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Nonlinear Hydromagnetic Flow with Radiation and Heat Source over a Stretching Surface with Prescribed Heat and Mass Flux Embedded in a Porous Medium

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ABSTRACT

Hydromagnetic steady, laminar, boundary layer flow of a viscous, incompressible electrically conducting gray fluid, with radiation heat transfer and mass transfer over a stretching surface with prescribed heat and mass flux embedded in a porous medium subject to suction in the presence of a uniform transverse magnetic field is analyzed in the presence of heat source. Exact solution of the equation of momentum is obtained. Nonlinear equations for energy and species concentration are transformed to nonlinear ordinary differential equations by introducing suitable similarity variables and the resulting nonlinear ordinary differential equations are solved using confluent hypergeometric functions by the usage of suitable transformations. The effect of radiation, magnetic field, porosity, permeability, Prandtl number, Schmidt number, heat source parameter, heat flux parameter, mass flux parameter over the flow field and other physical quantities are discussed with the help of numerical values by means of graphs.

Keywords: MHD, Radiation, Heat source, Boundary layer flow, Porosity, Permeability.

NOMENCLATURE

B_0	applied magnetic field
C	species concentration of the fluid
C_∞	species concentration of the fluid away from the wall
C_f	local skin friction co-efficient
C_p	specific heat of the fluid under constant pressure
D	diffusivity coefficient
E_0, E_1	positive constants
K	thermal conductivity
K_p	permeability of the medium
Q	volumetric rate of heat generation
T	fluid temperature
T_∞	Temperature of the fluid far away from the surface
v_0	constant suction velocity
a	constant called stretching rate
m_w	rate of mass transfer
m	heat flux parameter
n	mass flux parameter
q_r	radiative heat flux
q_w	rate of heat transfer
ψ	stream function
ν	kinematic viscosity
ρ	fluid density
σ	electrical conductivity of the fluid
σ^*	stefan-Boltzmann constant
α^*	rosseland mean absorption coefficient

1. INTRODUCTION

Recently, studies on the boundary layer flow and heat transfer due to a stretching surface have become more and more important in number of engineering applications that includes both metal and polymer sheets. For instance, it occurs in the extrusion of a polymer sheet from a die or in the drawing of plastic films, which are then cooled in a cooling bath and during cooling, reduction of both thickness and width takes place. The quality of the final product depends on the rate of heat transfer at the stretching surface. Sakiadis (1961) was the first person to consider the boundary layer flow on a moving continuous solid surface. Crane (1970) extended this concept to a stretching sheet with linearly varying surface speed. Magnetohydrodynamic heat transfer over a non-isothermal stretching sheet was analyzed analytically by Chaim (1997). The effect of power law surface heat flux in the heat transfer characteristics of a continuous linear stretching surface was investigated by Chen and Char (1998).

In certain porous media applications, such as that involving heat removal from nuclear fuel debris, underground disposal of radiative waste material, storage of food stuffs, the study of heat transfer is of much importance. Comprehensive reviews of the convection through porous media have been reported by Nield and Bejan (1992). Recently, Layek *et al.* (2007) investigated the structure of the boundary layer stagnation-point flow and heat transfer over a stretching sheet in a porous medium subject to suction/blowing and in the presence of internal heat generation/absorption using similarity analysis.

A new dimension is added to the study of flow and heat transfer in a viscous fluid over a stretching surface by considering the effect of thermal radiation. Thermal radiation effect might play a significant role in controlling heat transfer process in polymer processing industry. The radiative flows of an electrically conducting fluid with high temperature in the presence of a magnetic field are encountered in electrical power generation, astrophysical flows, solar power technology, space vehicle re-entry, nuclear engineering applications and other industrial areas. In view of this, many works have been reported on flow and heat transfer over a stretching surface in the presence of radiation. Plumb *et al.* (1981) was the first to examine the effect of horizontal cross-flow and radiation on natural convection from vertical heated surface in saturated porous media. Raptis (1998) analyzed radiation and free convection flow through a porous medium using Rosseland approximation for the radiative heat flux.

