$$

The corresponding boundary conditions are

$$\begin{aligned} &\eta = 0: \quad u_0 = 0,\ u_1 = 0, \theta_0' = -1, \theta_1' = 0,\ \phi_0' = -1,\ \phi_1' = 0 \\ &\eta \to \infty: \ u_0 \to 0, u_1 \to 0, \theta_0 \to 0, \theta_1 \to 0,\ \phi_0 \to 0, \phi_1 \to 0 \end{aligned} \qquad (25)$$

Solving equations (19) to (24) with the help of (25), we get

$$u_0 = A_3 e^{\alpha\eta} + A_4 e^{\beta\eta} + A_5 e^{\alpha\eta} + A_6 e^{\gamma\eta}$$
$$u_1 = 0$$

$$\theta_0 = A_1 e^{\alpha\eta} + A_2 e^{\beta\eta},\ \theta_1 = 0$$

$$\phi_0 = -\frac{1}{\alpha}e^{\alpha\eta}, \phi_1 = 0$$

In view of above,

$$u = A_3 e^{\alpha\eta} + A_4 e^{\beta\eta} + A_5 e^{\alpha\eta} + A_6 e^{\gamma\eta}$$

$$\theta = A_1 e^{\alpha\eta} + A_2 e^{\beta\eta}$$

$$\phi = -\frac{1}{\alpha}e^{\alpha\eta}$$

Skin – friction:

The skin-friction coefficient at the plate is given by

$$\tau = \left(\frac{\partial u}{\partial \eta}\right)_{\eta=0} = \alpha A_3 + \beta A_4 + \alpha A_5 + \gamma A_6$$

Heat Transfer:

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

$$Nu = \left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0} = \alpha A_1 + \beta A_2$$

4. Results and discussion

The governing coupled linear partial differential equations (6) – (8) subject to the initial and boundary conditions (9) corresponding to the three cases of motion of the plate have been solved analytically using perturbation technique without any restriction. The numerical results for the temperature, velocity, skin-friction and the Nusselt number are computed to carry out a parametric study showing influences of several system parameters. The temperature profiles for different values of chemical reaction (Kr), heat source (Q) and Prandtl number (Pr) are shown in figures (8) - (10). It is observed that the temperature decreases with increasing values of chemical reaction and heat source parameters. It is noted that an increase of Prandtl number results in a decreasing the thermal boundary layer thickness and more uniform temperature distribution across the boundary layer. The reason is that smaller values of Prandtl number (Pr) are equivalent to increasing the thermal conductivities and therefore heat is able to diffuse away from the heated surface more rapidly than for higher values of Pr. The velocity profiles are shown in figures (1) – (3) for different values of Grashof number, chemical reaction parameter and radiation absorption parameter. It is observed that the velocity increases with increasing thermal Grashof number (Gr), chemical reaction (Kr) and radiation absorption. Physically this is possible because as the Grashof number or time increases, the contribution from the buoyancy force near the plate becomes significant and hence a rise in the velocity near the plate is observed. Moreover, it is seen that the larger the value of radiation parameter, the thinner the momentum boundary layer size. The velocity profiles are shown in figure (5) for different values of Prandtl number (Pr) in the pure convection case due to uniform velocity of the plate. Moreover, the velocity of fluid decreases with increasing Prandtl number. This is consistent with the physical observation that the fluids with high Prandtl number have greater viscosity, which makes the fluid thick and hence move slowly.

Table: Skin friction coefficient (τ)

