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Unsteady MHD free convection flow and mass transfer near a moving vertical plate in the presence of thermal radiation

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ABSTRACT

The problem of unsteady MHD free convection flow and mass transfer near a moving vertical plate in the presence of thermal radiation has been examined in detail in this paper. The governing boundary layer equations of the flow field are solved by a closed analytical form. A parametric study is performed to illustrate the influence of radiation parameter, magnetic parameter, Grashof number, Prandtl number on the velocity, temperature, concentration and skin-friction. The results are discussed graphically and qualitatively. The numerical results reveal that the radiation induces a rise in both the velocity and temperature, and a decrease in the concentration. The model finds applications in solar energy collection systems, geophysics and astrophysics, aero space and also in the design of high temperature chemical process systems.

Key words: MHD, Radiation, unsteady, concentration and skin-friction.

INTRODUCTION

The phenomenon of magnetohydrodynamic flow with heat transfer has been a subject of growing interest in view of its possible applications in many branches of science and technology and also industry. Free convection flow involving heat transfer occurs frequently in an environment where difference between land and air temperature can give rise to complicated flow patterns. The study of effects of magnetic field on free convection flow is often found importance in liquid metals, electrolytes and ionized gasses. At extremely high temperatures in some engineering devices, gas, for example, can be ionized and so becomes an electrical conductor. The subject of magneto hydrodynamics has attracted the attention of a large number of scholars due to its diverse applications in several problems of technological importance. The ionized gas or plasma can be made to interact with the magnetic field and can frequently alter heat transfer and friction characteristics on the bounding surface. Heat transfer by thermal radiation is becoming of greater importance when we are concerned with space applications, higher operating temperatures and also power engineering. In astrophysics and geophysics, it is mainly applied to study the stellar and solar structures, interstellar matter, radio propagation through the ionosphere etc. In engineering, the problem assumes greater significance in MHD pumps, MHD journal bearings etc. Recently, it is of great interest to study the effects of magnetic field and other participating parameters on the temperature distribution and heat transfer when the fluid is not only an electrical conductor but also when it is capable of emitting and absorbing thermal radiation.

Viskanta (1963) had initiated the problem by examining the effects of transverse magnetic field on heat transfer of an electrically conducting and thermal radiating fluid flow in a parallel channel. Later, Grief *et al*. (1971) had investigated for an exact solution for the problem of laminar convective flow in a vertical heated channel in the optically thin film. Subsequently, Gupta *et al*. (1974) studied the effect of radiation on the combined free and forced convection of an electrically conducting fluid flowing inside an open ended vertical channel in the presence of uniform magnetic field. Soundalgekar (1979) had studied free convection effects on the flow past a vertical oscillating plate. Transformations of the boundary layer equation for free convection effects on flow past a vertical surface studied by Vedhanayagam *et al*. (1980). Kolar *et al*. (1988) had analyzed a free convection transpiration of radiation effects over a vertical plate while, Soundalgekar (1993) worked in hydromagnetic natural convection flow past a vertical surface and the problem of heat transfer by considering radiation as an important application of space and temperature related problems. Later, Takhar (1996) and Hossian *et al*. (1996) analyzed the effects of radiation using the Rosseland diffusion approximation for mixed convection of an optically dense viscous incompressible fluid in presence of magnetic field. Thereafter, Soundalgakar *et al*. (1997) generalized the problem by considering the effect of radiation on the natural convection flow of a gas past a semi infinite plate. The effects of critical parameters influencing the mass transfer on the MHD flow past an impulsively started infinite vertical plate with variable temperature or constant heat flux was discussed by Shankar *et al*. (1997). It has been reported that, in the optically thin film, the fluid does not absorb its own emitted radiation which means that there is no self absorption, but the fluid does absorb radiation emitted by the boundary. Hussain *et al*. (1999) reported interesting observations in 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 suction of fluid through the permeable surface. Revankar (2000) studied the free convection effects on the flow past an impulsively started or oscillating infinite vertical plate with different boundary conditions and thereafter, Hussain *et al*. (2000) discussed the effect of radiation on free convection from a porous vertical plate. Several investigators like Sahoo *et al*. (2003) Muthcumaraswamy *et al*. (2004) reported their observations on the heat and mass transfer effects on moving vertical plate in presence of thermal radiation. Recently, Shateyi *et al*. (2007) studied magnetohydrodynamic flow past a vertical plate with radiative heat transfer and Majumder *et al*. (1968) gave an exact solution for MHD flow past an impulsively started infinite vertical plate in presence of thermal radiation.

