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RADIATION AND CHEMICAL REACTION EFFECTS ON MHD FLOW FLUID OVER AN INFINITE VERTICAL OSCILLATING POROUS PLATE

G. Charan Kumar and G. V. Ramana Reddy*

Department of Mathematics, KL University, Guntur, INDIA-522502.

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ABSTRACT

An analysis is carried out to study the nonlinear MHD flow with heat and mass transfer characteristics of an incompressible, viscous, electrically conducting and Boussinesq fluid over a vertical oscillating porous permeable plate in presence of homogeneous chemical reaction of first order and thermal radiation effects. The problem is solved numerically using the perturbation technique for the velocity, the temperature, and the concentration field. The expression for the skin friction, Nusselt number and Sherwood number are obtained. The effects of various thermo-physical parameters on the velocity, temperature and concentration as well as the skin-friction coefficient, Nusselt number and Sherwood number has been computed numerically and discussed qualitatively.

Keywords: *Radiation, chemical reaction, heat transfer, MHD, vertical plate.*

1. INTRODUCTION

Magnetohydrodynamics (MHD) is the branch of continuum mechanics which deals with the flow of electrically conducting fluids in electric and magnetic fields. Many natural phenomena and engineering problems are worth being subjected to an MHD analysis. Magneto-hydrodynamic equations are ordinary electromagnetic and hydrodynamic equations modified to take into account the interaction between the motion of the fluid and the electromagnetic field. The formulation of the electromagnetic theory in a mathematical form is known as Maxwell's equation. The effect of the gravity field is always present in forced flow heat transfer as a result of the buoyancy forces connected with the temperature differences. Usually they are of a small order of magnitude so that the external forces may be neglected. There has recently been a considerable interest in the effect of body forces on forced convection phenomena. In certain engineering problems, however, they cannot be left out of consideration. It is important to realize that the heat transfer in mixed convection can be significantly different from that both in pure natural convection and in pure forced convection. The study of forced and free convection flow and heat transfer for electrically conducting fluids past a semi-infinite porous plate under the influence of a magnetic field has attracted the interest of many investigators in view of its applications in many engineering problems such as geophysics, astrophysics, boundary layer control in the field of aerodynamics. Engineers employ MHD principle, in the design of heat exchangers pumps and flow meters, in space vehicle propulsion, thermal protection, braking, control and re-entry, in creating novel power generating systems etc.

The radiation effects have important applications in physics and engineering, particularly in space technology and high temperature processes. But very little is known about the effects of radiation on the boundary layer. Thermal radiation effects on the boundary layer may play important role in controlling heat transfer in polymer processing industry where the quality of the final product depends on the heat controlling factors to some extent. High temperature plasmas, cooling of nuclear reactors, liquid metal fluids, power generation systems are some important applications of radiative heat transfer. Actually, many processes in new engineering areas occur at high temperatures and knowledge of radiation heat transfer beside the convective 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. Moreover, when radiative heat transfer takes place, the fluid involved can be electrically conducting since it is ionized due to the high operating temperature. Accordingly, it is of interest to examine the effect of the magnetic field on the flow. Studying such effect has great importance in the application fields where thermal radiation and MHD are correlative. In all these applications understanding the behaviour of MHD free and forced convective flow and the various problem parameters that influence is a very important asset to designers developing applications that aim to control this flow. For example, the process of fusing of metals in an electrical furnace by applying a magnetic field and the process of cooling of the first wall inside a nuclear reactor containment vessel where the hot plasma is isolated from the wall by applying a magnetic field.

Corresponding author: G. V. Ramana Reddy*.

Over the past years, this problem attracted the attention of several researchers. However, none of them included all relevant aspects that influence the flow behaviour. A summary of researcher's efforts is as follows: Merkin [1] investigated the mixed convection boundary layer flow on a semi-infinite vertical flat plate when the buoyancy forces aid and oppose the development of boundary layer. Watanabe [2] presented a laminar forced and free mixed convection flow on a flat plate with uniform suction or injection was theoretically investigated. Non-similar partial differential equations are transformed into non-similar ordinary ones by means of difference-differential method. Kafousias et al. [3] considered the effects of free convection currents on the flow field of an incompressible viscous fluid past an impulsively started infinite vertical porous limiting surface when the fluid is subjected to suction with uniform velocity using the Laplace transform technique. Recently, the study of heat and mass transfer on the free convective flow of a viscous incompressible fluid past an infinite vertical porous plate in presence of transverse sinusoidal suction velocity and a constant free stream velocity was presented by Ahmed [4]. Also, Ahmed and Liu [5] analyzed the effects of mixed convection and mass transfer of three-dimensional oscillatory flow of a viscous incompressible fluid past an infinite vertical porous plate in presence of transverse sinusoidal suction velocity oscillating with time and a constant free stream velocity. The non-linear coupled equations of the works were solved analytically by employing perturbation technique Soundalgekar [6] investigated the Hydromagnetic flow of a viscous incompressible fluid due to uniformly accelerated motion of an infinite flat plate in the presence of a magnetic field fixed relative to the plate and he found that velocity at any point and at any instant decreases when the strength of the magnetic field is increased. Kafousias and Georgantopoulos [7] studied the transverse magnetic effects on the free convective flow of an incompressible, electrically conducting fluid past a non-conducting and non-magnetic, vertical limiting surface, the governing equations were solved by the usual Laplace transform technique. Raptis and Soundalgekar [8] determined the effects of mass transfer on the flow of an electrically conducting fluid past a steadily moving infinite vertical porous plate under the action of a transverse magnetic field. Hussain *et al.* [9] considered the problem of natural convection boundary layer flow, induced by the combined buoyancy forces from mass and thermal diffusion from a permeable vertical flat surface with non-uniform surface temperature and concentration but a uniform rate of suction of fluid through the permeable surface. Abdelkhalek [10] presented for heat and mass transfer effect on hydromagnetic flow of a moving permeable vertical surface. The non-linear coupled boundary layer equations were transformed and the resulting ordinary differential equations were solved by perturbation technique.

