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Hydromagnetic Convection Squeezing Three-Dimensional Flow in a Rotating Channel

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Abstract: *The main objective of the present investigation is to study MHD effects on the three dimensional squeezing flow of an electrically conducting in a rotating channel and its heat and mass transfer characteristics. To the best of author's knowledge, such study has not received attention in the engineering sciences literature thus far. The governing equations are reduced to set of ordinary differential equations and then numerically solved by employing Runge-Kutta-Fehlberg fourth-fifth order method. Effect of pertinent parameters on velocity, temperature and concentration fields is examined through the plots. Skin-friction coefficients, Nusselt number and Sherwood number for different variations are studied numerically. The authors have hope that the results obtained in the present study not only provide useful information for applications, it also serves as a complement to the previous studies.*

Keywords: *Rotating Fluid, Vertical Channel, Heat Sources*

1. Introduction

The rotating viscous flow equation yields a layer known as Eckman boundary layer after the Swedish oceanographer Eckman who discovered it. Attempts to observe the structure of the Eckman layer in the surface layers of the sea have been successful. Eckman layers are easy to produce and observe in the laboratory. Such boundary layers or similar ones are required to connect principally geotropic flow in the interior of the fluid to the horizontal boundaries where conditions like a prescribed horizontal stress or no slip on a solid bottom are given. In a similar way other kinds of various boundaries have been studies so as to connect geotropic flow to vertical boundaries (for example a vertical well along which the depth varies) on which boundary conditions consistent with geotropic flow are given. Mahendra Mohan [31] has discussed the free and forced convections in rotating Hydromagnetic viscous fluid between two finitely conduction parallel plates maintained at constant temperature gradients. In view of many scientific and engineering applications of fluids flow through porous media, Mahendra Mohan and Srivastava [32] have studied the combined free and forced convection flow of an incompressible viscous fluid in a parallel plates channel bounded below by a permeable bed and rotating with a constant angular velocity about an axis perpendicular to the length of the plates. Rao et.al. [36] made an investigation of the combined free and forced convective effects on an unsteady Hydro magnetic viscous incompressible flow in a rotating porous channel. This analysis has been extended to porous boundaries by Sarojamma and Krishna [38]. An initial value investigation of the hydro magnetic and convective flow of a viscous electrically conducting fluid through a porous medium in a rotating channel has been made by Krishna et.al. [26]. In all these papers the viscous dissipative effect has not been considered. But the viscous dissipation has its importance when the natural convection flow fixed is of extreme size or the temperature is low or in higher gravity field. Seth and Ghosh [40] has investigated the unsteady hydromagnetic flow of viscous incompressible electrically conducting fluid in rotating channel under the influence of periodic pressure gradient and of uniform magnetic field, which is inclined with the axes of rotation. The problem of steady laminar micro polar fluid flow through porous walls of different permeability had been discussed by Agarwal and Dhanpal [2]. Steady and unsteady hydro magnetic flow of viscous incompressible electrically conducting fluid under the influence of constant and periodic pressure gradient in the presence of include magnetic field had been investigated by Ghosh [18] to study the effect of slowly rotating systems with low frequency of oscillation when the conductivity of the fluid is low and the applied magnetic field is weak. El-Mistikawy et.al. [17] were discussed the rotating disk flow in the presence of strong magnetic field and weak magnetic field. Hazim Ali Attia [19] was developed the MHD flow of incompressible, viscous and electrically conducting fluid above an infinite rotating porous disk was extended to flow starting impulsively from rest. The fluid was subjected to an external uniform magnetic field perpendicular to the plane of the disk. The effects of uniform suction or injection through the disk on the unsteady MHD flow were also considered. Circar and Mukherjee [15] have analyzed the effect of mass transfer and rotation on flow past a porous plate in a porous medium with variable suction in a slip flow regime. Balasubramanyam [10] and Madhusudhana Reddy [28] have investigated convective heat and mass transfer flow in horizontal rotating fluid under different conditions. Singh and Mathew [42] have studied on oscillatory free convective MHD flow in a rotating vertical porous channel with heat sources.

Rajasekhar et. al. [37] have analysed the effect of Hall current, thermal radiation and thermo-diffusion on convective heat and mass transfer flow of a viscous rotating fluid past a vertical porous plate embedded in a porous medium. Jafarunnisa [23] has discussed the effect of thermal radiation and thermo diffusion on unsteady convective heat and mass transfer flow in the rotating system with heat sources. Alam et. al. [4] have discussed the steady MHD combined heat and mass transfer flow through a porous medium past an infinite vertical plate with viscous dissipation and joule heating effects in a rotating system. Srirangavani [43] has considered the effect of thermo-diffusion on convective heat and mass transfer flow with radiation absorption. Jayasudha et al[24] have analysed the effect of thermo-diffusion on convective heat and mass transfer flow of viscous electrically conducting fluid in a vertical rotating plate in the presence of transverse magnetic field.

Kamalakar et. al. [25] have discussed the finite element analysis of chemical reaction effect on non-darcy convective heat and mass transfer flow through a porous medium in a vertical channel with heat sources. Muthcuumaraswamy et. al. [35] have studied the rotation effects on flow past an accelerated isothermal vertical plate with chemical reaction of first order. Jafarunnisa [23] has discussed the effect of thermal radiation and thermo diffusion on unsteady convective heat and mass transfer flow in the rotating system with heat sources. Alam et. al. [5] have discussed the steady MHD combined heat and mass transfer flow through a porous medium past an infinite vertical plate with viscous dissipation and joule heating effects in a rotating system. Recently Madhavilatha et al [27] have discussed the effect of non-linear density-temperature and concentration on rotating convective heat and mass transfer fluid flow past a porous stretching sheet with Soret and Dufour effects. Sukanya et al [44] have discussed combined influence of Hall Currents and Soret effect on convective heat and mass transfer flow past vertical porous stretching plate in rotating fluid and dissipation with constant heat and mass flux and partial slip.

On the other hand, an unsteady squeezing flow of an electrically conducting fluid occurs in many engineering and industrial applications such as lubrication, food industries, transient loading of mechanical components, power transmission, polymer processing, compression and injection modelling. Numerical solution for a fluid film squeezed between two parallel plane surfaces have been reported by Hamza and Macdonald [20]. Domairry and Aziz [16] studied the squeezing flow of viscous fluid between parallel disks with suction or blowing analytically. Heat and mass transfer in the unsteady squeezing flow between parallel plates is analyzed by Mustafa et al [34], Hamza [19] discussed the effect of suction and injection on the squeezing flow between parallel plates. It is noted that very little attention has been given to study the three-dimensional flow in a rotating channel. Munawar et al [33] studied the three-dimensional flow in a rotating channel of lower stretching sheet in the presence of MHD effects. The mathematical equations are modelled with the help of Navier-Stokes equation and then they are solved numerically. Hayat et al [21] have discussed an unsteady mixed convection three-dimensional squeezing flow of an incompressible Newtonian fluid between two vertical parallel planes. Mahantesh et al[29] have discussed the heat and mass transfer effects on the mixed convective flow of chemically reacting nanofluid past a moving / stationary vertical plate. Mahanthesh et al[29] have studied mixed MHD convection squeezing three-dimensional flow in a rotating channel filled with nanofluid.

