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FREE CONVECTIVE MHD FLOW OVER A STRETCHING SHEET IN PRESENCE OF RADIATION AND VISCOUS DISSIPATION WITH VARIABLE VISCOSITY AND THERMAL CONDUCTIVITY

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Abstract

A numerical analysis has been done on free convective MHD flow over a stretching vertical surface with heat and mass transfer. In this study thermal radiation and viscous dissipation are taken into consideration along with a non-uniform magnetic field. Also, the viscosity and the thermal conductivity are considered as variable. The flow governing non-linear partial differential equations are transformed into ordinary differential equations using suitable similarity transformations and Fourth order Runge-Kutta shooting method is used to solve them. The effects of different parameters involved such as viscosity parameter, thermal conductivity parameter, magnetic field parameter, radiation parameter, Prandtl number, Eckert number, Schimdt number etc. on velocity, temperature and species concentration fields are shown in graphs and interpreted. Values of skin friction coefficient, Nusselt number and Sherwood number for different values of the parameters are shown in tabulated form.

Keywords: *MHD, variable viscosity, variable thermal conductivity, free convection, viscous dissipation.*

I. INTRODUCTION

The study of the nature of fluid flow in the boundary layer near a stretching sheet has so many important roles in fluid dynamics. Heat transfer and mass transfer also occur in a number of engineering processes such as polymer processing, glass blowing, metallurgy, paper production, extrusion of plastic and rubber sheets, drying of papers and textiles etc. Magnetohydrodynamics has also vast applications in space and astrophysical plasmas. The application of magnetic field on a moving fluid gives varieties of phenomena which are also associated with many engineering processes.

Many researchers have studied various aspects of the problems associated with heat and mass transfer, stretching and shrinking sheet, magnetic field etc. Erickson *et al.* (1966) studied heat and mass transfer over a moving surface considering the effects of suction/injection. Pal (2009) studied the stagnation-point flow over a stretching surface with buoyancy force and thermal radiation. Chen (2004) analyzed heat and mass transfer in free convective flow in presence of magnetic field over a vertical surface with Ohmic heating and viscous dissipation. Mansour *et al.* (2008) studied the effects of chemical reaction and thermal stratification on MHD free convective heat and mass transfer over a vertical stretching surface in a porous medium. Rashidi *et al*. (2012) investigated a free convective flow of a visco-elastic fluid over a moving stretching surface. Turkyilmazoglu (2011, 2011) studied heat and mass transfer of viscoelastic fluid flow i presence of magnetic field over stretching and shrinking surfaces.

Ibrahim (2013) studied about the heat and mass transfer effects on steady MHD flow over an exponentially stretching surface with viscous dissipation, heat generation and radiation. Mabood, Khan and Ismail (2014) studied MHD flow over an exponential radiating stretching sheet. Ene and Marinca (2015) calculated the approximate solutions for steady boundary layer MHD viscous flow and radiative heat transfer over an exponentially porous stretching sheet. Reddy *et al.* (2015) studied the effects of viscous dissipation and heat source on unsteady MHD flow over a stretching sheet. Swain *et al*. (2015) studied a flow over exponentially stretching sheet through porous medium with source/sink. Heat transfer over a stretching sheet in porous medium with variable viscosity, viscous dissipation and heat source/sink was studied by Dessie and Kishan (2014). Rashidi *et al*. (2014) studied the free convective heat and mass transfer for MHD fluid flow over a vertical stretching sheet in presence of radiation and buoyancy effects. Chaudhary and Chaudhary (2016) analyzed heat and mass transfer of MHD flow near a stagnation point over a stretching or shrinking sheet. Sai *et al.* (2015) discussed about chemical reaction and radiation effects on MHD flow over an exponentially stretching sheet with viscous dissipation and heat generation. Hayat *et al*. (2016) studied the unsteady MHD flow over exponentially stretching sheet with slip conditions. Mistikawy (2018) studied heat transfer in MHD flow due to a linearly stretching sheet with induced magnetic field.

The main aim of this paper is to study the effect of radiation and viscous dissipation with temperature dependent viscosity and thermal conductivity on velocity, temperature and species concentration distributions on a steady MHD fluid flow over a stretching sheet. The governing equations are solved numerically by developing programming codes in MATLAB for fourth order Runge-Kutta shooting method.