The above studies have generally been confined to very small magnetic Reynolds numbers, allowing magnetic induction effects to be neglected. Such effects must be considered for relatively large values of the magnetic Reynolds number. Glauert [11] presented a seminal analysis for hydromagnetic flat plate boundary layers along a magnetized plate with uniform magnetic field in the stream direction at the plate. He obtained series expansion solutions (for both large and small values of the electrical conductivity parameter) for the velocity and magnetic fields, indicating that for a critical value of applied magnetic field, boundary-layer separation arise. Raptis and Soundalgekar [12] considered the problem of flow of an electrically conducting fluid past a steadily moving vertical infinite plate in presence of constant heat flux and constant suction at the plate and induced magnetic field is also taken into account. Recently, Bég *et al.* [13] obtained local non-similarity numerical solutions for the velocity, temperature and induced magnetic field distributions in forced convection hydromagnetic boundary layers, over an extensive range of magnetic Prandtl numbers and Hartmann numbers. Alom *et al.* [14] investigated the steady MHD heat and mass transfer by mixed convection flow from a moving vertical porous plate with induced magnetic, thermal diffusion, constant heat and mass fluxes and the non-linear coupled equations are solved by shooting iteration technique.

England and Emery [15] have studied the radiation effects of an optically thin gray gas bounded by a stationary plate. Raptis and Massalas [16] investigated the effects of radiation on the oscillatory flow of a gray gas, absorbing-emitting in presence induced magnetic field and analytical solutions were obtained with help of perturbation technique. They found out that the mean velocity decreases with the Hartmann number, while the mean temperature decreases as the radiation increases. The hydrodynamic free convective flow of an optically thin gray gas in the presence of radiation, when the induced magnetic field is taken into account was studied by Raptis *et al.* [17] using perturbation technique. They concluded that the velocity and induced magnetic field increase as the radiation increases. Hossain *et al.* [18] determined the effect of radiation on the natural convection flow of an optically dense incompressible fluid along a uniformly heated vertical plate with a uniform suction. The governing non-similar boundary-layer equations are analyzed using (i) a series solution; (ii) an asymptotic solution; and (iii) a full numerical solution. Magnetohydrodynamic mixed free–forced heat and mass convective steady incompressible laminar boundary layer flow of a gray optically thick electrically conducting viscous fluid past a semi-infinite vertical plate for high temperature and concentration differences have studied by Emad and Gamal [19]. Orhan and Kaya [20] investigated the mixed convection heat transfer about a permeable vertical plate in the presence of magneto and thermal radiation effects using the Keller box scheme, an efficient and accurate finite-difference scheme. They concluded that, an increase in the radiation parameter decreases the local skin friction parameter and increases the local heat transfer parameter. Ghosh *et al.* [21] considered an exact solution for the hydromagnetic natural convection boundary layer flow past an infinite vertical flat plate under the influence of a transverse magnetic field with magnetic induction effects and the transformed ordinary differential equations are solved exactly. As the importance of radiation in the fields of aerodynamics as well as space science technology, the present study is motivated towards this direction. The main objective of the present investigation will, therefore, be to study the effects of radiation and magnetic Prandtl number on the steady mixed convective heat and mass transfer flow of an optically thin gray gas over an infinite vertical porous plate with constant suction in presence of transverse magnetic field, by means of analytical solutions. These analytical approximate solutions under perturbation technique give a wider applicability in understanding the basic physics and chemistry of the problem, which are particularly important in industrial and technological fields.

In this paper, we consider the effects of chemical reaction as well as magnetic field on the heat and mass transfer of Newtonian fluids over an infinite vertical oscillating permeable plate with variable mass diffusion. The magnetic field is imposed transversely to the plate. The temperature and concentration of the plate is oscillating with time about a constant nonzero mean value. The dimensionless governing equations involved in the present analysis are solved using a closed analytical method and discussed qualitatively and graphically.

2. MATHEMATICAL ANALYSIS

Thermal radiation and mass transfer effects on unsteady MHD flow of a viscous incompressible fluid past along a vertical oscillating plate with variable temperature and also with variable mass diffusion in the presence of transverse applied magnetic field has been studied. The $x'-$axis is taken along the plate in the vertical upward direction and the $y'-$axis is taken normal to the plate. Initially it is assumed that the plate and fluid are at the same temperature T'_∞ in the stationary condition with concentration level C'_∞ at all the points. At time $t > 0$, the plate is given an oscillatory motion in its own plane with velocity $U_0 \cos\left(\omega' t'\right)$. At the same time the plate temperature is raised linearly with time and also mass is diffused from the plate linearly with time. A transverse magnetic field of uniform strength B_0 is assumed to be applied normal to the plate. The induced magnetic field and viscous dissipation is assumed to be negligible as the magnetic Reynolds number of the flow is taken to be very small. The fluid considered here is gray, absorbing/emitting radiation but a non-scattering medium. Then by usual Boussinesq's approximation, the unsteady flow is governed by the following equations.

$$\frac{\partial u'}{\partial t'} = \frac{\partial^2 u'}{\partial y^2} + g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) - \frac{u'}{K'} - \frac{\sigma}{\rho}B_0^2 u' \tag{1}$$

$$\frac{\partial T'}{\partial t'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p}\frac{\partial q'_r}{\partial y'} \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} - K'_r\left(C' - C'_\infty\right) \tag{3}$$