A few representative fields of interest in which combined heat and mass transfer plays an important role are designing of chemical processing equipment, formation and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of fruit trees, crop damage due to freezing, and environmental pollution. In this context Soundalgekar (1979) extended his own problem of (1977) to mass transfer effects. In the context of space technology and in processes involving high temperatures, the effects of radiation are of vital importance. Acharya *et al.* (1999) have studied heat and mass transfer over an accelerating surface with heat source in the presence of suction and blowing.

Recently, Cortell (2008) studied the effects of viscous dissipation and radiation on the thermal boundary layer over a nonlinearly stretching sheet. Nonlinear hydromagnetic flow with heat and mass transfer in a porous medium over a stretching porous surface with prescribed heat and mass flux in the presence of viscous dissipation has been analyzed analytically by Anjalidevi *et al.* (2009).

The problem of magneto-hydrodynamic mixed convective flow and heat transfer of an electrically conducting, power-law fluid past a stretching surface in the presence of heat generation/absorption and thermal radiation has been investigated by Chen-Hsin Chen (2009).

Pal Mondal (2010) have analyzed hydromagnetic non - Darcy flow and heat transfer over a stretching sheet in the presence of thermal radiation and Ohmic dissipation.

But so far, no contribution is made on MHD flow with radiation and heat source over a stretching surface with prescribed heat and mass flux embedded in a porous medium and hence the present work is carried out due to its abundant applications.

2. Formulation Of The Problem

A two-dimensional, steady, nonlinear hydromagnetic laminar boundary layer flow with thermal radiation and mass transfer of an incompressible, viscous electrically conducting and radiating fluid over a stretching plate in the x - direction with a velocity $u = ax$, with prescribed heat and mass flux embedded in a porous medium in the presence of a constant transverse magnetic field and heat source is considered. According to the Cartesian coordinate system, the x - axis is chosen along the stretching sheet in the direction of motion of the flow and y - axis is chosen perpendicular to it. A uniform magnetic field B_0 is applied normal to the sheet. In addition, uniform suction is imposed at the stretching surface in the y - direction.

The fluid properties are assumed to be constant. It is assumed that the components of velocity are (u, v) and further that the sheet issues from a thin slit at the origin $(0,0)$ and the speed at a point on the surface is proportional to its distance from the origin. The magnetic Reynolds number is assumed to be small, i.e., the fluid is non-magnetic and therefore no magnetic induction is present. The fluid is considered to be a gray, absorbing, emitting and electrically conducting but non-scattering medium and the Rosseland approximation is used to describe the radiative heat flux in the energy equation. It is also assumed that the effect of viscous and Joule dissipation are negligible in the energy equation.

Under the above assumptions, the governing boundary layer equations of continuity, momentum, energy and species concentration with initial and boundary conditions are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = \mathbf{0} \tag{1}$$

$$u\frac{\partial u}{\partial x} + \mathrm{v}\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} - \frac{\nu}{K_p}u - \frac{\sigma B_0^2 u}{\rho} \tag{2}$$

$$u\frac{\partial T}{\partial x} + \mathrm{v}\frac{\partial T}{\partial y} = \frac{K}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{\mathbf{1}}{\rho C_p}\frac{\partial q_r}{\partial y} + \frac{\mathbf{Q_0}}{\rho C_p}(\mathbf{T} - \mathbf{T}_\infty) \tag{3}$$

$$u\frac{\partial C}{\partial x}+\mathrm{v}\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2} \tag{4}$$

$$\left.\begin{aligned} &u=ax,\quad -K\frac{\partial T}{\partial y}=q_\omega=E_0x^m \\ &\mathrm{v}=-\mathrm{v}_0,\quad -D\frac{\partial C}{\partial y}=m_w=E_1x^n \end{aligned}\right\}\ \text{at}\ y=0 \tag{5}$$

$$u\to 0,\quad T\to T_\infty,\quad C\to C_\infty \quad \text{as}\ y\to\infty$$

The last term on the right hand side of Eq. (3) signifies the radiation effect. We now assume Rosseland approximation (Hossian *et al.* 1999) which leads to the radiative heat flux q_r is given by

$$q_r=\frac{-16\sigma^*}{3\alpha^*}T_\infty^3\frac{\partial T}{\partial y} \tag{6}$$

