DUFOUR AND SORET EFFECTS ON UNSTEADY MHD CONVECTIVE HEAT AND MASS TRANSFER FLOW DUE TO A ROTATING DISK

Kh. A. MALEQUE
Associate Professor, Department of Mathematics, American International University-Bangladesh, House-23, Road-17, Kemal Ataturk Avenue, Banani, Dhaka-1213, Bangladesh.
maleque@aiub.edu, khmaleque@yahoo.com

***Abstract*— An unsteady three dimensional MHD convective heat and mass transfer flow in an incompressible fluid due to a rotating disk is studied by taking into account the Dufour and Soret effects. The system of axial symmetric non-linear partial differential equations governing the unsteady flow, heat and mass transfer is written in cylindrical polar coordinates and reduced to nonlinear ordinary differential equations by similarity transformations. The resulting system of ordinary nonlinear differential equations is then solved numerically by a shooting method using Range-Kutta six order integration scheme. The flow, temperature and concentration fields are affected by the magnetic interaction parameter *M*, Rotational parameter *R*, Soret Number S_0 and Dufour number D_f respectively. The results of the numerical solution are presented graphically in the form of velocity, temperature and concentration profiles. The results for the wall flow, temperature and concentration gradients obtained are presented in tabular form for various values of the parameters *M*, *R*, S_0 and D_f.**

***Keywords*—** Dufour and Soret effects, MHD flow, Rotating Disk.

I. INTRODUCTION

The solution of the Navier-Stokes equations is furnished by the flow around a flat disk which rotates about an axis perpendicular to its plane with uniform angular velocity Ω, in a fluid otherwise at rest. The layer near the disk is carried by it through friction and is thrown outwards owing to the action of centrifugal forces. This is compensated by particles which flow in an axial direction towards the disk to be in turn carried and ejected centrifugally. Thus the case is seen to be one of fully three dimensional flows. The problem of flow over a rotating disk has a long history, with von-Karman (1921) originally describing similarity transformations that enable the Navier-Stokes equations for isothermal, impermeable rotating disk to be reduced to a system of coupled ordinary differential equations. Later, Cochran (1934) obtained more accurate results by patching two series expansions. It is found that the disk acts like a centrifugal fan, the fluid near the disk being thrown radially outwards. This in turn impulses an axial flow towards the disk to maintain continuity. Benton (1965) improved Cochran's solution and extended the hydrodynamics problem to flow starting impulsively from rest. Subsequently comprehensive studies have been carried out on rotating disk flow by many researchers, some of them are Wagner (1948), Sparrow and Gregg (1959), Kuiken (1971), Hassan and Attia (1997), Attia (1998) and Kelson and Desseaux (2000). Maleque and Sattar (2003) considered an implicit finite difference solution for an unsteady convective incompressible MHD flow due to an infinite rotating disk, taking into account heat absorption effect. Maleque and Sattar (2005a and 2005b) studied the effects of variable properties and Hall current on steady MHD laminar flow of a compressible electrically conducting fluid on a porous rotating disk. Sajid and Hayat (2008) studied the influence of thermal radiation on the boundary layer flow due to an exponentially stretching sheet. Recently, Hayat *et al.* (2008c) investigated the influence of heat transfer in an MHD second grade fluid film over an unsteady stretching sheet. More recently, Hayat *et al.* (2008d) studied hall and heat transfer effects on the steady flow of generalized Burgers' fluid induced by a sudden pull of eccentric rotating disks.

The effects of thermal diffusion on MHD convection of mass transfer flows have been considered by many investigators due to its important role particularly in isotope separation and in mixtures between gases with very light molecular weight (H_2, He) and medium molecular weight (N_2, air) (Eckert and Drake, 1972). Considering these aspects, many papers have been published on the effects on thermal diffusion on MHD convective and mass transfer flow. Some of them are Jha and Singh (1990), Kafousias (1992) and Alam and Sattar (1998). Sattar and Alam (2001) obtained an analytical solution on the free convection and mass transfer flow with thermal diffusion. Maleque and Sattar (2002) obtained the numerical solution of MHD free-convective and mass transfer flow over an infinite vertical porous plate with thermal diffusion effects. Recently, Hayat *et al.* (2008a) considered mixed convection flow of a micropolar fluid over a non-linearly stretching sheet. More recently Hayat *et al.* (2008b) studied heat and mass transfer analysis on the flow of a second grade fluid in the presence of chemical reaction. Considering the importance of thermal and mass diffusions of MHD convective heat and mass transfer flow due to rotating disk, in the present study a numerical solution is obtained for an unsteady three dimensional MHD convective heat and mass transfer flow in an incompressible fluid due to a rotating disk with thermal and mass diffusions. The governing partial differential equations of the MHD convective mass transfer flow are reduced to nonlinear ordinary differential equations by introducing suitable