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

$$t' \le 0 : u' = 0,\ \ T' = T'_\infty,\ C' = C'_\infty \ \ \forall\ y$$

$$t' > 0\begin{cases} u' = U_0\cos\left(\omega' t'\right),\ T' = T'_\infty + \varepsilon\left(T'_w + T'_\infty\right)e^{n't'},\ C' = C'_\infty + \varepsilon\left(C'_w - C'_\infty\right)e^{n't'} & \text{at} \quad y' = 0 \\ u' \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty & \text{as} \quad y' \to \infty \end{cases} \tag{4}$$

where u' is the velocity in the x' -direction, K' is the permeability parameter, β is the volumetric coefficient of thermal expansion , β^* is the volumetric coefficient of expansion for concentration, ρ is the density, σ is the electrical conductivity , $k-$the thermal conductivity, $g-$ the acceleration due to gravity, T' is the temperature, $T'_w -$ the fluid temperature at the plate, $T'_\infty -$ the fluid temperature in the free stream, C' is the species concentration, C_p is the specific heat at constant pressure, $C'_\infty -$Species concentration in the free stream, $C'_w -$ Species concentration at the surface, D is the chemical molecular diffusivity, q_r is the radiative flux.

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

$$\frac{\partial q_r}{\partial y'} = -4a'\sigma'\left(T'^4_\infty - T'^4\right) \tag{5}$$

where σ' and a' are the ***Stefan-Boltzmann constant*** and the ***Mean absorption coefficient***, respectively. Following Chamkha 4] and others, we assume that the temperature differences within the flow are sufficiently small so that T'^4

can be expressed as a linear function of T' after using Taylor's series to expand T'^4 about the free stream temperature T'_∞ and neglecting higher-order terms. This results in the following approximation:

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \tag{6}$$

$$\frac{\partial T'}{\partial t'} = \frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{16a'\sigma'}{\rho C_p} T'^3_\infty \left(T' - T'_\infty\right) \tag{7}$$

In order to write the governing equations and the boundary conditions in dimensionless from, the following non-dimensional quantities are introduced.

$$\left.\begin{array}{l} u = \dfrac{u'}{u_0}, y = \dfrac{u_0 y'}{\nu}, t = \dfrac{t' u_0^2}{\nu}, \theta = \dfrac{T' - T'_\infty}{T'_w - T'_\infty}, \phi = \dfrac{C' - C'_\infty}{C'_w - C'_\infty}, \omega = \dfrac{\omega' \nu}{u_0^2} \\ K = \dfrac{K' u_0^2}{\nu^2}, \Pr = \dfrac{\nu \rho C_p}{k},\ Sc = \dfrac{\nu}{D}, M = \dfrac{\sigma B_0^2 \nu}{\rho u_0^2}, Gr = \dfrac{\nu \beta g \left(T'_w - T'_\infty\right)}{u_0^3}, \\ Gm = \dfrac{\nu \beta^* g \left(C'_w - C'_\infty\right)}{u_0^3}, K_r = \dfrac{K'_r \nu}{u_0^2}, R = \dfrac{16 a' \nu \sigma' T'^3_\infty}{k u_0^2}, A = \dfrac{u_0^2}{\nu} \end{array}\right\} \tag{8}$$

Using the transformations (8), the non-dimensional forms of (1), (3) and (7) are

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gm\phi - \left(M + \frac{1}{K}\right)u \tag{9}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} - \frac{R}{\Pr}\theta \tag{10}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - Kr\phi \tag{11}$$

The corresponding boundary conditions are;

$$\begin{array}{llll} u = \cos(\omega t), & \theta = t, & \phi = t & \text{at} \quad y = 0 \\ U \to 0, & \theta \to 0, & \phi \to 0 & \text{as} \quad y \to \infty \end{array} \tag{12}$$

where $M, K, Gr, Gm, \Pr, Kr, Sc, R$ are the magnetic parameter, permeability parameter, Grashof number for heat transfer, Grashof number for mass transfer, Prandtl number, Chemical reaction parameter, Schmidt number and radiation parameter respectively.

3. METHOD OF SOLUTION

In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form, we assume the trial solution for the velocity, temperature and concentration as:

$$u(y,t) = u_0(y)e^{i\omega t} \tag{13}$$

$$\theta(y,t) = \theta_0(y)e^{i\omega t} \tag{14}$$

$$\phi(y,t) = \phi_0(y)e^{i\omega t} \tag{15}$$

Substituting Eqns (13), (14) and (15) in Eqns (9), (10) and (11), we obtain:

$$u_0'' - A_3^2 u_0 = -\left[Gr\theta_0 + Gm\phi_0\right] \tag{16}$$

$$\theta_0'' - A_2^2\theta_0 = 0 \tag{17}$$

$$\phi_0'' - A_1^2\phi_0 = 0 \tag{18}$$

Here the primes denote the differentiation with respect to y.