II. MATHEMATICAL FORMULATION

A steady two-dimensional laminar boundary layer flow of an electrically conducting incompressible fluid over a permeable stretching sheet is considered (Fig.1). The stretching velocity is assumed as $u_w(x) = c(x)^{1/3}$ (two equal and opposite forces are applied along the x – axis with the fixed origin) where c is a constant. The flow is induced for stretching. A non-uniform magnetic field of strength $B(x) = B_0(x)^{-1/3}$ is applied in the normal direction of the flow. All the fluid properties are considered as constant except the viscosity and the thermal conductivity. The induced magnetic field is neglected in comparison with the applied magnetic field.

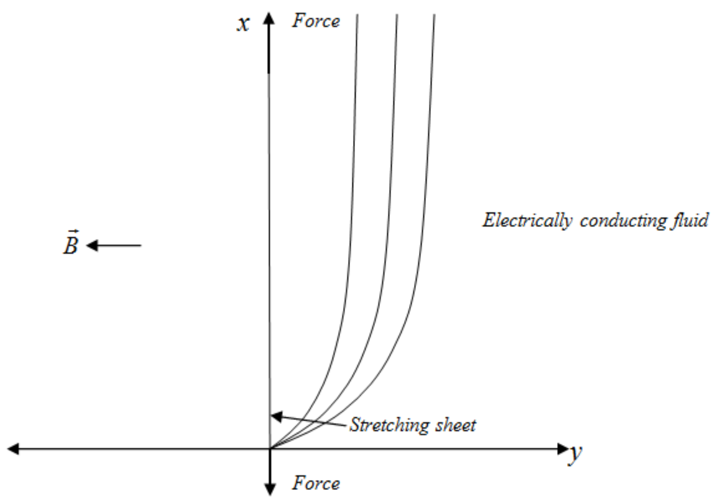

Fig.1: Flow configuration

Using the above assumptions together with the Boussinesq and the boundary layer approximations, the governing equations are as follows:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\frac{\partial^2 u}{\partial y^2} + \frac{1}{\rho}\frac{\partial \mu}{\partial y}\frac{\partial u}{\partial y} - \frac{\sigma B^2(x)u}{\rho} + g\{\beta_T(T - T_\infty) + \beta_C(T - T_\infty)\} \tag{2}$$

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$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{\rho C_p}\frac{\partial \lambda}{\partial y}\frac{\partial T}{\partial y}+\frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{16\sigma^* T_\infty^{\ 3}}{3\rho C_p \kappa_1}\frac{\partial^2 T}{\partial y^2} \tag{3}$$

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

Boundary conditions are-

$$\left.\begin{aligned} &y=0\ :\ u=u_w(x),\ v=v_w,\ -\lambda\frac{\partial T}{\partial y}=h_f(x)(T_w-T),\ C=C_w \\ &y\to\infty :\ u\to 0,\ T\to T_\infty,\ C\to C_\infty \end{aligned}\right\} \tag{5}$$

where u and v are the velocity components along and normal to the surface respectively, μ is the viscosity of the fluid, υ is the kinematic viscosity, ρ is the fluid density, σ is the electric conductivity, g is the acceleration due to gravity, β_T is the coefficient of thermal expansion, β_C is the volumetric coefficient of expansion with species concentration, T and C is the temperature and concentration of the fluid respectively, C_p is the specific heat at constant pressure, λ is the thermal conductivity, σ^* is the Stefan-Boltzman constant, κ_1 is the mean absorption coefficient and D_m is the coefficient of mass diffusivity.

In equation (3) Rosseland diffusion model has been considered. The radiation heat flux q_r is expressed for radiation heat transfer as $q_r=-\frac{4\sigma^*}{3\kappa_1}\frac{\partial T^4}{\partial y}$. T^4 may be expressed as a linear function of T using the Taylor's series and expanding it about T_∞ and neglecting the higher order terms, we get $T^4\cong 4T_\infty^{\ 3}T-3T_\infty^4$. T_∞ is the free stream temperature.

