SORET EFFECT ON A STEADY MIXED CONVECTIVE HEAT AND MASS TRANSFER FLOW WITH INDUCED MAGNETIC FIELD

C. S. Sravanthi[1], N.Bhuvanesh[2]

***Abstract*— This paper is focuses on the soret effect on a two dimensional, laminar, mixed convective heat and mass transfer flow of a viscous incompressible electrically conducting and radiating fluid over a vertical porous plate in the presence of a transverse applied magnetic field and constant suction, by taking induced magnetic field into account. The boundary layer equations have been transformed into dimensionless coupled non-linear ordinary differential equations by similarity transformations. The resultant dimensionless governing equations are solved by series solution technique. The influences of various thermo physical parameters on the velocity, temperature, concentration and induced magnetic fields are discussed. It is observed that the induced magnetic field increases with a rise in chemical reaction parameter or Hartmann number or radiation parameter or Schmidt number, whereas it decreases with an increase in the Soret number. This model finds applications in laminar magneto-aero dynamics, material process and MHD propulsion thermo fluid dynamics.**

***Index Terms*—Mixed convection, Magneto hydrodynamics, Heat and mass transfer, Soret effect, induced magnetic field, current density.**

I. INTRODUCTION

An energy flux can be generated not only due to the temperature gradients but also by composition gradients. The energy flux produced by a composition gradient is referred to as the diffusion-thermo (Dufour) effect, whereas, mass flux caused by temperature gradients is known as the thermal-diffusion (Soret) effect. In general, the diffusion-thermo effect and thermal-diffusion effect are of a smaller order of magnitude than the effects described by Fourier's or Fick's law.

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This is why, most of the studies of heat and mass transfer processes, however, considered constant plate temperature and concentration and have neglected the diffusion-thermo and thermal-diffusion terms from the energy and concentration equations, respectively. But in some exceptional cases, for instance, in mixture between gases with very light molecular weight (H_2, He) and of medium molecular weight (N_2 , air) the diffusion-thermo (Dufour) effect and in isotope separation the thermal-diffusion (Soret) effect was found to be of a considerable magnitude such that these effects cannot be ignored.

In view of the importance of this diffusion – thermo effect, similarity equations of the momentum energy and concentration equations are derived by introducing a time dependent length scale. Seddeek [1] has considered the influence of variable viscosity on mixed free-forced convective flow and mass transfer over an accelerating surface in the presence of Soret, Dufour and heat source effects. Combined chemical reaction and Soret/Dufour effects on free convection heat and mass transfer in Darcian porous media were studied also very recently by Postelnicu [2]. In these studies it has been identified that Soret and Dufour effects are important for intermediate molecular weight gases in coupled heat and mass transfer in chemical process systems. Bég et al. [3] presented theoretically the combined chemical reaction, Soret and Dufour effects on the mixed convection heat and mass transfer over vertical and inclined plates using the local non-similarity numerical method.The Dufour and Soret effects on steady MHD free convective heat and mass transfer flow past a semi-infinite vertical porous plate embedded in a porous medium have been studied by Alam and Rahman [4]. Next, Alam et al. [5] studied the Dufour and Soret effects on unsteady MHD free convection and mass transfer flow past an infinite vertical flat plate. Alam et al. [6] further extensively investigated the Dufour and Soret effects on steady

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MHD free-forced convective and mass transfer flow past a semi-infinite vertical plate.

In all the above mentioned studies, the magnetic Reynolds number is assumed to be very small, therefore the induced magnetic field is neglected. To accurately predict the flow behavior, such effect must be considered for larger values of magnetic Reynolds number. Glauert [7] 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 [8] 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.* [9] 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*. [10] 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 [11] have studied the radiation effects of an optically thin gray gas bounded by a stationary plate. Raptis and Massalas [12] 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*. [13] using perturbation technique. They concluded that the velocity and induced magnetic field increase as the radiation increases. Ghosh et *al*. [14] considered an exact solution for the hydro magnetic 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. Sahin Ahmed [15], investigated the influence of thermal radiation and magnetic prandtl number on the stady MHD heat and mass transfer by mixed convective flow of a gray gas, taking into account the induced magnetic field.