The corresponding boundary conditions can be written as

$$\begin{aligned} &u_0 = e^{-i\omega t}\cos(\omega t),\ \ \theta_0 = te^{-i\omega t},\ \ \phi_0 = te^{-i\omega t} \quad \text{at} \quad y=0 \\ &u_0 \to 0, \qquad \theta_0 \to 0, \quad \phi_0 \to 0 \quad \text{as} \quad y \to \infty \end{aligned} \tag{19}$$

The analytical solutions of equations (16) – (18) with satisfying the boundary conditions (19) are given by

$$u_0(y) = \left\{\left[\cos(\omega t) - A_4 - A_5\right]e^{-A_3 y} + \left(A_4 e^{-A_1 y} + A_5 e^{-A_2 y}\right)\right\}e^{-i\omega t} \tag{20}$$

$$\theta_0(y) = \left(te^{-A_2 y}\right)e^{-i\omega t} \tag{21}$$

$$\phi_0(y) = \left(t\,\mathrm{e}^{-A_1 y}\right)e^{-i\omega t} \tag{22}$$

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

$$u(y,t) = \left\{\left[\cos(\omega t) - A_4 - A_5\right]e^{-A_3 y} + \left(A_4 e^{-A_1 y} + A_5 e^{-A_2 y}\right)\right\} \tag{23}$$

$$\theta(y,t) = \left(te^{-A_2 y}\right) \tag{24}$$

$$\phi(y,t) = \left(t\,\mathrm{e}^{-A_1 y}\right) \tag{25}$$

It is now important to calculate the physical quantities of primary interest, which are the local wall shear stress, the local surface heat, and mass flux. Given the velocity field in the boundary layer, we can now calculate the local wall shear stress (i.e., skin- friction) is given by

$\tau_w^* = \mu\left(\dfrac{\partial u'}{\partial y'}\right)_{y'=0}$, and in dimensionless form, we obtain

$$C_f = -\left(\frac{\partial u}{\partial y}\right)_{y=0} = \left\{\left[\cos(\omega t) - A_4 - A_5\right]A_3 + A_1 A_4 + A_2 A_5\right\}$$

From temperature field, now we study the rate of heat transfer which is given in non -dimensional form as:

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = tA_2$$

From concentration field, now we study the rate of mass transfer which is given in non -dimensional form as:

$$Sh = -\left(\frac{\partial \phi}{\partial y}\right)_{y=0} = tA_1$$

where

$$A_1 = \sqrt{Sc(Kr + i\omega)},\ A_2 = \sqrt{\Pr i\omega + R},\ A_3 = \sqrt{M + i\omega + \frac{1}{K}}\ ,$$

$$A_4 = -Grt/\left(A_2^2 - A_3^2\right),\ A_5 = -Gmt/\left(A_1^2 - A_3^2\right),$$

4. RESULTS AND DISCUSSION

In order to get a physical insight in to the problem the effects of various governing parameters on the physical quantities are computed and represented in Figures 1-15 and discussed in detail.

The effect of magnetic field on velocity profiles in the boundary layer is depicted in Fig.1. From this figure it is seen that the velocity starts from minimum value at the surface and increase till it attains the peak value and then starts decreasing until it reaches to the minimum value at the end of the boundary layer for all the values of magnetic field parameter. It is interesting to note that the effect of magnetic field is to decrease the value of the velocity profiles throughout the boundary layer. The effect of magnetic field is more prominent at the point of peak value i.e. the peak value drastically decreases with increases in the value of magnetic field, because the presence of magnetic field in an electrically conducting fluid introduce a force called the Lorentz force, which acts against the flow if the magnetic field is applied in the normal direction, as in the present problem. This type of resisting force slows down the fluid velocity as shown in this figure. For the case of different values of thermal Grashof number the velocity profiles on the boundary layer are shown in Fig.2. As expected, it is observed that an increase in Grashof number leads to increase in the values of velocity due to enhancement in buoyancy force. Here the positive values of Grashof number correspond to cooling of the surface. Fig.3 shows the velocity profiles for different values of the radiation parameter, clearly as radiation parameter increases the peak values of the velocity tends to increases. Fig.4 represents typical velocity profiles in the boundary layer for various values of the modified Grashof number, while all other parameters are kept at some fixed values. The velocity distribution attains a distinctive maximum value in the vicinity of the plate surface and then decrease properly to approach the free stream value. As expected, the fluid velocity increases and the peak value more distinctive due to increase in the concentration buoyancy effects represented by modified Grashof number. This is evident in the increase in the value of velocity as modified Grashof number increases. For different values of the Schmidt number the velocity profiles are plotted in Fig.5. It is obvious that an increase in the Schmidt number results in decrease in the velocity within the boundary layer. Fig.6 illustrates the behavior velocity for different values of chemical reaction parameter Kr. It is observed that an increase in leads to a decrease in the values of velocity. Fig.7 shows the velocity profiles for different values of the permeability parameter, clearly as permeability parameter increases the peak values of the velocity tends to increase. For different values of time t on the velocity profiles are shown in Fig.8. It is noticed that an increase in the velocity with an increasing time t.

Fig.9 illustrates the temperature profiles for different values of Prandtl number. It is observed that the temperature decrease as an increasing the Prandtl number. The reason is that smaller values of Prandtl number 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 Prandtl number. Hence in the case of smaller Prandtl number the thermal boundary layer is thicker and the rate of heat transfer is reduced. Fig.10 has been plotted to depict the variation of temperature profiles for different values of radiation parameter R by fixing other physical parameters. From this Graph we observe that temperature decrease with increase in the radiation parameter Fig.11 displays the effect of Schmidt number ***Sc*** on the concentration profiles respectively. As the Schmidt number increases the concentration decreases. Fig.12 displays the effect of the chemical reaction on concentration profiles. We observe that concentration profiles decreases with increasing chemical reaction parameter.

The effect of magnetic parameter on the skin-friction is shown in Fig.13. As the magnetic parameter increases, the skin-friction is found to be increases. Fig.14 illustrates the effect of the radiation parameter on the Nusselt number of the fluid under consideration. As the radiation parameter increases, the Nusselt number is found to be increases. Fig.15 illustrates the effect of Schmidt number on Sherwood number of the fluid under consideration. As the Schmidt number increases the Nusselt number is found to be increases.