similarity transformations. The nonlinear similarity equations are then solved numerically by Nachtshiem-Swigert (1965) iteration technique. The results of the numerical solution are then presented graphically in the form of velocity, temperature and concentration profiles. The corresponding skin friction coefficients, the Nusselt number and the Sherwood number are also calculated and displayed in tables showing the effects of various parameters on them.

II. GOVERNING EQUATIONS

Unsteady, axially-symmetric, incompressible flow of a homogeneous electrically conducting fluid with heat and mass transfer due to an infinite rotating disk has been considered, assuming that the fluid is infinite in extent in the positive z-direction.

The disk rotates with constant angular velocity Ω and is placed at z=0, where z is the vertical axis in the cylindrical coordinates system with r and ϕ as the radial and tangential axes respectively. The components of the flow velocity are (u,v,w) in the directions of increasing (r,ϕ,z) respectively, the pressure is P and the density of the fluid is ρ. T and C are the fluid temperature and concentration respectively and the surface of the rotating disk is maintained at a uniform temperature c_w and uniform concentration T_w. Far away from the surface, the free stream is kept at a constant temperature T_∞, at a constant concentration C_∞ and at a constant pressure P_∞.

The fluid is assumed to be Newtonian, viscous and electrically conducting. The external uniform magnetic field is applied perpendicular to the surface of the disk and has a constant magnetic flux density B_0 which is assumed unchanged by taking small magnetic Reynolds number (R_{em}<<1). In addition, no electric field is assumed to exist and the Hall effect is negligible.

The physical model and geometrical coordinates are shown in Fig. 1. Due to axial symmetry, incompressible MHD laminar flow of a homogeneous fluid satisfies the following continuity, Navier-Stokes, energy and mass equations:

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}-\frac{v^2}{r}+w\frac{\partial u}{\partial z}+\frac{\sigma B_0^2}{\rho}u+\frac{1}{\rho}\frac{\partial p}{\partial r}=\nu\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{u}{r^2}+\frac{\partial^2 u}{\partial z^2}\right), \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+\frac{uv}{r}+w\frac{\partial v}{\partial z}+\frac{\sigma B_0^2}{\rho}v=\nu\left(\frac{\partial^2 v}{\partial r^2}+\frac{1}{r}\frac{\partial v}{\partial r}-\frac{v}{r^2}+\frac{\partial^2 v}{\partial z^2}\right), \tag{3}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial z}=\nu\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}+\frac{\partial^2 w}{\partial z^2}\right), \tag{4}$$

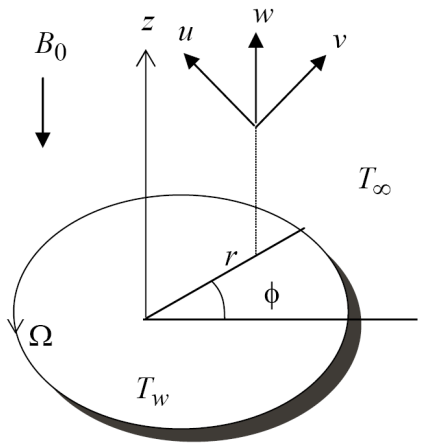

Fig.1 The flow configuration and the coordinate system.

$$\frac{\partial T}{\partial t}+\left(u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}\right)=\frac{\kappa}{\rho c_p}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{D_m k_T}{c_s c_p}\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}+\frac{\partial^2 C}{\partial z^2}\right) \tag{5}$$

$$\frac{\partial C}{\partial t}+\left(u\frac{\partial C}{\partial r}+w\frac{\partial C}{\partial z}\right)=D_m\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}+\frac{\partial^2 C}{\partial z^2}\right)+\frac{D_m k_T}{T_m}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right) \tag{6}$$

here, κ is the thermal conductivity of heat, σ is the electrical conductivity, c_p is the specific heat with constant pressure, D_m is the molecular diffusivity, T_m is the mean fluid temperature, k_T is the thermal diffusion ratio and c_s is the concentration susceptibility.

