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STUDY THE THERMAL-DIFFUSION AND DIFFUSION-THERMO EFFECT ON MAGNETOHYDRODYNAMIC (MHD) BOUNDARY LAYER FLOW OF HEAT & MASS TRANSFER OVER A STRETCHING SHEET IN A ROTATING SYSTEM

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Abstract*-The present work deals with the problem of steady two-dimensional magneto hydrodynamic (MHD) free convection, heat and mass transfer flow of an incompressible electrically conducting fluid over a stretching sheet in a rotating system under the influence of an applied uniform magnetic field with Hall current. The governing fundamental boundary layer equations are transformed to a system of non-linear ordinary differential equations by applying similarity transformations for momentum, thermal energy and concentration equations and which are then solved numerically by the shooting method along with Runge-Kutta fourth-fifth order integration scheme. The numerical results concerned with the primary velocity, secondary velocity, temperature and concentration profiles effects of various parameters on the flow fields are investigated and presented graphically for air with a Prandtl number of 0.71 and also for various values of considering others parameter. The results presented graphically illustrate that primary velocity field decrease due to increase of Dufour number, heat generation parameter and magnetic parameter but increase for the values of Hall parameter and Soret number. Again the secondary velocity is increased for the increasing values of magnetic and Hall parameter but there is no effect for remaining parameters. Temperature field increases in the presence of reaction parameter but reverse effect arises for the increasing values of Dufour number, Soret number, heat generation parameter and Prandtl number whereas there is no effect for magnetic parameter. Again, the concentration is increased for the increasing values of Dufour & Soret number and magnetic parameter but reverse results arises for the remaining parameters. Finally, the numerical values of the skin friction, wall temperature gradient and concentration gradient are also shown in a tabular form.*

Keywords: MHD, Hall current, Rotation effect, Stretching sheet

1. INTRODUCTION

MHD laminar boundary layer flow problems has become of its important applications in industrial manufacturing processes like plasma studies, petroleum industries, Magneto-hydrodynamics power generator, cooling of Nuclear reactors, boundary layer control in aerodynamics. Also , MHD laminar boundary layer behavior over a stretching surface is a significant type of flow having considerable practical applications in paper production, hot rolling, wire drawing, drawing of plastic films, metal and polymer extrusion, metal spinning and polymer processing. Magneto-hydrodynamics of rotating fluids is highly important due to its varied and wide applications in the areas of Geophysics, Astrophysics and fluid engineering. In this regard, various authors has been done a lot of works related to this field such as Venkatesulu and Rao [1] analyzed the effect of Hall Currents and Thermo-diffusion on convective heat and mass transfer flow of a viscous, chemically reacting rotating fluid through a porous medium past a vertical porous plate, Mathew *et al*. [2] studied Hall effects on heat and mass transfer through a porous medium in a rotating channel with radiation, Kumar and Singh [3] have been studied mathematical modeling of Soret and hall effects on oscillatory MHD free convective flow of radiating fluid in a rotating vertical porous channel filled with porous medium, Ruzicka [4] have also studied heat and mass transfer past a vertical flat porous plate through a porous medium with variable thermal conductivity, Singh *et al.* [5] considered the effect of Hall current on MHD slip flow and heat transfer through a porous medium over an accelerated plate in a rotating system, Islam & Mahmud Alam [6] studied Dufour and Soret effects on steady MHD free convection and mass transfer fluid flow through a porous medium in a rotating system, Alsaedi *et al.* [7] have been studied the effect of MHD on peristaltic transport of Prandtl fluid in a symmetric channel under the assumptions of long wave length, further Hayat *et al.* [8] studied the slip effects on peristaltic transport in an inclined channel with mass transfer and chemical reaction. In view of the importance, the present work is focused on steady MHD free convection, heat and mass transfer flow of an incompressible electrically conducting fluid over a stretching sheet in a rotating system under the influence of an applied uniform magnetic field.

2. FORMULATION OF THE PROBLEM AND SIMILARITY ANALYSIS

Let us consider steady two dimensional MHD free convection heat and mass transfer in an incompressible electrically conducting fluid flow over a hot stretching sheet in a rotating system under the influence of an applied uniform magnetic field. The flow is subjected to a transverse magnetic field of strength B_0 which is assumed to be applied in the positive y –direction normal to the surface. The pressure gradient, body force, viscous dissipation and joule heating effects are neglected compared with effects of with internal heat source/sink. Under the above assumptions and usual boundary layer approximation, the dimensional governing equations of continuity, momentum, concentration and energy under the influence of externally imposed magnetic field with the presence of Hall current are:

Equation of continuity: $\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$ (1)

Momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+g\beta\left(T-T_\infty\right)+g\beta^*\left(C-C_\infty\right)-\frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(u+mW\right)+2\Omega\, w \quad (2)$$

$$u\frac{\partial W}{\partial x}+v\frac{\partial W}{\partial y}=\nu\frac{\partial^2 W}{\partial y^2}+\frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(mu\text{-}W\right)\text{-}2\Omega\, u \quad (3)$$

Energy Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{Q_0}{\rho c_p}\left(T-T_\infty\right)+\frac{D_m K_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2} \quad (4)$$

Concentration Equation:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}-k_0\left(C-C_\infty\right)+\frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \quad (5)$$

Boundary conditions are:

$$u=ax,\ v=0, W=0, T=T_w, C=C_w \quad at \quad y=0,$$
$$and \quad u=0, v=0, T=T_\infty, C=C_\infty \quad as \quad y\to\infty$$

where u , v and W are the velocity components along X ,Yy and Z directions, T , T_w and T_∞ are the fluid temperature, the stretching sheet temperature and the free stream temperature respectively while C , C_w and C_∞ are the corresponding concentrations, C_p specific heat with constant pressure, C_s is the concentration susceptibility, μ is the coefficient of viscosity, ν is the kinematic viscosity , σ is the electrical conductivity, ρ is the fluid density, β is the thermal expansion coefficient, β * is the concentration expansion coefficient, m is the Hall parameter, Q_0 is the heat generation, Ω is the rotation, B_0 is the magnetic field intensity, a is the constant, g is the acceleration due to gravity, D_m is the coefficient of mass diffusivity, K_T is the thermal diffusion ratio, T_m is the mean fluid temperature, respectively.

To convert the governing equations into a set of similarity equations, we introduce the following similarity transformation:

$$W=ag_0(\eta),\ \eta=y\sqrt{\frac{a}{2\nu x}},\ \psi=\sqrt{2\nu xa}\, f(\eta),$$
$$\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\varphi(\eta)=\frac{C-C_\infty}{C_w-C_\infty},u=\frac{\partial\psi}{\partial y},v=-\frac{\partial\psi}{\partial x}$$

From the above transformations, the non-dimensional, nonlinear and coupled ordinary differential equations are obtained

$$f'''+ff''+Gr\theta+Gm\varphi-\frac{M}{1+m^2}f'+\left(R-\frac{Mm}{1+m^2}\right)g_0=0 \quad (6)$$

$$g_0''+fg_0'-\frac{M}{1+m^2}g_0+\left(R+\frac{Mm}{1+m^2}\right)f'=0 \quad (7)$$

$$\theta''+\Pr f\theta'-Q\theta+D_f\varphi''=0 \quad (8)$$

$$\varphi''+Scf\varphi'+S_0\theta''-Sc\lambda\varphi=0 \quad (9)$$

The transform boundary conditions:

$$f=0,\ f'=1,\ g_0=0,\ \theta=\varphi=1\ at\ \eta=0$$
$$and\ \ f'=g_0=\theta=\varphi\to 0\ \ as\ \eta\to\infty$$

Where f' , g_0 , θ and φ are the dimensionless primary velocity, secondary velocity, temperature and concentration respectively, η is the similarity variable, η_∞ is the value of

η at which boundary conditions is achieved, the prime denotes differentiation with respect to η . Also

$$M = \frac{2x\sigma B_0^2}{\rho a}, Gr = \frac{2g\,\beta(T_w - T_\infty)x}{a^2}, Gm = \frac{2g\beta^*(C_w - C_\infty)x}{a^2},$$
$$\Pr = \frac{\mu c_p}{k}, R = \frac{4\Omega x}{a}, Sc = \frac{\nu}{D_m}, \lambda = \frac{2k_0 x}{a}, S_0 = \frac{K_T(T_w - T_\infty)}{T_m(C_w - C_\infty)},$$
$$Q = \frac{2Q_0 \nu x}{U_0 k}\, and\ D_f = \frac{D_m K_T (C_w - C_\infty)}{c_s k (T_w - T_\infty)}$$

are the magnetic parameter, Grashof number, modified Grashof number, Prandtl number, Rotational parameter, Schmidt number, reaction parameter, Soret number, heat generation parameter and Dufour number respectively.