						Previous study		Present study	
Sc	**Gm**	**α**	**M**	**Pr**	Q_l	**Gr = 1.0**	**Gr = - 1.0**	**Gr = 1.0**	**Gr = - 1.0**
0.22	5.0	1.0	1.0	0.72	1.0	3.5985	-10.0124	3.4892	-10.4565
0.60	5.0	1.0	1.0	0.72	1.0	5.1542	-10.0045	4.6541	-10.1462
0.78	5.0	1.0	1.0	0.72	1.0	3.6742	-9.5125	3.4564	-9.2547
2.62	5.0	1.0	1.0	0.72	1.0	9.4567	-4.6388	9.2566	-4.2658
0.22	**1.0**	1.0	1.0	0.72	1.0	4.4589	-9.0236	4.7986	-9.2654
0.22	**2.0**	1.0	1.0	0.72	1.0	3.5785	-10.5865	3.2567	-10.2564
0.22	**3.0**	1.0	1.0	0.72	1.0	2.5458	-13.1568	2.1755	-12.9865
0.22	**4.0**	1.0	1.0	0.72	1.0	1.1895	-15.0256	1.0654	-15.1546
0.22	5.0	**1.0**	1.0	0.72	1.0	3.5682	-11.1242	3.3600	-10.7256
0.22	5.0	**2.0**	1.0	0.72	1.0	4.4256	-15.8963	4.1346	-15.1285
0.22	5.0	**3.0**	1.0	0.72	1.0	4.8954	-18.0124	4.5005	-17.9124
0.22	5.0	**4.0**	1.0	0.72	1.0	5.1145	-18.9856	4.6880	-19.6785
0.22	5.0	1.0	**1.0**	0.72	1.0	3.5869	-	3.3342	-
0.22	5.0	1.0	**2.0**	0.72	1.0	3.1247	-	2.6472	-
0.22	5.0	1.0	**3.0**	0.72	1.0	2.9568	-	2.4276	-
0.22	5.0	1.0	**4.0**	0.72	1.0	3.5681	-	2.8245	-

Conclusions:

The following are observed in this paper:

- Presence of foreign species reduces the velocity as well as thermal boundary layer and further reduction occurs with increasing Schmidt number in case of externally cooled plate.
- Greater cooling results in increase in velocity and thermal boundary layer thickness.
- Velocity of fluid layer decreases and thickness of thermal boundary layer increases with increasing Schmidt number in case of externally heated plate.
- Greater heating causes reduction in fluid velocity and increase in thermal boundary layer thickness.
- Porosity of the medium has considerable effect on velocity distribution. The profiles increase with increases in permeability parameter.

Appendix

$$\alpha = -\left(\frac{Sc + \sqrt{Sc^2 + 4KrSc}}{2}\right), \beta = -\left(\frac{\Pr + \sqrt{\Pr^2 + 4\Pr\left(R+Q\right)}}{2}\right) B_1 = \left(\frac{1}{\alpha} + M\right)$$

$$A_1 = -\frac{\Pr Q_l}{\alpha^3 - \Pr\alpha^2 - \Pr\alpha\left(R+\phi\right)}, \quad A_2 = -\frac{1}{\beta}\left(1 + A_1\alpha\right), \gamma = -\left(\frac{1+\sqrt{1+4B_1}}{2}\right)$$

$$A_3 = -\frac{GrA_1}{\alpha^2 + \alpha - B_1}, A_4 = -\frac{GrA_2}{\beta^2 + \beta - B_1}, A_5 = \frac{Gr}{\alpha^3 + \alpha^2 - B_1}, A_6 = -\left(A_3 + A_4 + A_5\right)$$

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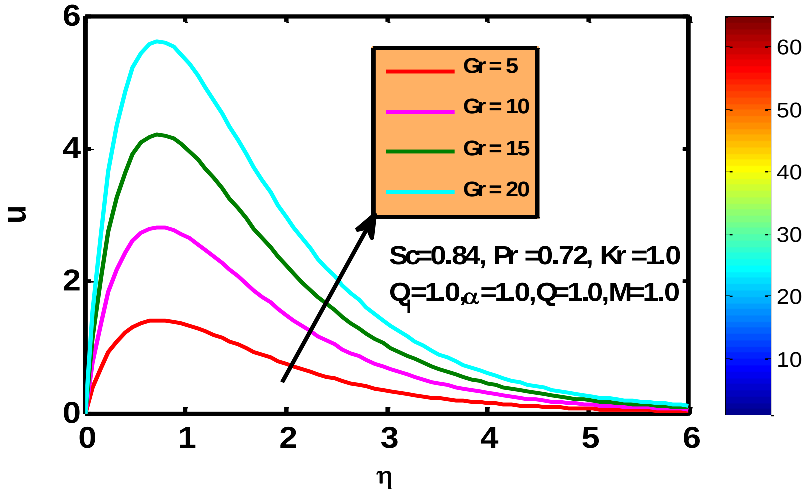