Appropriate boundary conditions are given by

$$\left.\begin{array}{l} u=0,\ v=\Omega r,\ w=0,\ T=T_w \\ \text{and } C=C_w \text{ at } z=0 \\ u\to 0,\ v\to 0,\ T\to T_\infty, \\ C\to C_\infty\ p\to p_\infty \text{ as } z\to\infty. \end{array}\right\} \tag{7}$$

III. MATHEMATICAL FORMULATIONS

To solve the governing Eqs. (1-7), they are converted to some suitable form by introducing the following dimensionless quantities:

$$\left.\begin{array}{l} \eta=\dfrac{z}{\delta},\quad u=r\,\Omega\,F'(\eta), \\ v=r\,\Omega\,G(\eta),\ \ w=-2\,\delta\,\Omega\,F(\eta), \\ p-p_\infty=\nu\,\rho\,\Omega\,P(\eta), \\ T-T_\infty=\Delta T\,\theta(\eta) \\ \text{and}\ \ C-C_\infty=\Delta C\,\varphi(\eta) \end{array}\right\} \tag{8}$$

where δ is a scale factor and is a function of time as $\delta = \delta(t)$.

$$F''' + \frac{\delta}{\nu}\frac{d\delta}{dt}\eta F'' + R(2FF'' - F'^2 + G^2 - M F') = 0, \quad (9)$$

$$G'' + \frac{\delta}{\nu}\frac{d\delta}{dt}\eta G' + R(2FG' - 2F'G - MG) = 0, \quad (10)$$

$$\theta'' + D_f P_r \varphi'' + P_r\left[\eta\frac{\delta}{\nu}\frac{d\delta}{dt} + 2RF\right]\theta' = 0, \quad (11)$$

$$\varphi'' + S_r S_C \theta'' + S_C\left[\eta\frac{\delta}{\nu}\frac{d\delta}{dt} + 2RF\right]\varphi' = 0, \quad (12)$$

$R\left(=\frac{\Omega\delta^2}{\nu}\right)$ is the rotational parameter. $M = \frac{\sigma B_0^2\,\delta^2}{\rho\,\nu}$ is the magnetic interaction parameter which represents the ratio of the magnetic force to the fluid inertia force, $\Pr = \frac{\rho\,\nu\,c_p}{\kappa}$ is the Prandtl number, $S_c = \frac{\nu}{D_m}$ is the Schmidt number and $S_0 = \frac{D_m\,k_T\,\Delta T}{\nu\,T_m\,\Delta C}$ is the Soret number and $D_f = \frac{D_m\,k_T\,\Delta C}{c_s\,c_p\,\nu\,\Delta T}$ is the Dufour number, where, $\Delta T = T_w - T_\infty$ and $\Delta C = C_w - C_\infty$.

The Eqs. (10)— (12) depend on a single similarity variable η except a time dependent term $\frac{\delta}{\nu}\frac{d\delta}{dt}$ where time t appears explicitly. Thus the similarity condition requires that $\frac{\delta}{\nu}\frac{d\delta}{dt}$ must be a constant quantity. We therefore assume that

$$\frac{\delta}{\nu}\frac{d\delta}{dt} = C \text{ (a constant).} \quad (13)$$

Integrating (13), we obtain

$$\delta = \sqrt{2C\nu t} + L, \quad (14)$$

where the constant of integration L is determined through the condition that δ=L when t=0.. Here C=0 implies that δ=L represents the length scale for steady flow and C≠0 that is, δ represents the length scale for unsteady flow. Let us now consider a class of solutions for which C=2 and hence the length scale δ from Eq. (14) becomes

$$\delta = 2\sqrt{\nu t} + L, \quad (15)$$

which exactly corresponds to the usual scaling factor considered for various unsteady boundary layer flows Schlichting (1968). Since δ is a scaling factor as well as a similarity parameter, any other values of C in Eq. (14) would not change the nature of the solution except that the scale would be different. Finally, introducing Eq. (15) in Eqs (9-12) respectively, we have the following dimensionless ordinary non-linear differential equations

