

# Mixed Convective Squeezing Three-Dimensional Hydro Magnetic Flow in a Rotating Channel with Thermal Radiation and Thermodiffusion

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**Abstract:** An attempt has been made to investigate the influence of thermal radiation and thermo diffusion on MHD convective heat and mass transfer flow of a chemically reacting, rotating fluid in vertical channel with squeezing effects. 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.

**Keywords:** Squeezing flow, rotating fluid, MHD, thermal radiation, thermo diffusion, heat sources, chemical reaction.

## 1. INTRODUCTION

The motion of rotation fluids enclosed with in a body or vice versa, was given by Greenspan [22], discussed these problems relating to the boundary layers and their interaction in rotating flows and gave so many examples relating to such interaction. 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 [36] 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 [37] 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. [44] 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 [47]. 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. [31]. 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 [49] 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 [20] 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. [19] were discussed the rotating disk flow in the presence of strong magnetic field and weak magnetic field. Hazim Ali Attia [26] 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 [16] 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 [33] have investigated convective heat and mass transfer flow in horizontal rotating fluid under different conditions. Singh and Mathew [53] have studied on oscillatory free convective MHD flow in a rotating vertical porous channel with heat sources. Madhavi et al[32] have investigated heat and mass transfer flow of a rotating fluid in a vertical channel with stretching and stationary walls. Sukanya et al[59] have studied the effect of non-uniform heat sources on convective heat and mass transfer flow in vertical channel bounded by Stretching walls.

Rajasekhar et. al. [45] 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 [28] has discussed the effect of thermal radiation and thermo diffusion on unsteady convective heat and mass transfer flow in the rotating system with heat surces. 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 [56] has considered the effect of thermo-diffusion on convective heat and mass transfer flow with radiation absorption. Jayasudha et al[29] 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. 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[48] 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.

Recently Sreevani [57] has discussed squeezing effect on hydromagnetic convective heat and mass transfer flow of rotating fluid in vertical channel in the presence of heat sources and chemical reaction effects.

When heat and mass transfer occur simultaneously in a moving fluid, the relation between the fluxes and the driving potentials are of more intricate nature. Mass fluxes can be created by temperature gradients and this is the Soret effect or thermo-diffusion effect. Adrian Postelnicu [1] has studied thermo-diffusion and diffusion thermo effects on combined heat and mass transfer through a porous medium under different conditions. On the other hand, Barletta [12] and Zanchini [62] pointed out that relevant effects of viscous dissipation on the temperature profiles and the Nusselt number may occur in the fully developed convection in tubes. In view of this, several authors, notably, [Barletta [12], Zanchini [62] and Sreevani [57]] have studied the effect of viscous dissipation on the convective flows past an infinite vertical plate and through vertical channels and ducts. Sivaiah et. al. [54] have studied the Thermo-Diffusion effects on convective heat and mass transfer through a porous medium in Ducts. Indudhar et. al. [27] have investigated the effect of thermo-diffusion on convective heat and mass transfer in a vertical channel. Madhusudhan Reddy et. al. [33] have investigated the effect of

thermo-diffusion and chemical reaction on non-darcy convective heat and mass transfer flow in a vertical channel with radiation. Kamalakar et. al. [30] 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. Muthcumaraswamy et. al. [40] have studied the rotation effects on flow past an accelerated isothermal vertical plate with chemical reaction of first order. Jafarunnisa [28] 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. Srirangavani [56] has considered the effect of thermo-diffusion on convective heat and mass transfer flow with radiation absorption. Jayasudha [29] has discussed combined influence of thermo-diffusion and radiation absorption on convective heat and mass transfer flow past a stretching sheet with constant wall heat and mass transfer. Recently Madhavilatha et al [32] 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 [59] 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. The squeezing flow of a fluid was first introduced by Stefan [58]. Following this work, many researchers have investigated such flow with different aspects. Numerical solution for a fluid film squeezed between two parallel plane surfaces have been reported by Hamza and Macdonald [24]. Domairry and Aziz [18] 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 [39], Hamza [23] 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 [38] 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 [25] have discussed an unsteady mixed convection three-dimensional squeezing flow of an incompressible Newtonian fluid between two vertical parallel planes. Mahantesh et al [34] have discussed the heat and mass transfer effects on the mixed convective flow of chemically reacting nanofluid past a moving / stationary vertical plate. Mahantesh et al [34] have studied mixed MHD convection squeezing three-dimensional flow in a rotating channel filled with nanofluid.