A stream function ψ is defined by $u=\frac{\partial\psi}{\partial y}$ and $\mathrm{v}=-\frac{\partial\psi}{\partial x}$. The following similarity transformations are introduced to transform the nonlinear partial differential Eqs. (1) to (4) subject to Eq. (5).

$$\left.\begin{aligned} &\psi=\sqrt{a\nu}\;x f(\eta),\quad T-T_\infty=\frac{E_0}{K}\sqrt{\nu/a}\;x^m\theta(\eta) \\ &\eta=\sqrt{a/\nu}\;y,\qquad C-C_\infty=\frac{E_1}{D}\sqrt{\nu/a}\;x^n\varphi(\eta) \end{aligned}\right\} \tag{7}$$

The resulting nonlinear differential equations with boundary conditions are given by

$$f'''+ff''-f'^2-(M^2+\frac{1}{\lambda})f'=0 \tag{8}$$

$$\theta''+\beta f\theta'-\beta(mf'-S_h)\theta=0 \tag{9}$$

$$\phi''-nSc\,f'\phi+Scf\phi'=0 \tag{10}$$

$$f'(0)=1,\qquad f(0)=S,\qquad f'(\infty)=0 \tag{11}$$

$$\theta'(0)=\varphi'(0)=-1\qquad \theta(\infty)=\varphi(\infty)=0 \tag{12}$$

where the prime denotes differentiation with respect to η, $\beta=\frac{3\Pr R_d}{3R_d+4}$, $R_d=\frac{K\alpha^*}{4\sigma^*T_\infty^3}$ is the radiation parameter, $\Pr=\frac{\mu C_p}{K}$ is the Prandtl number, $M^2=\frac{\sigma B_0^2}{\rho a}$ is the Magnetic interaction parameter, $\lambda=\frac{K_p a}{\nu}$ is the permeability parameter, $S_h=\frac{Q}{a\rho C_p}$ is the heat generation parameter, $Sc=\frac{\nu}{D}$ is Schmidt number, $S=\frac{\mathrm{v}_0}{\sqrt{\nu a}}$ $(\mathrm{v}_0>0)$ is the suction parameter.

3. Solution Of The Problem

The exact solution of Eq. (8) subject to the boundary conditions Eq. (11) was obtained by Gupta and Gupta (1977) and is given by

$$f(\eta)=S+\frac{1}{\alpha}(1-e^{-\alpha\eta}) \tag{13}$$

where $\alpha=\frac{1}{2}\left(S+\sqrt{S^2+4(1+M^2+1/\lambda)}\right)$.

Hence, the velocity components are

$$u=axe^{-\alpha\eta}\ \text{and}\ \mathrm{v}=-\sqrt{a\nu}[S+\frac{1}{\alpha}(1-e^{-\alpha\eta})] \tag{14}$$

The dimensionless shear stress at the wall is given by $\tau^*=\mu\left(\partial u/\partial y\right)$ and the local skin friction co-efficient C_f is given by

$$C_f=\left(\frac{\tau^*}{\mu ax\left(a/\nu\right)}\right)=f''(0)=-\alpha \tag{15}$$

In order to solve the energy Eq. (9) and species concentration Eq. (10), new variables ξ and ς are defined respectively as follows:

$$\xi=\frac{-\Pr}{\alpha^2}e^{-\alpha\eta}$$
$$\varsigma=\frac{-Sc}{\alpha^2}e^{-\alpha\eta} \tag{16}$$