A numerical study of the natural convection heat and mass transfer about a vertical surface embedded in a saturated porous medium under the influence of a magnetic field has been done by Postelnicu [16], taking into account the diffusion-thermo and thermal-diffusion effects. Pantokratoras [17] and Postelnicu [18] and Hossain and Khatun [19] investigated the Dufour effect on combined heat and mass transfer of a steady laminar mixed free-forced convective flow of viscous incompressible electrically conducting fluid above a semi-infinite vertical porous surface under the influence of an induced magnetic field.

However, the Soret effect in the presence of induced magnetic field have not been studied. Hence an attempt is made to analyse Soret effect on a MHD steady mixed convective heat and mass transfer flow over a semi-infinite vertical porous plate taking into account the induced magnetic field. The governing equations are solved employing a regular perturbation technique.

II. MATHEMATICAL ANALYSIS

A two-dimensional mixed convective heat and mass transfer flow of a viscous, incompressible, electrically conducting fluid past a continuously moving semi-infinite vertical porous plate under the influence of a transversely applied magnetic field is considered. It is assumed that :

1) The fluid considered is an optically thin gray gas.
2) All the fluid properties except the density in the buoyancy force term are constant.
3) The Eckert number, Ec is small.
4) The magnetic Reynolds number of the flow is not taken to be small enough so that the induced magnetic field is not negligible.
5) The wall is maintained at constant temperature $\overline{T_w}$ and concentration $\overline{C_w}$ higher than the ambient temperature $\overline{T_\infty}$ and concentration $\overline{C_\infty}$ respectively.
6) The suction velocity is taken to be $\bar{v} = -v_0$.

Following the Cartesian coordinate system, the flow is assumed to be in the $\bar{X}$-direction, which is taken along the vertical plate in the upward direction, where $\bar{Y}$-direction normal to the plate. Since the plate is infinite in length in $\bar{X}$-direction, therefore, all the

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physical quantities except possibly the pressure are assumed to be independent of $\bar{X}$.Let $\bar{q} = (\bar{U}(y), \bar{V}, 0)$ be the fluid velocity and $\bar{H} = (\overline{H_x}(y), \overline{H_y}, 0)$ be the magnetic induction vector at a point $(\bar{X}, \bar{Y}, \bar{Z})$ in the fluid.

Within the frame of such assumptions and under the Oberbeck- Boussinesq's approximation and in consistency with boundary layer theory, the governing equations relevant to the problem are

$$\frac{\partial \bar{v}}{\partial \bar{y}} = 0 \quad (1)$$

$$-v_0 \frac{\partial \bar{u}}{\partial \bar{y}} = g\beta(\bar{T} - \overline{T_\infty}) + g\bar{\beta}(\bar{c} - \overline{c_\infty}) + \upsilon \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + \frac{\mu_0 H_0}{\rho} \frac{\partial \overline{H_x}}{\partial \bar{y}} \quad (2)$$

$$-v_0 \frac{\partial \bar{T}}{\partial \bar{y}} = \frac{\kappa}{\rho c_p} \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial \bar{y}} \quad (3)$$

$$-v_0 \frac{\partial \overline{H_x}}{\partial \bar{y}} = \frac{1}{\sigma \mu_0} \frac{\partial^2 \overline{H_x}}{\partial \bar{y}^2} + H_0 \frac{\partial \bar{u}}{\partial \bar{y}} \quad (4)$$

$$-v_0 \frac{\partial \bar{c}}{\partial \bar{y}} = D \frac{\partial^2 \bar{c}}{\partial \bar{y}^2} - \bar{k}(\bar{c} - \overline{c_\infty}) + D_T \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} \quad (5)$$

