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Flow, Heat and Mass Transfer about a Permeable Vertical Rotating Cone

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Abstract

The problem of flow, heat and mass transfer about a permeable rotating vertical cone in presence of thermal radiation and chemical reaction effects has been investigated. The governing nonlinear partial differential equations have been treated numerically by using MATLAB's built in solver bvp4c. A parametric study for the tangential velocity component of the fluid, the temperature of the fluid and the concentration of the rarer and lighter component of the fluid is presented graphically. The local skin friction, the local Nusselt number and the local Sherwood number are tabulated.

Keywords – Permeable Rotating cone, radiation, chemical reaction, bvp4c.

I. INTRODUCTION

The heat and mass transfer problems over a rotating cone–shaped body are often encountered in many engineering applications because of their uses in turbines, various propulsion devices for aircraft, spin-stabilised missiles, satellites, space vehicles, nuclear reactors and in the modelling of several geophysical vortices. Moreover, applications of heat and mass transfer from a rotating cone are used to design of canisters for nuclear waste disposal, nuclear reactor cooling system and geothermal reservoirs.

The problem of flow, heat and mass transfer about a cone was investigated by many researchers. Hartnett and Deland (1961) examined the influence of Prandtl number on the heat transfer by rotating bodies. The effects of an axial magnetic field on the flow and heat transfer about a rotating disk have been analyzed by Sparrow and Cess (1962). Heiring and Grosh (1962) discussed the free convection by a rotational non-isothermal cone at low Prandtl number. Tien and Tsuji (1965) presented a theoretical analysis of laminar forced flow and heat transfer about a rotating cone. Krieth (1968) presented the study of the flow and heat transfer in rotating systems. S Roy (1974) investigated free convection from a vertical cone at high Prandtl numbers. An approximate method of solution for the heat transfer from vertical cones in laminar natural convection was examined by Alamgir (1979). Vira and Fan (1981) discussed the flow and heat transfer on a spinning cone in a corotating fluid. Himashekhar et al. (1989) investigated the buoyancy induced flow and temperature fields around a vertical rotating cone for a wide range of Prandtl numbers. Boundary layers on rotating cone, disc and axisymmetric surfaces with a concentrated heat sources have been reported by Wang (1990). Effects of mass transfer on free convective flow of a viscous and incompressible fluid past a vertical isothermal cone surface were numerically solved by Kafoussias (1992). Kumari and Pop (1998) investigated the free convection over a vertical rotating cone with constant wall heat flux. Yih (1999) investigated numerically the effect of radiation on natural convection about a truncated cone. Chamkha (2001) studied coupled heat and mass transfer by natural convection about a truncated cone in the presence of magnetic field and radiation effects. Takhar et al. (2003) investigated unsteady mixed convection flow from a rotating vertical cone with a magnetic field. Anilkumar and Roy (2004) studied numerically the unsteady mixed convection flow on a rotating cone in a rotating fluid. Afify (2004) discussed the effect of radiation on free convective flow and mass transfer past a vertical isothermal cone surface with chemical reaction in the presence of a transverse magnetic field. Chamkha and Al-Mudhaf (2005) investigated the unsteady heat and mass transfer from a rotating vertical cone with a magnetic field and heat generation or absorption effects. El-Kabeir and Modather (2007) studied chemical reaction, heat and mass transfer on MHD flow over a vertical isothermal cone surface in micropolar fluids with heat generation or absorption. Osalusi et al. (2008) studied the effect of combined viscous dissipation and joule heating on unsteady mixed convection MHD flow on a rotating cone in a rotating fluid with variable properties in the presence of Hall and ion-slip currents. Sharma and Singh (2008) studied barodiffusion and thermal diffusion of a binary fluid mixture confined between two parallel discs in presence of a small axial magnetic field. Pullepu et al. (2008) investigated numerically the laminar free convection flow past a non-isothermal vertical cone by using finite difference method. Kishore et al. (2010) studied viscoelastic buoyancy driven MHD free convective heat and mass transfer past a vertical cone with thermal radiation and viscous dissipation effects. Mahdy (2010) studied the effects of chemical reaction and heat generation or absorption on double-diffusive convection from a vertical truncated cone in porous media with variable viscosity. Sharma and Singh (2010) analyzed the separation of species of a binary fluid mixture confined between two concentric rotating circular cylinders in presence of a strong radial magnetic field. Mohiddin et al. (2010) discussed numerically the unsteady free convective heat and mass transfer in a Walters-B viscoelastic flow along a vertical cone. Patil and Pop (2011) considered the effects of surface mass transfer on unsteady mixed convection flow over a vertical cone with chemical reaction. Basiri et al. (2013) discussed MHD boundary layer flow over a stretching surface with internal heat generation or absorption. The effects of chemical reaction on unsteady free convective and mass transfer flow from a vertical cone with heat generation or absorption in presence of variable wall temperature and variable wall concentration have been investigated by Pullepu et al. (2014).