Fig. (1): Velocity profile for Gr

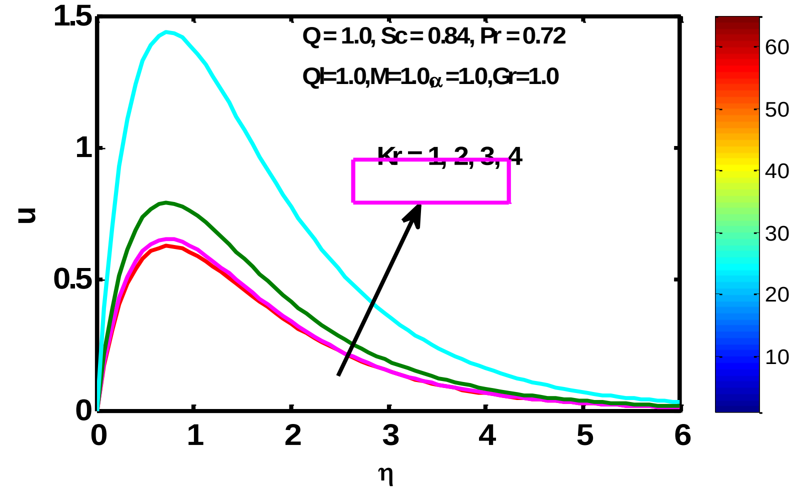


Fig. (2): Velocity profiles for Kr

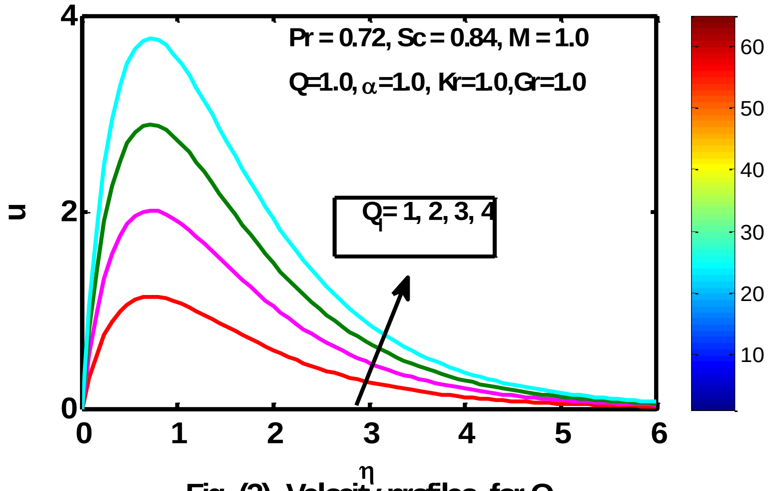


Fig. (3). Velocity profiles for Q_l

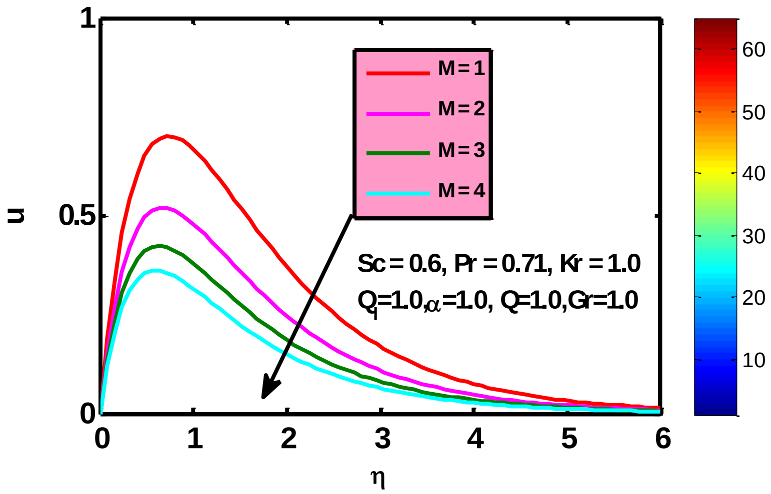


Fig. (4): Velocity profiles for M