Introducing Eq. (16), Eq. (9) and Eq. (10) are obtained with the boundary conditions as

$$\xi\frac{d^2\theta}{d\xi^2}+[1-\gamma-\xi]\frac{d\theta}{d\xi}+[m+S_h\frac{\beta}{\alpha^2\xi}]\theta=0 \tag{17}$$

$$\varsigma\frac{d^2\phi}{d\varsigma^2}+[1-\varsigma-\gamma_1]\frac{d\phi}{d\varsigma}+n\phi=0 \tag{18}$$

$$\frac{d\theta}{d\xi}=\frac{-\alpha}{\beta}\ \text{at}\ \xi=\frac{-\beta}{\alpha^2},$$
$$\theta(\xi)=0\ \text{at}\ \xi=0 \tag{19}$$

$$\frac{d\varphi}{d\varsigma}=\frac{-\alpha}{\mathrm{Sc}}\ \text{at}\ \varsigma=\frac{-Sc}{\alpha^2}$$
$$\varphi(\varsigma)=0\ \text{at}\ \varsigma=0 \tag{20}$$

Using the transformation $\theta(\xi)=\xi^r\chi(\xi)$, Eq. (17) become

$$\xi\frac{d^2\chi}{d\xi^2}+[(1+A)-\xi]\frac{d\chi}{d\xi}+(m-r)\chi=0 \tag{21}$$

where

$$\gamma = \frac{\beta}{\alpha^2}(1+S\,\alpha)$$

$$\gamma_1 = \frac{Sc}{\alpha^2}(1+S\,\alpha)$$

$$A = \sqrt{\gamma^2 - 4\,S_h\left(\beta/\alpha^2\right)} \tag{22}$$

$$r = \frac{A+\gamma}{2}$$

Equations (18) and (21) are confluent hypergeometric (Kummer's) equations. The analytical solutions of Eq. (21) and Eq. (18) subject to boundary conditions Eq. (19) and Eq. (20) in terms of confluent hypergeometric function ${}_1F_1(a,c;x)$ (Abramowitz and Stegun 1965) are

$$\theta(\eta) = \frac{\left(\frac{\alpha}{\beta}\right) e^{-\alpha r \eta}\, {}_1F_1[r-m\,,A+1\,;-\left(\frac{\beta}{\alpha^2}\right)e^{-\alpha\eta}]}{\left[\left(\frac{\alpha^2 r}{\beta}\right)a_1 - \left(\frac{r-m}{A+1}\right)a_2\right]}$$

$$\varphi(\eta) = \frac{\left(\frac{\alpha}{Sc}\right) e^{-\alpha \gamma_1 \eta}\, {}_1F_1[\gamma_1-n\,,\gamma_1+1\,;\left(-\frac{Sc}{\alpha^2}\right)e^{-\alpha\eta}]}{\left[\left(\frac{\alpha^2 \gamma_1}{Sc}\right)b_1 - \left(\frac{\gamma_1-n}{\gamma_1+1}\right)b_2\right]}$$

where

$$a_1 = {}_1F_1\left(r-m\,,A+1\,;-\frac{\beta}{\alpha^2}\right)$$

$$a_2 = {}_1F_1\left(r-m+1\,,A+2\,;-\frac{\beta}{\alpha^2}\right)$$

$$b_1 = {}_1F_1\left(\gamma_1-n\,,\gamma_1+1\,;-\frac{Sc}{\alpha^2}\right)$$

$$b_2 = {}_1F_1\left(\gamma_1-n+1\,,\gamma_1+2\,;-\frac{Sc}{\alpha^2}\right)$$

4. Results And Discussions

The solutions for the velocity, temperature and concentration distributions are presented in the previous section and they are affected dominantly by the influence of various physical parameters. In general the results show that dimensionless longitudinal velocity, transverse velocity, temperature and concentration distribution are affected by suction parameter (S), Permeability parameter (λ) and Magnetic interaction parameter (M^2). Further, temperature is affected by Radiation parameter (R_d), heat source parameter (S_h), Permeability parameter (λ), heat flux parameter (m) and the Prandtl number *(Pr)* whereas concentration is affected by mass flux parameter (n) and Schmidt number (Sc).

Comparison values of wall temperature $\theta(0)$ for $S=1, M^2=5$, $S_h=0.1$ and $m=2$ with Chaim (1997) are given by Table 1.