The purpose of the present paper is to solve analytically the problem of the unsteady free convection flow and mass transfer of an optically thin viscous, electrically conducting incompressible fluid near an infinite vertical plate which moves with time dependent velocity in presence of transverse uniform magnetic field and thermal radiation. The flow phenomena has been characterized with the help of flow parameter and the effect of these parameters on the velocity field, temperature, concentration and skin friction have been analyzed and the results with respect to various flow entities have been presented graphically and discussed qualitatively.

2. Mathematical formation of problem

We consider unsteady free convection flow and mass transfer of a viscous incompressible, electrically conducting and radiating fluid along an infinite non-conducting vertical flat plate (or surface) in presence of a uniform transverse magnetic field B_0 applied in the direction of the flow. On this plate an arbitrary point has been chosen as the origin of a coordinate system with x'- axis is along the plate in the upward direction and the y'-axis normal to plate. Initially for time $t' \le 0$, the plate and the fluid are at same constant temperature T'_∞ in a stationary condition, with the same species concentration C'_∞ at all points. Subsequently $(t' > 0)$, the plate is assumed to be accelerating with velocity $U_0 f(t')$ in its own plane along the x'- axis; instantaneously the temperature of the plate and the concentration are raised to T'_w and C'_w respectively which are hereafter regarded as a constant. For free convection flows, here we also assume that all the physical properties of the fluid is assumed to be in the direction of the x'-axis, so the physical variables are functions of the space co-ordinate y' and time t' only. Under the assumptions, the fully developed flow of a radiating fluid is governed by the following set of equations are:

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

$$\rho C_P \frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{3}$$

In view if the physics of the problem, following are the initial and boundary conditions:

$$\begin{aligned}
&\text{For } t \le 0: u' = 0,\ T' = T'_\infty, C' = C'_\infty, \quad \forall y' \\
&\text{For } t > 0, u' = U_0 f(t')\ T' = T'_w\ C' = C'_w, \quad \forall \quad y' = 0 \\
&\text{and } u' \to 0, T' \to T'_\infty, C' \to C'_\infty, \text{ as } y' \to \infty
\end{aligned} \tag{4}$$

Where u' is the velocity in the x' -direction, υ the kinematics viscosity, k' is the thermal diffusivity, 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 , κ the thermal conductivity, g is the acceleration due to gravity, T' is the temperature of the fluid near the plate, T_∞ is the temperature of the fluid far away from the plate, C' is the species concentration, C_p is the specific heat at constant pressure, D is the chemical molecular diffusivity, q_r is the radiative flux.

In the situation of optically thick film, the fluid does not absorb its own emitted radiation, where there is no self absorption but it does absorb radiation emitted by the boundaries. It has been shown by Cogly *et al* [1] that in the optically thick limit for a non gray gas near equilibrium is:

$$\frac{\partial q_r}{\partial y'} = 4\left(T' - T'_\infty\right)\int_0^\infty K_{\lambda\zeta}\left(\frac{de_{b\lambda}}{dT'}\right)_\zeta d\lambda = 4I_1\left(T' - T'_\infty\right) \tag{5}$$

where $K_{\lambda\zeta}$ is the absorption coefficient, $e_{b\lambda}$ is Planck function and the subscript ζ refers to values at the wall.