The above partial differential equations can be transformed into ordinary form using a stream function ψ and similarity variable η as given below. It is assumed that the temperature and concentration vary in the $x-$ direction, i.e., $T_w=T_\infty+ax$ and $C_w=C_\infty+bx$.

$$\eta=yc^{1/2}x^{-1/3}\upsilon_\infty^{\ -1/2} \tag{6}$$

$$\psi=x^{2/3}c^{1/2}\upsilon_\infty^{\ 1/2}f(\eta) \tag{7}$$

The viscosity and thermal conductivity of the fluid is assumed to be an inverse linear function of temperature (Lai and Kulacki (1990), Khound and Hazarika (2000)) as

$$\frac{1}{\mu}=\frac{1}{\mu_\infty}\left[1+\gamma\left(\bar{T}-\bar{T}_\infty\right)\right] \tag{8}$$

and

$$\frac{1}{\lambda}=\frac{1}{\lambda_\infty}\left[1+\xi\left(\bar{T}-\bar{T}_\infty\right)\right] \tag{9}$$

We introduce two parameters viz. viscosity parameter and thermal conductivity parameter respectively as $\theta_r = \dfrac{T_r - T_\infty}{T_w - T_\infty}$ and $\theta_k = \dfrac{T_k - T_\infty}{T_w - T_\infty}$.

Using these two parameters in (8) and (9) we have the viscosity and thermal conductivity respectively as

$$\mu = -\frac{\mu_\infty \theta_r}{\theta - \theta_r} \text{ and } \lambda = -\frac{\lambda_\infty \theta_k}{\theta - \theta_k}. \tag{10}$$

Then the Eqs. (2) to (4) becomes:

$$\frac{\theta_r}{\theta - \theta_r} f''' - \frac{2}{3} ff'' + \frac{\theta_r}{(\theta - \theta_r)^2} f''\theta' + \frac{1}{3} f'^2 + Mf' - (\lambda_T \theta + \lambda_C \varphi) = 0 \tag{11}$$

$$\left(Kr - \frac{\theta_k}{\theta - \theta_k}\right)\theta'' + \frac{\theta_k}{(\theta - \theta_k)^2}\theta'^2 + \frac{Pr}{3}(2f\theta' - 3f'\theta) - \frac{\theta_r}{\theta - \theta_r} Ec \cdot Pr\ f''^2 = 0 \tag{12}$$

$$\frac{\theta_r}{(\theta - \theta_r)}\varphi'' - \frac{\theta_r}{(\theta - \theta_r)^2}\theta'\varphi' - \frac{Sc}{3}(2f\varphi' - 3f'\varphi) = 0 \tag{13}$$

where $M = \dfrac{\sigma B_0^2}{\rho C_p}$ is the magnetic field parameter, $\lambda_T = \dfrac{g\beta_T (T_w - T_\infty) x^{1/3}}{c^2} = \dfrac{g\beta_T (T_w - T_\infty) x}{c^2 x^{2/3}} = \dfrac{Gr}{Re^2}$ is the buoyancy parameter (where $Gr = \dfrac{g\beta_T (T_w - T_\infty) x^3}{\upsilon_\infty^2}$ is the Grashof number), $Re = \dfrac{u_w x}{\upsilon_\infty}$ is the Reynolds number, $\lambda_C = \dfrac{g\beta_C (C_w - C_\infty) x^{1/3}}{c^2}$ is the concentration buoyancy parameter, $Kr = \dfrac{16\sigma^* T_\infty^3}{3\lambda_\infty \kappa_1}$ is the radiation parameter, $Pr = \dfrac{\mu C_p}{\lambda_\infty}$ is the Prandtl number, $Ec = \dfrac{c^2}{C_p (T - T_0)}$ is the Eckert number and $Sc = \dfrac{\upsilon_\infty}{D}$ is the Schmidt number.

Corresponding boundary conditions are-

$$\left.\begin{aligned} &\eta = 0 \ : f(\eta) = f_w,\ f'(\eta) = 1,\ \varphi'(\eta) = -Bi[1 - \theta(0)],\ \varphi(\eta) = 1 \\ &\eta \to \infty : f'(\eta) = 0,\ \theta(\eta) = 0,\ \varphi(\eta) = 0 \end{aligned}\right\} \tag{14}$$

where $f_w = -\dfrac{3x^{1/3} v_w}{2\upsilon^{1/2} c^{1/2}}$ is the suction/injection parameter ($f_w > 0$ is for suction and $f_w < 0$ is for injection) and $Bi = \dfrac{\upsilon^{1/2} x^{1/3} h_f}{\lambda c^{1/2}}$ is the Biot number.