Table 1 Comparison between Chaim (1997) and author's work

Pr	$Ec=0$ Chaim (1997) $\theta(0)$	$R_d=10^9$, $\lambda=10^9$ Author's work $\theta(0)$
0.72	0.84948	0.849479
5	0.15387	0.153867

In order to illustrate the physical effects very clearly, numerical values are obtained by fixing certain typical values for physical parameters and these results are shown graphically.

The influence of magnetic field over the dimensionless transverse and longitudinal velocity is disclosed through Figs. 1 and 3. It is seen that the effect of M^2 is to decelerate both transverse and longitudinal velocity. The physical reason for such behavior is that, the Lorentz force opposes the flow field.

The influence of suction is to decelerate the non-dimensional transverse velocity and to accelerate the non-dimensional longitudinal velocity which is elucidated through Figs. 2 and 4. It is inferred from Fig. 4 that the boundary layer thickness is reduced due to the effect of porosity.

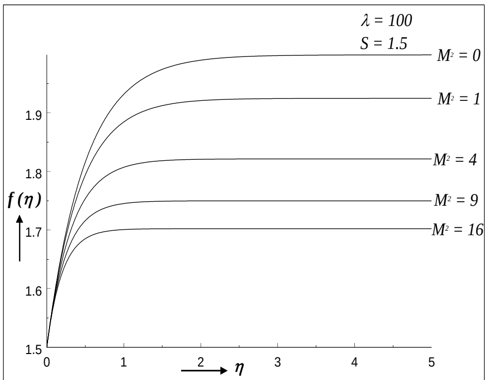

Fig.1 Effect of M² on dimensionless Transverse Velocity

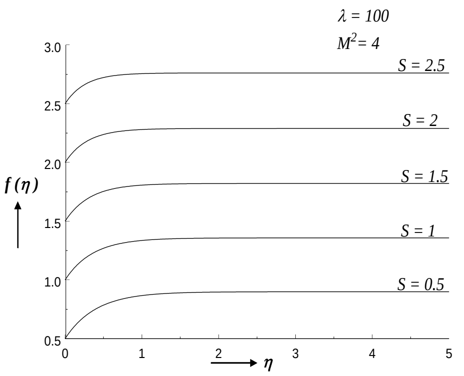

Fig.2 Dimensionless Transverse Velocity profiles for various S

[Figures 5 and 6] illustrate the effect of magnetic field and porosity over skin friction coefficient. It is observed that the effect of M^2 and S is to suppress the skin friction coefficient. It is also interesting to note that, as we move away from the wall the effect of magnetic field and suction are found to be uniform.