The relevant boundary conditions are

$$\bar{u}=0, \bar{T} = \overline{T_w}, \overline{H_x} = 0, \bar{C} = \overline{C_w} \quad \text{at } \bar{y} = 0$$

$$\bar{u} \to U_0, \bar{T} \to \overline{T_\infty}, \overline{H_x} \to 0, \bar{C} \to \overline{C_\infty} \text{ as } \bar{y} \to \infty \quad (6)$$

where g is the acceleration due to gravity , β is the coefficient of thermal expansion, $\bar{\beta}$ is the concentration expansion coefficient, υ is the kinematic viscosity of the fluid, μ_0 is the magnetic permeability, H_0 is the applied constant magnetic field, H_x is induced magnetic field, ρ is the density of the fluid, σ is the electrical conductivity, κ is thermal conductivity, D is the chemical molecular diffusivity, c_p is the specific heat capacity of the fluid at constant pressure and $\bar{k}$ is chemical reaction parameter.

The non-dimensional quantities are

$$y = \frac{v_0 \bar{y}}{\upsilon}, u = \frac{\bar{u}}{U_0}, \theta = \frac{\bar{T} - \overline{T_\infty}}{\overline{T_w} - \overline{T_\infty}},$$

$$\phi = \frac{\bar{C} - \overline{C_\infty}}{\overline{C_w} - \overline{C_\infty}}, Sc = \frac{\upsilon}{D}, Pr = \frac{\rho \upsilon c_p}{\kappa},$$

$$Gr = \frac{\upsilon g \beta (\overline{T_w} - \overline{T_\infty})}{U_0 v_0^2}, Gm = \frac{\upsilon g \bar{\beta} (\overline{C_w} - \overline{C_\infty})}{U_0 v_0^2}$$

$$Prm = \sigma \upsilon \mu_0, M = \sqrt{\frac{\mu_0}{\rho}} \frac{H_0}{v_0}, H \sqrt{\frac{\mu_0}{\rho}} \frac{\overline{H_x}}{v_0},$$

$$R = \frac{64 a \upsilon \bar{\sigma} \bar{T}_\infty^3}{\rho v_0^2 c_p}, K = \frac{\bar{K} \upsilon}{v_0^2}, S_0 = \frac{D_T (\overline{T_w} - \overline{T_\infty})}{\upsilon (\overline{C_w} - \overline{C_\infty})} \quad (7)$$

For the case of an optically thin gray gas, the local radiation absorption is expressed as

$$\frac{\partial q_r}{\partial \bar{y}} = -4a\bar{\sigma}(\bar{T}_\infty^4 - \bar{T}^4) \quad (8)$$

where 'a' is the mean absorption coefficient and $\bar{\sigma}$ is the Stefan-Boltzmann constant. It is assumed that the temperature differences within the flow are sufficiently small such that $\bar{T}^4$ may be expressed as linear function of the temperature $\bar{T}$.This is accomplished by expanding $\bar{T}^4$ in Taylor series about $\bar{T}_\infty$ and neglecting higher order terms, thus

$$\bar{T}^4 \cong 4\bar{T}_\infty^3 \bar{T} - 3\bar{T}^4 \quad (9)$$

Using the transformations (7) and with the help of (8),(9) the non-dimensional forms of (2)-(5) are

$$\frac{d^2 u}{dy^2} + \frac{du}{dy} + M\frac{dH}{dy} + \theta Gr + \phi Gm = 0 \quad (10)$$

$$\frac{d^2 \theta}{dy^2} + Pr\frac{d\theta}{dy} - \frac{PrR}{4} = 0 \quad (11)$$

$$\frac{d^2 H}{dy^2} + Prm\frac{dH}{dy} + MPrm\frac{du}{dy} = 0 \quad (12)$$

$$-\frac{d\phi}{dy} = \frac{1}{Sc}\frac{d^2\phi}{dy^2} - K\phi + S_0\frac{d^2\theta}{dy^2} \quad (13)$$