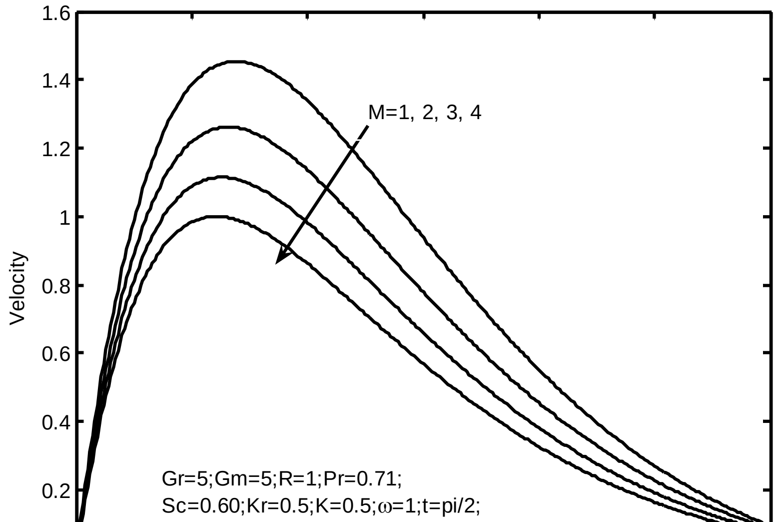

Fig. - 1. Velocity profiles for different values of magnetic parameter.

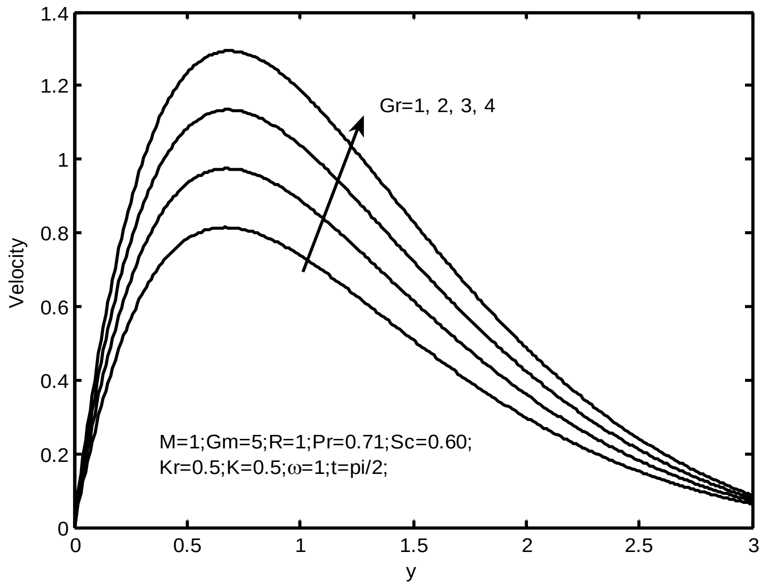

Fig. - 2. Velocity profiles for different values of Grashof number.

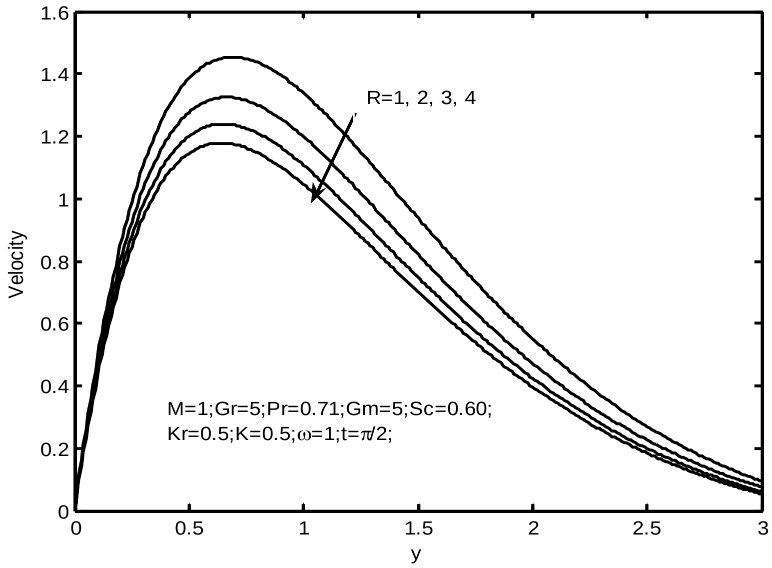

Fig. - 3. Velocity profiles for different values of radiation parameter.

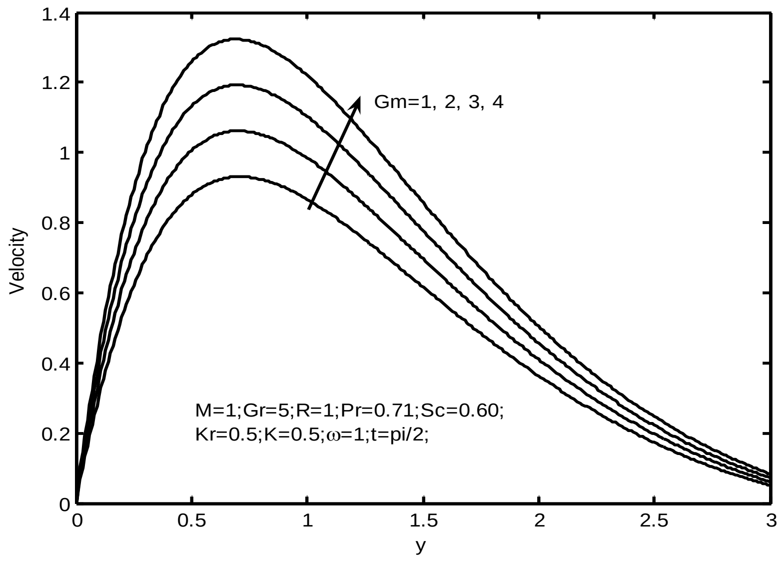

Fig. - 4. Velocity profiles for different values of modified Grashof number.