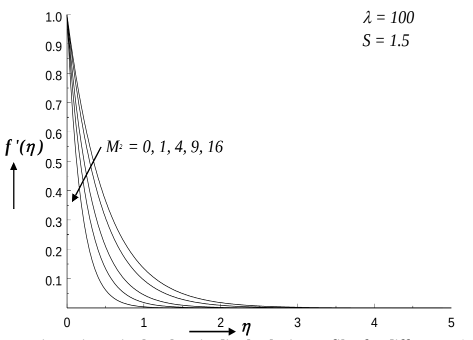

Fig.3 Dimensionless longitudinal velocity profiles for different M²

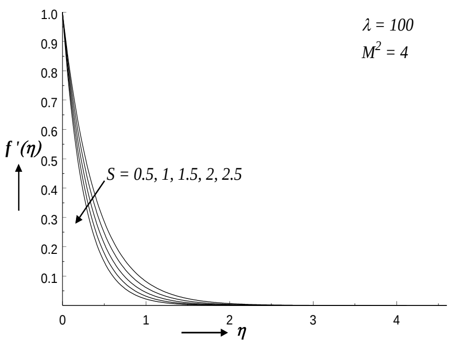

Fig.4 Dimensionless longitudinal velocity profiles for different S

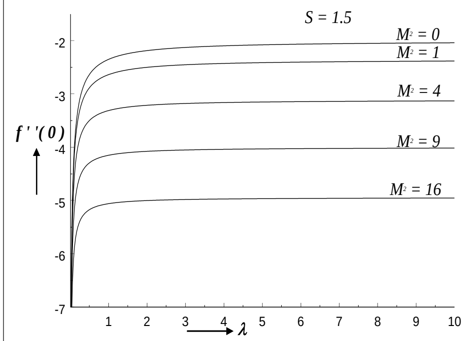

Fig.5 Skin friction coefficient for different M²

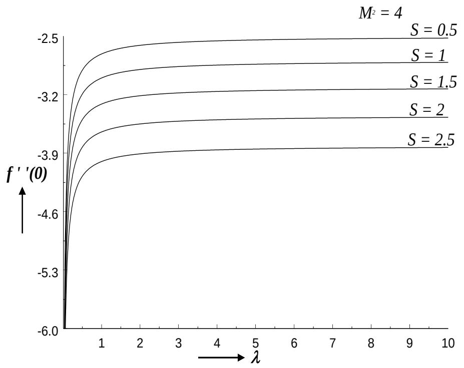

Fig.6 Skin friction coefficient for different S

Figure 7 depicts the non-dimensional temperature profiles for different values of M^2. The effect of magnetic field in the presence of suction is to increase the temperature field. Variation in dimensionless temperature due to the variation of suction parameter S is visualized through Fig. 8. As the suction parameter S increases, the temperature reduces.

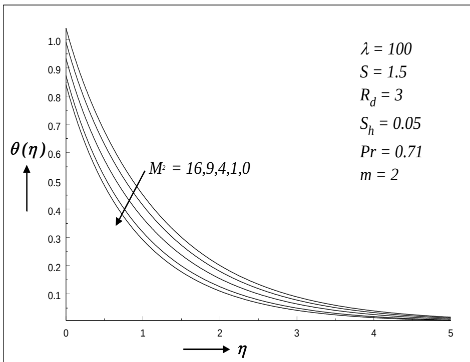

Fig.7 Influence of M² on temperature distribution

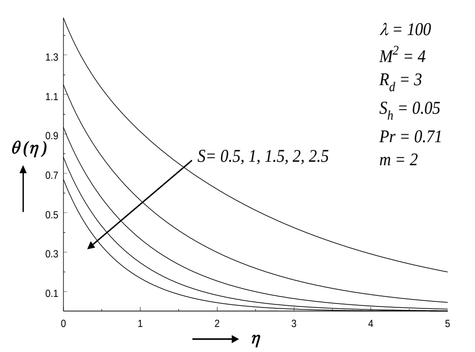

Fig.8 Effect of S over temperature distribution

The effect of radiation parameter (R_d) over temperature distribution is shown through Fig. 9. It is noted that the effect of R_d is to decrease $\theta(\eta)$.

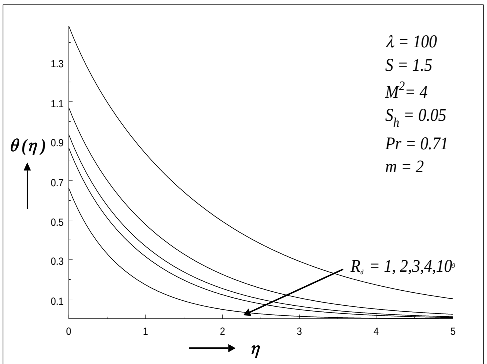

Fig.9 Temperature distribution for various R_d

The graph of non-dimensional temperature $\theta(\eta)$ for various values of the heat source parameter (S_h) are represented through Fig. 10. It is noted that the temperature field increases as S_h increases and the increased temperature are seen only near the wall.