$$F''' + 2\eta F'' + R(2FF'' - F'^2 + G^2 - M F') = 0, \quad (16)$$

$$G'' + 2\eta G' + R(2FG' - 2F'G - MG) = 0, \quad (17)$$

$$\theta'' + 2P_r[\eta + RF]\theta' + D_f P_r \varphi'' = 0, \quad (18)$$

$$\varphi'' + 2S_C[\eta + RF]\varphi' + S_r S_C \theta'' = 0. \quad (19)$$

The boundary conditions (7) then become

$$\left.\begin{array}{l} F = 0,\ F' = 0,\ G = 1, \\ \theta = 1,\ \varphi = 1 \text{ at } \eta = 0, \\ F' = 0,\ G = 0,\ \theta = 0, \\ \varphi = 0 \text{ as } \eta \to \infty. \end{array}\right\} \quad (20)$$

In all the above equations primes denote the differentiation with respect to η. Equation (16) to (19) are solved numerically under the boundary conditions (20) using Nachtsheim-Swigert iteration technique.

IV. NUMERICAL SOLUTIONS

Equations (15)–(18) are solved numerically under the boundary conditions (19) using Nachtsheim and Swigert (1965) iteration technique. Thus adopting this numerical technique, a computer program was set up for the solutions of the basic non-linear differential equations of our problem where the integration technique was adopted as the six ordered Range-Kutta method of integration. The results of this integration are then displayed graphically in the form of velocity, temperature and concentration profiles in Figs. (2)-(10). In the process of integration, the local skin-friction coefficients, the local rates of heat and mass transfer to the surface, which are of chief physical interest are also calculated out. From these solutions we may obtain derivatives of the G and F' functions at the disk surface (η=0) which are required for the calculation of the tangential shear stress τ_t and the radial shear stress τ_r. To find the tangential shear stress τ_t and the radial shear stress τ_r, we apply the Newtonian formulae

$$\tau_t = \mu\left(\frac{\partial v}{\partial z} + \frac{1}{r}\frac{\partial w}{\partial \phi}\right)_{z=0} \propto G'(0) \quad (20)$$

and

$$\tau_r = \left[\mu\left(\frac{\partial u}{\partial z} + \frac{1}{r}\frac{\partial w}{\partial \phi}\right)\right]_{z=0} \propto F''(0). \quad (21).$$

The heat flux (q_w) and the mass flux (M_w) at the surface are given by

$$q_w = -\kappa\left(\frac{\partial T}{\partial z}\right)_{z=0} \propto -\theta'(0) \quad (22)$$

and

$$M_w = -D_M\left(\frac{\partial C}{\partial z}\right)_{z=0} \propto -\varphi'(0). \quad (23)$$

Table 1(a): Numerical values of the radial and tangential skin frictions and the rate of heat and mass transfer coefficients obtained for P_r=0.71, S_c=0.6, M=0.5, D_f=0.2 and S_o=0.5.

R	F''	G'	$-\theta'$	$-\varphi'$
0.5	0.12776	-1.23457	0.96550	0.75868
1.0	0.23618	-1.34275	0.97371	0.76682
2.0	0.40916	-1.55744	0.99693	0.78963
3.0	0.54510	-1.75796	1.02319	0.81520

Table 1(b): Numerical values of the radial and tangential skin frictions obtained for P_r=0.71, S_c=0.6, R=0.5, D_f=0.2 and S_o=0.5.

M	F''	G'
0.0	0.13632	-1.14361
0.5	0.12776	-1.23457
1.0	0.12033	-1.32143
2.0	0.10825	-1.47436

Table 1(c): Numerical values of the rate of heat and mass transfer coefficients obtained for P_r=0.71, S_c=0.6 and R=0.5.

D_f	$-\theta'$	S_o	$-\varphi'$
0.0	0.95639	0.0	0.89661
0.5	0.78480	0.5	0.75868
1.0	0.58927	1.0	0.61366
2.0	0.08717	2.0	0.03788

These above coefficients are then obtained from the procedure of the numerical computations and are sorted in Table 1. In the above equations prime denotes derivative with respect to similarity variable η.