3. METHODOLOGY

The governing fundamental equations of momentum, thermal and concentration in Newtonian fluids are essentially nonlinear coupled ordinary or partial differential equations. Generally, the analytical solution of these nonlinear differential equations is almost difficult, so a numerical approach must be made. However no single numerical method is applicable to every nonlinear differential equation. The various types of methods that are available to solve these nonlinear differential equations are finite difference method, shooting methods, quasi-linearization, local similarity and non-similarity methods, finite element methods etc. Among these, the shooting method is an efficient and popular numerical scheme for the ordinary differential equations. This method has several desirable features that make it appropriate for the solution of all parabolic differential equations. Hence, the system of reduced nonlinear ordinary differential equations together with the boundary conditions have been solved numerically using fourth-order Runge-Kutta scheme with a shooting technique. Thus adopting this type of numerical technique described above, a computer program will be setup for the solution of the basic nonlinear differential equations of our problem where the integration technique will be adopted as the fourth order Runge-Kutta method along with shooting iterations technique. First of all, higher order non–linear differential equations are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem applying the shooting technique. Once the problem is reduced to initial value problem, then it is solved using Runge -Kutta fourth order technique. The effects of the flow parameters on the velocity, temperature and species concentration are computed, discussed and have been graphically represented in figures and also the values of skin friction, rate of temperature and rate of concentration shown in Table 1 for various values of different parameters. In this regard, defining new variables by the equations

$$y_1 = f, y_2 = f', y_3 = f'', y_4 = g_0, y_5 = g_0',$$
$$y_6 = \theta, y_7 = \theta', y_8 = \varphi, y_9 = \varphi'$$

The higher order differential Eq. (6) – Eq. (9) may be transformed to nine equivalent first order differential equations and boundary conditions respectively are given below:

$$dy_1 = y_2, dy_2 = y_3, dy_3 = -y_1 y_3 - Ry_4 - Gr\, y_6 - Gm\, y_8 + \frac{M}{1+m^2} y_2 + \frac{Mm}{1+m^2} y_4, dy_4 = y_5, dy_5 = -y_1 y_5 + \frac{M}{1+m^2} y_4 + \frac{Mm}{1+m^2} y_2 - Ry_2, dy_6 = y_7, dy_7 = \frac{-\Pr y_1 y_7}{1 - D_f S_o} + \frac{Qy_6}{1 - D_f S_o} + \frac{D_f Scy_1 y_9}{1 - D_f S_o} - \frac{D_f Sc\lambda c_8}{1 - D_f S_o}, dy_8 = y_9,$$
$$dy_9 = -\frac{Scy_1 y_9}{1 - D_f S_o} - \frac{QS_o y_6}{1 - D_f S_o} + \frac{\Pr S_o y_1 y_7}{1 - D_f S_o} + \frac{Sc\lambda c_8}{1 - D_f S_o}$$

The boundary conditions are as

$$y_1 = 0, y_2 = 1, y_4 = 0, y_6 = y_8 = 1 \quad at\ \eta = 0,$$
$$and\, y_2 = y_4 = y_6 = y_8 \to 0 \quad as \quad \eta \to \infty$$