Introducing the following dimensionless variables and parameters as:

$$y = \frac{U_0 y'}{\upsilon},\ u = \frac{u'}{U_0}, t = \frac{t' U_0^2}{\upsilon},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\ \phi = \frac{C' - C'_\infty}{C'_w - C'_\infty},\quad K = \frac{k' U_0^2}{\upsilon^2}$$

$$Gr = \frac{g\beta\upsilon(T'_w - T'_\infty)}{U_0^3},\quad Gc = \frac{g\beta^*\upsilon(C'_w - C'_\infty)}{U_0^3},\ \Pr = \frac{\mu Cp}{\kappa}, Sc = \frac{\upsilon}{D}, F = \frac{4I_1\upsilon^2}{\kappa U_0^2} \tag{6}$$

Where Pr is the Prandtl number, Gr is the thermal Grashof number, Gc is the mass Grashof number, M is the magnetic parameter, F is the radiation parameter and Sc is the Schmidt number. With the help of Eqn (6), the governing Eqns (1) - (3) reduce to:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gc\phi - \left(M + \frac{1}{K}\right)u \tag{7}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} - \frac{F}{\Pr}\theta \tag{8}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} \tag{9}$$

The corresponding initial and boundary conditions in non-dimension form are:

$$\left.\begin{array}{lll} u = 0,\ \ \theta = 0,\ \ \varphi = 0 & \forall\ y > 0,\ t \le 0 \\ u = f(t),\ \ \theta = 1,\ \ \phi = 1 & \text{at}\ \ y = 0,\ t > 0 \\ u = 0, \theta = 0,\ \ \phi = 0 & \text{as}\ \ y \to \infty \end{array}\right\} \tag{10}$$

The system Eqns (7) - (9) subject to the boundary conditions (10), includes the effect of free convection and mass transfer on the flows near a moving isothermal vertical plate.

3. Solution of problem

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:

$$u(y,t) = u_0(y)e^{i\omega t} \tag{11}$$

$$\theta(y,t) = \theta_0(y)e^{i\omega t} \tag{12}$$

$$\phi(y,t) = \phi_0(y)e^{i\omega t} \tag{13}$$

In view of the above, the corresponding boundary conditions can be re written as

$$\left.\begin{array}{ll} u_0 = f(t)e^{-i\omega t},\ \theta_0 = e^{-i\omega t},\ \ \phi_0 = e^{-i\omega t}\ \ \text{as} & y = 0 \\ u_0 = 0,\ \ \theta_0 = 0,\ \ \phi_0 = 0\ \ \text{as} & y \to \infty \end{array}\right\} \tag{14}$$

The solutions of Eqs.(11) – (13) satisfying the boundary conditions (14) are given by

$$u(y,t) = e^{-Ny} f(t) + \frac{Gr}{m_2^2 - N}\left(e^{-Ny} - e^{-m_2 y}\right) + \frac{Gm}{m_1^2 - N}\left(e^{-Ny} - e^{-m_2 y}\right) \tag{15}$$

$$\theta(y,t) = e^{-m_2 y} \tag{16}$$

$$\phi(y,t) = e^{-m_1 y} \tag{17}$$

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

$$-\left(\frac{\partial u}{\partial y}\right)_{y=0} = Nf(t) - \frac{Gr}{m_2^2 - N}(m_2 - N) - \frac{Gm}{m_1^2 - N}(m_1 - N) \tag{18}$$

$$m_1 = \sqrt{i\omega Sc}$$

$$m_2 = \sqrt{F + i\omega \Pr}$$

$$N = M + i\omega + 1/K$$

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 1-17 and discussed in detail.