V. RESULTS AND DISCUSSIONS

Considered here involves a number of parameters on the basis of which a wide range of numerical results have been derived. Of this results a small section are presented here for brevity. The numerical results of the velocity, temperature and concentration profiles are shown in Figs.2-4.

The parameters entering into the fluid flow are Magnetic parameter M, Rotational parameter R, Dufour number D_f and Soret number S_o. It is, therefore, pertinent to inquire the effects of variation of each of them when the others are kept constant. The numerical results are thus presented for different values of M, R, D_f and S_o for Prandlt number P_r=0.71 and Schmidt number S_c=0.6 are considered.

The representative velocity, temperature and concentration profiles and the values of the physically important parameters, i.e. the local shear stress, the local rates of heat and mass transfer, are illustrated for uniform wall temperature and species concentration in Figs. 2—9 and in Table 1(a, b, c). In Figs. 2-4, the radial, tangential and axial velocity profiles are shown respectively for different values M (0, 1 and 2). From these figures it is observed that the increase in the magnetic field leads to the decrease in the velocity field indicating that the magnetic field retards the velocity field. In Fig. 5 – Fig. 7, we have plotted the radial, tangential and axial velocity for air (P_r=0.71) at 20ºC and at one atmospheric pressure showing the effect of variation of Rotational parameter R. It is thus apparent that the rotational parameter R has increasing effects on radial and axial velocity profiles but decreasing effects on tangential velocity profiles.

The parameter D_f (Dufour number) does not enter directly into the momentum and mass equations. Thus the effect of Dufour number on velocity and mass profiles is not apparent. Figure 8 shows the variation of temperature profiles for different values of D_f.

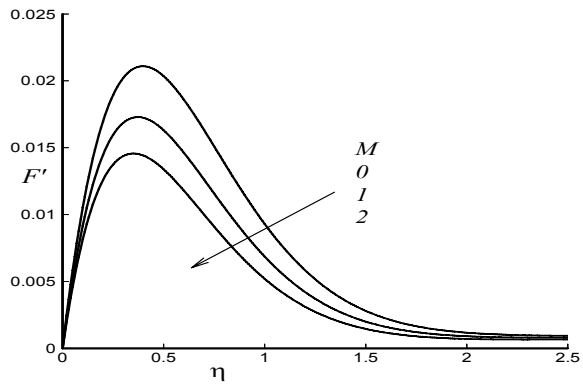

Fig. 2. Effects of M on the radial velocity profiles for P_r=0.71, R=0.5, S_c=0.6, D_f=0.2 and S_o=0.5.

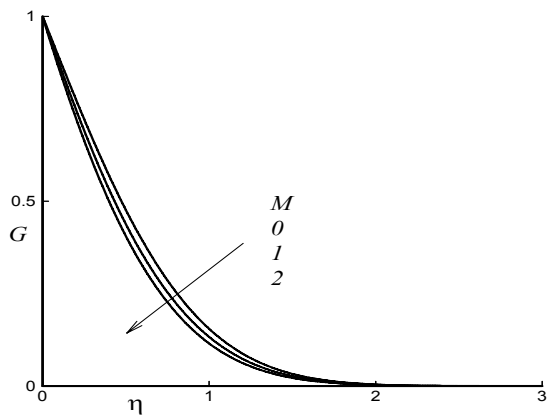

Fig. 3. Effects of M on the tangential velocity profiles for P_r=0.71, R=0.5, S_c=0.6, D_f=0.2 and S_o=0.5.

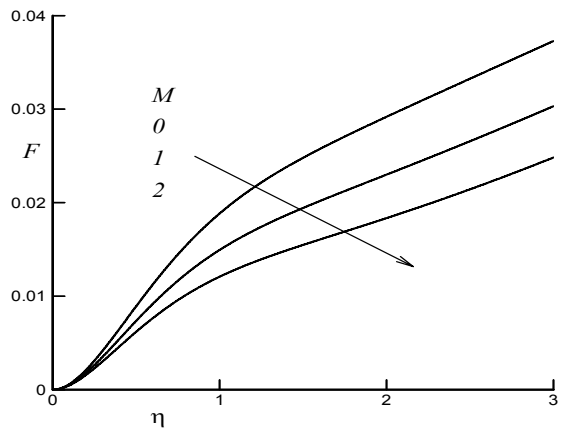

Fig. 4. Effects of M on the axial velocity profiles for P_r=0.71, R=0.5, S_c=0.6, D_f=0.2 and S_o=0.5.