The radiative heat transfer has encountered a variety of applications such as nuclear power plants, gas turbines and propulsion devices for space vehicles, missiles and aircraft. Additionally, heat and mass transfer under the influence of chemical reaction has also attracted considerable attention of many authors due to their wide range of applications. Keeping this in view, conjugate heat and mass transfer flow past a vertical permeable plate with thermal radiation and chemical reaction is investigated by Pal and Talukdar [43]. They found that, the thermal radiation and chemical reaction effect decreases the velocity and concentration profiles. Numerical investigation of heat and mass transfer of an electrically conducting fluid over a moving surface with first order chemical reaction effect is carried out by Chamkha [15]. Uwanta and Omokhuale [61] have analysed the influence of radiation and chemical reaction effect on heat and mass transfer of a viscoelastic fluid in a fixed plane. The combined effects of radiation and chemical reaction on the MHD free convection flow of an electrically conducting viscous fluid over an inclined plate have been studied by Aly et al [6] and have obtained a closed form solution by employing Laplace transform technique. Das et al [17] have discussed the effect of radiation on unsteady free convective heat and mass transfer flow using Laplace transform method. Several attempts have been made to analyse the effect of thermal radiation and chemical reaction under different physical situations [Seth et al [49], Das [17], Muthcumaraswamy [41], Makinde [35], Gireesha [21], Turkyilmazoglu [60], Sheikholeslami [52], Nanda et al [42], Pal et al [43], Seth et al [50], Seth et al [51], Soundalgekar et al [55]].

The main objective of the present investigation is to study combined influence of thermal radiation and thermo diffusion on MHD convective heat and mass transfer flow of a chemically reacting, rotating fluid in vertical channel with squeezing effects. 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.

## 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  $C_0$ . The temperature at the other plane is  $T_h$  and located at a variable distance  $h(t) = \sqrt{v_f(1 - \alpha t)}$ . In negative  $y$ -direction, the fluid is squeezed with a time dependent velocity  $V_h = dh/dt = -\alpha/2\sqrt{v_f/\alpha(1 - \alpha t)}$ . 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  $Q = \frac{Q_0}{(1 - \alpha t)}$ ,  $k'_c = \frac{kc}{(1 - \alpha t)}$

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, temperature and concentration fields in the presence of internal heating source/sink under Rosseland approximation are given by [Hayat et al 2015, Munawar et al 2012].

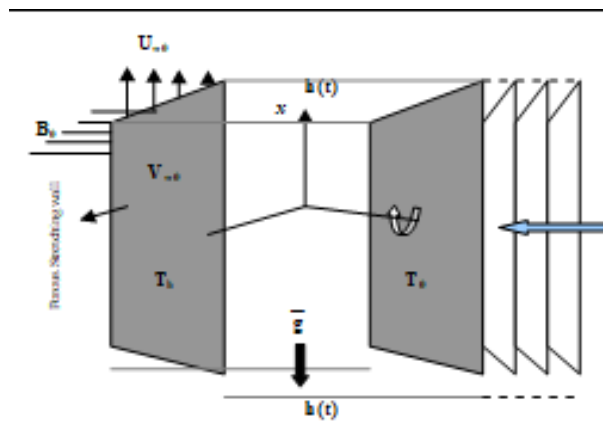


Fig1. Flow configuration and coordinate

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

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

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right), \tag{3}$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} - 2 \frac{\omega}{1 - \alpha t} w = \nu_r f \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) - \frac{\sigma B_0^2}{\rho(1 - \alpha t)} w, \tag{4}$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k_f}{(\rho C_p)} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{Q_0}{(\rho C_p)(1-\alpha)} (T - T_0) + \frac{16\sigma^* T_0^3}{3\beta_R} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (5)$$

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_B \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + \frac{D_B K_T}{T_m} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - \frac{k_c}{(1-\alpha)} (C - C_0) \quad (6)$$

where  $u, v$  and  $w$  are velocity components along  $x, y$  and  $z$  directions respectively,  $p$  is pressure.  $B_0$  is the magnetic field,  $\sigma$  is the electrical conductivity,  $g$  is the magnitude of acceleration due to gravity,  $\alpha$  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,  $k_c$  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,  $D_m$  is the molecular diffusivity,  $T_m$  is the mean fluid temperature,  $K_T$  is the thermal diffusion ratio,  $\rho_{nf}$  is effective density of the nanofluid,  $\nu_{nf} = \mu_{nf} / \rho_{nf}$  is effective kinematic viscosity of the nanofluid,  $k_f$  and  $(\rho C_p)$  are thermal conductivity and heat capacity of the fluid respectively.  $\rho_f$  is the density of base fluid,  $\mu_f$  is the dynamic viscosity of the base fluid,  $(\rho C_p)_f$  is the heat capacity of the base fluid,  $k_f$  is the thermal conductivity of the base fluid The approximate boundary conditions for the present problem are;