The effect of Prandtl number is noticed in Fig .1. For a constant value of Schmidt number, as the Prandtl number increases, the velocity field is found to be decreasing. Further, it is observed that as we move away from the plate, the velocity increases and thereafter it is found to be decreasing. Also, far away from the plate, it is noticed that the variation in the velocity is not significant even if the Prandtl number increases. Therefore, it can be concluded that the effect of Prandtl number is increasing the velocity field is only up to some level and thereafter, its contribution is not that significant. For a fixed value of Prandtl number, the contribution of Schmidt number is seen in Fig.2. The increase in the value of Schmidt number, contributes to the decreasing in the velocity field. In the boundary layer region the fluid velocity observed to be decreasing and thereafter, as we move away from the plate, the velocity is found to be decreasing. The effect of radiation parameter on the velocity field is illustrated in Fig.3. Increase in the radiation parameter contributes to the decrease in the velocity field. However, the trend seems to have been reversed as we move away from the plate. Therefore, the velocity field seems to behave differently in each of these situations. The decrease in the velocity in boundary layer region can be attributed to the fact that the intra molecular forces within the fluid decreases which would have contributed to the increase in the velocity. But the presences of magnetic field suppress such an increase as a result of which the velocity reduces. However, in the later stage, it is observed that as we move far away from the plate, the influence of the magnetic field is not felt resulting in the increase of fluid velocity. The contribution of the Magnetic field on the velocity profiles is noticed in Fig .4. It is observed that as the magnetic intensity increases, the velocity field decreases throughout the analysis as long as the radiation parameter is held constant. Further, it is also noticed that the velocity of the fluid medium raises within the boundary layer region and thereafter, it decreases which clearly indicates that the radiation parameter has not that much of significant effect as was in the initial stage. The contribution of the porosity factor of the fluid bed on the velocity field is illustrated in Fig.5. In general, it is noticed that, as the porosity decreases, the velocity also decreases for a constant Gr. Further, as we move far away from the fluid bed, the effect of both velocity and *Gr* on the velocity is found to be almost zero. The influence of frequency of excitation for a constant Prandtl number (Pr) is shown in Fig.6. In general it is noticed that increase in the frequency of excitation, contributes to the decrease in the velocity of the fluid medium. Further, as was seen in all other earlier situations, as we move away from the plate the velocity decreases. The influence of thermal Grashof number on the velocity field is illustrated graphically in Fig.7. When *Gm* is held constant, and as the thermal Grashof number is increased, in general the fluid velocity increases. However, as we move away from the bounding surface of the fluid, it is noticed that irrespective of the nature of thermal Grashof number, the velocity remains to be zero and hence the influence of thermal Grashof number do not qualitatively contributes to the velocity field. The effect of mass Grashof number for a constant value of thermal Grashof Number is illustrated in Fig.8. For a fixed thermal Grashof Number, the increase in the mass Grashof number, in general contributes to the increase in the velocity field. However, it does not have any influence as we move away from the bounding surface.

The influence of frequency of excitation for a constant radiation parameter on the temperature is studied in Fig.9. When the radiation parameter is held constant and as the frequency of excitation is increased, it is noticed that, the temperature decreases. Relatively when the frequency of excitation is very small, the profiles for the temperature are found to be linear of course with a negative slope. But when it is increased, the profiles for the temperature are found to be parabolic in nature. In tune with all earlier observations, it is noticed that, in this situation, the effect of frequency of excitation is not significant as we move away from the bounding surface. For a constant value of the Prandtl Number, the influence of radiation parameter on the temperature field is studied in Fig.10. Increase, in the radiation parameter contributes in general to decrease in the temperature. The effect of such radiation parameter is not significant as we move away from the boundary. As the radiation parameter increases, the profiles for the temperature field are found to be more parabolic in nature. The influence of Prandtl number for a fixed radiation parameter is illustrated graphically in Fig.11. It is noticed that, as the Prandtl number increases, in general the temperature falls down. Also, the increase in Prandtl number contributes to the parabolic nature of temperature profiles. Further, the effect is found to be significant in the initial stages and not that predominant as we move away from the plate. The influence of the frequency of excitation on the temperature profiles when the Prandtl number is held constant is illustrated in Fig.12. As the frequency of excitation is increased, in general it is seen the temperature decreases. Such as effect is found to be more dispersive and pre dominant within the boundary layer region. However, the contribution of both participating parameters as we move away from the plate is not significant.