The corresponding boundary conditions are

$$u = 0, \theta = 1, H = 0, \phi = 1 \quad \text{at} \quad y = 0$$

$$u \to 1, \theta \to 0, H \to 0, \phi \to 0 \quad \text{as } y \to \infty \quad (14)$$

III. SOLUTION OF THE PROBLEM

Solving equations (11) and (13) subject to the boundary conditions (13) we get

$$\theta = e^{-\xi y}, \ \phi = A_1 e^{-\xi y} + A_2 e^{-\eta y} \quad (15)$$

Now, in order to solve the coupled equations (10) and (12) under the boundary conditions (13), it is assumed that the solutions of the equations to be of the forms

$$R(y) = R_0(y) + Ec\, R_1(y) + O(Ec^2) \quad (16)$$

which R denotes a general dependent variable u, H and Ec is the Eckert number, which is very small for an incompressible fluid.

Substituting (16) in (10) and (12) and equating the coefficients of the same degree terms and neglecting terms of O (Ec^2), the following ordinary differential equations are obtained.

$$u_0'' + u_0' + MH_0' + Gr\theta + Gm\phi = 0 \quad (17)$$

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$u_1'' + u_1' + MH_1' = 0$ (18)
$H_0'' + MPrm\, u_0' + Prm\, H_0' = 0$ (19)
$H_1'' + MPrm\, u_1' + Prm\, H_1' = 0$ (20)

The corresponding boundary conditions are

$u_0 = 0, u_1 = 0, H_0 = 0, H_1 = 0$ at $y = 0$
$u_0 \to 1, u_1 \to 1, H_0 \to 0, H_1 \to 0$ as $y \to \infty$ (21)

Solutions of the velocity and induced magnetic field subject to the boundary conditions (21) are

$u(y) = 1 + A_3 e^{-\xi y} + A_4 e^{-\eta y} + A_5 e^{-\lambda y}$ (22)
$H(y) = A_6 e^{-\lambda y} + A_7 e^{-\xi y} + A_8 e^{-\eta y} + A_9 e^{-pr_m y}$ (23)

where, the mathematical expressions for the constants involved in equations (22) and (23) are given in Appendix A.

The skin-friction, Nusselt numbr and Sherwood number are important physical parameters for this type of boundary layer flow.

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

$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -(\xi A_3 + \eta A_4 + \lambda A_5)$ (24)

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

$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -\xi$ (25)

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

$sh = \left(\frac{\partial \phi}{\partial y}\right)_{y=0} = -(\xi A_1 + \eta A_2)$ (26)

The non dimensional current density at the plate y=0 is given by

$J = \left(\frac{\partial H}{\partial y}\right)_{y=0} = -(\xi A_7 + \eta A_8 + \lambda A_6 + pr_m A_9)$ (27)

IV. RESULTS AND DISCUSSION

Comprehensive solutions have been obtained and are presented in figures (1) to (11). The problem comprises of one independent variable (y), four dependent variables (u, θ, H, ϕ) and nine thermo physical and body force control parameters *Gr, Gm, M, K,* S_o*, Sc, Prm, Pr* and *R*.

Velocity profiles:

For the case of different values of thermal Grashof number *Gr,* the velocity profiles in the boundary layer are shown in Fig. 1. It is observed that an increase in *Gr* leads to a rise in the velocity due to the enhancement in buoyancy force. Here, the positive values of *Gr* correspond to cooling of the surface. In addition, the curve show that the peak values of the velocity increases near the porous plate as Grashof number increases and then decays to the free stream velocity.

(21)

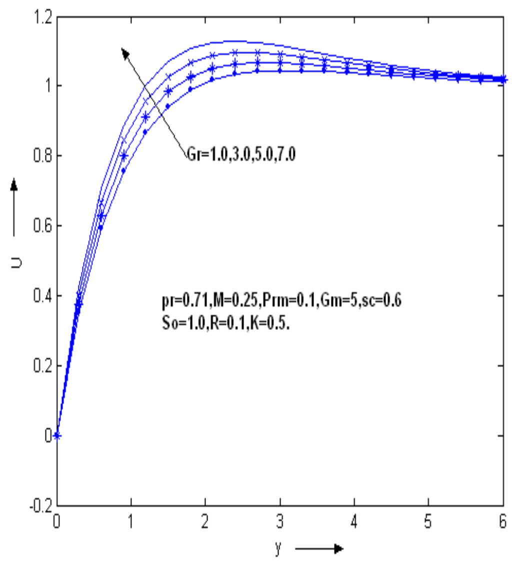

Fig. 1: Effect of *Gr* on the velocity.