4. RESULTS AND DISCUSSION

The system of ordinary differential Eq. (6) - Eq. (9) subject to the boundary conditions is solved numerically by Runge- Kutta fourth-fifth order method along with shooting technique. First of all, higher order non-linear differential Eq. (6) - Eq. (9) are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem by applying the shooting technique. Numerical calculation for distribution of the primary velocity, secondary velocity, temperature and concentration profiles across the boundary layer are displayed in Fig. l- Fig.17 for different values of M, m, R, λ, D_f, S_0, Pr and Sc and for fixed values of Gr and Gm. The values of Prandtl number Pr are chosen for 0.71, 1.00 and 7.00 which are correspond to air, salt water and fresh water. The values of Schmidt number are taken 0.22 which correspond to hydrogen. Throughout the calculations, the bouncy parameter Gr = -2.0 and Gm = -2.0 are taken which correspond to a hot plate and other parameters are chosen arbitrary. The effects of various parameters on primary velocity profile are shown in Fig. 1- Fig. 4. In Fig. 1 it is observed that the velocity decreases with an increase in the magnetic parameter M. The magnetic parameter is found to retard the velocity at all points of the flow field. It is because that the application of transverse magnetic field will result in a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. Again, negligible decreasing effect for Dufour number on primary velocity profile whereas reverse result arises in case of Soret number which are shown in Fig.2 and Fig.3 because Dufour number increased means bouncy force is decreased as a result velocity is decreased and Soret number increased means bouncy force is increased as a result velocity is increased. From Fig.4 it is observed that there is no effect of rotational parameter on primary velocity profile. Fig.5- Fig.8 display the effect of various entering parameters on secondary velocity profile. From these figures it is seen that the secondary velocity starts from minimum value at the plate and increases until it attains the maximum value within the boundary layer and then starts decreasing until it reaches the free stream area satisfying the far field boundary condition. The noticeable increasing effect of magnetic and Hall parameter on secondary velocity profile are observed which are shown in Fig.5 and Fig.6. Again, it is interesting to note that the others mentioned parameters has no effect on secondary velocity profile which are shown in Fig.7 and Fig.8. The effect of various parameters on temperature profile are shown in Fig.9-Fig.12. From these figures we see that, the temperature profile is starting at the highest point of the plate surface and asymptotically decreases to zero far away from the plate satisfying the boundary condition which assist the accuracy of the numerical results obtained. It is observed that an increase in the Prandtl number, diffusion thermo (Dufour) parameter and thermal-diffusion (Soret) parameter decreases the temperature distribution in the thermal boundary layer leading to a decrease in the thickness of the thermal boundary layer as depicted in Fig. 10 - Fig.12. Since, Prandtl number is a property of fluids; a fluid with smaller values of Prandtl number, in general, has high thermal conductivity. Due to this property heat is able to diffuse away from the heated plate more rapidly than for higher values of Pr. Hence in the case of bigger Prandtl numbers as the boundary layer is thinner and the rate of heat transfer is increased whereas Dufour and Soret number increased means thermal diffusion ration is increased as a result the temperature is decreased. Again, there is no effect for magnetic parameter on temperature profile which are shown in Fig.9. Again, Fig. 13 - Fig. 17 shows the concentration profiles obtained by the numerical simulation for various values of entering non-dimensional parameters. From these figures the increasing effect are observed for the increasing values of magnetic parameter, Dufour & Soret number which are depicted in Fig.13, Fig. 15 and Fig. 16. Since the velocity is decreased for increasing values of magnetic parameter and Dufour number which leads to a decrease in mass diffusion as a result the concentration is increased. In Fig. 17 the effect of Sc is found to decrease the concentration because increasing in Sc decreases molecular diffusivity which result a decrease of the boundary layer. Hence the concentration of the species in lower for large values of Sc. Similar results arises for the effect of reaction parameter which are shown in Fig.14. Again, from Table 1 it is seen that the skin friction is decreased for magnetic parameter and Dufour number but increased for Soret number whereas there is no effect for rotational parameter. Also, the rate of temperature is increased for Dufour and Soret number as a result the thermal boundary layer is decreased. Again, the rate of temperature is increased for Dufour & Soret number but there is no effect for magnetic parameter. Again, the rate of concentration is decreased for magnetic parameter, Dufour and Soret number and increased for reaction parameter.

Table 1: Values of skin friction $f''(0)$, rate of heat transfer -$\theta'(0)$ and rate of concentration $-\varphi'(0)$ for different values of M, R, D_f, λ and S_0 with Pr = 0.71, Sc = 0.22.

M	R	D_f	λ	S_0	$f''(0)$	$\theta'(0)$	$-\varphi'(0)$
0.5	0.2	0.5	1.0	0.5	-3.02759	1.9928	0.1788
1.0	0.2	0.5	1.0	0.5	-3.09080	1.9928	0.1975
1.5	0.2	0.5	1.0	0.5	-3.15210	1.9928	0.2135
0.5	**0.6**	0.5	1.0	0.5	-3.02759	-	-
0.5	**1.0**	0.5	1.0	0.5	-3.02759	-	-
0.5	0.2	**0.7**	1.0	0.5	-3.03388	2.1159	0.0879
0.5	0.2	**0.9**	1.0	0.5	-3.04247	2.2415	0.1132
0.5	0.2	0.5	**1.2**	0.5	-	-	0.0514
0.5	0.2	0.5	**1.4**	0.5	-	-	0.0253
0.5	0.2	0.5	1.0	**0.7**	-3.01353	2.1490	0.3124
0.5	0.2	0.5	1.0	**0.9**	-2.9932	2.2935	0.4231