In many industrial and engineering applications, the heat and mass transfer is a consequence of buoyancy effects caused by thermal diffusion and chemical species. Therefore the study of conjugate effects of heat and mass transfer is handy for improving many technologies such as underground energy transport, polymer and ceramic production, enhanced oil recovery, food processing, formation and dispersion of fog, the distribution of temperature and moisture over agricultural fields, and environmental pollution. The heat and mass transfer flow of an electrically conducting fluid in the presence of transverse magnetic field also finds a variety of applications such as MHD generators, pumps, flow meters, nuclear reactors, accelerators and in metallurgical industries. Its relevance is also seen in many practical applications in geophysical and astrophysical situations. Sarpkya[39] was the first to study the effectiveness of MHD flows in fluids. A few recent studies [3-14] regarding MHD heat and mass transfer with different physical conditions.

2. Mathematical Formulation

Consider an unsteady three-dimensional squeezing flow of an electrically conducting incompressible viscous fluid in a vertical rotating channel. The plane positioned at $y = 0$ is stretched with velocity $U_{wo} = ax/(1 - \alpha t)$ in x-direction and maintained at the constant temperature T_0 and concentration Co. The temperature at the other plane is T_h and located at a variable distance $h(t) = \sqrt{\nu_f (1-\alpha t)}$. In negative y-direction, the fluid is squeezed with a time dependent velocity $V_h = dh/dt = -\alpha / 2\sqrt{\nu_f / \alpha(1-\alpha t)}$. The fluid and the channel are rotated about y-axis with angular velocity $\vec{\Omega} = \omega \hat{j} /(1-\alpha t)$. The transverse magnetic field is assumed to be variable kind $\vec{B} = B_0 / \sqrt{(1-\alpha t)}$ and it is applied along y-axis. The fluid is sucked/injected from the plane located at $y = 0$ as shown in figure 1.The strength of the heat source Q and chemical reaction parameter kc are assumed to be $Q = \frac{Q_o}{(1-\alpha t)}, k_c^{'} = \frac{kc}{(1-\alpha t)}$ The magnetic Reynolds number is assumed to be small thus induced magnetic field is negligible. In addition, effects of Hall current, viscous dissipation and Joule heating are neglected.

Under those assumptions, the governing equations for the velocity and temperature fields in the presence of internal heating source/sink are given by [*Hayat et al* 2015, *Munawar et al* 2012].

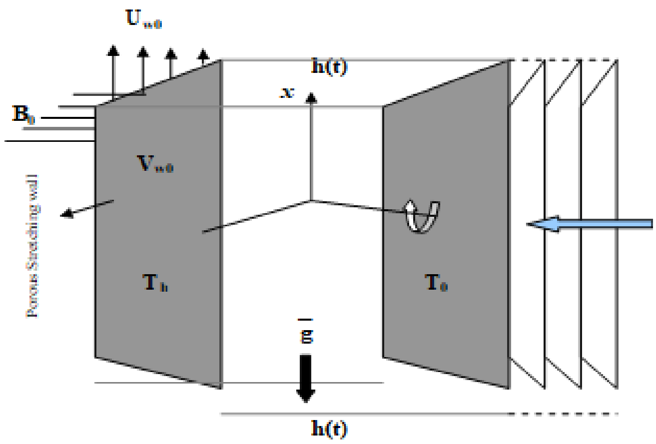

Fig1. *Flow configuration and coordinate*

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{2.1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + 2\frac{\omega}{1-\alpha t}w = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\sigma B_0^2}{\rho(1-\alpha t)}u + \frac{g\beta_T}{\rho}(T-T_0) + \frac{g\beta_c}{\rho}(C-C_0), \tag{2.2}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), \tag{2.3}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} - 2\frac{\omega}{1-\alpha t}u = \nu_{rf}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) - \frac{\sigma B_0^2}{\rho(1-\alpha t)}w, \tag{2.4}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_f}{(\rho C_p)}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q_0}{(\rho C_p)(1-\alpha t)}(T-T_0) \tag{2.5}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)-\frac{k_c}{(1-\alpha t)}(C-C_o) \tag{2.6}$$

where u, v and w are velocity components along x,y and z directions respectively, p is pressure. B_0 is the magnetic field, σ is the electrical conductivity, g is the magnitude of acceleration due to gravity, α is characteristic parameter with the dimension of reciprocal of time t and $\alpha t < 1$. T is temperature of the fluid ,C is the concentration, kc is the chemical reaction coefficient,Q_0 is uniform volumetric heat generation/ absorption; here $Q_0<0$ and $Q_0 > 0$ are respectively corresponds to internal heat absorption and generation, Dm is the molecular diffusivity, ρ_f is effective density of the nanofluid, $\nu_f = \mu_f / \rho_f$ is effective kinematic viscosity of the nanofluid, k_f and (ρC_p) are thermal conductivity and heat capacity of the fluid respectively.ρ_f is the density of base fluid, μ_f is the dynamic viscosity of the base fluid, The approximate boundary conditions for the present problem are;

$$\left.\begin{array}{ll} u(x,y,t)=U_{w0}, & v(x,y,t)=V_{w0}, \\ w(x,y,t)=0, & T(x,y,t)=T_0,\ C(x,y,t)=C_0, \end{array}\right| \quad \text{at } y=0 \tag{2.7}$$

$$\left.\begin{array}{ll} u(x,y,t)=0, & v(x,y,t)=V_h, \\ w(x,y,t)=0, & T(x,y,t)=T_h,\ C(x,y,t)=C_h \end{array}\right| \quad \text{at } y=h(t) \tag{2.8}$$

where $T_h = T_0 + T_0/(1-\alpha t),\ C_h = C_0 + C_0/(1-\alpha t), V_{w0} = -V_0/(1-\alpha t)$. Here V_0 is constant, $V_{w0} < 0$ corresponds injection whereas $V_{w0} > 0$ corresponds wall suction.