$$\left. \begin{aligned} u(x, y, t) = U_{w0}, & \quad v(x, y, t) = V_{w0}, \\ w(x, y, t) = 0, & \quad T(x, y, t) = T_0, C(x, y, t) = C_0, a \end{aligned} \right| \text{ at } y = 0 \quad (7)$$

$$\left. \begin{aligned} u(x, y, t) = 0, & \quad v(x, y, t) = V_h, \\ w(x, y, t) = 0, & \quad T(x, y, t) = T_h, C(x, y, t) = C_h \end{aligned} \right| \text{ at } y = h(t) \quad (8)$$

where  $T_h = T_0 + T_0/(1-\alpha)$ ,  $C_h = C_0 + C_0/(1-\alpha)$ ,  $V_{w0} = -V_0/(1-\alpha)$ . 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].

$$\psi = \sqrt{\frac{\alpha \nu_f}{1-\alpha}} x f(\eta), \quad \eta = \frac{y}{h(t)}, T = T_0 + \frac{T_0}{1-\alpha} \theta(\eta), C = C_0 + \frac{C_0}{1-\alpha} C(\eta), \quad (9)$$

$$u = U_{w0} f_\eta \eta, \quad v = -\sqrt{\frac{\alpha \nu_f}{1-\alpha}} f(\eta), \quad w = U_{w0} g(\eta),$$

where a suffix  $\eta$  denote the differentiation with respect to  $\eta$  and  $\nu_f$  is the kinematic viscosity of the fluid. Using the above transformations (9), the equation (1) is automatically satisfied, while the equation (2) – (5) are respectively reduces to the following nonlinear ordinary differential equations;

$$f_\eta \eta = \left[ f f_\eta \eta - f_\eta^2 - \beta \left( f_\eta \frac{\eta}{2} f_\eta \eta \right) - 2Rg - M^2 f_\eta + G(\theta + NC) \right] = \frac{(1-\alpha)^2}{\rho a^2 x} \frac{\partial p}{\partial x}, \quad (10)$$

$$f_\eta \eta - \left[ -f f_\eta + \frac{\beta}{2} (f + \eta f_\eta) \right] = -\frac{1-\alpha}{\rho \nu_f a} p_\eta, \quad (11)$$

$$g_\eta \eta + \left[ f g_\eta - f_\eta g - \beta \left( g \frac{\eta}{2} g_\eta \right) + 2Rf_\eta \right] - M^2 g = 0, \quad (12)$$

$$\left( 1 + \frac{4Rd}{3} \right) \theta_\eta \eta + Pr \left[ \beta \left( \theta + \frac{\eta}{2} \theta_\eta \right) + f \theta_\eta \right] - Q\theta = 0. \quad (13)$$

$$C_\eta \eta + Sc \left[ \beta \left( C + \frac{\eta}{2} C_\eta \right) + f C_\eta \right] + Sr \theta_\eta \eta - \gamma C = 0 \quad (14)$$

Reduced boundary conditions are;

$$f_\eta = 1, \quad f = S, \quad g = 0, \quad \theta = 0, C = 0 \quad \text{at} \quad \eta = 0$$



$$f_\eta = 0, \quad f = \frac{\beta}{2}, \quad g = 0, \quad \theta = 1, \quad C = 1 \quad \text{at} \quad \eta = 1 \quad (15)$$

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,  $G = g\beta_T T_0 x^3/v_f^2(1-\alpha)$  is Grashof 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,  $Sr = \frac{D_m K_T T_0}{a T_m C_0}$  is the Soret parameter

$\gamma = \frac{kc}{a}$  is the chemical reaction parameter,  $Rd = \frac{4\sigma^* T_0^3}{\beta_R k_f}$  is the Radiation 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,  $\beta = 0$  represents plates are stationary,  $\beta > 0$  corresponds to the plate which is located at  $y = h(t)$  moves towards the plate which is located at  $y = 0$  and  $\beta < 0$  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 (10)-(13) takes the following form;

$$f_{\eta\eta\eta} - \left[ \frac{\beta}{2} (3f_{\eta\eta} + \eta f_{\eta\eta\eta}) f_\eta f_{\eta\eta} - f f_{\eta\eta\eta} + 2Rg_\eta \right] - M^2 f_{\eta\eta} + G(\theta_\eta + NC_\eta) = 0 \quad (16)$$

$$g_{\eta\eta} + \left[ f g_\eta - f_\eta g - \beta \left( g + \frac{\eta}{2} g_\eta \right) + 2Rf_\eta \right] - M^2 g = 0 \quad (17)$$

$$\left( 1 + \frac{4Rd}{3} \right) \theta_{\eta\eta} - Pr \left( \left\{ \beta \left( \theta + \frac{\eta}{2} \theta_\eta \right) + f\theta_\eta \right\} - Q\theta \right) = 0 \quad (18)$$

$$C_{\eta\eta} - Sc \left( \left\{ \beta \left( C + \frac{\eta}{2} C_\eta \right) + fC_\eta \right\} - \gamma C + Sr\theta' \right) = 0 \quad (19)$$