The skin friction coefficient C_f, Nusselt number Nu and Sherwood number Sh are given by

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$$C_f = -\frac{2\theta_r}{\theta - \theta_r} Re^{-1/2} f''(0) \qquad (15)$$

$$Nu = \frac{\theta_k}{1-\theta_k} Re^{1/2} \theta'(0) \qquad (16)$$

$$Sh = \frac{\theta_r}{1-\theta_r} Re^{1/2} \varphi'(0) \qquad (17)$$

III. RESULTS AND DISCUSSION

The system of ordinary differential equations (11) to (13) together with the boundary conditions (14) are solved numerically by fourth order Runge-Kutta shooting method. This analysis has been done to study the effects of various parameters such as θ_r, θ_k, M, Pr, Kr, Ec, Sc etc. on velocity, temperature and species concentration profiles. The numerical results are shown graphically in Figs. (2) to (14). The values of skin friction coefficient, Nusselt number and Sherwood number for various values of the parameters are shown in tabulated form. In the following discussion, the values of the parameters are taken as $\theta_r = 5$, $\theta_k = 5$, $M = 0.5$, $\Pr = 0.71$, $Kr = 0.05$, Ec=0.3, $Sc = 0.22$, $f_w = 0.5$ and $Bi = 0.5$, unless otherwise stated.

The effects of viscosity parameter θ_r on velocity, temperature and species concentration distribution are plotted in Fig.2 to Fig.4. Fig. 2 displays that dimensionless velocity $f'(\eta)$ decreases with the increases of θ_r. This is due to the fact that with the increase of the viscosity parameter the thickness of the velocity boundary layer decreases. Physically, this is because of that a larger θ_r implies higher temperature difference between the fluid and the surface. Fig.3 shows that a very negligible change occurs in temperature profile $\theta(\eta)$ with the increase in θ_r. The species concentration $\varphi(\eta)$ decreases for increasing value of θ_r (Fig.4).

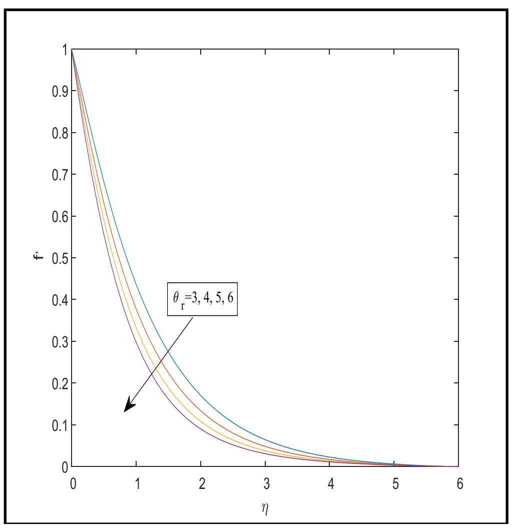

Fig.2: Effects of θ_r on velocity distribution

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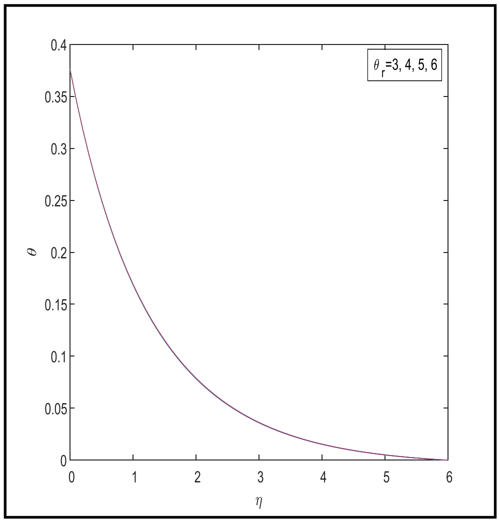

Fig.3: Effects of θ_r on temperature distribution

Fig.5 depicts the distribution of velocity with the variation of the thermal conductivity parameter θ_k. Velocity increases with the increasing value of θ_k. Temperature decreases with the increasing value of θ_k which implies decreasing of viscosity and so velocity increases. With the increase of θ_k temperature increases (Fig.6).