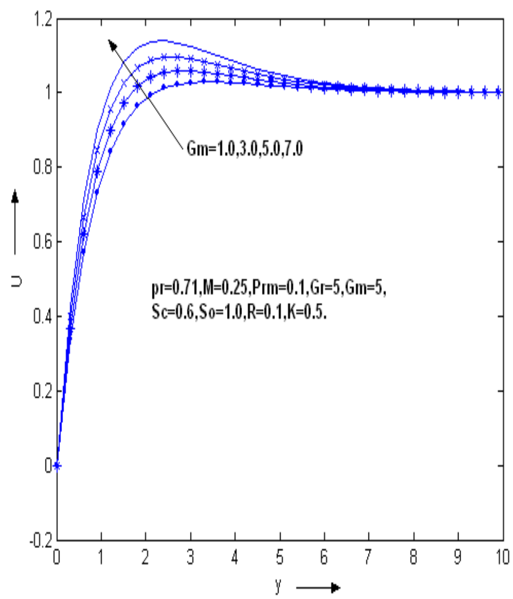

Fig. 2: Effect of *Gm* on the velocity.

Fig. 2 presents typical velocity profiles in the boundary layer for various values of the solutal Grashof number *Gm*. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases properly to approach the free stream value. As expected, the fluid velocity increases and the peak values are more distinctive

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due to increase in the concentration buoyancy effects represented by *Gm*.

For different values of the Hartmann number (*M*), the velocity profiles are is plotted in Fig. 3. It is obvious that the effect of increasing the values of the parameter *M* results in a decreasing velocity distribution across the boundary layer. The effect of radiation parameter (*R*) on the velocity field has been illustrated in Fig. 4. It is seen that as the radiation parameter increases the velocity field decreases. This may be attributed to the fact that an increase in *R* implies less interaction of radiation with the momentum boundary layer.

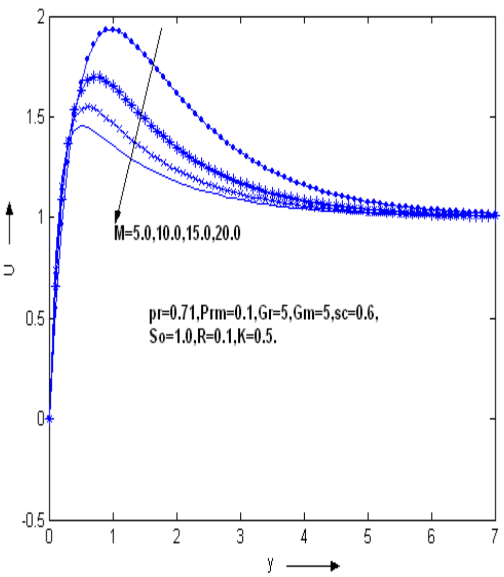

Fig. 3: Effect of *M* on the velocity

Fig. 5 depicts the effect of Soret number (S_o) on the fluid velocity and it is observed that the fluid velocity increases as Soret number (S_o) increases. This is because an increase in the volumetric rate of generation increases the buoyancy force thereby increasing the fluid velocity.