The aim of this paper is to study numerically the problem of flow, heat and mass transfer about a vertical rotating cone with a uniform angular velocity Ω in presence of the thermal radiation, the chemical reaction, the suction / injection effects and the effect of Schmidt number. The nonlinear partial differential equations are converted into ODEs by using suitable substitutions and then the system of ordinary differential equations governing the flow, heat and mass transfer problem have been solved by using MATLAB'S built in solver bvp4c.

II. FORMULATION OF THE PROBLEM

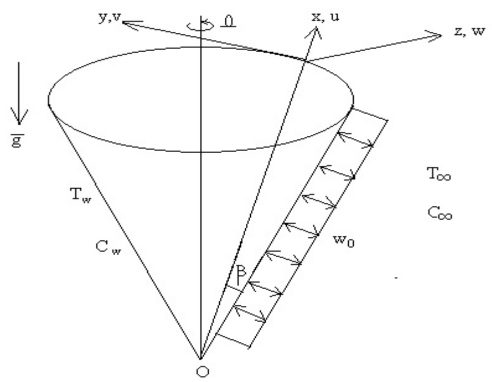

Figure.1 Physical model and co-ordinate system

Consider a steady, laminar, hydromagnetic, boundary layer flow of an electrically conducting and chemically reacting incompressible viscous fluid along an axi-symmetric, heated and vertical cone in ambient fluid rotating with uniform angular velocity Ω around the axis of the cone. A uniform magnetic field of strength B_0 is applied in the direction of z-axis. The acceleration due to gravity $\bar{g}$ is acting downward parallel to the axis of the cone. Uniform suction / injection of the fluid with velocity w_0 is taking place at the surface of the cone. The physical model and the co-ordinate system are shown in the Fig.1. Consider the rectangular curvilinear co-ordinate system (x, y, z), where x is measured along a tangential direction, y-axis is along a circumferential direction and z-axis is measured along the normal direction to the cone. Let u, v, w are the velocity components along the tangential, circumferential and normal direction to the cone respectively. The surface temperature T_w and concentration C_w are assumed to vary linearly with the distance x and ambient temperature T_∞ and ambient concentration C_∞ are constants.

The following assumptions are made

1. The magnetic field is constant.

2. The system is considered as axi-symmetric.
3. The magnetic Reynold number is small so that the induced magnetic field is neglected.
4. The Joule heating of the fluid is neglected.
5. The Hall Effect of magneto-hydrodynamics is neglected.
6. The medium is optically thin with relatively low density.

Under the above assumptions and Boussinesq approximation, the dimensional boundary layer equations governing the flow, heat and mass transfer can be expressed as

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

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}-\frac{v^2}{x}=\nu\frac{\partial^2 u}{\partial z^2}+\bar{g}\beta_T\cos\beta(T-T_\infty)$$
$$+\bar{g}\beta_C\cos\beta(C-C_\infty)-\frac{\sigma B_0^{\,2}u}{\rho}, \tag{2}$$

$$u\frac{\partial v}{\partial x}+w\frac{\partial v}{\partial z}-\frac{uv}{x}=\nu\frac{\partial^2 v}{\partial z^2}-\frac{\sigma B_0^{\,2}v}{\rho}, \tag{3}$$

$$u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z}=\frac{1}{\rho C_p}\left(k\frac{\partial^2 T}{\partial z^2}+Q_0(T-T_\infty)-\frac{\partial q_r}{\partial z}\right) \tag{4}$$

and

$$u\frac{\partial C}{\partial x}+w\frac{\partial C}{\partial z}=D_m\frac{\partial^2 C}{\partial z^2}-k_C(C-C_\infty) \tag{5}$$

together with the boundary conditions

$$u=0,\ v=\Omega x\sin\beta,\ w=w_0, T=T_w(x),\ C=C_w(x)\ \text{ when } z=0 \tag{6}$$

