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EFFECTS OF THE CHEMICAL REACTION AND RADIATION ABSORPTION ON FREE CONVECTION FLOW THROUGH POROUS MEDIUM WITH VARIABLE SUCTION IN THE PRESENCE OF UNIFORM MAGNETIC FIELD

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Abstract

The aim of the present work is to study the effects of chemical reaction and thermal radiation on free convection flow of an incompressible fluid through a porous medium with variable suction in the presence of magnetic field. The equations of continuity, energy and diffusion, which govern the flow field, are solved by using a regular perturbation method. The effects of various variables like magnetic parameter, chemical reaction parameter, porosity parameter, radiation parameter, etc. on the real part of velocity, temperature and concentration fields have been discussed with the help of graphs plotted against y.

1. Introduction

Free convection flow through porous media occurs in several engineering

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problems such as those encountered in the design of pebble-bed nuclear reactors, catalytic reactors, and compact heat exchangers, in geothermal energy conversion, in the use of fibrous materials, in the thermal insulation of buildings, in the heat transfer from storage of agricultural products which generate heat as a result of metabolism, in petroleum reservoirs, in nuclear wastes, etc. Excellent reviews of the natural convection flows in porous media have been presented by many authors [2, 3, 5, 7, 13, 16, 20]. Cheng and Minkowycz [5] have presented similar solutions for free thermal convection from a vertical plate in a fluid-saturated porous medium. Xu [20] analyzed the nonlinear stability of the motionless state of the thermosolutal Rivlin-Ericksen fluid in porous medium. The free convection process in a fluid-saturated porous medium along a sinusoidal wavy surface under variable heat flux condition has been analyzed by Shalini and Kumar [16].

On the other hand, when a conductive fluid moves through a magnetic field, an ionized gas is electrically conductive, the fluid may be influenced by the magnetic field. Magnetohydrodynamic (MHD) natural convection heat transfer flow in porous and non-porous media is of considerable interest in the technical field due to its frequent occurrence in industrial technology and geothermal application, high temperature plasmas applicable to nuclear fusion energy conversion, liquid metal fluids, and (MHD) power generation systems. Sparrow and Cess [18] studied the effect of magnetic field on the natural convection heat transfer. Takhar and Ram [19] studied the magnetohydrodynamic free convection flow of water through a porous medium. Damseh [8] studied the magnetohydrodynamics-mixed convection heat transfer problem from a vertical surface embedded in a porous medium. EL-Kabeir et al. [10] studied the unsteady MHD combined convection over a moving vertical sheet in a fluid-saturated porous medium. Hayat et al. [12] examined the effects of Hall current and heat transfer on the rotating flow of a second grade fluid subject to a transverse applied magnetic field past a porous plate. Ali and Mehmood [1] studied the unsteady boundary layer flow of a viscous fluid through porous medium with uniform suction/injection at the wall. EL-Kabeir et al. [11] solved magnetohydrodynamic free convection flow over inclined permeable surface embedded in porous medium in the presence of a uniform magnetic field.

Moreover, radiation heat transfer effects on free convection flow are very important in space technology and high temperature process, and very little is known about the effects of radiation on the boundary layer of a radiate-MHD fluid past a body. The inclusion of radiation effects in the energy equation had led to a highly nonlinear partial differential equation. The effects of thermal radiation and magnetic field on natural convection heat transfer from an inclined plate embedded in a variable porosity porous medium analyzed recently by Chamkha et al. [4]. The effect of radiation heat transfer fluxes for an optically thick fluid included in the energy equation has been described by Sivasankaran et al. [17]. EL-Hakiem and Rashad [9] used Rosseland diffusion approximation in studying the effect of radiation on free convection from a vertical cylinder embedded in a fluid-saturated porous medium. Seddeek et al. [15] have studied the effects of chemical reaction, radiation on hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media with variable viscosity.

The aim of the present work is to study the effects of chemical reaction and radiation on free convection flow of an incompressible fluid through a porous medium with variable suction in the presence of magnetic field.