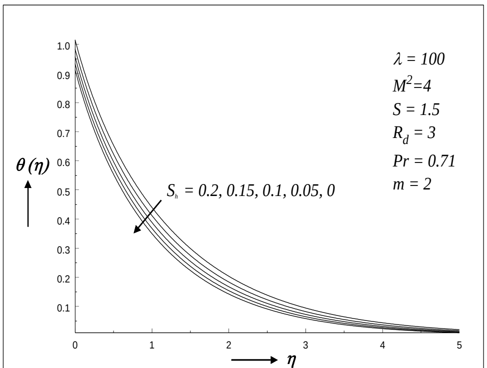

Fig.10 Temperature distribution for different S_h

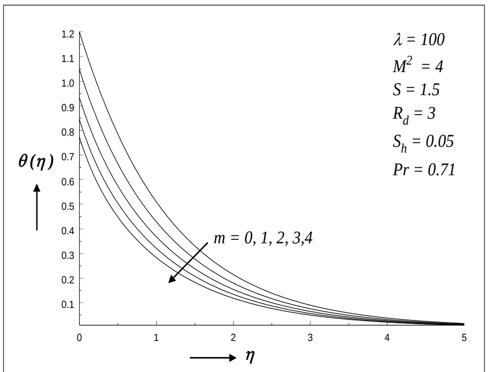

Fig.11 Influence of m on temperature distribution

Figure 11 clearly discloses the effect of heat flux parameter (m) over the temperature field when there is suction and magnetic field. It is observed that temperature reduces with increase of m.

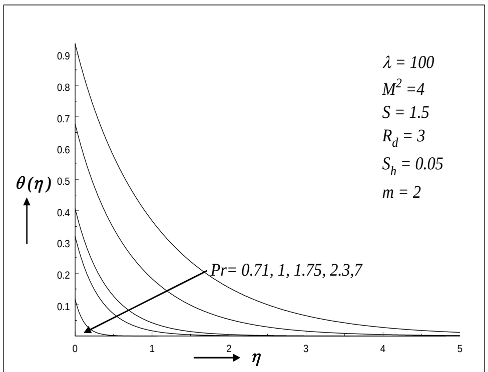

Fig.12 Pr variation over temperature distribution

The dimensionless temperature is greatly influenced by the Prandtl number (Pr)and it is portrayed in Fig. 12. It is evident that the temperature at a given point (fixed η) decreases with an increase in Pr. This is in agreement with the physical fact that the thermal boundary layer thickness decrease with increasing Pr.

Figure 13 discloses the effect of magnetic field over concentration distribution. As M^2 increases, the concentration also increases. The non-dimensional concentration distribution for various values of suction parameter is illustrated in Fig. 14. As suction parameter increases, the species concentration decreases.

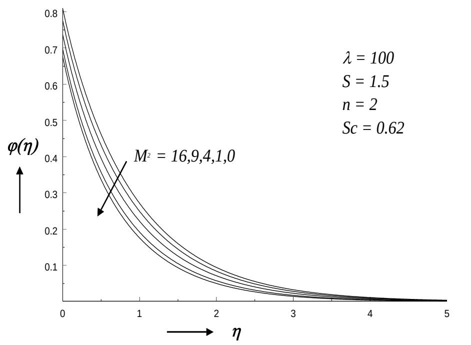

Fig.13 Influence of M^2 on concentration distribution

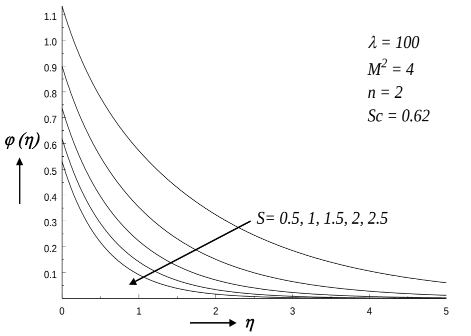

Fig.14 Concentration distribution for different S

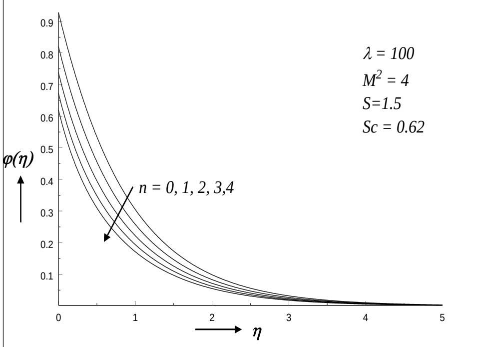

Fig.15 Effect of n on concentration distribution

The effect of mass flux parameter (n) over concentration distribution is shown through Fig. 15. It is noted that the effect of mass flux parameter is to decrease the concentration distribution. Fig.16 portrays the dimensionless concentration profiles for various values of Schmidt number. As Sc increases, the concentration decreases. Species concentration reaches higher near the wall.