and

$$u\to 0,\ v\to 0,\ T\to T_\infty, C\to C_\infty\ \text{ when } z\to\infty \tag{7}$$

where T is the temperature of the fluid, C is the concentration of the fluid mixture, k is the thermal conductivity, C_p is the specific heat at constant pressure, $\bar{g}$ is the acceleration due to gravity, ν is the kinematic viscosity, β is the semi vertical angle of the cone, σ is the electrical conductivity, ρ is the density of the fluid, q_r is the radiation heat flux, β_T and β_C are coefficients of thermal expansion and mass expansion, D_m is the mass diffusion coefficient, Q_0 is the co-efficient of the heat generation, k_c is the dimensional chemical reaction parameter respectively.

Dimensional boundary layer Eqs.(1)-(6) can be made dimensionless by using the following transformations:

$$\eta=\left(\frac{\Omega\sin\beta}{\nu}\right)^{\frac{1}{2}}z,\ u(x,z)=-\frac{1}{2}\Omega x\sin\beta f'(\eta)$$

$$v(x,z)=\Omega x\sin\beta g(\eta),\ w(x,z)=(\nu\Omega\sin\beta)^{\frac{1}{2}}f(\eta),$$

$$T(x,z)-T_\infty=(T_w-T_\infty)\theta(\eta)\frac{x}{L},$$

and

$$C(x,z)-C_\infty=(C_w-C_\infty)\phi(\eta)\frac{x}{L} \tag{8}$$

Here prime represents derivative with respect to η.

For optically thin medium the radiation heat flux is given by the expression

$$\frac{\partial q_r}{\partial z}=-4a\sigma^*(T^4_\infty - T^4) \tag{9}$$

where a and σ^* are absorption coefficient and the Stefan Boltzmann constants respectively. It is assumed that temperature differences within the flow are sufficiently small such that T^4 can be expanded in a Taylor's series about T_∞ and after rejecting higher order terms it becomes

$$T^4 = 4T^3_\infty T - 3T_\infty^4 \tag{10}$$

With these transformations Eq. (1) is identically satisfied and Eqs. (2) to (5) reduces to the following system of equations:

$$f''' - ff'' + \frac{1}{2}\left(f'\right)^2 - 2g^2 - 2\lambda(\theta + N\phi) - Mf' = 0, \tag{11}$$

$$g'' - (fg' - f'g) - Mg = 0, \tag{12}$$

$$\theta'' - \Pr(f\theta' - \frac{1}{2}f'\theta) + \delta \Pr\theta - \Pr R_d\theta = 0 \tag{13}$$

and

$$\phi'' - Sc(f\phi' - \frac{1}{2}f'\phi) - Sc\gamma\phi = 0 \tag{14}$$

where $Gr = \frac{\bar{g}\beta_T\cos\beta(T_w - T_\infty)L^3}{\nu^2}$, $\lambda = \frac{Gr}{Re^2}$, $\Pr = \frac{\mu C_p}{k}$, $Re = \frac{\Omega L^2\sin\beta}{\nu}$, $N = \frac{\beta_C(C_w - C_\infty)}{\beta_T(T_w - T_\infty)}$,

$M = \frac{\sigma B_0^2}{\rho\Omega\sin\beta}$, $Sc = \frac{\nu}{D_m}$, $\delta = \frac{Q_0}{\rho C_p\Omega\sin\beta}$, $R_d = \frac{16\nu a\sigma^* T_\infty^3}{k\Omega\sin\beta}$, $\gamma = \frac{k_C}{\Omega\sin\beta}$

and $f_w = \frac{W_0}{(\nu\Omega\sin\beta)^{\frac{1}{2}}}$

together with the boundary conditions

$$f' = 0,\ f = f_w,\ g = 1,\ \theta = 1,\ \phi = 1 \text{ when } \eta \to 0 \tag{15}$$

and

$$f' = 0,\ g = 0,\ \theta = 0,\ \phi = 0 \text{ when } \eta \to \infty \tag{16}$$

where Gr, λ, Pr, Re, N, M, Sc, δ, R_d, f_w and γ are Grashof number, Buoyancy parameter, Prandtl number, Reynolds number, ratio of thermal Grashof to mass Grashof numbers, magnetic parameter, Schmidt number, heat generation parameter, radiation parameter, suction / injection parameter and chemical reaction parameter respectively. $\frac{W_0}{(\nu\Omega\sin\beta)^{\frac{1}{2}}} = f_w$ is the suction / injection velocity. $f_w = 0$ corresponds to the case of an impermeable rotating cone, $f_w < 0$ is for suction, $f_w > 0$ is for injection. The skin friction coefficient in the tangential direction is $Re_x^{\frac{1}{2}} C_{fx} \propto -f''(0)$ the Nusselt number is $Re_x^{-\frac{1}{2}} Nu_x \propto -\theta'(0)$ and the Sherwood number is $Re_x^{-\frac{1}{2}} Sh_x \propto -\phi'(0)$