The influence of Schmidt number on the concentration of fluid medium is shown graphically in Fig.13. The relation for the Schmidt number on the concentration is perfectly found to linear and of course inversely. As the Schmidt number increases, the concentration decreases as long as the frequency of excitation is held constant. The influence of frequency of excitation on the concentration field is studied graphically in Fig.14. It is observed that, as the frequency of excitation increases, a significant drop in the temperature is noticed. Also, it is seen that as the frequency of excitation is increased, the temperature profiles are found to be more parabolic in nature.

The influence of Schmidt number on Skin friction with respect to the frequency of excitation is shown graphically in Fig.15. When the magnetic intensity is held constant and the Schmidt number is increased, the skin friction reduces quite significantly. Though not much of variation is seen on the boundary, its effect is found to be highly dispersive. The consolidated contribution of the frequency of excitation and Prandtl number on the skin friction is illustrated graphically in Fig.16. In general, it is seen that as the frequency of excitation is increased, the skin friction decreases when the magnetic intensity is held constant throughout the investigation. The influence of magnetic field with respect to the Schmidt Number on skin friction is illustrated graphically in Fig.17. When the radiation parameter is held constant and the magnetic intensity is increased, the skin friction increases quite significantly. Further, for a constant magnetic intensity, as the Schmidt Number increases, the skin friction decreases.

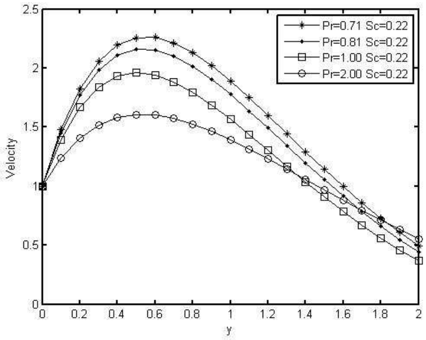

Fig. 1: Effect of Pr on the velocity field

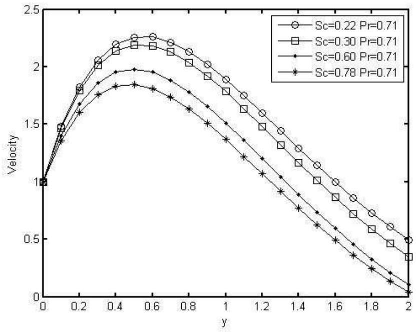

Fig.2. Effect of Sc on the velocity field

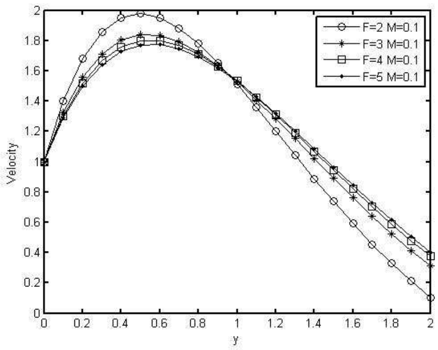

Fig.3: Effect of F on the velocity field.