2. Mathematical Analysis

We consider the two-dimensional free convective flow of heat and mass transfer of an incompressible, electrically conducting, chemically reacting past an infinite vertical porous plate in the presence of thermal radiation is considered. It is assumed that: (i) The plate temperature is oscillating with time about a constant non-zero mean value. (ii) Viscous and Darcy's resistance terms are taken into account with constant permeability of the medium. (iii) Boussinesq approximation is valid. (iv) The suction velocity normal to the plate is a function of the time and we shall take it in the form $\nu^* = -\nu_0(1 + \varepsilon A e^{i\omega t})$, where A is a real positive constant and ε is small such that $\varepsilon \ll 1$. A system of rectangular co-ordinates $O(x^*, y^*, z^*)$ is taken such that $y^* = 0$ is on the plate and z^* axis is along its leading edge. All the fluid properties are considered constant except that the influence of the density variation with the temperature is considered only the body force term. Under the usual Boussinesq's approximation, the equations of continuity, linear momentum, energy and diffusion can be written as follows:

Continuity

$$\frac{\partial v^*}{\partial y^*} = 0, \tag{2.1}$$

Linear momentum

$$\frac{\partial u^*}{\partial t^*} + \nu^* \frac{\partial u^*}{\partial y^*}$$

$$= \rho g \beta_0 (T^* - T_\infty) + g\beta^* (C^* - C^*_\infty) + \nu \frac{\partial^2 u^*}{\partial y^{*2}} - \nu \frac{u^*}{k^*} - \sigma \frac{B_0^2 u^*}{\rho}, \tag{2.2}$$

Energy

$$\rho C_p \left[\frac{\partial T^*}{\partial t^*} + \nu^* \frac{\partial T^*}{\partial y^*} \right] = \kappa \left[\frac{\partial^2 T^*}{\partial y^{*2}} \right] + \frac{\partial q_r}{\partial y^*}, \tag{2.3}$$

Diffusion

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D^* \frac{\partial^2 u^*}{\partial y^{*2}} - K_r' (C^* - C_\infty), \tag{2.4}$$

where x^*, y^* and t^* are the dimensional 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 concentration and temperature, respectively, ρ is the fluid density, ν is the kinematic viscosity, C_p is the specific heat at constant pressure, σ is fluid electrical conductivity, g is the acceleration due to gravity, β_0 and β^* are the thermal and concentration expansion coefficients, respectively, K^* is the permeability of the porous medium, B_0 is the magnetic induction, D^* is the chemical molecular diffusivity, K_r' is the chemical reaction parameter and k is the fluid thermal conductivity. The magnetic and viscous dissipations are neglected in this study. The first and second terms on the right hand side of the momentum equation (2.2) denote the thermal and concentration buoyancy effects, respectively.

The appropriate boundary conditions for the velocity, temperature and concentration fields are

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

$$u^* \to 0, \quad T^* = T_\infty^*, \quad C^* \to C_\infty^* \quad \text{as} \quad y^* \to \infty, \tag{2.5}$$

where u, C_w^* and T_w are the wall dimensional velocity, concentration and temperature, respectively. C_∞^* and T_∞ are the free stream dimensional concentration and temperature, respectively.

It is clear from equation (2.1) that the suction velocity normal to the plate is either a constant or a function of time. Hence it is assumed in the form:

$$\nu^* = -\nu_0(1 + \varepsilon A e^{i\omega t}), \tag{2.6}$$

where A is a real positive constant, ε and εA are small less than unity, and ν_0 is a scale of suction velocity which is a non-zero positive constant. The negative sign indicates that the suction is towards the plate.

In order to write the governing equations and the boundary conditions dimensionless form, the following non-dimensional quantities are introduced:

$$y = \frac{v_0 y^*}{\upsilon}, \quad u = \frac{u^*}{v_0}, \quad \theta = \frac{T^* - T_\infty^*}{T_w - T_\infty}, \quad K = \frac{K^* \nu_0^2}{\upsilon}, \quad P = \frac{\mu C p}{k},$$

$$t = \frac{t^* v_0^2}{\upsilon}, \quad \mathrm{Sc} = \frac{\upsilon}{D}, \quad \phi = \frac{C^* - C_\infty^*}{C_w^* - C_\infty}, \quad \omega = \frac{\upsilon \omega^*}{v_0^2}, \quad R = \frac{4\upsilon I}{\rho C_p v_0^2},$$

$$\mathrm{Gr} = \frac{\upsilon g \beta_0 (T_w - T_\infty)}{v_0^3}, \quad M = \frac{\sigma \upsilon B_0^2 w}{\rho v_0^2}, \quad N = \frac{\beta^* \Delta C}{\beta_0 \Delta T}, \quad Kr = \frac{Kr' \nu}{v_0^2}, \tag{2.7}$$

where R, M, Pr, Sc, Gr, N, K, ω and Kr represent radiation parameter, magnetic field parameter, Prandtl number, Schmidt number, buoyancy ratio, porosity parameter, frequency parameter and chemical reaction parameter, respectively.