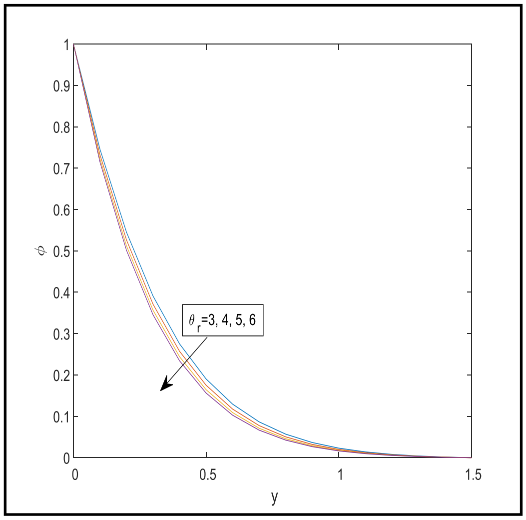

Fig.4: Effects of θ_r on species concentration

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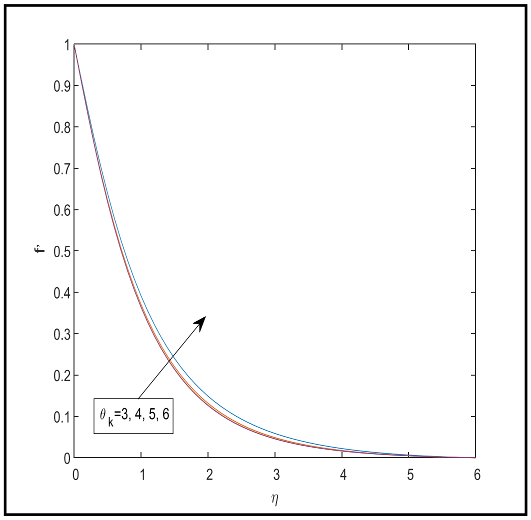

Fig.5: Effects of θ_k on velocity distribution

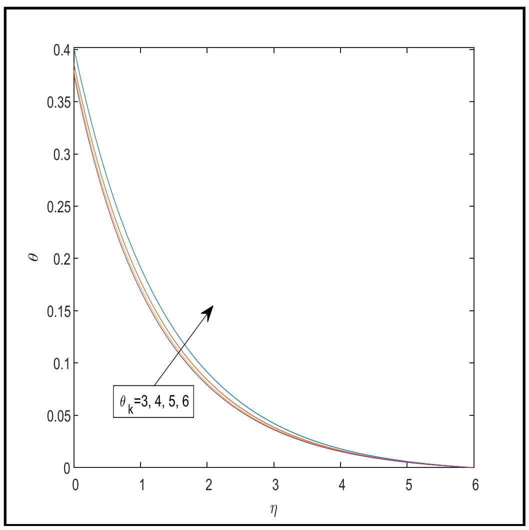

Fig.6: Effects of θ_k on temperature distribution

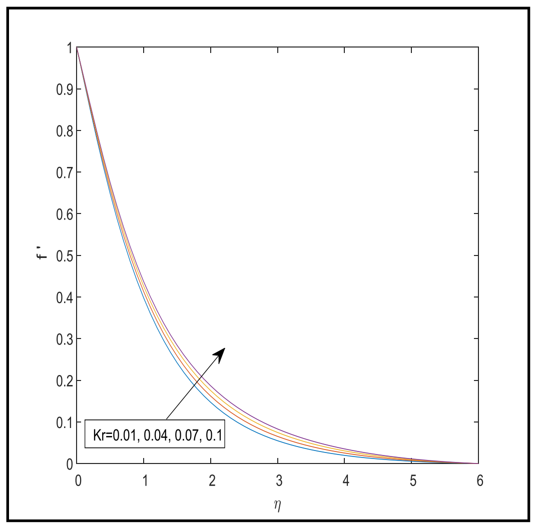

Fig.7: Effects of Kr on velocity distribution

Increasing the value of radiation parameter Kr enhances the velocity (Fig.7). In Fig.8, it is noticed that with the increase of Kr temperature increases. This is due to the fact that the thermal boundary layer thickness increases with the increase of Kr and hence temperature.