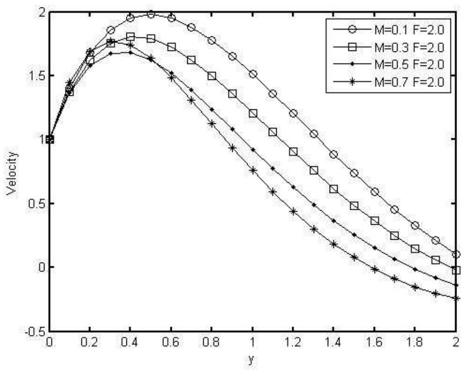

Fig – 4: Effect of M on the velocity field

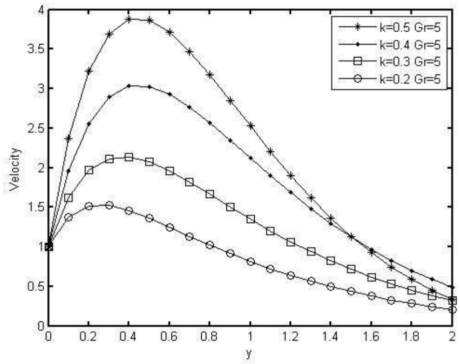

Fig – 5: Effect of k on the velocity field

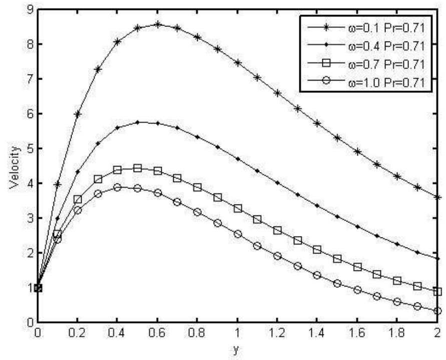

Fig – 6: Effect of ω on the velocity field

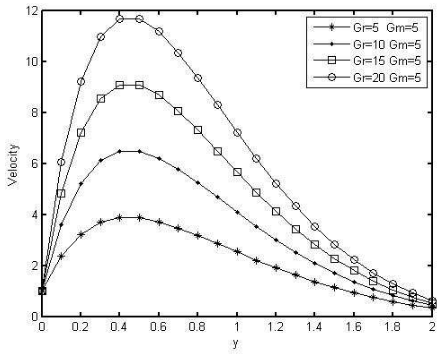

Fig – 7: Effect of Gr on the velocity field

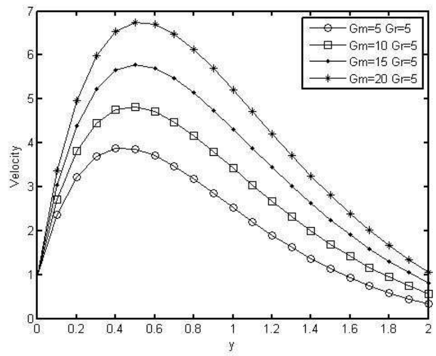

Fig – 8: Effect of Gm on the velocity field

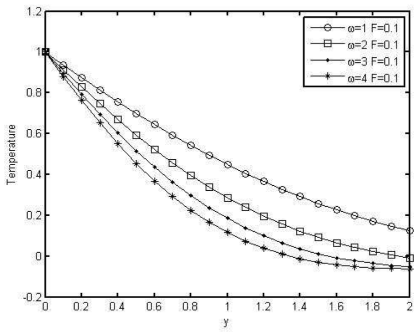

Fig – 9: Effect of ω on the temperature field.