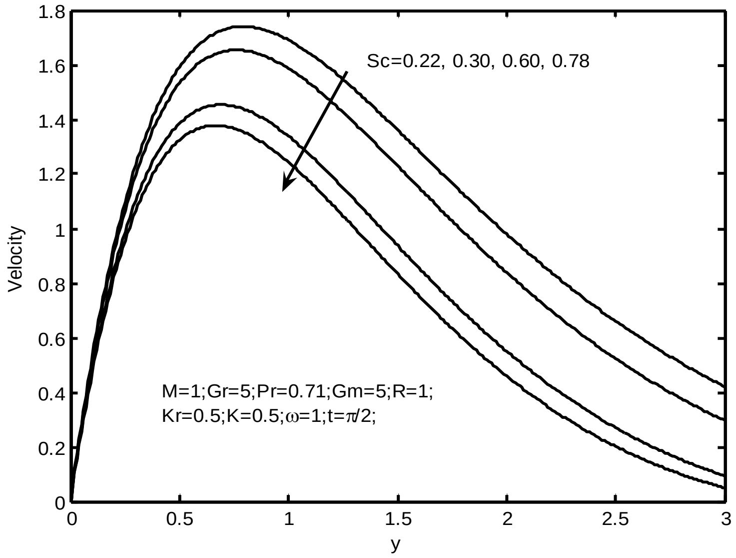

Fig. - 5. Velocity profiles for different values of Schmidt number.

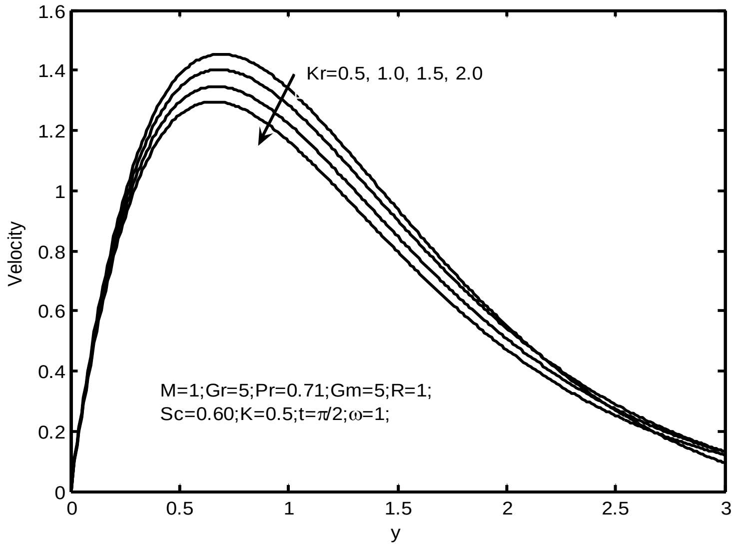

Fig. - 6. Velocity profiles for different values of chemical reaction parameter.

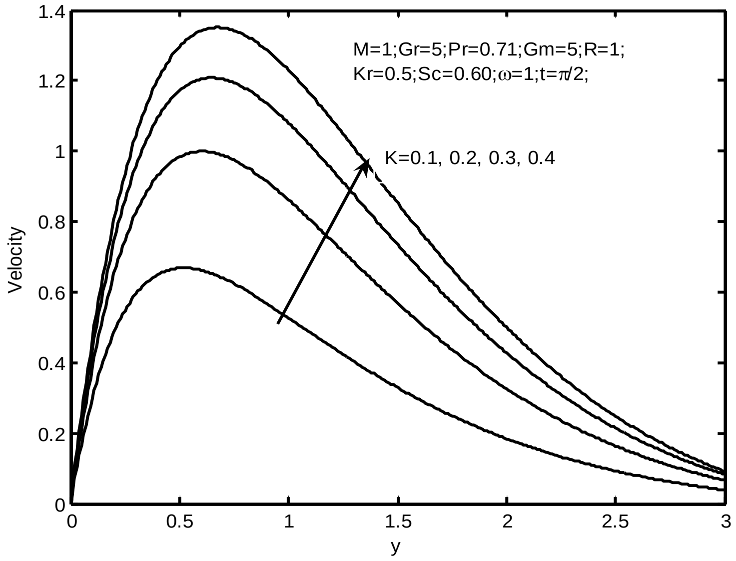

Fig. - 7. Velocity profiles for different values of permeability parameter.