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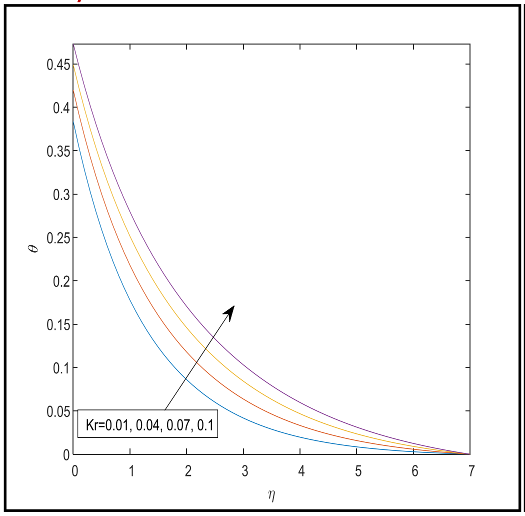

Fig.8: Effects of Kr on temperature distribution

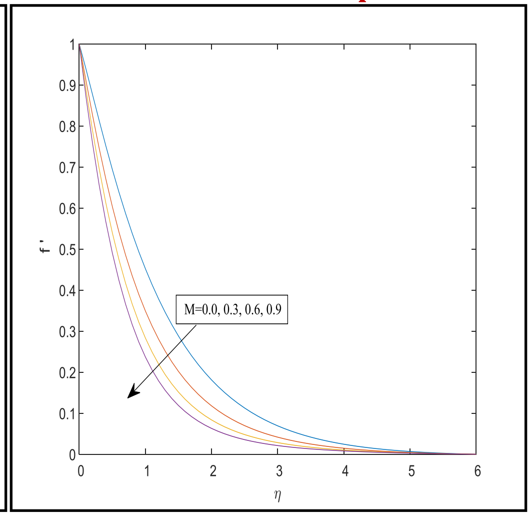

Fig.9: Effects of M on velocity distribution

In Fig.9, it is seen that with the increasing value of the Hartmann number M , velocity decreases. The presence of magnetic field in the normal direction of the flow in an electrically conducting fluid produces Lorentz force which opposes the flow. To overcome this opposing force, some extra work should be done which is transformed to heat energy. Hence temperature increases (Fig.10). With the increase of M species concentration also increases (Fig.11).

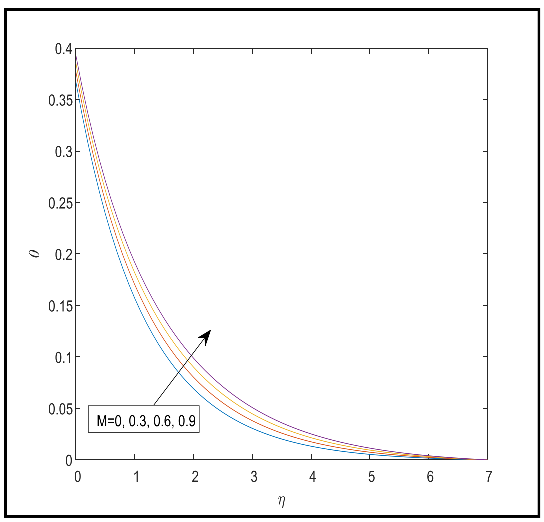

Fig.10: Effects of M on temperature distribution

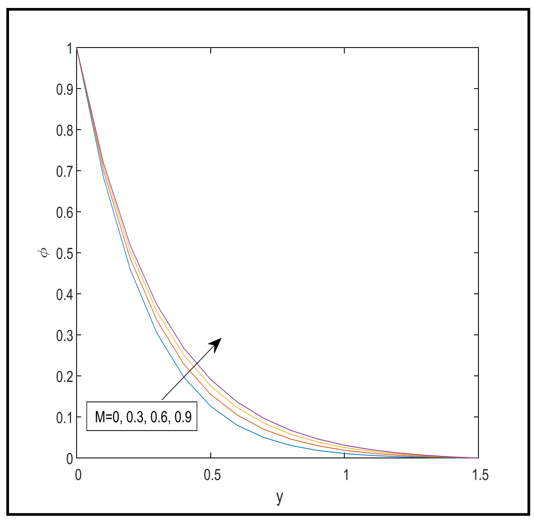

Fig.11: Effects of M on species concentration distribution

Velocity decreases with the increasing value of Prandtl number Pr (Fig.12). This is due to the fact that with the increase of Pr , viscosity increases, so velocity decreases. In Fig.13 it is noticed that with the increasing value of Pr temperature of the fluid decreases. For higher Prandtl number the fluid has a relatively high thermal conductivity which decreases the temperature.