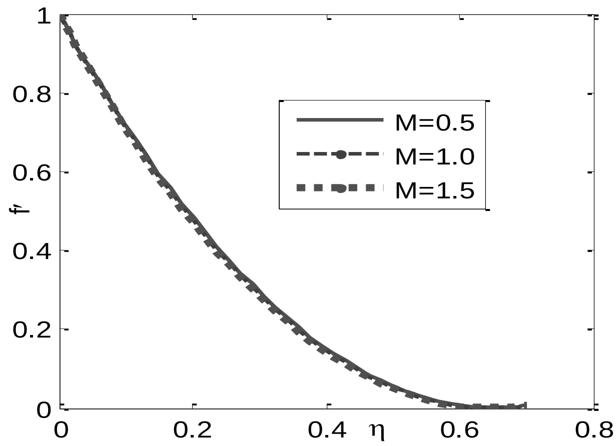

Fig.1: Primary velocity profile for various values of M

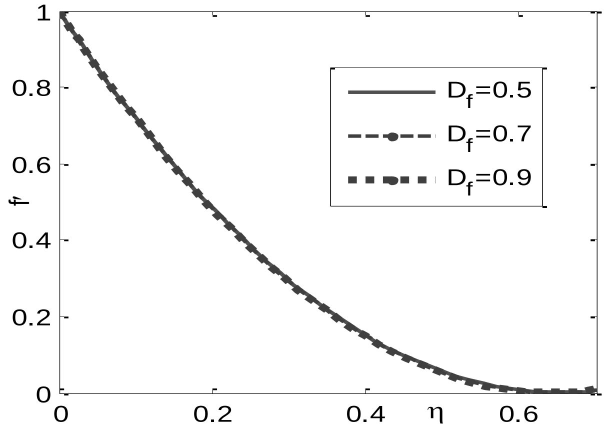

Fig.2: Primary velocity profile for various values of D_f

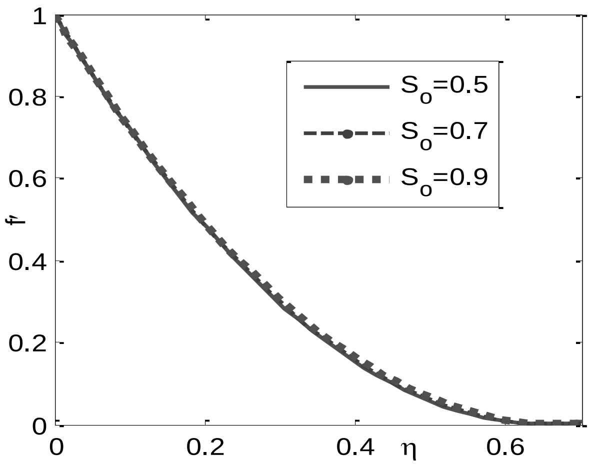

Fig.3: Primary velocity profile for various values of S_0

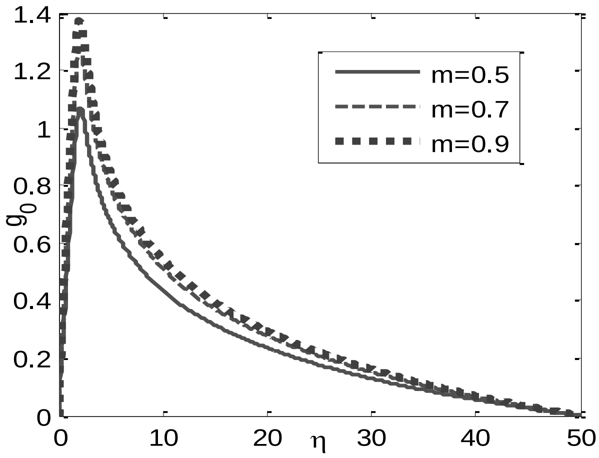

Fig.6: Secondary velocity profile for various values of m

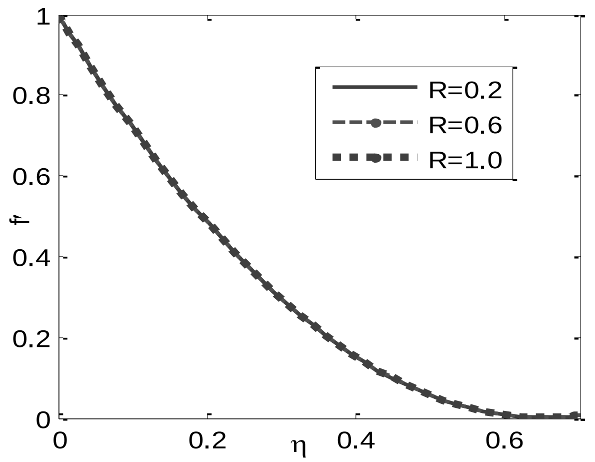

Fig.4: Primary velocity profile for various values of R

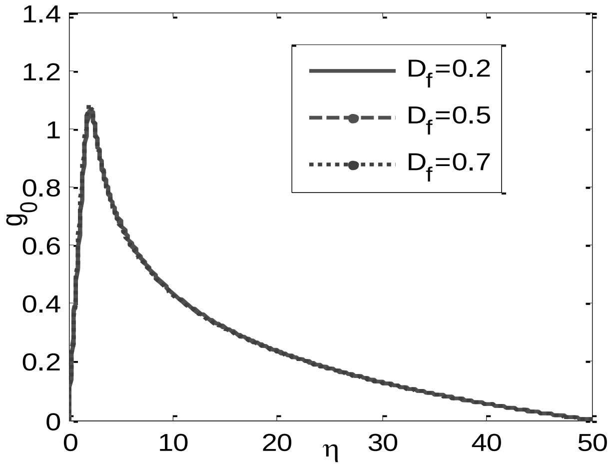

Fig.7: Secondary velocity profile for various values of D_f

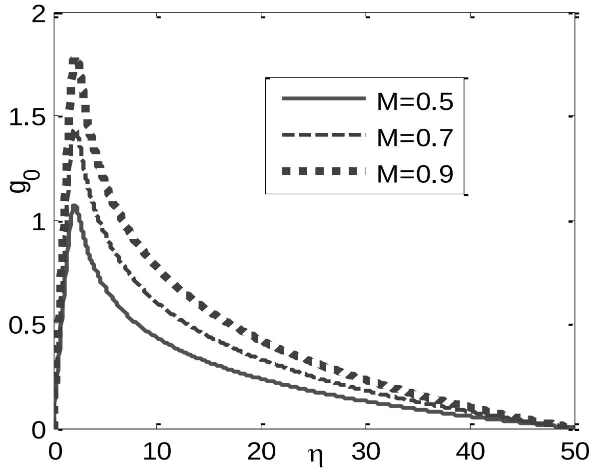

Fig.5: Secondary velocity profile for various values of M

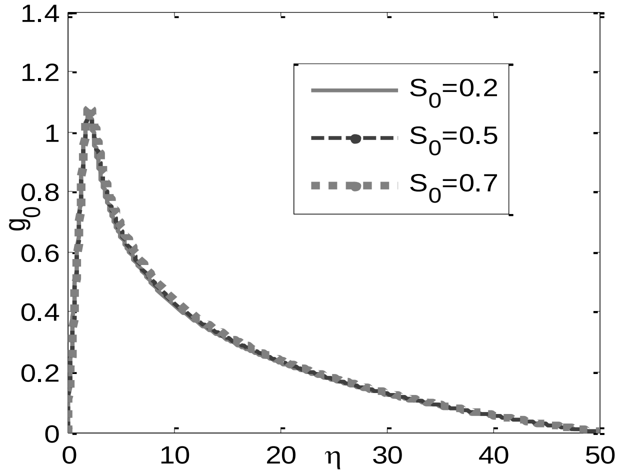

Fig.8: Secondary velocity profile for various values of S_0

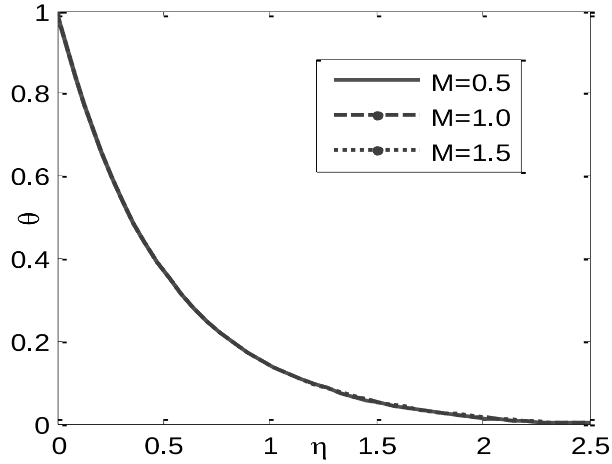

Fig.9: Temperature profile for various values of M

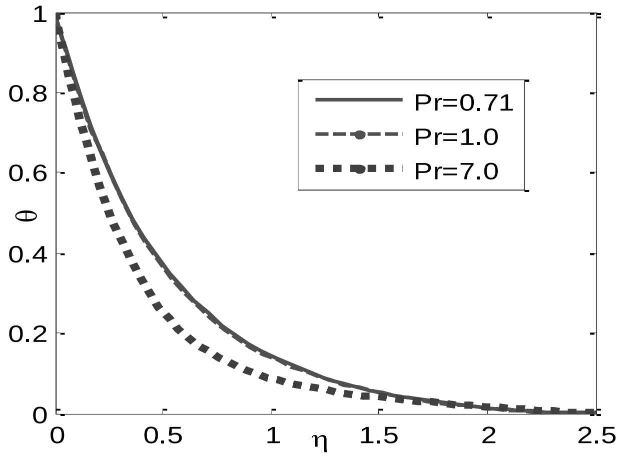

Fig.10: Temperature profile for various values of Pr

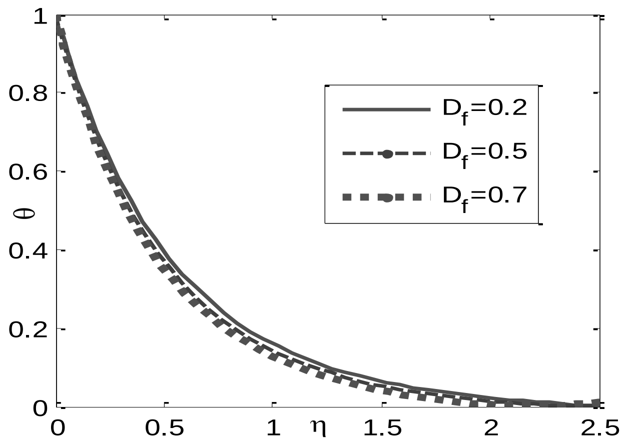

Fig.11: Temperature profile for various values of D_f

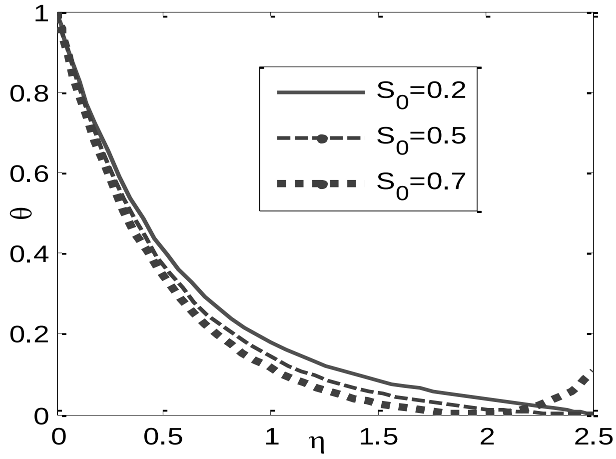

Fig.12: Temperature profile for various values of S_0

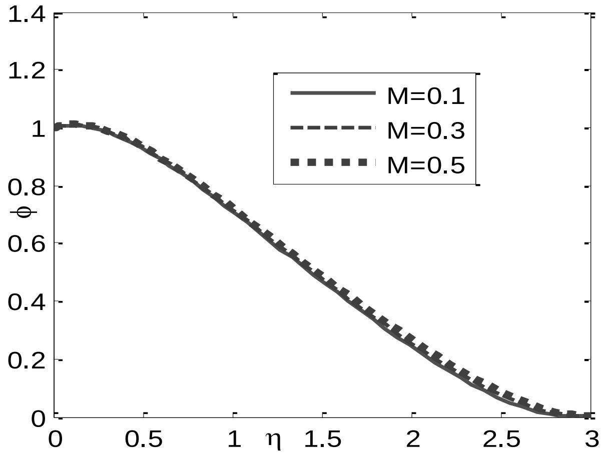

Fig.13: Concentration profile for various values of M