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;

$$C_{f^*} \text{ at } y=0 = \frac{(\tau_{xy})_{y=0}}{\rho_f \eta f U_{w0}^2}, \quad C_{f^*} \text{ at } y=h(t) = \frac{(\tau_{xy})_{y=h(t)}}{\rho_f \eta f U_{w0}^2}, \quad (20)$$

$$Nu^* \text{ at } y=0 = \sqrt{\frac{vf}{a}} \frac{(q_{xy})_{y=0}}{k_f T_0}, \quad Nu^* \text{ at } y=h(t) = \sqrt{\frac{vf}{a}} \frac{(q_{xy})_{y=h(t)}}{k_f T_0}, \quad (21)$$

$$Sh^* \text{ at } y=0 = \sqrt{\frac{vf}{a}} \frac{(m_{xy})_{y=0}}{D_m C_0}, \quad Sh^* \text{ at } y=h(t) = \sqrt{\frac{vf}{a}} \frac{(m_{xy})_{y=h(t)}}{D_m C_0}, \quad (22)$$

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

$$\tau_{xt} = \mu \eta f \left( \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right), \quad q_{xt} = -k \eta f \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} \right) \text{ and } m_{xt} = -D_m \left( \frac{\partial C}{\partial x} + \frac{\partial C}{\partial y} \right) \quad (23)$$

In view of equation (23) and similarity transformations (9); equations (20)-(22) will takes the following form;

$$C_{f^*} \text{ at } y=0 = \sqrt{Re} C_{f^*} \text{ at } y=0 = f_{\eta\eta}(0),$$

$$C_{f^*} \text{ at } y=h(t) = \sqrt{Re} C_{f^*} \text{ at } y=h(t) = f_{\eta\eta}(1),$$

$$Nu^* \text{ at } y=0 = (1-\alpha)^{1.5} Nu^* \text{ at } y=0 = -\theta_\eta(0),$$

$$Nu_{\text{ at } y=h(t)} = (1-\alpha)^{1.5} Nu^*_{\text{ at } y=h(t)} = -\theta_{\eta}(1) \tag{24}$$

$$Sh_{\text{ at } y=0} = (1-\alpha)^{1.5} Sh^*_{\text{ at } y=0} = -C_{\eta}(0),$$

$$Sh_{\text{ at } y=h(t)} = (1-\alpha)^{1.5} Sh^*_{\text{ at } y=h(t)} = -C_{\eta}(1)$$

### 3. NUMERICAL METHOD AND VALIDATION

A set of non-similar equations (16)-(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 condition (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  $10^{-6}$ . The effects of development of the squeezing three-dimensional flow and heat transfer in a rotating channel are studied for different values of squeezing parameter, rotation parameter, radiation parameter, Soret parameter 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 the parameters are considered as:  $Q=0.5, R=0.5, \beta=0.5, Sr=0.5, \gamma=0.5$ . In order to analyse the effects of various pertinent parameters on velocity, temperature and concentration profiles, several graphs are plotted.

The influence of rotation parameter(  $R$  ) on  $f', g, \theta$  and  $C$  can be observed from the figs.2a-2d. 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 influence of thermal radiation on  $f', g, \theta$  and  $C$ . It can be seen from the profiles(figs.2a-2d) that there is a significant depreciation in the magnitude of the velocity component  $f'$  and  $g$  in the presence of thermal radiation throughout the flow region.

Figs.3a-3d 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.3a-3b). From figs.3c&3d 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.3d).

The effect of chemical reaction on  $f', g, \theta$  and  $C$  can be seen from figs.4a-4d. It can be seen from the fig.4a 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  $\gamma > 0$  and for  $\gamma < 0$ , the axial velocity enhances, the transverse velocity reduces in the flow region(figs.4a&4b). The temperature and concentration reduce in the degenerating chemical reaction case and enhance in the generating chemical reaction case(figs.4c&4d).