To reduce the governing equations into a set of similarity equations, introduce the following similarity transformations [*Munawar et al* 2012].

$$\psi=\sqrt{\frac{\alpha \nu_f}{1-\alpha t}}\,x f(\eta),\quad \eta=\frac{y}{h(t)}, T=T_0+\frac{T_0}{1-\alpha t}\theta(\eta), C=C_0+\frac{C_0}{1-\alpha t}C(\eta),$$
$$u=U_{w0} f_\eta \eta,\qquad v=-\sqrt{\frac{\alpha \nu_f}{1-\alpha t}}\,f(\eta),\qquad w=U_{w0}g(\eta), \tag{2.9}$$

where a suffix η denote the differentiation with respect to η and ν_f is the kinematic viscosity of the fluid. Using the above transformations (2.9), the equation (2.1) is automatically satisfied, while the equation (2.2) – (2.5) are respectively reduces to the following nonlinear ordinary differential equations;

$$f_{\eta\eta\eta}=\left[f\, f_{\eta\eta}-f_\eta^2-\beta\left(f_\eta \frac{\eta}{2} f_{\eta\eta}\right)-2Rg-M^2 f_\eta+G(\theta+NC)\right] = \frac{(1-\alpha t)^2}{\rho\ a^2 x}\frac{\partial p}{\partial x}, \tag{2.10}$$

$$f_{\eta\eta}-\left[-f\ f_\eta+\frac{\beta}{2}\left(f\ +\eta f_\eta\right)\right]=-\frac{1-\alpha t}{\rho \nu_f a}p_\eta, \tag{2.11}$$

$$g_{\eta\eta}+\left[f\, g_\eta-f_\eta g-\beta\left(g\ \frac{\eta}{2}g_\eta\right)+2Rf_\eta\right]-M^2 g=0, \tag{2.12}$$

$$\theta_{\eta\eta}+\Pr\left[\left\{\beta\left(\theta+\frac{\eta}{2}\theta_\eta\right)+f\theta_\eta\right\}-Q\theta\right]=0\,. \tag{2.13}$$

$$C_{\eta\eta}+Sc\left[\left\{\beta\left(C+\frac{\eta}{2}C_\eta\right)+fC_\eta\right\}-\gamma C\right]=0 \tag{2.14}$$

Reduced boundary conditions are;

$$f_\eta=1,\quad f=S,\quad g=0,\quad \theta=0, C=0 \qquad \text{at} \qquad \eta=0$$
$$f_\eta=0,\quad f=\frac{\beta}{2},\quad g=0,\quad \theta=1\quad ,C=1 \qquad \text{at} \qquad \eta=1 \tag{2.15}$$

where

$\beta = \alpha/\alpha$ is the squeezing parameter, $R = \omega/\alpha$ is rotation parameter, $M^2 = \sigma B_0^2 / \alpha\rho_f$ is magnetic parameter, $Gr = G / Re^2$ is mixed convection parameter, $G = g\beta_T T_0 x^3 / v_f^2 (1-\alpha t)$ is Grashaf number, $Re = xU_{w0} / v_f$ is Reynolds number, $N = \beta_c C_0 / \beta_T T_0$ is the buoyancy ratio,$Pr = (\mu c_p)_f / k_f$ is the Prandtl number, $Sc = \frac{v_f}{D_m}$ is the Schmidt number, $\gamma = \frac{kc}{a}$ *is the chemical reaction parameter,,* $Q = Q_0 / \alpha(\rho C_p)_f$ is heat source / sink parameter and $S = V_{w0} / \alpha h$ is suction / injection parameter.

It is important to mention that, β = 0 represents plates are stationary, β > 0 corresponds to the plate which is located at $y = h(t)$ moves towards the plate which is located at $y = 0$ and β <0 corresponds to the plate at $y = y(t)$ moves apart with respect to the plate at $y= 0$.

Now in order to reduce the number of independent variables by cross differentiation; the set of equations (2.10)-(2.13) takes the following form;

$$f_{\eta\eta\eta} - \left[\frac{\beta}{2}\left(3 f_{\eta\eta} + \eta f_{\eta\eta\eta}\right) f_\eta f_{\eta\eta} - f\, f_{\eta\eta\eta} + 2Rg_\eta\right] - M^2 f_{\eta\eta} + G(\theta_\eta + NC_\eta) = 0 \tag{2.16}$$

$$g_{\eta\eta} + \left[f\, g_\eta - f_\eta g - \beta\left(g + \frac{\eta}{2} g_\eta\right) + 2R\, f_\eta\right] - M^2 g = 0 \tag{2.17}$$

$$\theta_{\eta\eta} - \Pr\left(\left\{\beta\left(\theta + \frac{\eta}{2}\theta_\eta\right) + f\theta_\eta\right\} - Q\theta\right) = 0 \tag{2.18}$$

$$C_{\eta\eta} - Sc\left(\left\{\beta\left(C + \frac{\eta}{2} C_\eta\right) + f\theta_\eta\right\} - \gamma C\right) = 0 \tag{2.19}$$

For engineering and industrial point of view, one has usually less interest in velocity and temperature profiles nature than in the value of the skin-friction and rate of heat transfer. Therefore expression for the local skin-friction coefficient and the local Nusselt number at both the walls are defined as;

$$C_{f,\ \text{at}\ y=0}^{*} = \frac{(\tau_{xy})_{y=0}}{\rho_{nf} U_{w0}^2}, \qquad C_{f,\ \text{at}\ y=h(t)}^{*} = \frac{(\tau_{xy})_{y=h(t)}}{\rho_{nf} U_{w0}^2}, \tag{2.20}$$

$$Nu^{*}_{\text{at}\ y=0} = \sqrt{\frac{v_f}{a}} \frac{(q_{xy})_{y=0}}{k_f T_0}, \qquad Nu^{*}_{\text{at}\ y=h(t)} = \sqrt{\frac{v_f}{a}} \frac{(q_{xy})_{y=h(t)}}{k_f T_0}, \tag{2.21}$$

$$Sh^{*}_{\text{at}\ y=0} = \sqrt{\frac{v_f}{a}} \frac{(m_{xy})_{y=0}}{D_m C_0}, \qquad Sh^{*}_{\text{at}\ y=h(t)} = \sqrt{\frac{v_f}{a}} \frac{(m_{xy})_{y=h(t)}}{D_m C_0}, \tag{2.22}$$

where τ_{xy} is the shear stress , q_{xy} is the heat flux, and m_{xy} is the mass flux which are given by

$$\tau_{xt} = \mu_{nf}\left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y}\right),\ q_{xt} = -k_{nf}\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y}\right) \text{ and } m_{xt} = -D_m\left(\frac{\partial C}{\partial x} + \frac{\partial C}{\partial y}\right) \tag{2.23}$$

In view of equation (2.23) and similarity transformations (2.9); equations (2.20)-(2.22) will takes the following form;

$$\begin{aligned}
&C_{f,\ \text{at}\ y=0}^{*} = \sqrt{\text{Re}}\, C_{f,\ \text{at}\ y=0}^{*} = f_{\eta\eta}(0),\\
&C_{f,\ \text{at}\ y=h(t)}^{*} = \sqrt{\text{Re}}\, C_{f,\ \text{at}\ y=h(t)}^{*} = f_{\eta\eta}(1),\\
&Nu_{\text{at}\ y=0} = (1-\alpha t)^{1,5}\, Nu^{*}_{\text{at}\ y=0} = -\theta_\eta(0),\\
&Nu_{\text{at}\ y=h(t)} = (1-\alpha t)^{1,5}\, Nu^{*}_{\text{at}\ y=h(t)} = -\theta_\eta(1)\\
&Sh_{\text{at}\ y=0} = (1-\alpha t)^{1,5}\, Sh^{*}_{\text{at}\ y=0} = -C_\eta(0),\\
&Sh_{\text{at}\ y=h(t)} = (1-\alpha t)^{1,5}\, Sh^{*}_{\text{at}\ y=h(t)} = -C_\eta(1)
\end{aligned} \tag{2.24}$$