III. METHOD OF SOLUTION

Eqs. (11) to (14) are coupled nonlinear ODEs and exhibit no closed-form solution. Therefore they must be solved numerically subject to the boundary conditions Eqs. (15) to (16). To solve our BVP we have used collocation method with collocation code solver bvp4c. It is a powerful method to solve the two point BVP resulting from the optimality conditions.

The quantities of physical interest are local skin friction in the tangential directions, the local Nusselt number and the local Sherwood number. They are $Cf_x = -Re_x^{-\frac{1}{2}} f''(0)$, $Nu_x = -Re_x^{\frac{1}{2}} \theta'(0)$ and $Sh_x = -Re_x^{\frac{1}{2}} \phi'(0)$ shown in tables 1-4. Here $Re_x = \dfrac{\Omega x^2 \sin\beta}{\nu}$ is the local Reynolds number.

IV. RESULTS AND DISCUSSIONS

The numerical results for the tangential velocity, temperature and concentration profiles are presented graphically to gain some insight into the effects of various parameters involved in the problem. Figs. (2-4) represent the tangential velocity, the temperature and the concentration profiles of the fluid for values of R_d = [0.5, 1, 1.5], $\delta = 0.5$; $Pr = 0.71$; $\lambda = 1$; $Sc = 0.6$; $M=0.5$; $N = 1$; $\gamma = 0.5$ and $f_w= 0$.

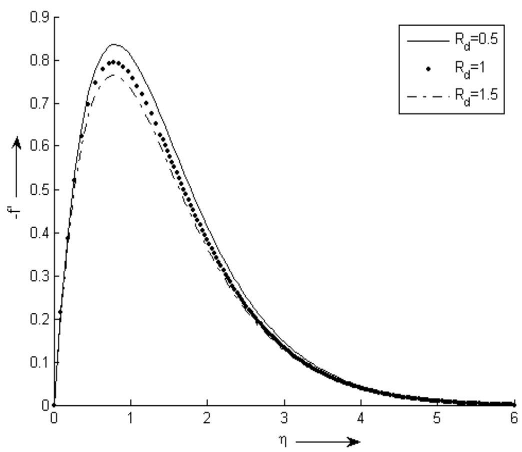

Figure.2 Effects of R_d on the tangential velocity profiles

Fig.2 shows that the tangential velocity component of the fluid first increases near the surface of the rotating cone; attains its peak value and then decreases monotonically towards the end of the boundary layer. But the effect of increase in the value of the radiation parameter R_d decreases the tangential velocity component of the fluid at any point in the boundary layer. Moreover maximum value of the tangential velocity component of the fluid are found to be 0.8336, 0.7903 and 0.7604 at η = 0.8485. Thus there is 8.78 % of decrease in the tangential velocity component of the fluid as the value of the radiation parameter R_d increases from 0.5 to 1.5.

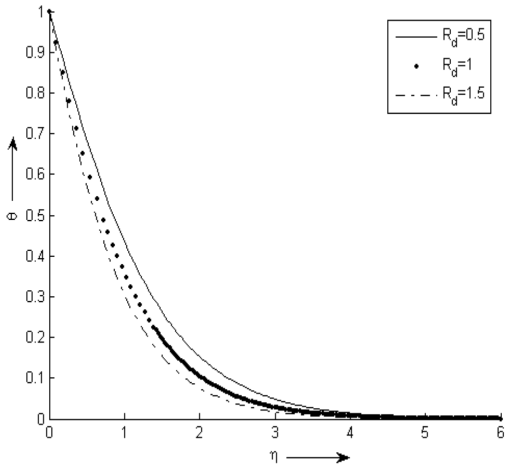

Figure.3 Effect of R_d on the temperature profiles

Fig.3 reveals that the effect of the increase in the value of the radiation parameter R_d decreases the temperature of the fluid at any point in the boundary layer.