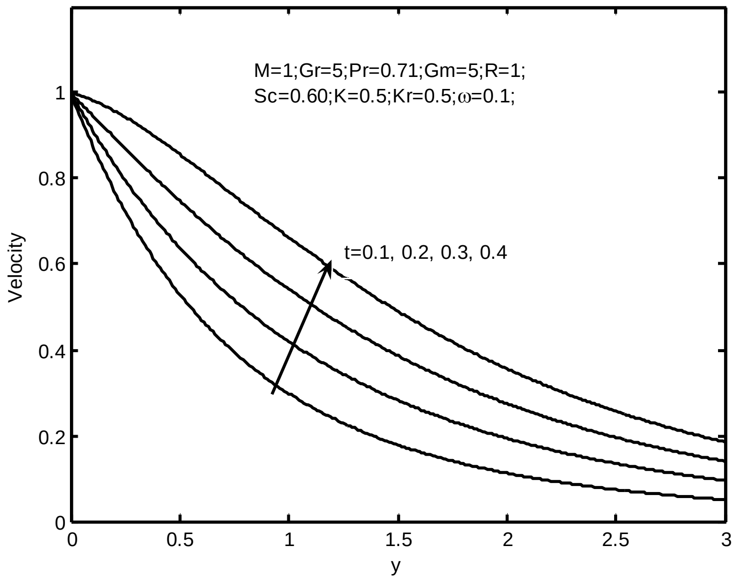

Fig. - 8. Velocity profiles for different values of time.

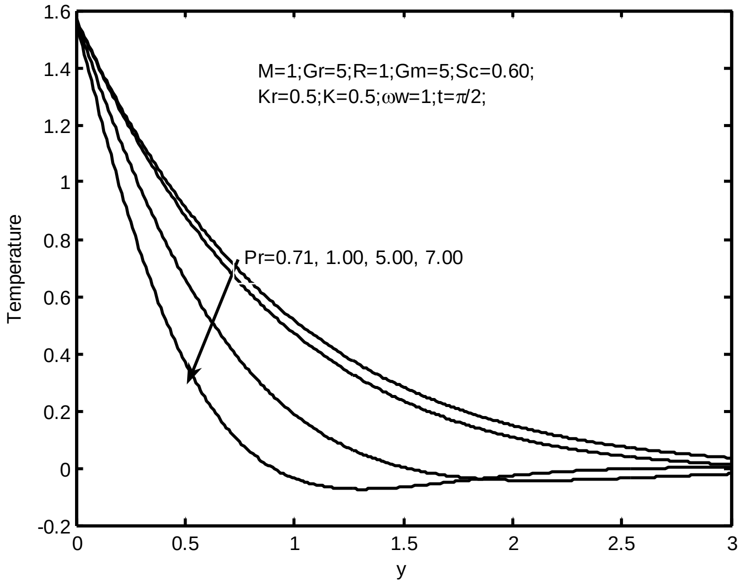

Fig. - 9. Temperature profiles for different values of Prandtl number.

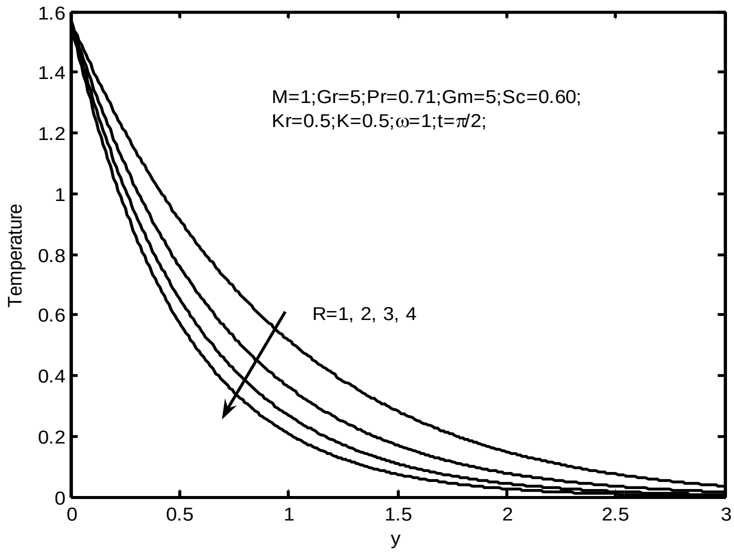

Fig. - 10. Temperature profiles for different values of radiation parameter.

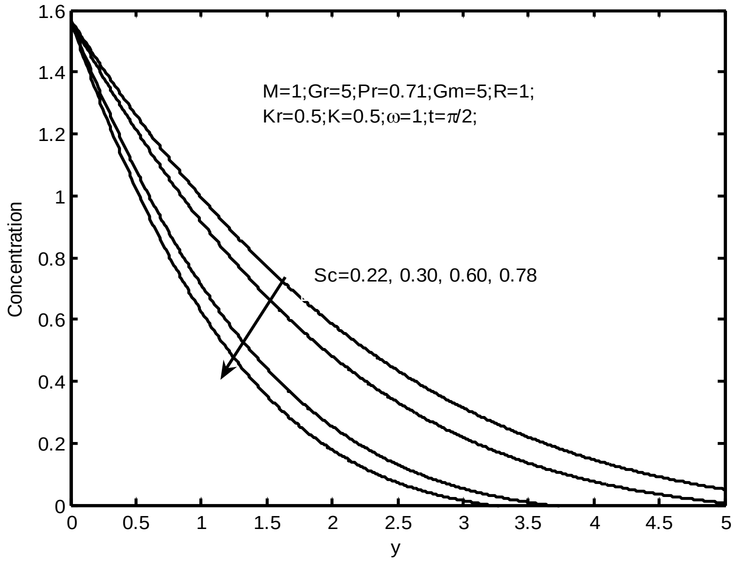

Fig. - 11. Concentration profiles for different values of Schmidt number.