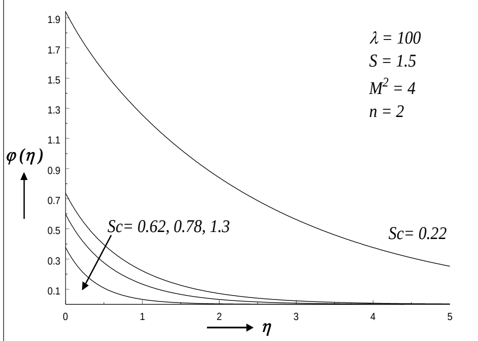

Fig.16 Influence of Sc on concentration distribution

Table 2 Wall temperature $\theta(0)$ for $\lambda = 100$

M^2	S	R_d	S_h	m	Pr	$\theta(0)$
0 1 4 9 16	1.5	3	0.05	2	0.71	0.841346 0.873394 0.934112 0.992198 1.04114
4	0.5 1.0 1.5 2.0 2.5	3	0.05	2	0.71	1.489909 1.1501 0.934112 0.782259 0.670091
4	1.5	1 2 3 4 10^9	0.05	2	0.71	1.48326 1.07033 0.934112 0.866164 0.662487
4	1.5	3	0.0 0.05 0.1 0.15 0.2	2	0.71	0.913135 0.934112 0.957609 0.984347 1.01544
4	1.5	3	0.05	0 1 2 3 4	0.71	1.20064 1.04854 0.934112 0.844841 0.773213
4	1.5	3	0.05	2	0.71 1.0 1.75 2.3 7.0	0.934112 0.678116 0.407243 0.31876 0.117817

Knowledge about the values of the wall temperature $\theta(0)$ cited in Table 2 and values of the wall concentration $\phi(0)$ as given in Table 3 are useful in many technological applications. It is noted that, for permeability parameter $\lambda = 100$, an increase in suction parameter, radiation parameter, heat flux parameter, Prandtl number results in lowering the wall temperature. The effect of magnetic field and heat source enhances the wall temperature. The concentration decreases for increasing values of suction parameter, mass flux parameter, Schmidt number whereas it increases for increasing values of Magnetic interaction parameter.

Table 3 Wall temperature $\phi(0)$ for $\lambda = 100$

M^2	S	n	Sc	$\phi(0)$
0 1 4 9 16	1.5	2	0.62	0.676774 0.697755 0.737861 0.776667 0.80968
4	0.5 1.0 1.5 2.0 2.5	2	0.62	1.1328 0.900561 0.737861 0.619963 0.531763
4	1.5	0 1 2 3 4	0.62	0.928268 0.820423 0.737861 0.672572 0.619609
4	1.5	2	0.22 0.62 0.78 1.3	1.94274 0.737861 0.598923 0.378869

5. CONCLUSION

In general, the flow field, temperature distribution and concentration distribution are affected by the physical parameters. In the absence of radiation effect in non-porous medium the present result is in good agreement [see Table 1] with that of Chaim (1997). Without radiation effect and heat source the results are compared with Anjalidevi et al. (2009) when there is no dissipation effects, we observed similar trends in velocity, temperature and Concentration. From the previous results and discussion the following conclusion is arrived.

1. The effect of magnetic field reduces the non-dimensional transverse velocity, longitudinal velocity and skin friction coefficient where as it enhances the dimensionless temperature and concentration.

2. The dimensionless longitudinal velocity, skin friction coefficient, temperature and concentration distribution decreases with increase in suction where as its effect on transverse velocity is to increase it.

3. It is interesting to note that the temperature reduces due to increase in radiation parameter, heat flux parameter and Prandtl number while it increases due to increase in heat source parameter.

An increase in mass flux parameter and Schmidt number results in lowering the concentration distribution steadily.

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