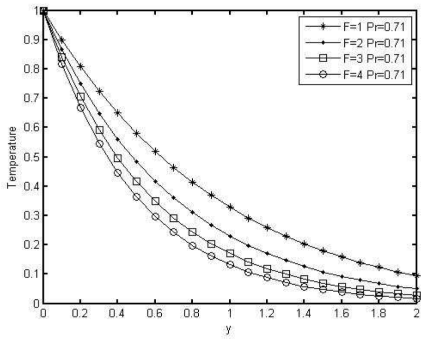

Fig – 10: Effect of F on the temperature field

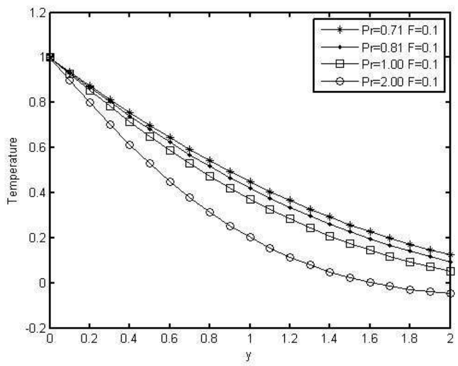

Fig – 11: Effect of Pr on the temperature field

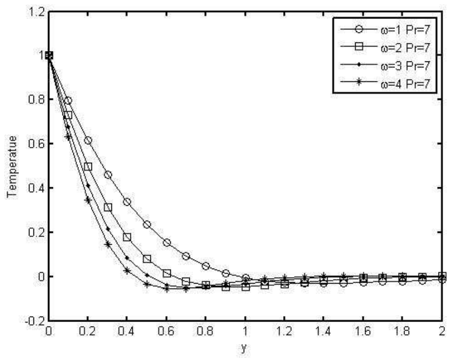

Fig – 12: Effect of ω on the temperature field

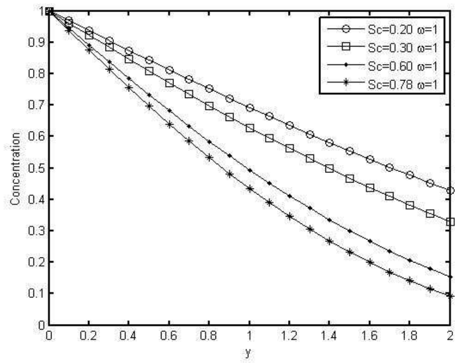

Fig – 13: Effect of Sc on the concentration field

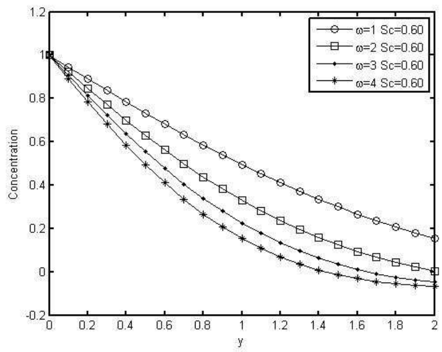

Fig – 14: Effect of ω on the concentration field

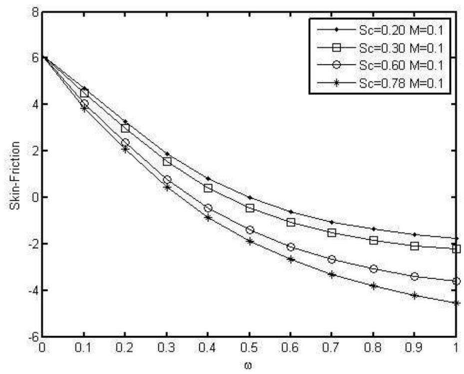

Fig – 15: Effect of Sc on Skin-friction

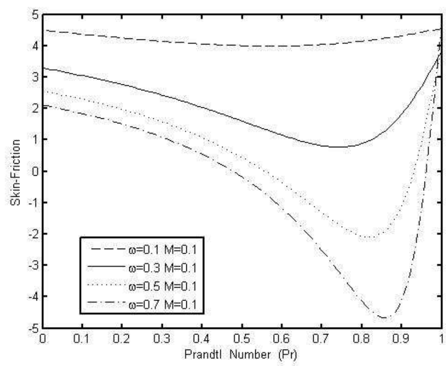

Fig – 16: Effect of Pr on the Skin-friction

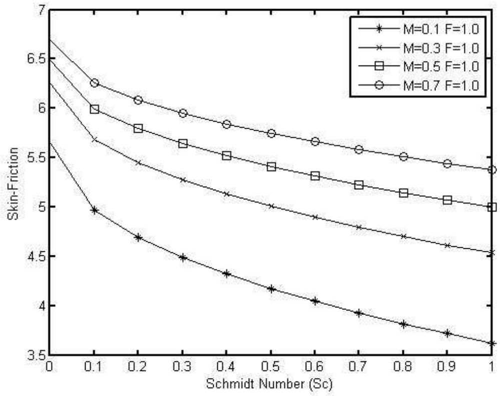

Fig – 17: Effect of M on the Skin-friction

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