It has been noticed from the Fig.4 that the effect of increase in the value of the radiation parameter R_d increases the concentration of the rare and lighter component of the fluid at any point in the boundary layer. It is also clear that the radiation parameter R_d has little effect in the concentration of the rarer and lighter component of the fluid as the term R_d comes from the energy equation and not from species diffusion equation.

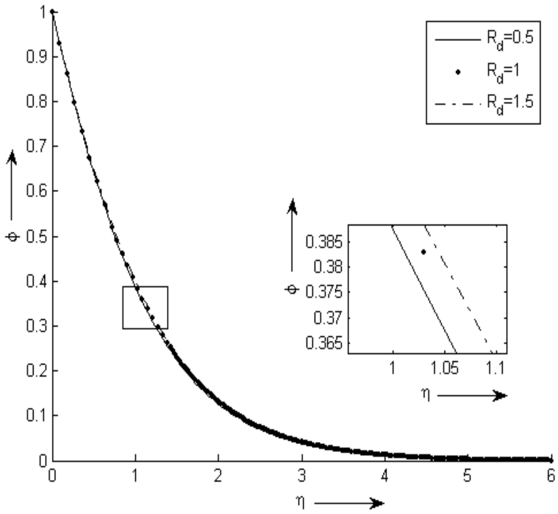

Figure.4 Effect of R_d on the concentration profiles

Figs.5-7 represent the tangential velocity, the temperature and the concentration profiles of the fluid for values of γ = [0, 0.5, 1], δ = 0.5; Pr = 0.71; R_d = 0.5, λ = 1; Sc = 0.6; M = 0.5; N = 1and f_w = 0.

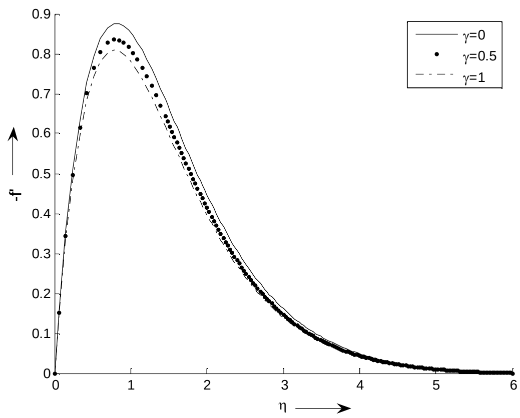

Figure.5 Effect of γ on the tangential velocity profiles

From the Fig.5 it is clear that the effect of increase in the value of the chemical reaction parameter γ decreases the tangential velocity component of the fluid at any point in the boundary layer.

Fig.6 reveals that the effect of the increase in the value of the chemical reaction parameter γ increases the temperature of the fluid slightly at any point in the boundary layer. The chemical reaction parameter γ has little effect on the temperature of the fluid as this parameter comes from the species diffusion equation and not from the energy equation.

It has been noticed from the Fig.7 that the effect of increase in the value of the chemical reaction parameter γ decreases the concentration of the rare and lighter component of the fluid at any point in the boundary layer.