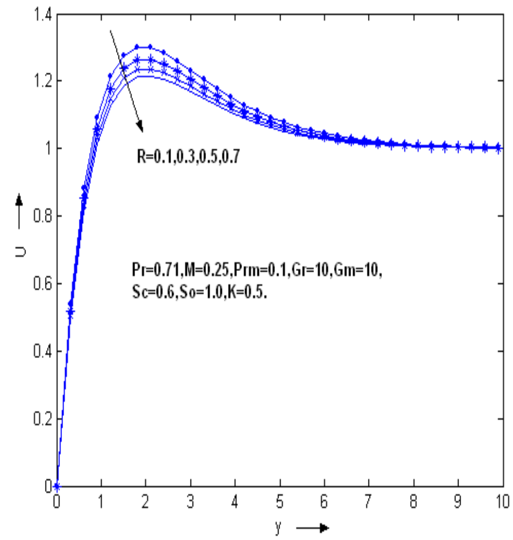

Fig. 4: Effect of *R* on the velocity.

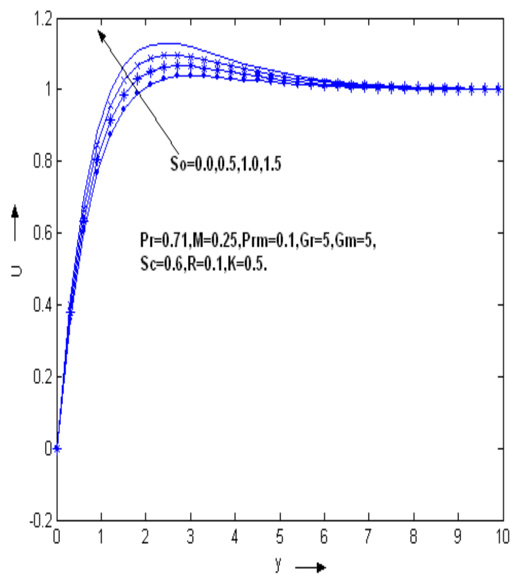

Fig. 5: Effect of S_o on the velocity.

Temperature profiles:

The variation of temperature for different values of the Prandtl number (*Pr*) is shown in Fig. 6. The results show that an increase of the Prandtl number results in a decrease in the thermal boundary layer thickness and a more uniform temperature distribution across the boundary layer. The reason is that the smaller values of *Pr* are equivalent to increasing the thermal conductivities and therefore, heat is able to diffuse away from the heated surface more rapidly than for the larger values of *Pr*.

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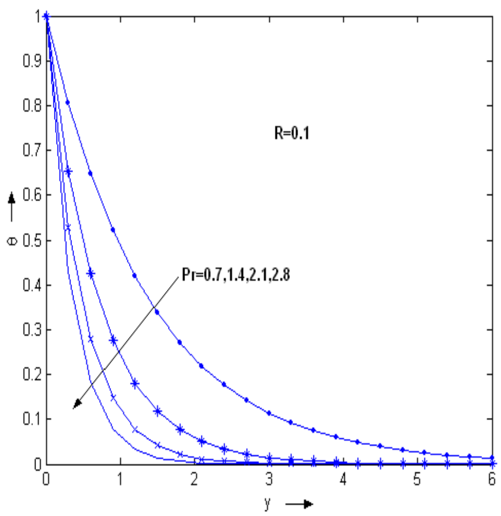

Fig. 6: Effect of *Pr* on the temperature.

Concentration profiles:

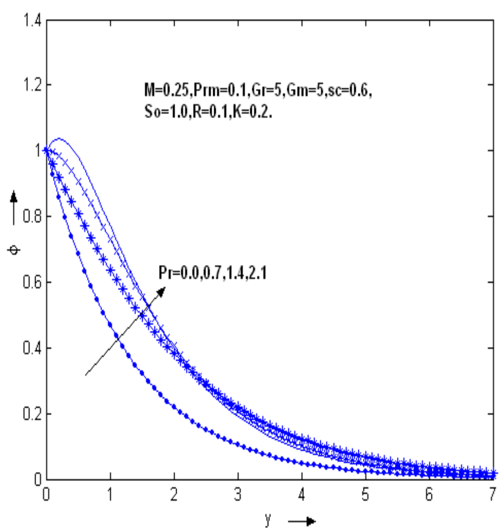

Fig. 7: Effect of *Pr* on the concentration

Fig. 7 shows the effect of Prandtl number (*Pr*) on the concentration. It is observed that as *Pr* increases, the concentration increases. This may be due to the reason that at high Prandtl number ,the fluid has low velocity, which in turn also implies that at lower fluid velocity the species diffusion is comparatively lower and hence higher species concentration is observed at high Prandtl number. The influence of Soret number (S_o) on the concentration of the fluid is shown in Fig. 8. In general it is noted that an increase in the Soret number contributes to an increase in the concentration of the medium.