The radiative heat flux q_r is assumed as Cogley et al. [6],

$$\frac{\partial q_r}{\partial y} = 4(T^* - T_\infty^*) I;$$

$I = \int_0^\infty K_{\omega n} \frac{\partial e_{b\omega}}{\partial T} d\omega,$ where I is absorption coefficient, $K_{\omega n}$ is radiation absorption coefficient at the wall and $e_{b\omega}$ is Plank's function.

In view of (2.6) and (2.7), equations (2.2)-(2.4) reduce to the non-dimensional forms

$$\frac{\partial u}{\partial t} - (1 + \varepsilon A e^{i\omega t})\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + \mathrm{Gr}(\theta + N\phi) - \left(\frac{1}{K} + M\right)u, \tag{2.8}$$

$$\frac{\partial \theta}{\partial t} - (1 + \varepsilon A e^{i\omega t})\frac{\partial \theta}{\partial y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 \theta}{\partial y^2} + R\theta, \tag{2.9}$$

$$\frac{\partial \phi}{\partial t} - (1 + \varepsilon A e^{i\omega t})\frac{\partial \phi}{\partial y} = \frac{1}{\mathrm{Sc}}\frac{\partial^2 \phi}{\partial y^2} + Kr\phi. \tag{2.10}$$

The corresponding boundary conditions are

$$u = 0, \quad \theta = 1 + \varepsilon e^{i\omega t}, \quad \phi = 1 + \varepsilon e^{i\omega t} \quad \text{at} \quad y = 0,$$

$$u \to 0, \quad \theta \to 0, \quad \phi \to 0 \quad \text{at} \quad y \to \infty. \tag{2.11}$$

3. Solution of the Problem

In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form, we may represent the translational velocity, temperature and concentration in the neighbourhood of the plate as

$$u(y, t) = u_0(y) + \varepsilon u_1(y) e^{i\omega t},$$

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

$$\phi(y, t) = \phi_0(y) + \varepsilon \phi_1(y) e^{i\omega t}. \tag{3.1}$$

Substituting equation (3.1) into equations (2.8)-(2.10), equating the harmonic and non-harmonic terms, and neglecting the higher-order terms of $O(\varepsilon^2)$, we obtain the following pairs of equations for (u_0, θ_0, C_0) and (u_1, θ_1, C_1):

$$u_0'' + u_0' - \left(\frac{1}{K} + M\right)u_0 = -\mathrm{Gr}(\theta_0 + N\phi_0), \tag{3.2}$$

$$u_1'' + u_1' - \left(\frac{1}{K} + M + i\omega\right)u_1 = -Au_0' - \mathrm{Gr}(\theta_1 + N\phi_1), \tag{3.3}$$

$$\theta_0''' + \theta_0' \,\mathrm{Pr} + \mathrm{Pr}\, R\theta_0 = 0, \tag{3.4}$$

$$\theta_1'' + \Pr\theta_1' + \Pr(R - i\omega)\theta_1 = -A\Pr\theta_0', \tag{3.5}$$

$$\phi_0''' + \phi_0'\mathrm{Sc} - Kr\mathrm{Sc}\phi_0 = 0, \tag{3.6}$$

$$\phi_1'' - \mathrm{Sc}\phi_1' + (Kr - i\omega\mathrm{Sc})\phi_1 = -A\mathrm{Sc}\phi_0', \tag{3.7}$$

where the primes denote differentiation with respect to y, only.