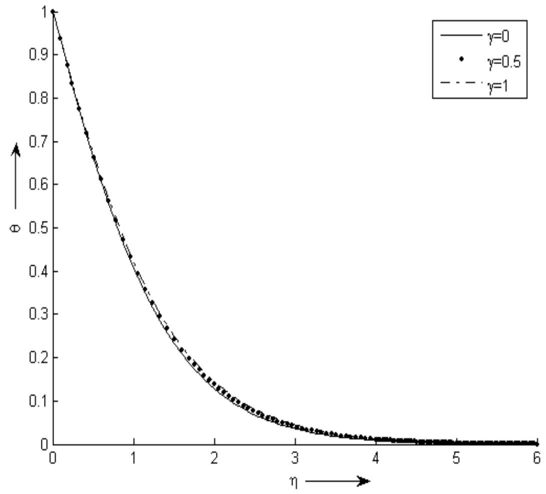

Figure.6 Effect of γ on the temperature profiles

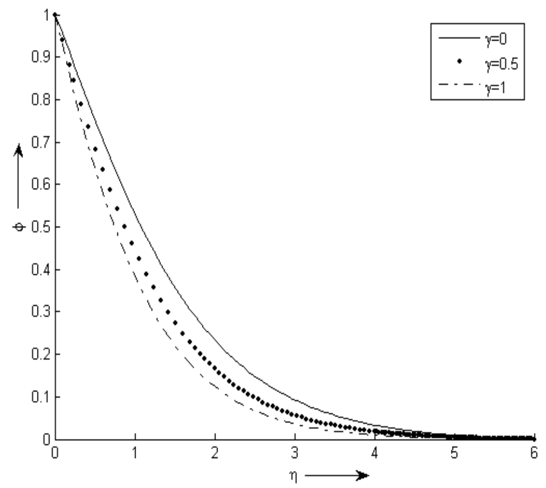

Figure.7 Effect of γ on the concentration profiles

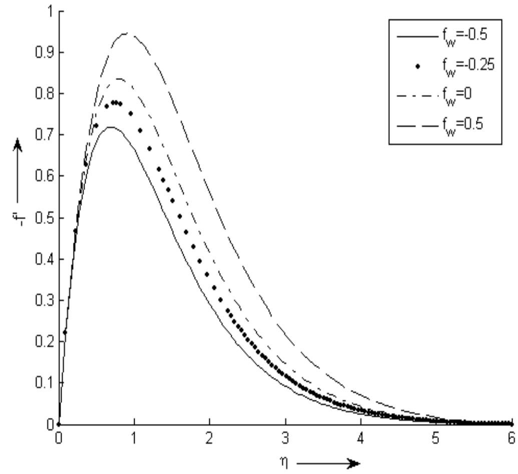

Figure.8 Effect of f_w on the tangential velocity profiles

Fig.8-10 show the tangential velocity, the temperature and the concentration profiles for values of f_w= [-0.5, -0.25, 0, 0.5], δ = 0.5; Pr = 0.71; R_d = 0.5, λ = 1; Sc = 0.6; M = 0.5; N = 1and γ = 0.5.

Figs.8-10 reveal that the effect of the increase in the value of the suction/injection parameter f_w the tangential velocity component, the temperature of the fluid and the concentration of the rarer and lighter component of the fluid increases.

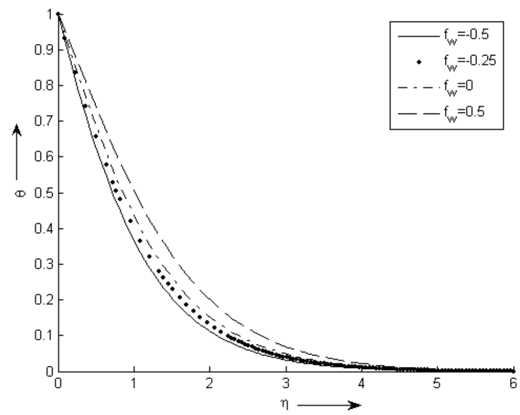

Figure.9 Effect of f_w on temperature profiles

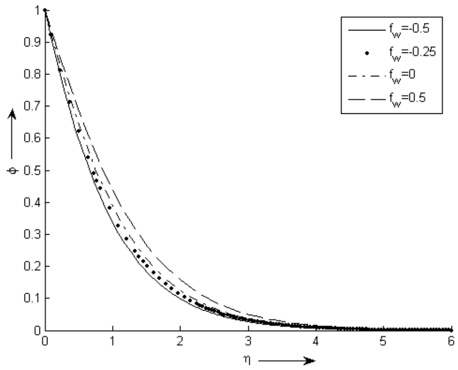

Figure.10 Effect of f_w on concentration profiles

Fig.11-13 show the tangential velocity, the temperature and the concentration profiles for values of Sc= [0.2, 0.5, 0, 0.8], δ = 0.5; Pr = 0.71; R_d = 0.5, λ = 1; M = 0.5; N = 1and γ=0.5.

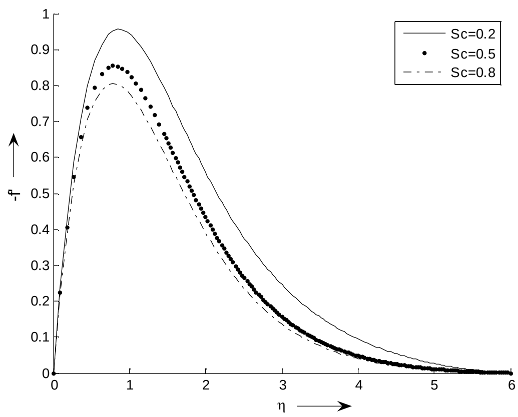

Figure.11 Effect of Sc on the tangential velocity profiles

Fig.11 depicts that as the value of Schmidt number increases the tangential velocity component of the fluid decreases. Maximum tangential velocity component of the fluid are recorded as 0.0.9566, 0.8537 and 0.8033 at η = 0.8485. Thus there is 16% decrease in tangential velocity component of the fluid as Sc increases from 0.2 to 0.8.