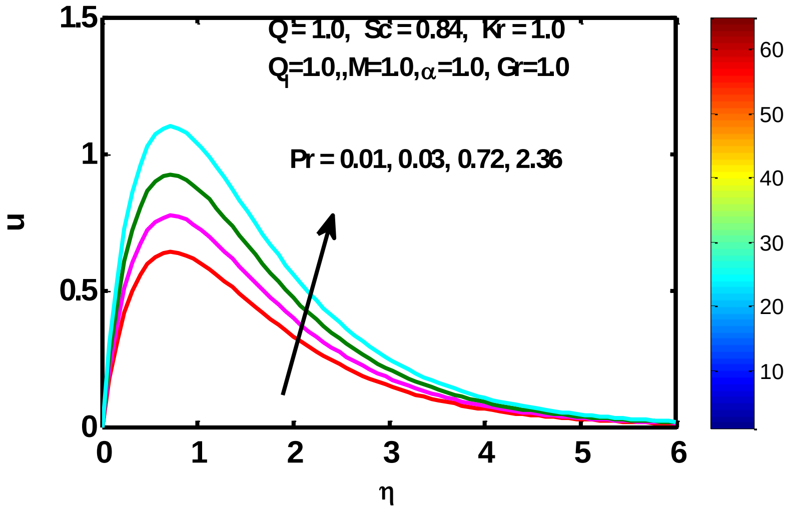


Fig. (5): Velocity profiles for Pr

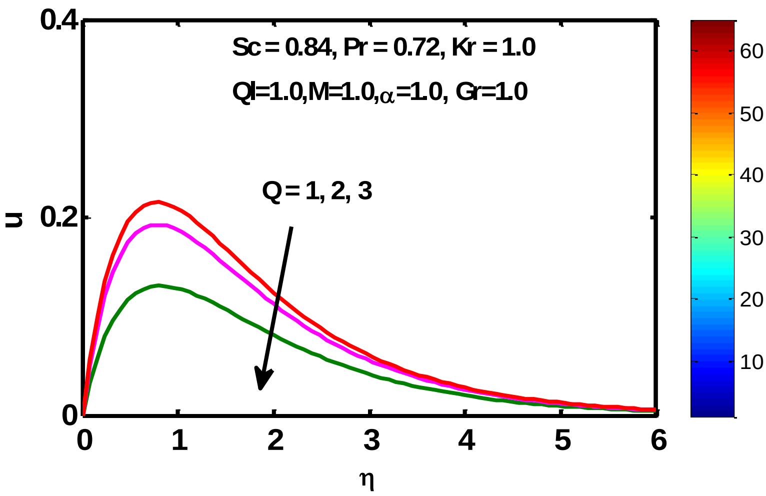


Fig. (6): Velocity profiles for Q

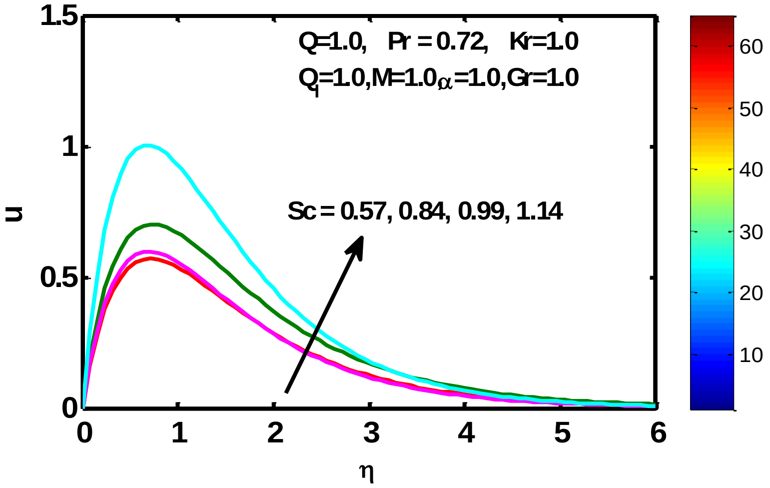


Fig. (7). Velocity Profiles for Sc

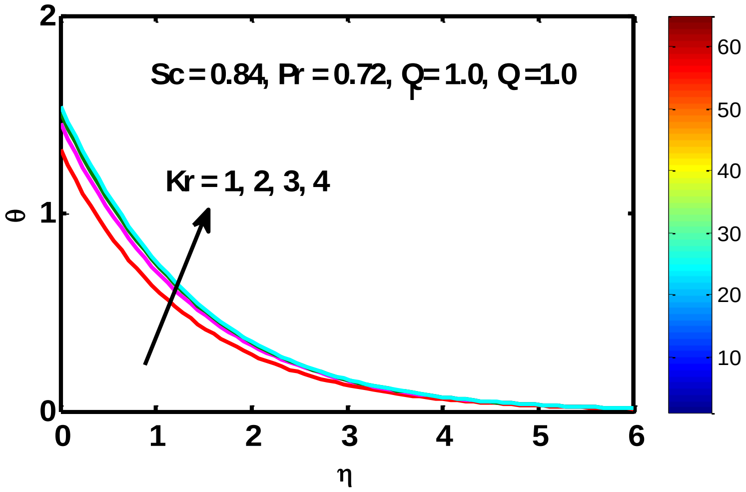