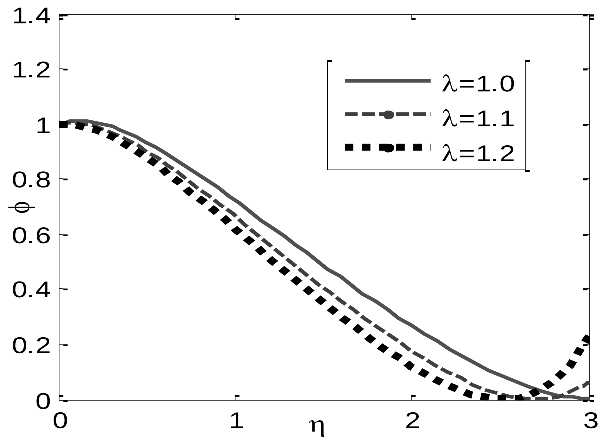

Fig.14: Concentration profile for various values of λ

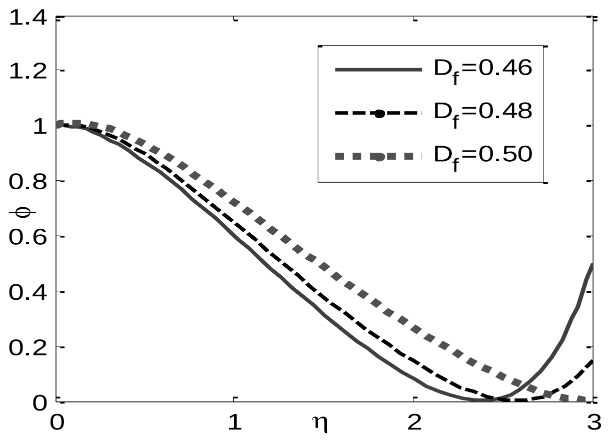

Fig.15: Concentration profile for various values of D_f

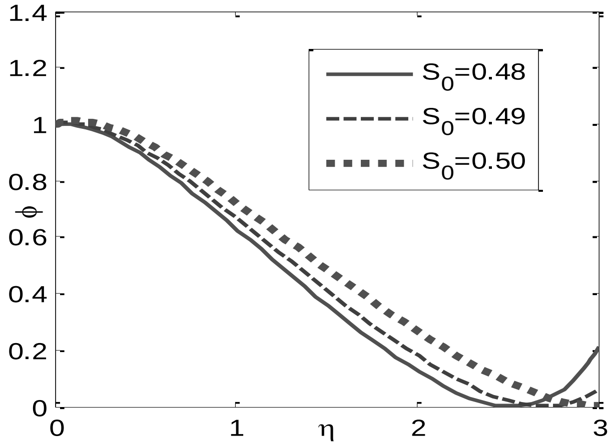

Fig.16: Concentration profile for various values of S_0

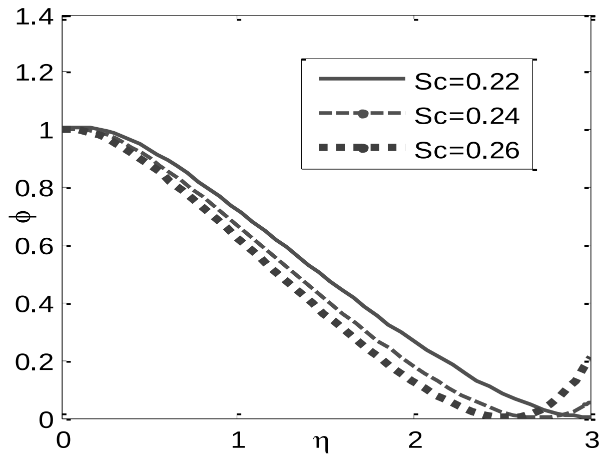

Fig.17: Concentration profile for various values of S_c

5. CONCLUSIONS

In the present paper is an investigation of steady MHD free convection, heat and mass transfer flow of an incompressible electrically conducting fluid over a stretching sheet in a rotating system under the influence of an applied uniform magnetic field with Hall current. The leading equations are solved numerically by the shooting method along with Runge- Kutta fourth-fifth order integration scheme. Following are the conclusions made from above analysis:

- The magnitude of primary velocity profile decreases with increasing magnetic parameter. The magnetic parameter is found to retard the velocity at all points of the flow field. It is because that the application of transverse magnetic field will result in a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity but there is no effect on primary velocity profile for rotational and reaction parameter.