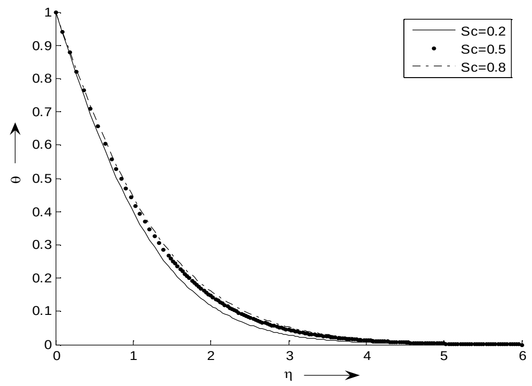

Figure.12 Effect of Sc on temperature profiles

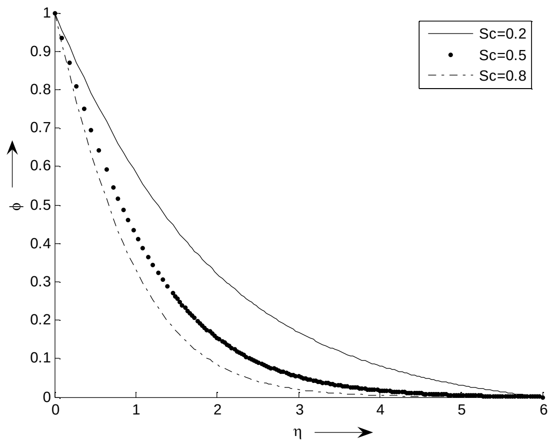

Figure.13 Effect of Sc on concentration profiles

Fig.12-13 reveal that increase in the value of Schmidt number Sc increases the temperature of the fluid and decreases the concentration of the rarer and lighter component of the fluid.

Finally the local skin friction, the Nusselt number and the Sherwood number which have practical importance are tabulated. The behaviours of these parameters are self evident and hence any further discussion about them seems to be redundant.

For Table: 1 f_w= 0, $\delta = 0.5$; $Pr = 0.71$; $\lambda = 1$;$Sc = 0.6$; $M = 0.5$; $N = 1$ and γ=0.5.

R_d	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.2	2.7523	0.5134	0.8144
0.4	2.7104	0.6140	0.8084
0.6	2.6753	0.7044	0.8035

Table:1

For Table: 2 f_w= 0, $\delta = 0.5$; $Pr = 0.71$; $\lambda = 1$;$Sc = 0.6$; $M = 0.5$; $N = 1$and R_d=0.5

γ	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	2.7598	0.6750	0.6212
0.5	2.6921	0.6603	0.8058
1	2.6424	0.6499	0.9609

Table:2

For Table: 3 $\delta = 0.5$; $Pr = 0.71$; $\lambda = 1$; $Sc = 0.6$; $M = 0.5$; $N = 1$; $R_d = 0.5$ and $\gamma=0.5$.

f_w	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
-1	2.6754	1.0643	1.1299
0	2.6921	0.6603	0.8058
1	2.4384	0.3781	0.5559

Table:3

For Table: 4 $\delta = 0.5$; $Pr = 0.71$; $\lambda = 1$; $M = 0.5$; $N = 1$; $f_w=0$; $R_d=0.5$ and $\gamma=0.5$.

Sc	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.2	2.8691	0.7044	0.4879
0.5	2.7227	0.6677	0.7418
0.8	2.6438	0.6490	0.9173

Table:4

V. CONCLUSION

From the above discussions it can be concluded that

1. The tangential velocity component and the temperature of the fluid decrease but the concentration of the rarer and lighter component of the fluid increases with the increase in the value of the radiation parameter R_d.
2. The tangential velocity component and the concentration of the rarer and lighter component of the fluid decrease but the temperature of the fluid increases with the increase in the value of the chemical reaction parameter γ.
3. The tangential velocity component, the temperature and the concentration of the rarer and lighter component of the fluid increases for suction/injection.
4. The tangential velocity component of the fluid and the concentration of the rarer and lighter component of the fluid decrease but the temperature of the fluid increases with the increase in the value of the Schmidt number Sc.

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