The corresponding boundary conditions can be written as

$$u_0 = 0, \quad u_1 = 0, \quad \theta_0 = 1, \quad \theta_1 = 0, \quad \phi_0 = 1, \quad \phi_1 = 1 \quad \text{at} \quad y = 0,$$

$$u_0 \to 0, \quad u_1 \to 0, \quad \theta_0 \to 1, \quad \theta_1 \to 0, \quad \phi_0 \to 0, \quad \phi_1 \to 0 \quad \text{as} \quad y \to \infty. \tag{3.8}$$

Solving equations (3.2)-(3.7) under the boundary conditions (3.8), we get

$$u_0 = m_1 e^{-c_2 y} - m_2 e^{-b_1 y} - m_3 e^{-a_2 y},$$

$$u_1 = m_4 e^{-d_5 y} + c_3 e^{-c_{31} y} - m_5 e^{-b_1 y} + m_6 e^{-a_2 y} - c_6 e^{-a_2 y} - c_8 e^{-a_1 y},$$

$$\theta_0 = e^{-b_1 y},$$

$$\theta_1 = (1 - b)e^{-d_1 y} + be^{-b_1 y},$$

$$\phi_0 = e^{-a_1 y},$$

$$\phi_1 = \left(1 - \frac{iA\mathrm{Sc}}{\omega}\right)e^{-a_1 y} + \frac{iA\mathrm{Sc}}{\omega} be^{-a_2 y}.$$

In view of the above solutions, the velocity, temperature and concentration distributions in the boundary layer become

$$u(y, t) = m_1 e^{-c_2 y} - m_2 e^{-b_1 y} - m_3 e^{-a_2 y}$$
$$+ \varepsilon e^{i\omega t}(m_4 e^{-d_5 y} + c_3 e^{-c_{31} y} - m_5 e^{-b_1 y} + m_6 e^{-a_2 y} - c_6 e^{-a_2 y} - c_8 e^{-a_1 y}),$$

$$\theta(y, t) = e^{-b_1 y} + \varepsilon e^{i\omega t}((1 - b)e^{-d_1 y} + be^{-b_1 y}),$$

$$\phi(y, t) = e^{-a_1 y} + \varepsilon e^{i\omega t}\left(1 - \frac{iA\mathrm{Sc}}{\omega}\right)e^{-a_1 y} + \frac{iA\mathrm{Sc}}{\omega} be^{-a_2 y}.$$

Knowing the velocity field in the boundary layer, we can now calculate the skin friction at the plate, which in the dimensional form is given by

$$\tau_w = \mu \frac{\partial u^*}{\partial y^*}\bigg|_{y^*=0} = m_{15} + \varepsilon e^{i\omega t} m_{16}.$$

Knowing the temperature field in the boundary layer, we can calculate the heat transfer coefficient at the porous plate, which in terms of Nusselt number is given by

$$\mathrm{Nu}_x = x \frac{\partial T/\partial y^* \big|_{y^*=0}}{T_w - T_\infty}$$

$$= -b_1 + \varepsilon e^{i\omega t} m_{17}.$$

Knowing the concentration field in the boundary layer, we can calculate the mass transfer coefficient at the porous plate, which in terms of Sherwood number is given by

$$\mathrm{Sh}_x = \frac{j_w x}{D^*(C_w^* - C_\infty^*)},$$

where

$$j_w = -D^* \frac{\partial C^*}{\partial y^*}\bigg|_{y^*=0}$$

$$= -a_2 + \varepsilon e^{i\omega t}\left(-a_1 + \frac{iAa_2(a_1 - a_2)}{\omega}\right).$$

Here

$$m_1 = \mathrm{Gr}(b_2 + Nc_1), \quad m_2 = \mathrm{Gr}b_2, \quad m_3 = \mathrm{Gr}Nc_1,$$

$$m_4 = (-c_3 + c_4 + c_5 + c_6 + c_7 + c_8 + c_9), \quad m_5 = -c_4 - c_7, \quad m_6 = -c_5 - c_9,$$

$$m_7 = d_3(b_1 - c_2), \quad m_8 = d_4(a_2 - c_2), \quad m_9 = c_3(d_5 - c_2), \quad m_{10} = c_4(b_1 - d_5),$$

$$m_{11} = c_5(a_2 - d_5), \quad m_{12} = c_6(d_1 - d_5), \quad m_{13} = c_7(b_1 - d_5),$$

$$m_{14} = c_8(a_1 - d_5) + c_9(a_2 - d_5), \quad m_{15} = m_7 + m_8,$$

$$m_{16} = m_9 + \cdots + m_{14}, \quad m_{17} = -d_1 + bd_1 - bb_1,$$

$$c_1 = \frac{1}{a_2^2 - a_2 - \left(\frac{1}{K} + M\right)}, \quad c_2 = \frac{1 + \sqrt{1 + 4\left(\frac{1}{K} + M\right)}}{2}, \quad c_3 = \frac{Ac_2\mathrm{Gr}(b_2 + Nc_1)}{(c_2^2 - c_2 - d_2)},$$