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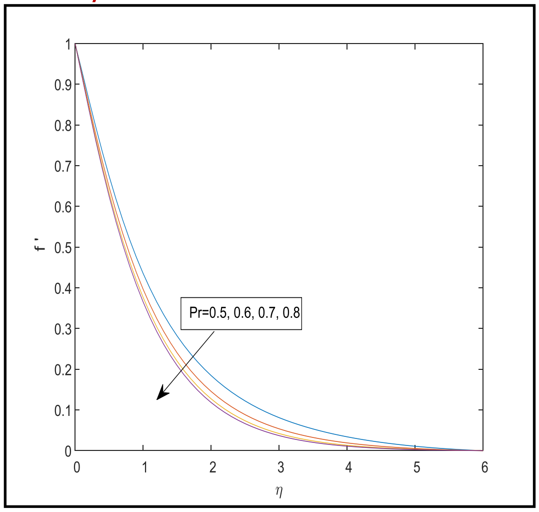

Fig.12: Effects of Pr on velocity distribution

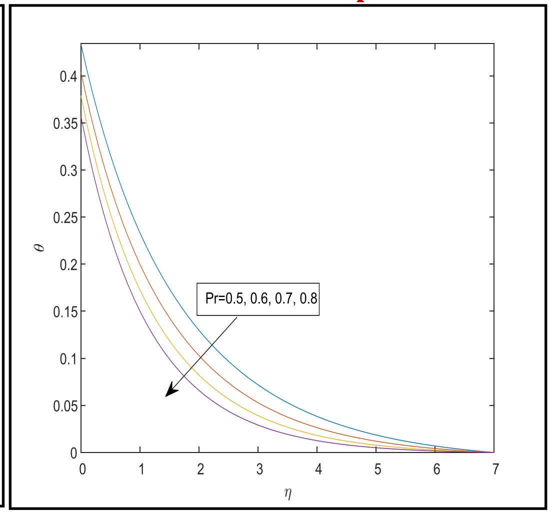

Fig.13: Effects of Pr on temperature distribution

With the increasing value of *Ec*, the thickness of both velocity boundary layer and thermal boundary layer increase. Hence, both the velocity and the temperature increase with increasing *Ec* (Fig.14 and Fig.15).

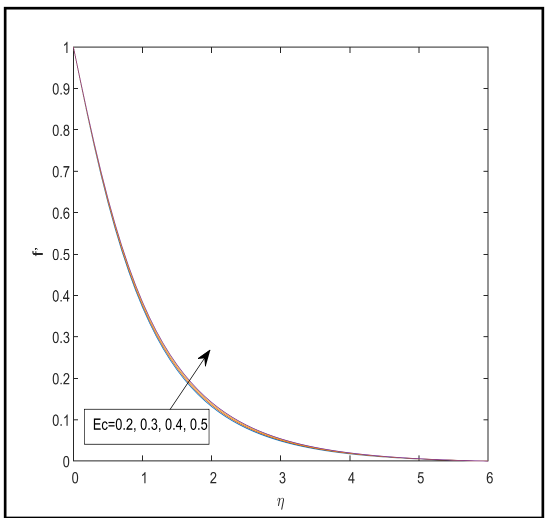

Fig.14: Effects of Ec on velocity distribution

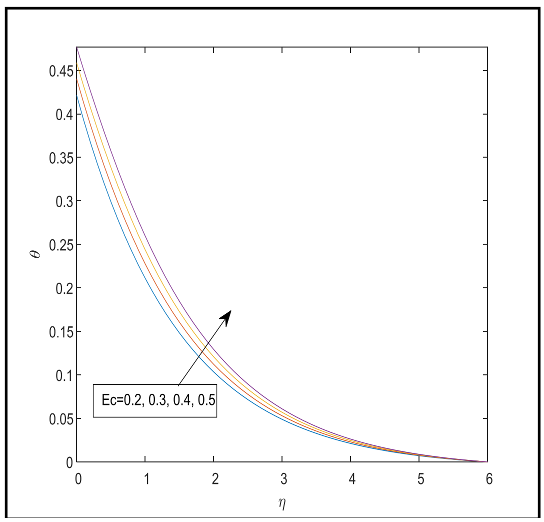

Fig.15: Effects of Ec on temperature distribution

Fig.16 shows the variation of velocity profile with the variation of Schmidt number *Sc*. As *Sc* is increased the concentration boundary layer becomes thinner than the viscous boundary layer, as a result of which velocity reduces. With thinner concentration boundary layer the concentration gradients are enhanced causing a decrease in concentration of species in the boundary layer (Fig. 17).