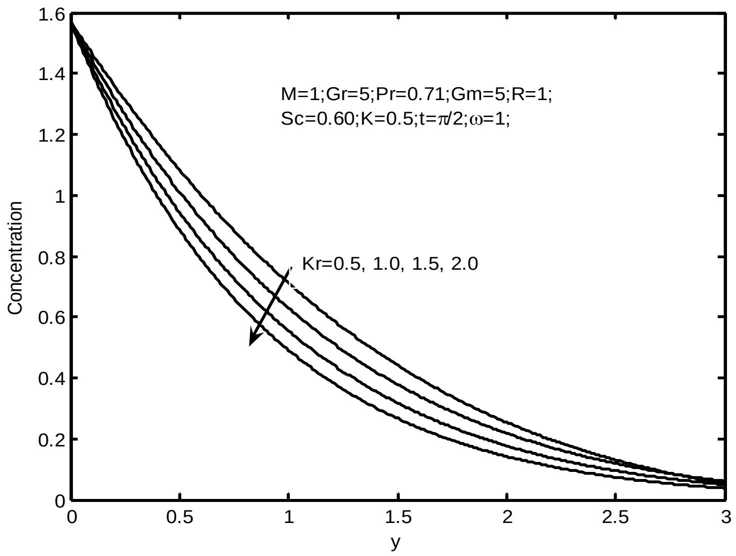

Fig. - 12. Concentration profiles for different values of chemical reaction parameter.

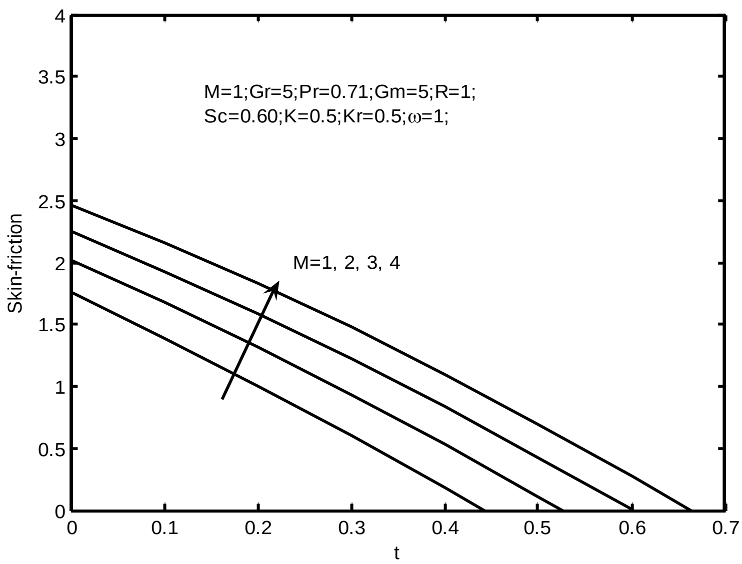

Fig. - 13. Effect of magnetic parameter on skin-friction.

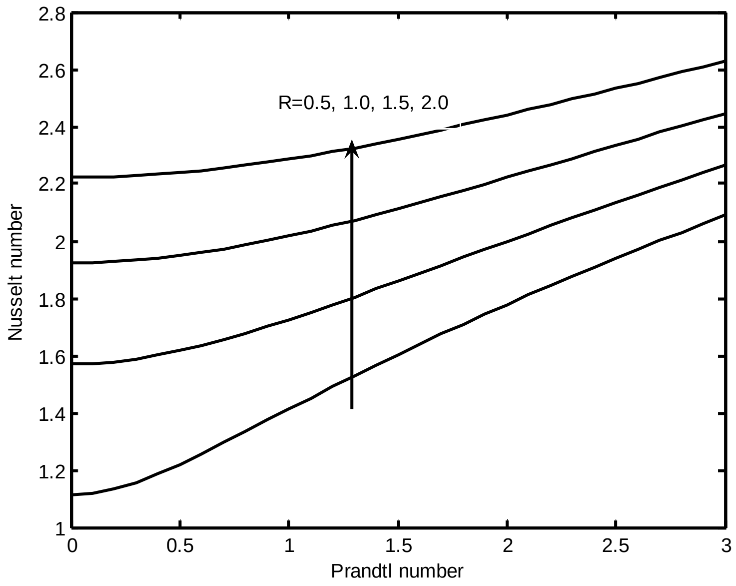

Fig. - 14. Effect of radiation parameter on Nusselt number.

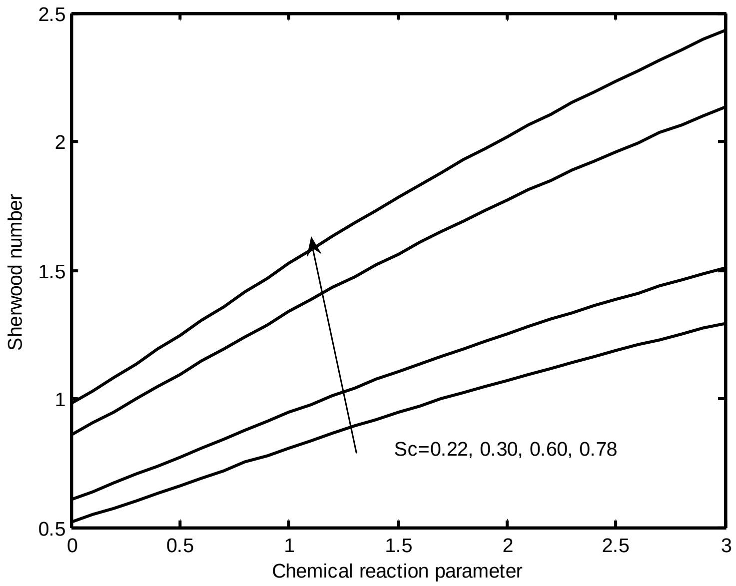

Fig. - 16. Effect of Schmidt number on Sherwood number.

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