$$c_4 = \frac{A\mathrm{Gr}b_2b_1}{(b_1^2 - b_1 - d_2)}, \quad c_5 = \frac{A\mathrm{Gr}Nc_1a_2}{(a_2^2 - a_2 - d_2)}, \quad c_6 = \frac{\mathrm{Gr}(1 - b)}{(\mathrm{Pr}^2 - \mathrm{Pr} - d_2)},$$

$$c_7 = \frac{\mathrm{Gr}b}{(b_1^2 - b_1 - d_2)}, \quad c_8 = \frac{\mathrm{Gr}N\left(1 - \frac{iAa_2}{\omega}\right)}{(a_1^2 - a_1 - d_2)}, \quad c_9 = \frac{iA\mathrm{Gr}Nc_1a_2}{(a_1^2 - a_1 - d_2)},$$

$$b_1 = \frac{\mathrm{Pr} + \sqrt{\mathrm{Pr}^2 - 4R\,\mathrm{Pr}}}{4}, \quad d_1 = \frac{\mathrm{Pr} + \sqrt{\mathrm{Pr}^2 - 4(R - i\omega)\mathrm{Pr}}}{2}, \quad d_2 = \frac{1}{K} + M - i\omega,$$

$$b = \frac{\mathrm{Pr}\, b_1 A}{b_1^2 - \mathrm{Pr}\, b_1 + (R - i\omega)\mathrm{Pr}}, \quad a_1 = \frac{\mathrm{Sc} + \sqrt{\mathrm{Sc}^2 + 4i\omega\mathrm{Sc}}}{2},$$

$$a_2 = \frac{\mathrm{Sc} + \sqrt{\mathrm{Sc}^2 + 4Kr^2\mathrm{Sc}}}{2}, \quad b_2 = \frac{1}{b_1^2 - b_1 - \left(\frac{1}{K} + M\right)}.$$

4. Results and Discussion

In the preceding sections, we have formulated and solved the problem of the chemical reaction and radiation on free convection flow of an incompressible fluid through a porous medium with variable suction in the presence of magnetic field. This enables us to carry out the numerical calculations for the distribution of the equations of continuity, energy and diffusion, which govern the flow field, are solved by using a regular perturbation method. The effects of various variables like Kr, K, R, M, Sc on the real part of velocity, temperature and concentration fields have been discussed with the help of graphs plotted against y by considering $A = 1$, $\varepsilon = 0.2$.

For different values of the magnetic field parameter M, the velocity profile is plotted in Figure 1. It is obvious that the effect of increasing values of M-parameter results in a decreasing velocity distribution. Figures 2(a) and 2(b) display results for the velocity and concentration profiles against y for different values of chemical reaction parameter Kr. It is seen that the effect of increasing values of the chemical reaction parameter Kr results in a decreasing velocity distribution. The results also show that the concentration increases with a decrease in chemical reaction parameter Kr.

Velocity distribution against y is plotted in Figure 3. Clearly as K increases the peak value of velocity across the boundary layer tends to increase rapidly near wall of the porous plate. For different values of the radiation parameter R, the velocity and temperature are plotted in Figures 4(a) and 4(b). It is obvious that an increase in radiation parameter R results a decreasing in the velocity and temperature profiles.

For different values of the Schmidt number Sc, velocity and the concentration profiles are plotted in Figures 5(a) and 5(b). It is obvious that the effect of increasing values of Sc results in a decreasing velocity distribution across the boundary layer. Furthermore, the results show that the concentration is decreased as Sc increases.

Conclusions

In this paper, we have theoretically studied the effects of chemical reaction and thermal radiation on free convection flow of an incompressible fluid through a porous medium with variable suction in the presence of magnetic field. The method of solution can be applied for small perturbation. Numerical results are presented to illustrate the details of the flow, heat and mass transfer characteristics and their dependence on material parameters.

1. It was found that the velocity profiles increased due to decreases in chemical reaction parameter, the Schmidt number, radiation parameter, and magnetic field parameter while it increased due to increases in porosity parameter.

2. However, an increase temperature profile is a function of an increase in radiation parameter.

3. Also, it was found that the concentration profile increased due to decreases in the chemical reaction parameter C and the Schmidt number Sc.