Fig. (8): Temperature profiles for Kr

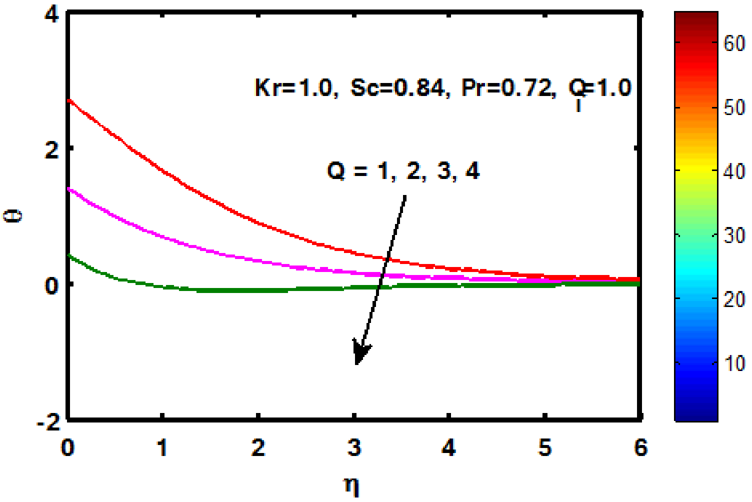
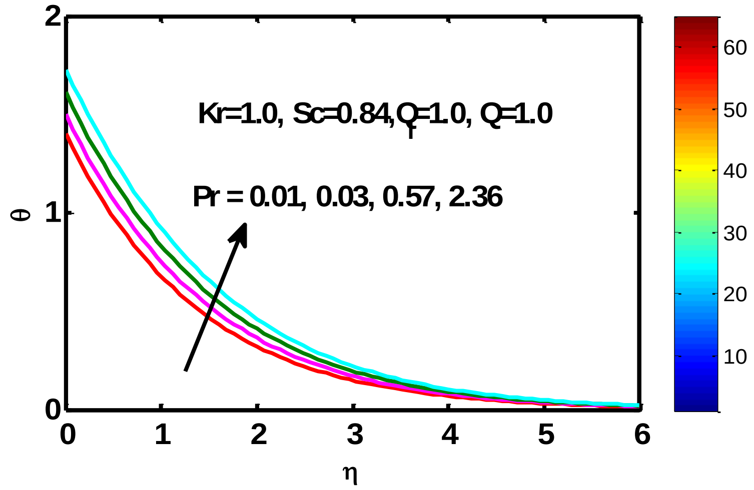


Fig. (9): Temperature profiles for Q



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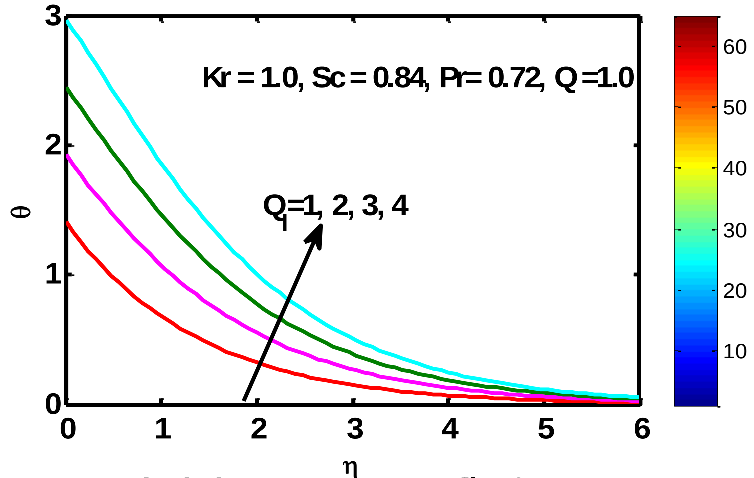