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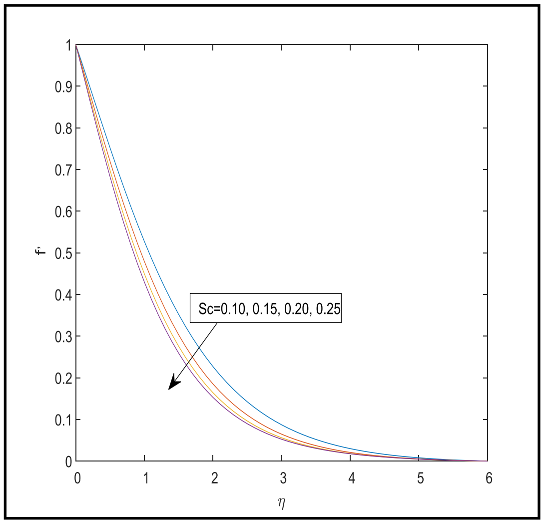

Fig.16: Effects of Sc on velocity distribution

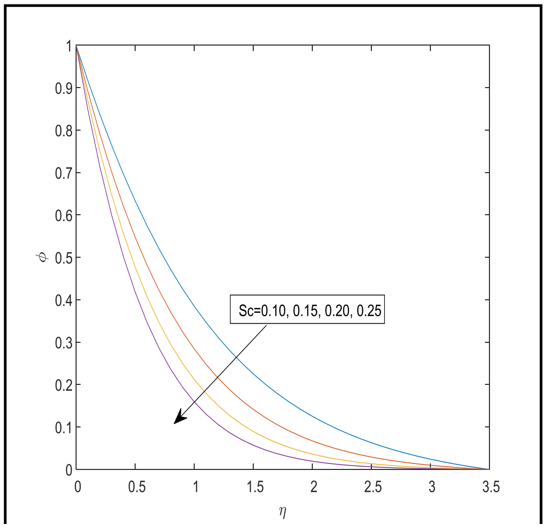

Fig.17: Effects of Sc on species concentration distribution

Table 1. Values of C_f , Nu and Sh for different values of θ_r , θ_k , M, Kr and Ec

θ_r	θ_k	M	Kr	Ec	C_f	Nu	Sh
3	5	0.5	0.05	0.3	-0.036564	1.682735	0.004371
4					-0.036695	1.661868	0.005749
5					-0.036787	1.652238	0.009203
6					-0.036848	1.646702	0.025162
5	3	0.5	0.05	0.3	-0.037276	2.986268	0.004549
	4				-0.037020	2.080723	0.004442
	5				-0.036910	1.789655	0.004396
	6				-0.036848	1.646702	0.004371

5	5	0.1 0.4 0.7 1.0	0.05	0.3	-0.030377 -0.034056 -0.038359 -0.043415	1.733759 1.681187 1.629774 1.581060	0.006463 0.005159 0.004003 0.003001
5	5	0.5	0.01 0.04 0.07 0.10	0.3	-0.036917 -0.036876 -0.036834 -0.036790	1.688881 1.663862 1.637974 1.611174	0.004352 0.004366 0.004380 0.004394
5	5	0.5	0.05	0.2 0.3 0.4 0.5	-0.037564 -0.037208 -0.036848 -0.036484	1.981497 1.813657 1.646702 1.480604	0.004206 0.004371 0.004542 0.004719

IV. CONCLUSION

From the above analysis following conclusions may be derived:

(i) With the increase of viscosity parameter velocity and species concentration decreases while a negligible change is noticed in case of temperature.
(ii) Velocity and temperature increases with the increase of thermal conductivity parameter.
(iii) Temperature and species concentration increases while velocity decreases with the increase of magnetic field parameter.
(iv) Both velocity and temperature decreases with the increase of Prandtl number.
(v) With the increase of the radiation parameter and Eckert number velocity and temperature increases.
(vi) Velocity and species concentration decreases due to the increase of the Schmidt number.
(vii) Skin friction coefficient increases for increasing viscosity parameter and magnetic field parameter but decreases for increasing thermal conductivity parameter, radiation parameter and Eckert number.
(viii) With the increasing value of viscosity parameter, thermal conductivity parameter, magnetic field parameter, radiation parameter and Eckert number, Nusselt number decreases.
(ix) Increasing of viscosity parameter, radiation parameter and Eckert number increases the Sherwood number whereas thermal conductivity parameter and magnetic field parameter decreases it.

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