3. Numerical Method and Validation

A set of non-similar equations (2.16)-(2.19) are nonlinear in nature and possess no analytical solution, thus, a numerical treatment would be more appropriate. These set of ordinary differential equations together with the boundary conditions (2.15) are numerically solved by employing fourth-fifth order Runge-Kutta-Fehlberg scheme with the help of Maple. This algorithm in Maple is proven to be precise and accurate and which has been successfully used to solve a wide range of nonlinear problem in transport phenomena especially for flow and heat transfer problems. In this study, we set the relative error tolerance to 10^{-6}. Comparison results are recorded in table 1 and are found to be in excellent agreement. The effects of development of the squeezing three-dimensional flow and heat transfer in a rotating channel utilizing nanofluid are studied for different values of squeezing parameter, rotation parameter, magnetic parameter, suction/injection parameter, mixed convection parameter, radiation parameter, Prandtl number and heat source/sink parameter. In the following section, the results are discussed in detail with the aid of plotted graphs and tables.

We make an investigation of the three dimensional squeezing convective flow, heat and mass transfer flow of an electrically conducting fluid in a rotating channel in the presence of internal heat generating heat source/sink. In our numerical simulation the default values of te\he parameters are considered as: S=0.4, M^2=0.5,, Q=0.5.R=0.5, β=0.5, Pr=0.71,Sc=1.3,γ=0.5.In order to analyse the effects of various pertinent parameters on velocity, temperature and concentration profiles, several graphs are plotted.

Fig.2a-2d represent the effect of magnetic field on f′,g,θ and C. It can be found from the profiles that the velocity component g reduces with increase in M in the entire flow region(fig.2b),while the axial velocity f ′ reduces in the right half (0,0.5) and enhances in the left half (0.5,1.0) of the channel(fig.2a). The thickness of the thermal and solutal boundary layers enhance with increase in M which results in a rise in the temperature and concentration in the flow region (figs.2c&2d).

The influence of rotation parameter(R) on ,f′,g,θ and C can be observed from the figs.3a-3d.The transverse velocity g reduces with increase in R. The temperature and concentration distributions experience an enhancement in the entire flow region with increase in rotation parameter (R). This is due to the fact thickness of the thermal and solutal boundary layers increase with R.

The effect of buoyancy ratio(N) on f′,g,θ and C can be seen from the figs.4a-4d.It can be found from the profiles that when the molecular buoyancy force dominates over the thermal buoyancy force the axial velocity f ′(η) reduces in the region(0,0.5) and enhances in the region(0.5,1) when the buoyancy forces are in the same direction while for the forces acting in opposite directions, it enhances in the left half and reduces in the right half of the channel. The transverse velocity g(η) reduces with N>0 and enhances with N<0 in the left half and in the right half of the channel, it enhances with N>0,reduces with N<0.From figs.4c &4d we find that the temperature and concentration experience an enhancement with N>0 and reduction with N<0 in the entire flow region(0,1).

Figs.5a-5d are plotted to illustrate the effect of heat source parameter (Q) on the flow variables. It can be seen from the profiles that the axial and transverse velocity components reduce in the flow region with increase in the strength of the heat generating source and enhances in the case of heat absorbing source case. This may be attributed to the fact that in the presence of heat generating source, energy is absorbed in the flow region while in the case of heat absorbing heat source, energy is generating in the flow region.(figs.5a-5b). From figs.5c&5d we find that in the presence of heat generating source, energy is absorbed in the flow region, which results in a reduction in the temperature while in the presence of heat absorbing source, energy is generated which leads to an enhancement in the temperature. The effect of heat source parameter (Q) on the concentration is to reduce C with Q>0 and enhance with Q<0 in the entire flow region (fig.5d).

The effect of Schmidt number (Sc) on the flow variables are exhibited in figs.6a-6d. From the profiles we find that the axial and transverse velocities enhance with rise in Schmidt number. This is due to the fact that lesser the molecular diffusivity smaller the thickness of the momentum boundary layers (figs.6a-6b).An increase in Sc leads to a rise in thermal boundary later thickness and fall in the solutal boundary layer thickness(figs.6c&6c).

The effect of chemical reaction on f′,g,θ and C can be seen from figs.7a-7d.It can be see from the fig.8a the axial velocity and transverse velocity enhances in the degenerating case and reduces in the generating case in the left half while in the right half of the channel ,the axial velocity reduces, transverse velocity enhances for γ>0 and for γ<0,the axial velocity enhances ,the transverse velocity reduces in the flow region(figs.7a&7b).The temperature and concentration reduce in the degenerating chemical reaction case and enhance in the generating chemical reaction case(figs.7c&7d).

Figs.9a-9d present the typical profiles namely, f ′,g,θ and C respectively for different values of the squeezing parameter(β).From figs.9a&9b show that the magnitude of the axial velocity (f ′) is an increasing function and the transverse velocity g is a decreasing function of squeezing parameter. This implies that squeezing effect on flow field is accumulated by it An increase in β results in a reduction in the temperature and concentration (figs.9c&9d).

Figs.12a-12d illustrate the effect of suction /injection on the flow variables .It can be seen from the profiles that an increase in suction/injection parameter(fw>0,fw<0) enhances the transverse velocity component while the axial velocity component f ′ ′reduces with suction parameter and increases with injection parameter(fw<0)(figs.12a-12b).From figs.12c&12d we find that the temperature and concentration reduce with suction parameter(fw>0) and enhances with injection parameter (fw<0).

The Skin friction components τx,τy, Nusselt number and Sherwood number on the walls ($(\eta = 0{,}1)$ are exhibited in tables.1 for different parametric variations. The skin friction component τx enhances with increase on the left wall (η= 0) and reduces on the right wall (η=+1) with increase in M, while τz reduces on both walls with increases in G and M. An increase in rotation parameter (R) reduces τx and τz enhances on the left wall and while on the right wall, they enhance with R. With reference to buoyancy ratio(N) we find that when the molecular buoyancy force dominates over the thermal buoyancy force , τx enhances, τz reduces on the left wall and on the right wall, τx reduces , τz enhances when the buoyancy forces are in the sane direction and for the forces acting in opposite directions, τx, τz reduces on the left wall and enhances on the right wall .Lesser the molecular diffusivity smaller the skin friction component τx on both the walls while larger τz on $\eta = 0{,}1$.The variation of skin friction components with heat source parameter(Q) shows that τx enhances with increase in the strength of the heat generating source and depreciates with that of heat absorption source at both the walls . τz reduces with Q>0 and enhances with Q<0 at both the walls. With respect to chemical reaction parameter (γ),we find that τx reduces , τz enhances in the degenerating chemical reaction case while in the generating case, τx enhances, τz reduces on the left wall. On the right wall, τx enhances and τz reduces on the right wall in both the degenerating and generating chemical reaction cases. An increase in the squeezing parameter (β) smaller τx and larger τz at the left wall while on the right wall, they experience a reduction with increase in β.With reference to suction parameter (fw) we find that τx, τz at enhance with increase in suction parameter fw>0 at η=0, while for fw<0, τx reduces and τz enhances at the left wall. On the right wall (η=+1), skin friction components, experience an enhancement with increase in suction/injection parameters.