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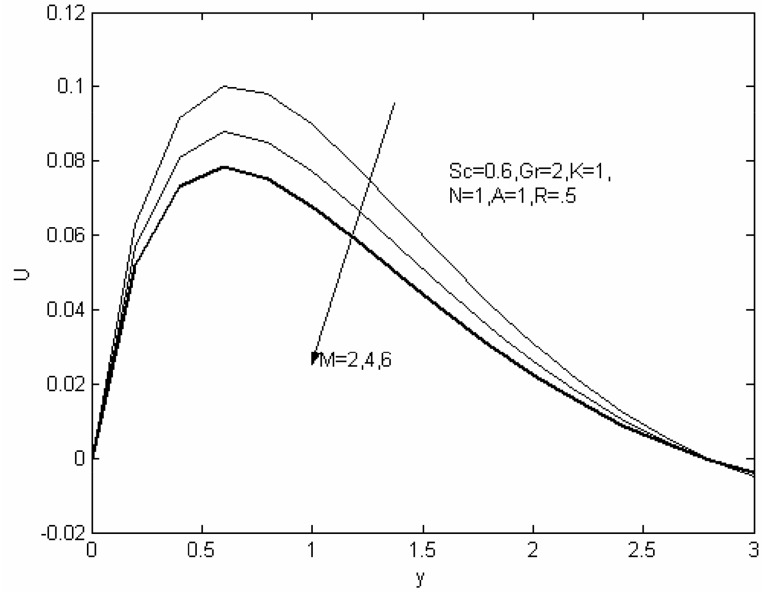

Figure 1. Velocity distribution against *y* for different *M* values.

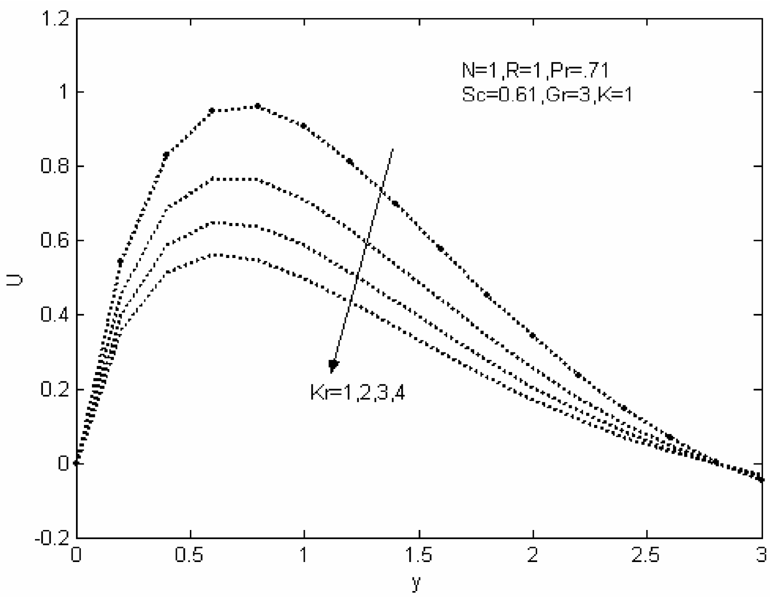

Figure 2(a). Velocity distribution against *y* for different *Kr* values.

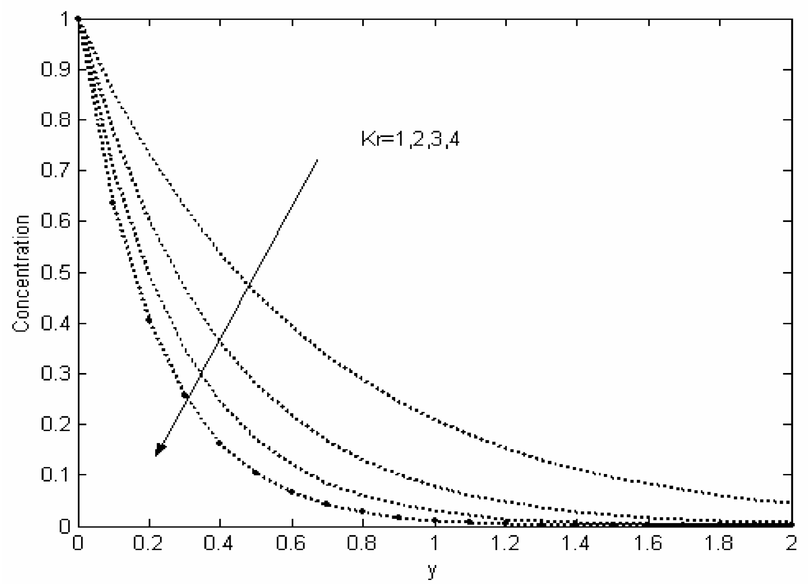

Figure 2(b). Concentration distribution against y for different Kr.