The parameter D_f has marked effects on the temperature profiles. It is observed that the temperature profiles increase with the increasing values of D_f. It is also observed from this figure that when $D_f = 1.0$, that is, when the ratio between temperature and concentration gradient is very small the temperature profile shows its usual trend of gradual decay. As Dufour number D_f becomes large the profiles overshoot the uniform temperature close to the boundary.

The parameter S_o (Soret number) does not enter directly into the momentum and energy equations. Thus the effect of Soret number on velocity and temperature profiles is not apparent. Figure 9 shows the variation of concentration profiles for different values of S_o. The parameter S_o has marked effects on the concentration profiles. It is observed that the concentration profiles increase with the increasing values of S_o. It is also observed from this figure that when S_o=1.0, that is, when the ratio between concentration and temperature gradient is very small the concentration profile shows its usual trend of gradual decay. As Soret number S_o becomes large the profiles overshoot the uniform concentration close to the boundary.

The radial and tangential skin-frictions, the heat transfer and the mass transfer coefficients are tabulated in Table 1 for various values of M, R, D_f and S_o. We observe from Table 1(a) that the radial skin-friction, heat and mass transfer coefficients increase while the tangential skin-friction decreases with the increase in the rotational parameter R. It has been found from Table 1(b) that the radial skin-friction and tangential skin friction decrease with the increase in the magnetic parameter M. The Table 1(c) shows that the heat transfer coefficient decreases with the increasing values of the Dufour number D_f. It is also observed from Table 1(c) that as thermal diffusion (S_0) intensifies mass transfer coefficient decreases.

In order to highlight the validity of the numerical computations adapted in the present investigation, some of our results have been compared with those of Sparrow and Gregg (1959) in Table 2. The comparison shows excellent agreement, hence an encouragement for the use of the present numerical computations.

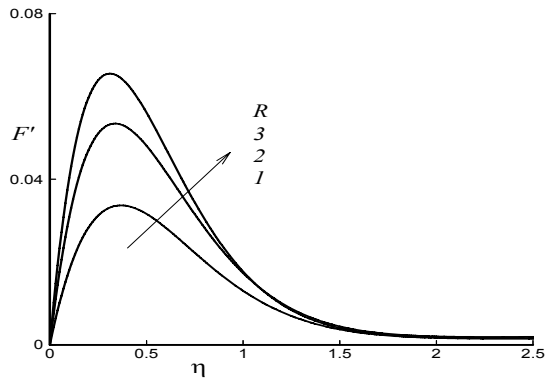

Fig. 5. Effects of R on the radial velocity profiles for P_r=0.71, M=0.5, S_c=0.6, D_f=0.2 and S_o=0.5.

Table 2: Comparison between the (analytical) results of Sparrow and Gregg (1959) and present work. Heat transfer coefficients -θ'(0) for S_c=0.6, D_f=0, S_o=0, M=C=0 and R=1.

Pr	Sparrow and Gregg(1959)	Present
1.0	0.39625	0.39623
10.0	1.13410	1.13331
100	2.68710	2.68682

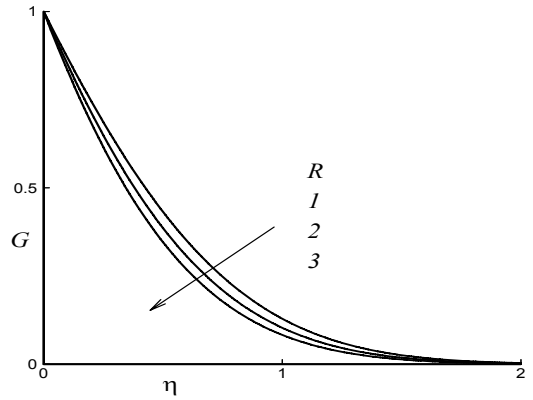

Fig. 6. Effects of R on the tangential velocity profiles for P_r=0.71, M=0.5, S_c=0.6, D_f=0.2 and S_o=0.5.