The rate of heat transfer (Nu) and mass transfer (Sh) at $\eta = 0{,}1$ are shown in table.1. The rate heat transfer enhances at the left wall and reduces at the right wall with increase in M, An increase in Sc enhances Nu at both the walls. The rate of heat transfer reduces at the left wall and enhances at the right wall with increase in R or β.When the molecular buoyancy force dominates over the thermal buoyancy force Nu reduces at the left wall irrespective of the buoyancy forces while at the right wall, Nu reduces with N>0 and enhances with N<0.An increase in Q>0,enhances Nu at the left wall and reduces at the right wall while Nu reduces at both the walls with Q<0.Also Nu reduces with γ>0 and enhances with γ<0 at the left wall while a reversed effect is noticed in Nu at the right wall. An increase in the suction parameter (fw>0) reduces Nu at the left wall and enhances at the right wall while a reversed effect is noticed in Nu with increase in fw<0.

An increase in M enhances the rate of mass transfer (Sh) at the left wall (η=0) and reduces at the right wall(η=+1). Sh reduces at both the walls with rotation parameter. The rate of mass transfer reduces at η=0 and enhances at η=+1 with increase in Sc,β.Sh reduces with N irrespective of the directions of the buoyancy forces at η=0 while at η=+1,Sh reduces with N>0 and enhances with N<0.Sh enhances at η=0 and reduces at η=+1 with increase in the strength of the heat generating/absorbing source. An increase in chemical reaction parameter (γ>0) reduces Sh at η=0 and enhances at η=+1 while a reversed effect is noticed in Sh with increase in γ<0.An increase in fw>0 reduces Sh at the left wall and enhances at the right wall while a reversed behaviour is noticed in Sh with fw<0.