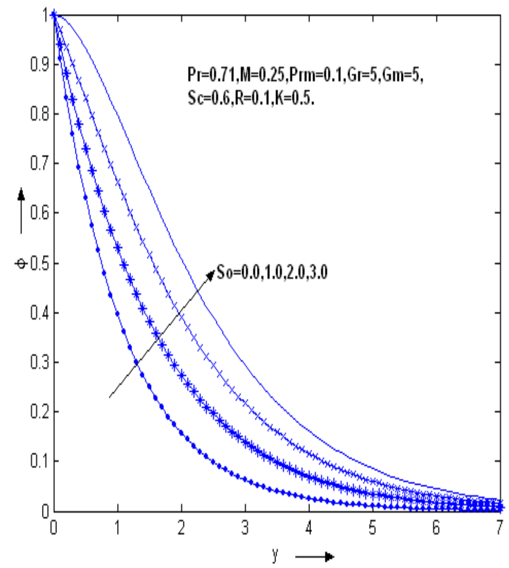

Fig. 8: Effect of S_o on the concentration.

Induced magnetic field profiles:

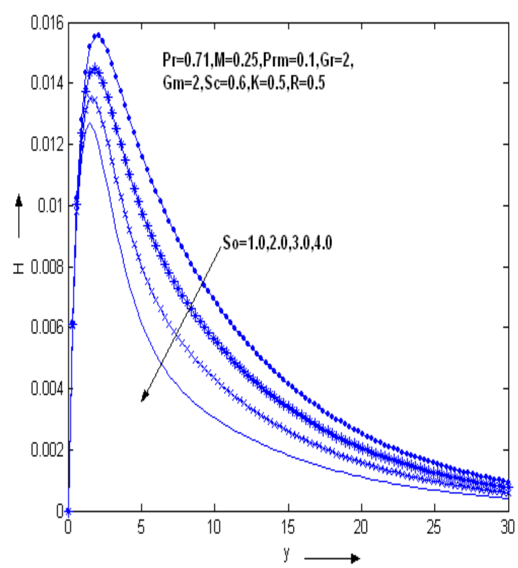

Fig. 9: Effect of S_o on the induced magnetic field

The effect of Soret number (S_o) on the induced magnetic field is illustrated in Fig. 9. It is observed that, an increase in the Soret number leads to a decrease in the induced magnetic field. Fig. 10 shows the influence of the radiation parameter (*R*) on the induced magnetic field (*H*), for Pr=0.71. With an

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increase in R from 0.0 (non-radiating) through 1.5, there is a clear increase in H. Fig. 11 shows the current density (J) for different values of magnetic Prandtl number (*Prm*) over the Hartmann number (M). It is seen that the current density increases substantially with the increase of *Prm*.