- The secondary velocity starts from minimum value at the plate and increases until it attains the maximum value within the boundary layer and then starts decreasing until it reaches the free stream area satisfying the far field boundary condition. Therefore the noticeable increasing effect of magnetic and Hall parameter on secondary velocity profile are observed. It is interesting to note that the others mentioned parameters has no effect on secondary velocity profile.
- The temperature profile is starting at the initial point of the plate surface and increases until it attains the maximum value within the boundary layer and then starts decreasing until it reaches to zero far away from the plate satisfying the boundary condition. So noticeable decreasing effect are observed on temperature profile for Prandtl number, Dufour and Soret number whereas there is no effect for magnetic parameter. The temperature decreases with an increase in the Prandtl number, which implies viscous boundary layer is thicker than the thermal boundary layer. From these plots it is evident that large values of Prandtl number result in thinning of the thermal boundary layer. In this case temperature asymptotically approaches to zero in free stream region.
- The effect of Sc is found to decrease the concentration profile because increasing in Sc decreases molecular diffusivity which result a decrease of the boundary layer. Hence the concentration of the species in lower for large values of Sc. Similar results arises for increasing values of stretching and heat generation parameter. Again, noticeable increasing effect are observed on concentration profile for the increasing values of Dufour and Soret number.

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8. NOMENCLATURE

Symbol	Meaning	Unit
u	Velocity component along *X* axis	ms^{-1}
v	Velocity component along *Y* axis	ms^{-1}
W	Velocity component along *Z* axis	ms^{-1}
T	Fluid temperature	k^{-1}
T_w	Surface temperature	k^{-1}
$T\infty$	Free steam temperature	
C	Concentration	kgm^{-3}
C_w	Surface concentration	kgm^{-3}
$C\infty$	Free steam concentration	
μ	Coefficient of viscosity	$kgm^{-1}s^{-1}$
v	Kinematic viscosity	m^2s-1
σ	Electrical conductivity	sm^{-1}
β	Thermal expansion coefficient	k^{-1}
β	Concentration expansion coefficient	$\mu mm^{-1}k^{-1}$
D_m	Coefficient of mass diffusivity	m^2s-1
ρ	Fluid density	kgm^{-3}
κ	Thermal conductivity	$wm^{-1}K^{-1}$
c_p	Specific heat at constant pressure	$Jkg^{-1}K^{-1}$
g	Acceleration due to gravity	ms^{-2}
B_0	Magnetic field intensity	Am^{-1}