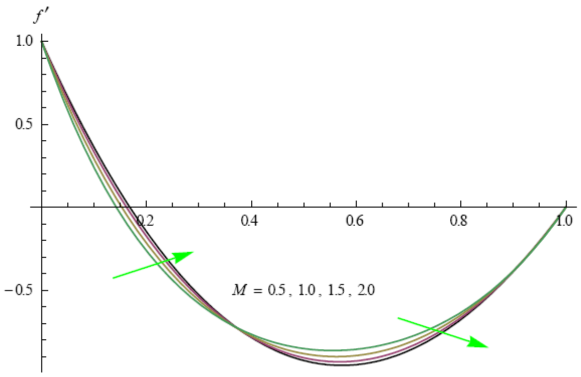

Fig2a. *Effect of M on f ′(η) profiles*

R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5,β=0.5

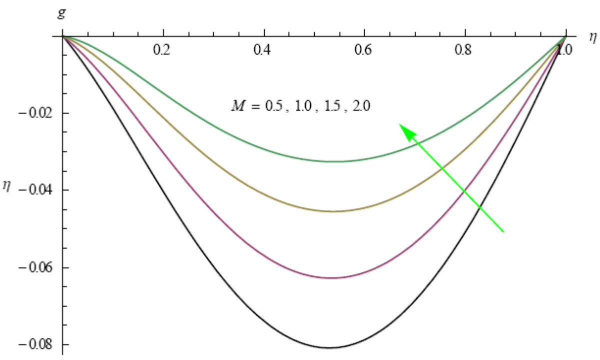

Fig2b. *Effect of M on g(η) profiles*

R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5,β=0.5

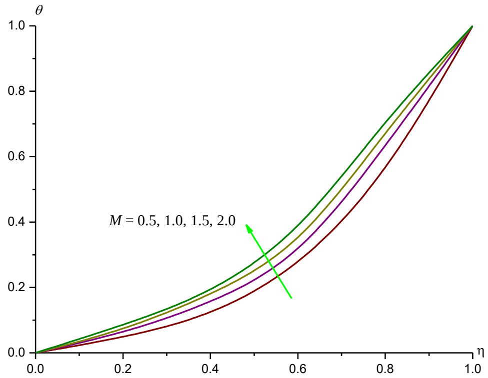

Fig2c. *Effect of M on temperature θ(η) profiles*

R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5,β=0.5

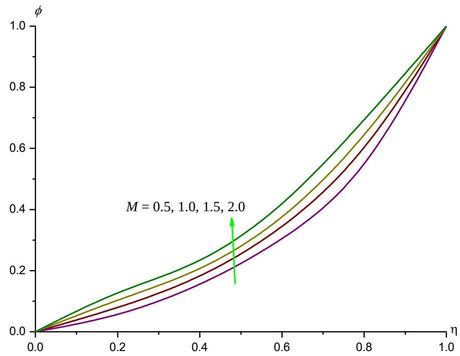

Fig2d. *Effect of M on Concentration ϕ(η) profiles*

R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5,β=0.5

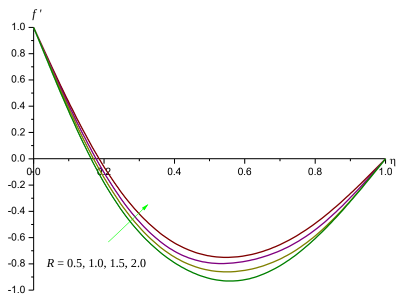

Fig3a. *Effect of R on f ′(η) profiles*

M=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5,β=0.5

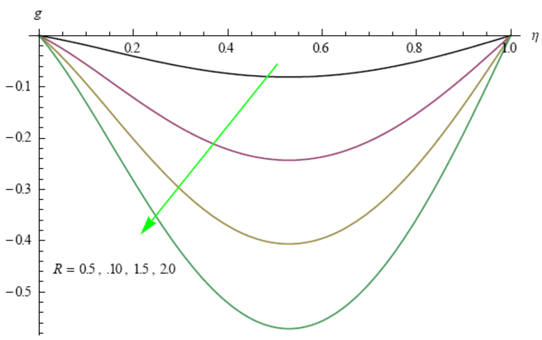

Fig3b. *Effect of R on g(η) profiles*

M=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5,β=0.5

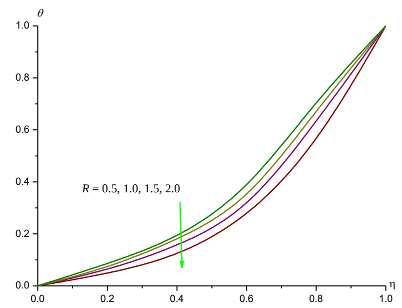

Fig3c. *Effect of R on temperature* $\theta(\eta)$ *profiles*

$G=2, M=0.5, N=0.5, Sc=1.3, Q=0.5, fw=0.2, \gamma=0.5, \beta=0.5$

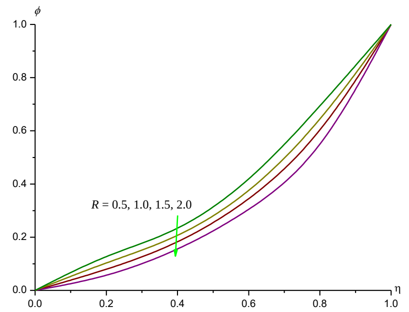

Fig3d. *Effect of R on Concentration* $\phi(\eta)$ *profiles*

$M=0.5, N=0.5, Sc=1.3, Q=0.5, fw=0.2, \gamma=0.5, \beta=0.5$

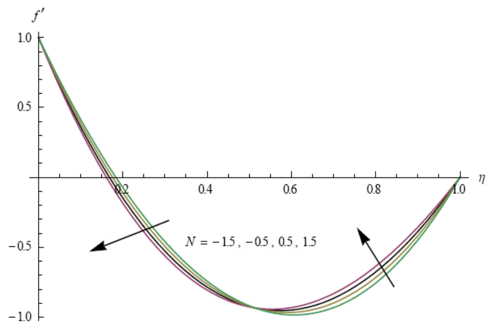

Fig4a. *Effect of N on* $f'(\eta)$ *profiles*

$M=0.5, R=0.5, Sc=1.3, Q=0.5, fw=0.2, \gamma=0.5, \beta=0.5$

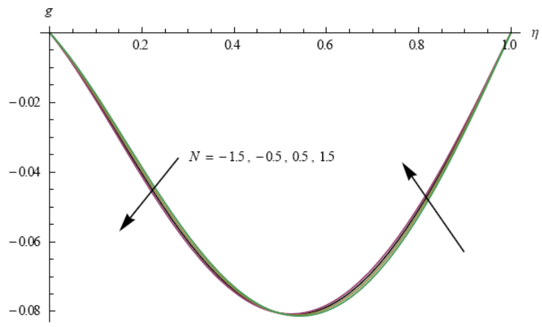

Fig4b. *Effect of N on* $g(\eta)$ *profiles*

$M=0.5, R=0.5, Sc=1.3, Q=0.5, fw=0.2, \gamma=0.5, \beta=0.5$

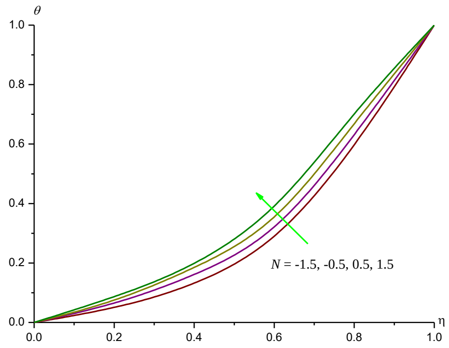

Fig4c. *Effect of N on temperature* $\theta(\eta)$ *profiles*

$M=0.5, R=0.5, Sc=1.3, Q=0.5, fw=0.2, \gamma=0.5, \beta=0.5$

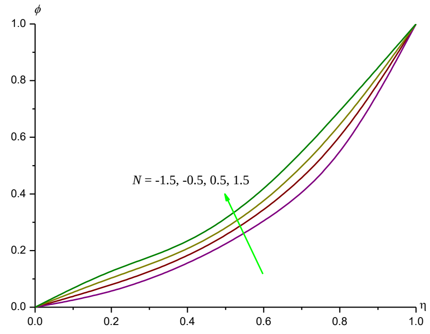

Fig4d. *Effect of N on Concentration* $\phi(\eta)$ *profiles*

$M=0.5, R=0.5, Sc=1.3, Q=0.5, fw=0.2, \gamma=0.5, \beta=0.5$

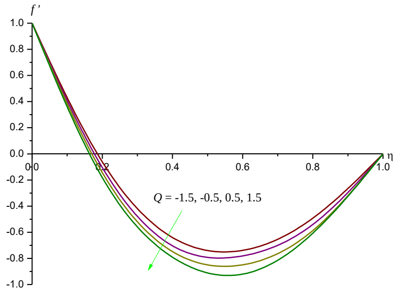

Fig5a. *Effect of Q on* $f'(\eta)$ *profiles*

$M=0.5, R=0.5, N=0.5, Sc=1.3, fw=0.2, \gamma=0.5, \beta=0.5$

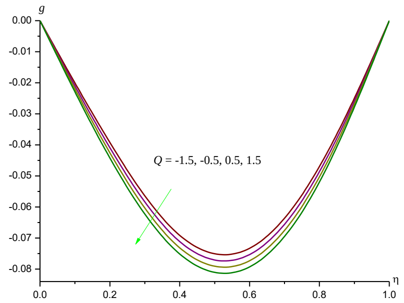

Fig5b. *Effect of Q on* $g(\eta)$ *profiles*

$M=0.5, R=0.5, N=0.5, Sc=1.3, fw=0.2, \gamma=0.5, \beta=0.5$

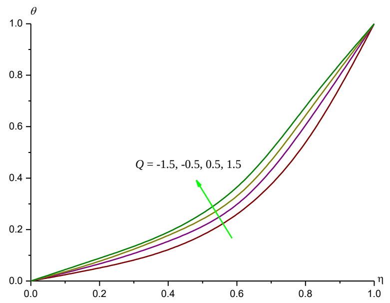

Fig5c. *Effect of Q on temperature θ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,fw=0.2,γ=0.5,β=0.5

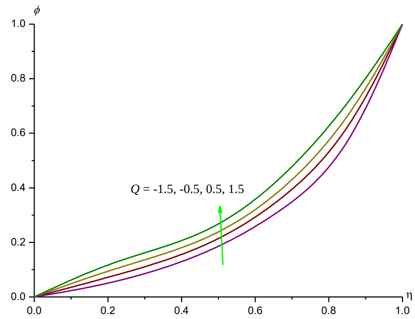

Fig5d. *Effect of Q on Concentration ϕ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,fw=0.2,γ=0.5,β=0.5