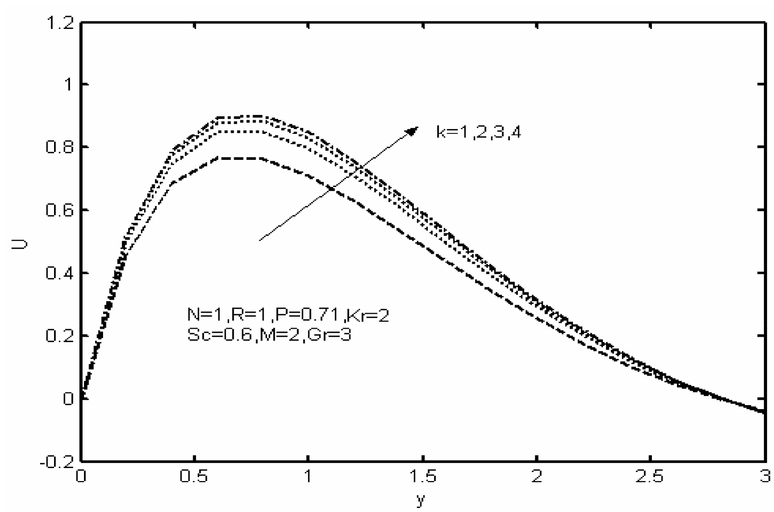

Figure 3. Velocity distribution against y for different K values.

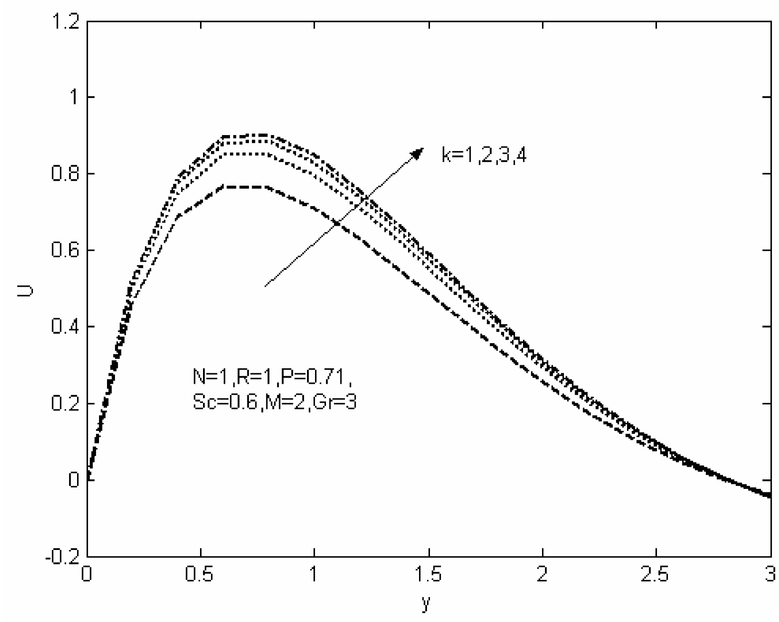

Figure 4(a). Velocity profile against *y* for different *R* values.