Fig. (11): Temeperature profiles for Q_f

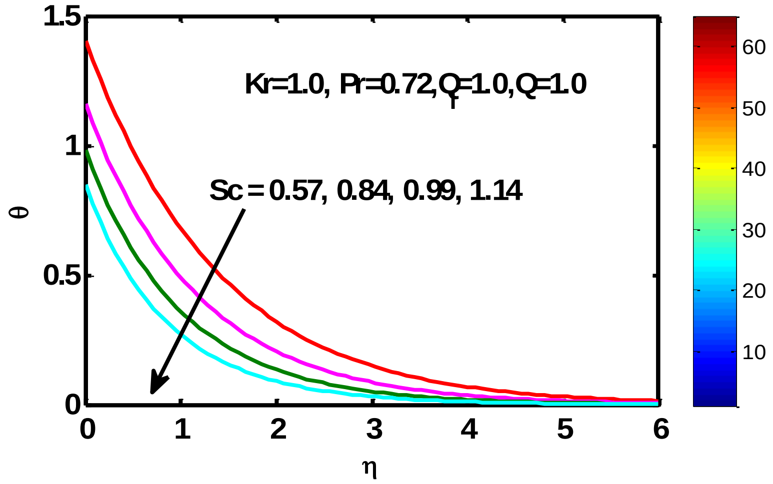

Fig.(12): Temperature profiles for Sc

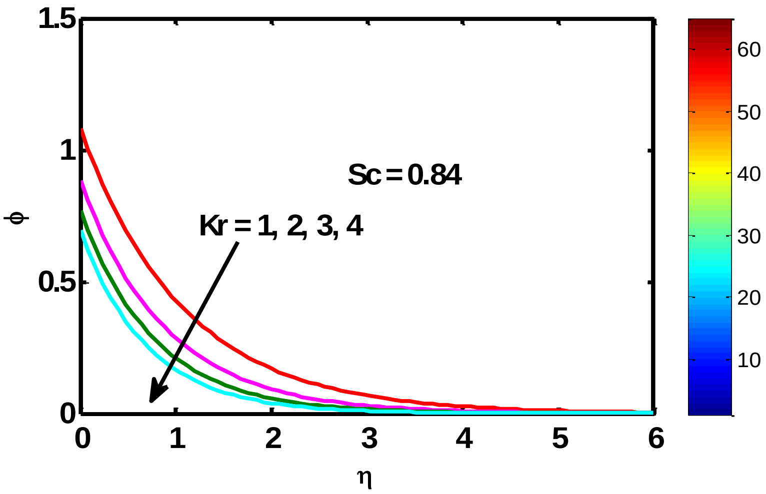

Fig. (13): Concentration profiles of Kr

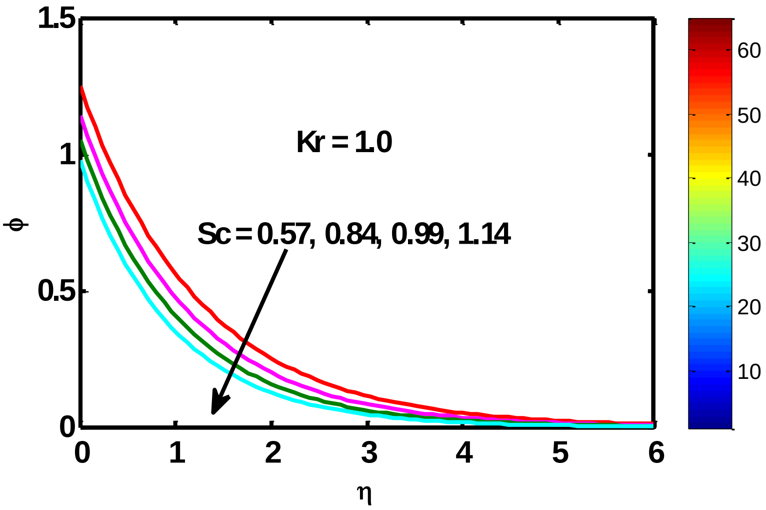

Fig. (14). Concentration profiles for Sc