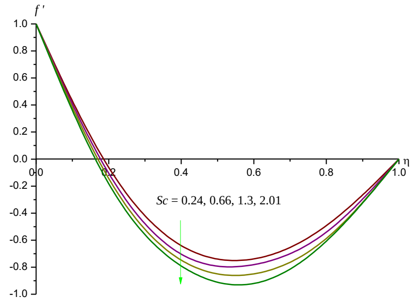

Fig6a. *effect of Sc on f ′(η) profiles*

M=0.5,R=0.5,N=0.5,Q=0.5,fw=0.2,γ=0.5,β=0.5

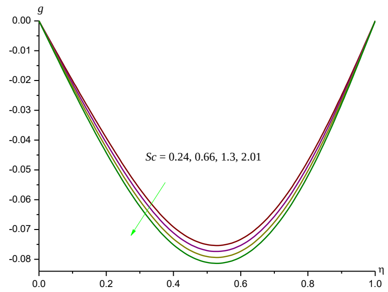

Fig6b. *Effect of Sc on g(η) profiles*

M=0.5,R=0.5,N=0.5,Q=0.5,fw=0.2,γ=0.5,β=0.5

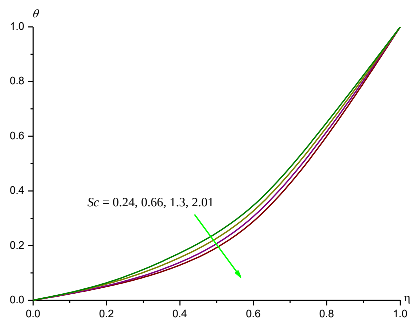

Fig6c. *Effect of Sc on temperature θ(η) profiles*

M=0.5,R=0.5,N=0.5,Q=0.5,fw=0.2,γ=0.5,β=0.5

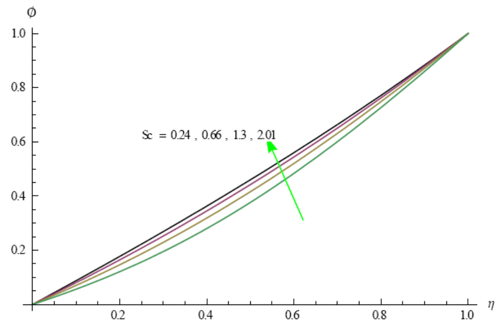

Fig6d. *Effect of Sc on Concentration ϕ(η) profiles*

M=0.5,R=0.5,N=0.5,Q=0.5,fw=0.2,γ=0.5,β=0.5

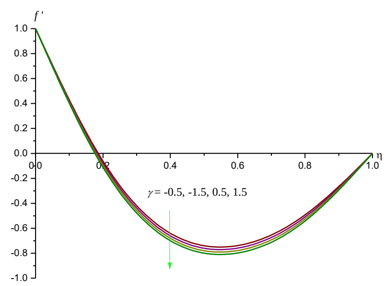

Fig7a. *Effect of γ on f ′(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,β=0.5

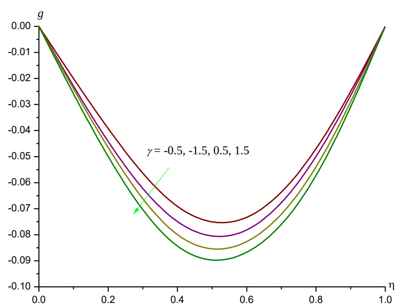

Fig7b. *Effect of γ on g(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,β=0.5

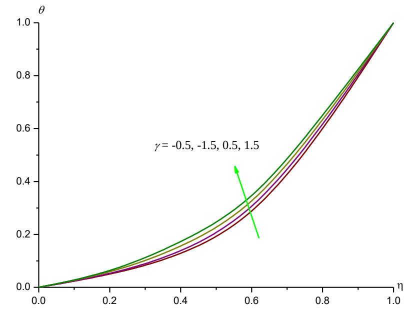

Fig7c. *Effect of γ on temperature θ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,β=0.5

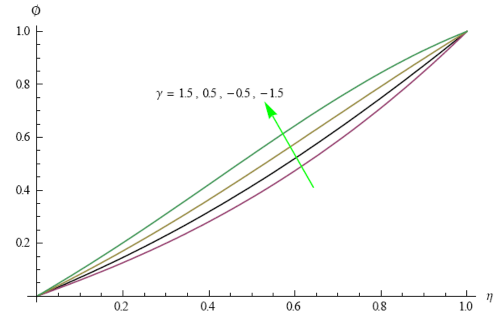

Fig7d. *Effect of γ on Concentration ϕ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,β=0.5

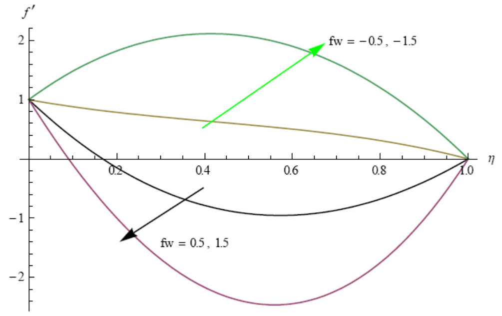

Fig8a. Effect of fw on f ′(η) profiles

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,γ=0.5,β=0.5

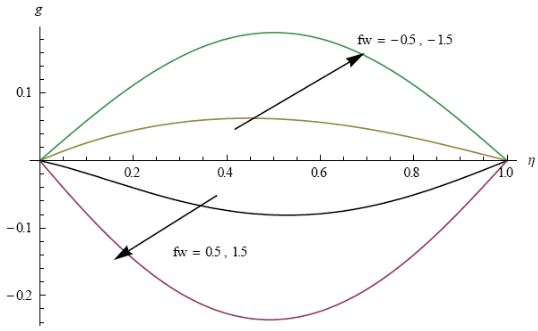

Fig8b. *Effect of fw on g(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,γ=0.5,β=0.5

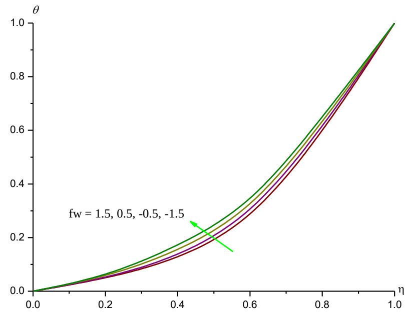

Fig8c. *Effect of fw on temperature θ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,γ=0.5,β=0.5

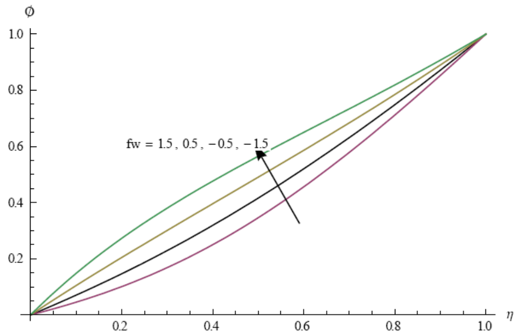

Fig8d. *Effect of fw on Concentration ϕ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,γ=0.5,β=0.5