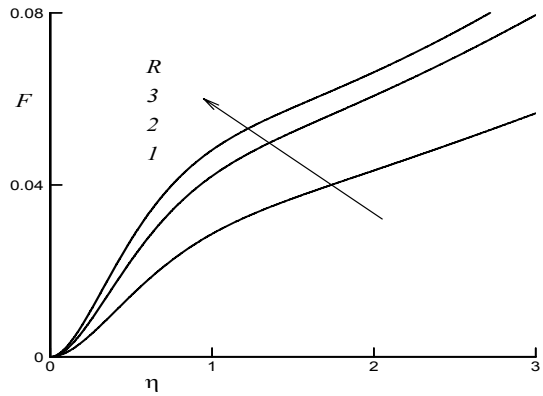

Fig. 7. Effects of R on the axial velocity profiles for P_r=0.71, M=0.5, S_c=0.6, D_f=0.2 and S_o=0.5.

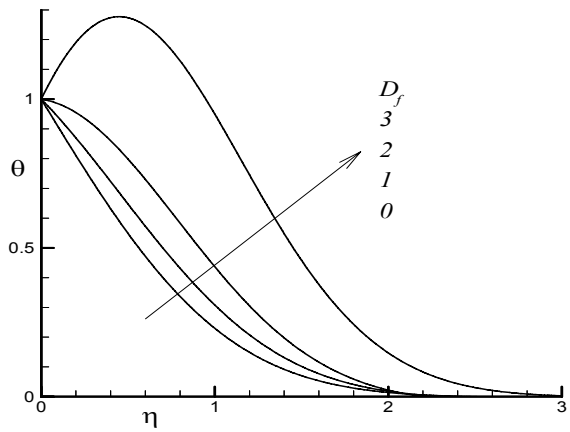

Fig. 8. Effects of D_f on the temperature profiles for P_r=0.71, M=0.5, S_c=0.6, R=0.5 and S_o=0.5.

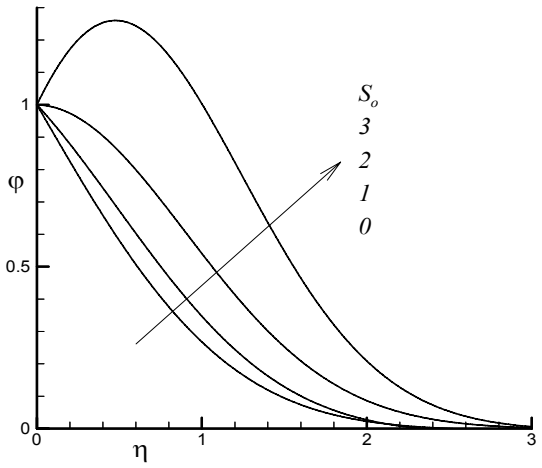

Fig. 9. Effects of S_o on the concentration profiles for P_r=0.71, M=0.5, S_c=0.6, R=0.5 and D_f=0.2.

VI. CONCLUSIONS

In this paper, an unsteady three dimensional MHD convective heat and mass transfer flow in an incompressible fluid due to an infinite rotating disk is studied. The Nachtsheim and Swigert (1965) iteration technique based on sixth-order Range-Kutta and shooting methods has been employed to complete the integration of the resulting solutions.

The following conclusions can be drawn as a result of the computations:

1. The rotational parameter R has marked effect on the velocity profiles. It is observed that, radial and axial velocity profiles increase while tangential velocity profiles decrease with the increasing values of R. It is observed that the tangential shearing stress decreases and the radial shearing stress, the rate of heat and mass transfer coefficients increase owing to the increase of rotating parameter R.
2. The effect of Lorentz force or the usual resistive effect of the magnetic field on the velocity profiles is apparent. It has been found that the radial skin-friction and tangential skin friction decrease with the increase in the magnetic parameter M.
3. It is observed that the temperature and concentration profiles increase with the increasing values of D_f and S_0 respectively. The heat transfer and mass transfer coefficients decrease with the increasing values of the D_f and S_0, respectively.

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Received: July 22, 2008.
Accepted: June 10, 2009.
Recommended by Subject Editor Walter Ambrosini.