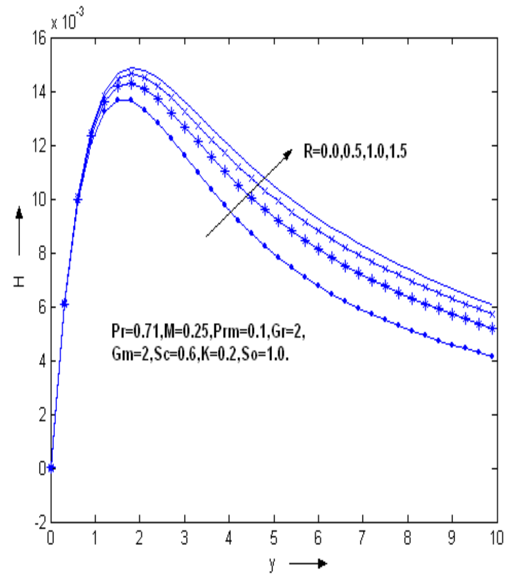

Fig. 10: Effect of R on the induced magnetic field

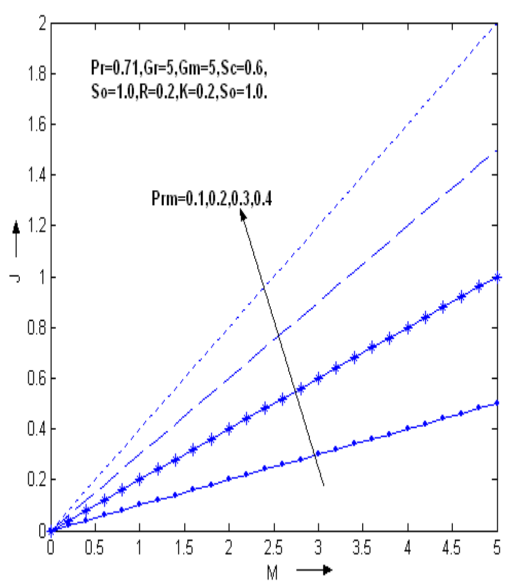

Fig. 11: Effect of *Prm* on the current density.

V. CONCLUSION

An analysis of the two dimensional steady laminar mixed convective heat and mass transfer of a viscous incompressible electrically conducting fluid over a vertical porous plate is presented under the action of a transverse applied magnetic field. The thermo-diffusion (Soret) effect is taken into consideration. The transformed system of non-linear, coupled, ordinary differential equations governing the problem were solved analytically by using perturbation technique. A comprehensive set of graphical results for the velocity, temperature, concentration and induced magnetic field is presented and their dependence on some physical parameters is discussed. The observations are:

a) An increase in S_o (Soret number) leads to a decrease in the values of induced magnetic field. However, there is an increase in both the velocity and concentration with an increase in S_o.
b) An increase in K (chemical reaction parameter) increases the induced magnetic field where as it decreases the velocity and concentration.
c) Temperature decreases with an increase in the Prandtl number (Pr) or radiation parameter (R).
d) An increase in Hartmann number (M) decreases the velocity but increases the induced magnetic field.
e) Current density rises with the magnetic Prandtl number (*Prm*).
f) The dimensionless skin-friction coefficient is found to increase with increasing values of S_o or K.

APPENDIX A

$$\xi = \frac{Pr + \sqrt{Pr^2 + PrR}}{2}$$

$$\eta = \frac{Sc + \sqrt{Sc^2 + 4KSc}}{2}$$

$$\lambda = \frac{(Pr_m + 1) + \sqrt{(1 - Pr_m)^2 + 4Pr_m M^2}}{2}$$

$$A_1 = \frac{-ScS_o\xi^2}{\xi^2 - Sc\xi - KSc}$$

$$A_2 = 1 - A_1$$

$$A_3 = \frac{MPr_m(Gr + GmA_1)}{-\xi^3 + (Pr_m + 1)\xi^2 - Pr_m(1 - M^2)\xi}$$

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$$A_4 = \frac{MPr_m GmA_2}{-\eta^3 + (Pr_m + 1)\eta^2 - Pr_m(1 - M^2)\eta}$$

$$A_5 = -(1 + A_3 + A_4)$$

$$A_6 = \frac{MPr_m A_5 \lambda}{\lambda^2 - Pr_m \lambda}$$

$$A_7 = \frac{MPr_m A_3 \xi}{\xi^2 - Pr_m \xi}$$

$$A_8 = \frac{MPr_m A_4 \eta}{\eta^2 - Pr_m \eta}$$

$$A_9 = -(A_6 + A_7 + A_8)$$

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