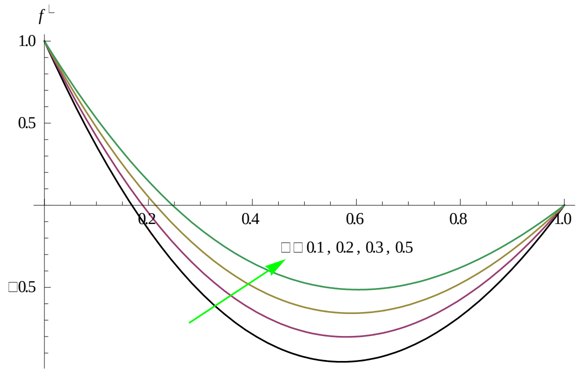

Fig9a. *Effect β on f ′(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5

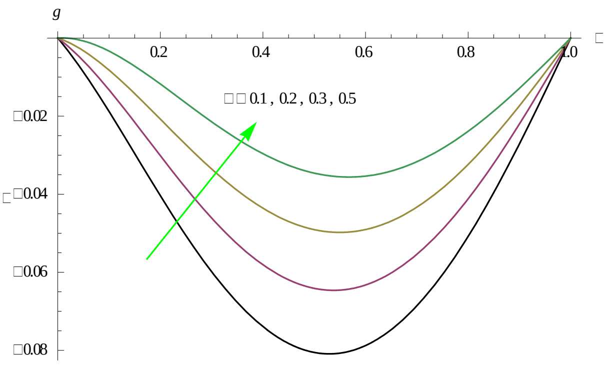

Fig9b. *Effect of β on g(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5

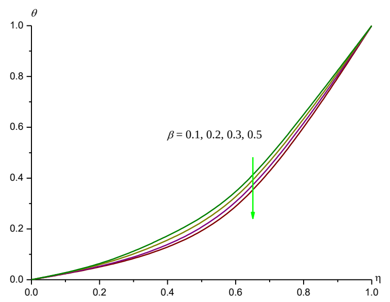

Fig9c. *Effect of β on temperature θ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5

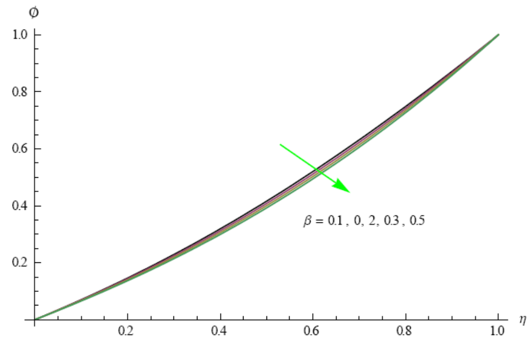

Fig9d. *Effect of β on Concentration ϕ(η) profiles*

M=0.5,R=0.5,N=0.5,Sc=1.3,Q=0.5,fw=0.2,γ=0.5

Table1. *Skin friction, Nusselt Number (Nu) and Sherwood Number (Sh) at η = 0&1*

Parameter		$\tau_x(0)$	$\tau_x(1)$	$\tau_z(0)$	$\tau_z(1)$	Nu(0)	Nu(1)	Sh(0)	Sh(1)
M	0.5	-3.64299	3.34299	-0.123687	0.257668	-0.999983	-1.00001	-0.678867	-1.31302
	1.0	-3.39487	3.39487	-0.099013	0.209074	-0.999996	-0.99991	-0.680826	-1.31128
	1.5	-3.49758	3.49758	-0.0493261	0.142466	-0.999999	-0.99886	-0.683623	-1.30892
	2.0	-3.66172	3.66172	-0.0216062	0.109722	-1.009983	-0.98765	-0.686811	-1.30635
R	0.5	-6.85256	3.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.0	-6.70169	3.28684	-0.460612	0.833542	-0.999983	-0.99966	-0.678729	-1.31305
	1.5	-6.59933	3.21431	-0.766162	1.391062	-0.999977	-0.99979	-0.678452	-1.31311
	2.0	-6.34424	3.10494	-1.069352	1.951422	-0.999969	-0.99989	-0.678024	-1.31322
N	0.5	-6.85256	3.34299	-0.153687	0.277668	-0.999955	-1.00001	-0.678867	-1.31302
	1.5	-7.11655	3.60221	-0.160138	0.271037	-0.999983	-0.99989	-0.682075	-1.30861
	-0.5	-6.49004	3.78487	-0.147259	0.284309	-0.999982	-0.98976	-0.675671	-1.31744
	-1.5	-6.12901	4.22783	-0.140853	0.290961	-0.999979	-0.99879	-0.672488	-1.32186
Sc	0.24	-6.85834	3.34218	-0.153648	0.277703	-0.999983	-1.00001	-0.871433	-1.18944
	0.66	-6.65611	3.34817	-0.153666	0.277687	-0.999986	-1.00005	-0.790292	-1.23831
	1.3	-6.55256	3.34299	-0.153687	0.277668	-0.999989	-1.00011	-0.678867	-1.31302
	2.01	-6.34666	3.33573	-0.153706	0.277652	-0.999995	-1.00021	-0.530181	-1.43098
γ	0.5	-6.85256	3.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.5	-7.00199	3.33981	-0.153604	0.277757	-0.999979	-1.00011	-0.583192	-1.59163
	-0.5	-6.96493	3.34739	-0.153777	0.277659	-0.999989	-0.99899	-0.797585	-1.00051
	-1.5	-7.00971	3.35347	-0.153874	0.277464	-0.999999	-1.00006	-0.947508	-0.64352
Q	0.5	-6.85256	3.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.5	-	3.34302	-0.153697	0.277671	-	-1.00022	-	-

		6.55256				0.999986		0.678865	1.31302
	-0.5	-6.45255	3.34289	-0.153667	0.277662	-0.999979	-1.00002	-0.678869	-1.31301
	-1.5	-6.05255	3.34279	-0.153647	0.277668	-0.999975	-0.99987	-0.678871	-1.31301
β	0.1	-6.85256	3.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	0.2	-6.09337	2.67161	-0.0958119	0.225586	-0.999977	-1.00002	-0.663103	-1.36765
	0.3	-5.27256	2.03904	-0.042952	0.177955	-0.999972	-1.00003	-0.648176	-1.42139
	0.5	-5.05864	1.41319	-0.028338	0.132139	-0.999968	-1.00004	-0.633338	-1.47682
fw	0.5	-6.85256	3.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.5	-8.87826	6.53222	-0.614385	0.758683	-0.999955	-1.00002	-0.408349	-1.50195
	-0.5	-1.15441	-1.44868	0.303601	-0.179279	-1.00001	-0.999998	-1.076812	-1.12831
	-1.5	-4.53239	-6.32726	0.720494	-0.602771	-1.00004	-0.999987	-1.624222	-0.95561

4. CONCLUSIONS

The effect of squeezing on rotating convective heat and mass transfer of an electrically conducting fluid in a vertical channel in the presence of heat sources has been analysed. It is found that an increase in squeezing parameter (β) enhances f ′ and reduces g. The temperature and concentration enhances with Rotation and soret parameter, reduces with squeezing parameter (β). Higher the thermal radiation larger the temperature and smaller the concentration in the flow region. The Nusselt number enhances with R,β while the Sherwood number reduces with R, and enhances with β on η=+1.

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