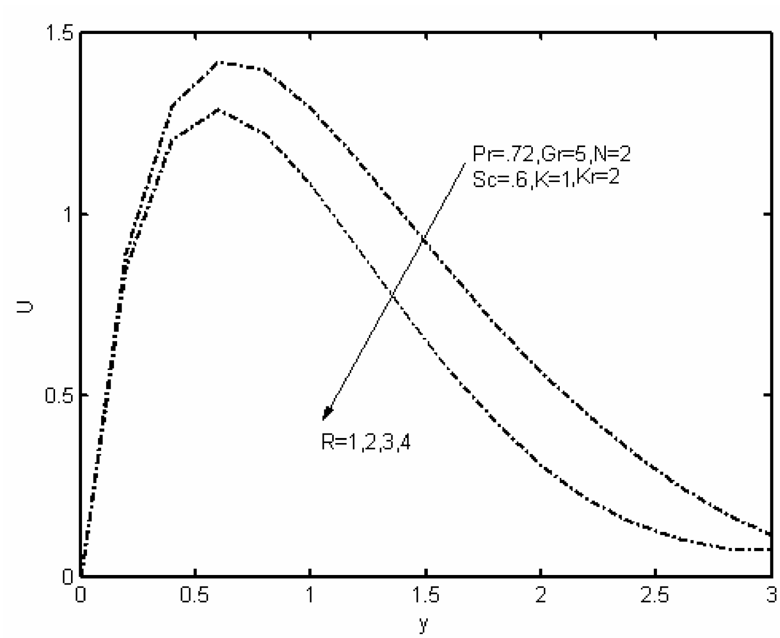

Figure 4(b). Temperature distribution against *y* for different *R* values.

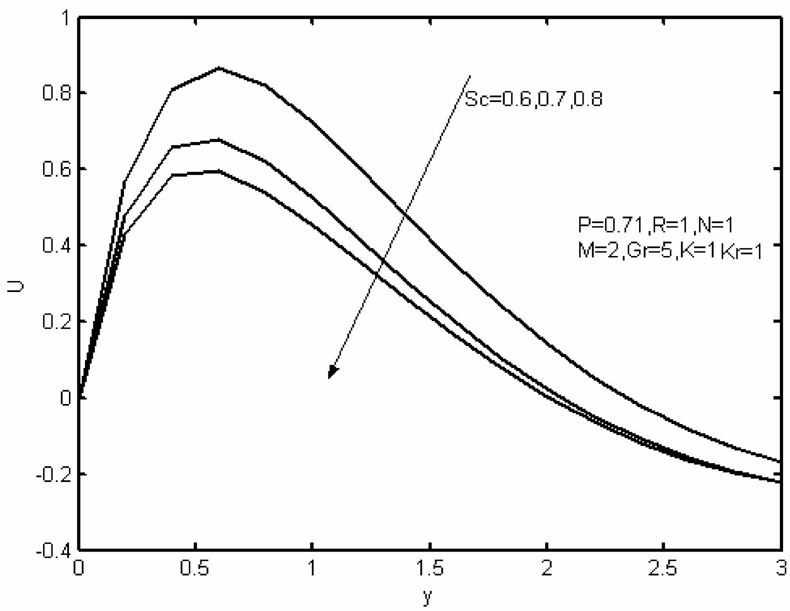

Figure 5(a). Velocity distribution against *y* for different Sc values.

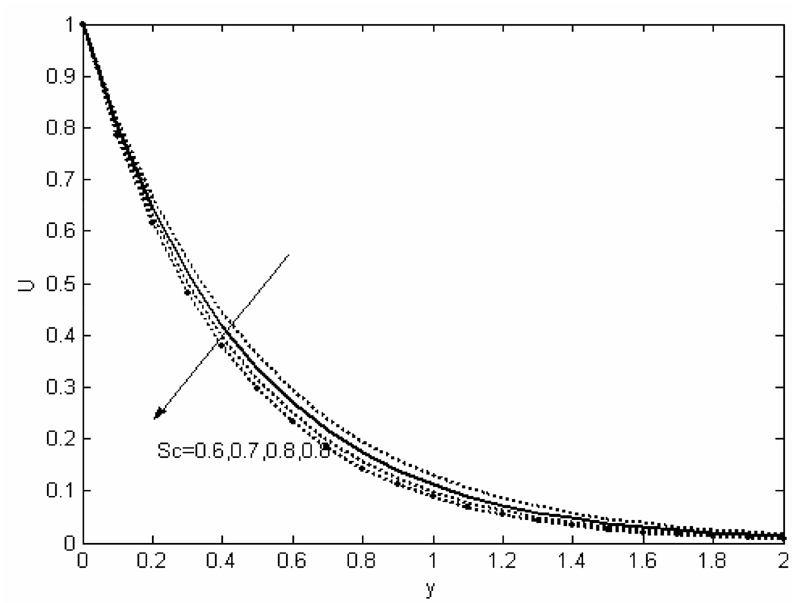

Figure 5(b). Concentration distribution against *y* for different Sc values.