The effect of thermo-diffusion on  $f', g, \theta$  and  $C$  is depicted in figs.5a-5d. It can be seen from the profiles that higher the thermo-diffusion smaller all the axial, transverse velocity components(figs.5a-5b). From figs.5c&5d we find that a rise in Soret parameter( $Sr$ ) results in an increment in the thermal and solutal boundary layers thickness which leads to a rise in temperature and concentration in the entire flow region.

From Figs.6a-6d represents the radiation parameter is found to reduce the hydrodynamic boundary layers along  $x$  and  $y$ -directions. The presence of the thermal radiation is very significant on the

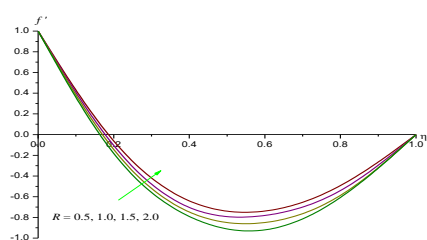
variation of temperature. It is seen that the temperature increases rapidly in the presence of thermal radiation parameter throughout the flow region. This may be attributed to the fact that as the Roseland radiative absorption parameter  $R^*$  diminishes the corresponding heat flux diverges and thus rising the rate of radiative heat transfer to the fluid causing a rise in the temperature of the fluid. The thickness of the thermal boundary layer also increases with increase in  $Rd$ (fig.6c).The effect of mass concentration can be seen from fig.6d.We find a depreciation in the concentration with a rise in  $Rd$ , owing to a fall in the thickness of the solutal boundary layer.

Figs.7a-7d present the typical profiles namely,  $f', g, \theta$  and  $C$  respectively for different values of the squeezing parameter( $\beta$ ).From figs.7a&7b 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  $\beta$  results in a reduction in the temperature and concentration (figs.7c&7d).

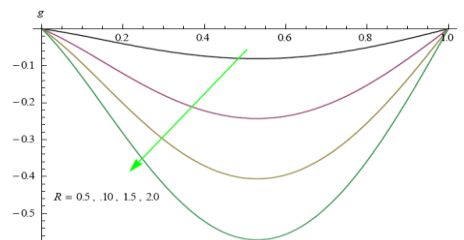
The Skin friction components  $\tau_x, \tau_y$ , Nusselt number and Sherwood number on the walls ( $\eta = 0, 1$ ) are exhibited in table.1 for different parametric variations. An increase in rotation parameter ( $R$ ) reduces  $\tau_x$  and  $\tau_z$  enhances on the left wall and while on the right 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,  $\tau_x$  enhances,  $\tau_z$  reduces on the left wall and on the right wall,  $\tau_x$  reduces,  $\tau_z$  enhances when the buoyancy forces are in the same direction and for the forces acting in opposite directions,  $\tau_x, \tau_z$  reduces on the left wall and enhances on the right wall. Higher the radiative heat flux larger the skin friction components on both the walls. Lesser the molecular diffusivity smaller the skin friction component  $\tau_x$  on both the walls while larger  $\tau_z$  on  $\eta = 0, 1$ . The variation of skin friction components with heat source parameter( $Q$ ) shows that  $\tau_x$  enhances with increase in the strength of the heat generating source and depreciates with that of heat absorption source at both the walls.  $\tau_z$  reduces with  $Q > 0$  and enhances with  $Q < 0$  at both the walls. With respect to chemical reaction parameter ( $\gamma$ ), we find that  $\tau_x$  reduces,  $\tau_z$  enhances in the degenerating chemical reaction case while in the generating case,  $\tau_x$  enhances,  $\tau_z$  reduces on the left wall. On the right wall,  $\tau_x$  enhances and  $\tau_z$  reduces on the right wall in both the degenerating and generating chemical reaction cases. Higher the thermo-diffusion effect larger  $\tau_x$  and smaller  $\tau_z$  at both the walls. An increase in the squeezing parameter ( $\beta$ ) smaller  $\tau_x$  and larger  $\tau_z$  at the left wall while on the right wall, they experience a reduction with increase in  $\beta$ .

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  $Rd$ . An increase in  $Sr$  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  $\beta$ . 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  $\gamma > 0$  and enhances with  $\gamma < 0$  at the left wall while a reversed effect is noticed in  $Nu$  at the right wall.

An increase in  $Sr$  enhances the rate of mass transfer ( $Sh$ ) at the left wall ( $\eta = 0$ ) and reduces at the right wall ( $\eta = +1$ ).  $Sh$  reduces at both the walls with rotation parameter. The rate of mass transfer reduces at  $\eta = 0$  and enhances at  $\eta = +1$  with increase in  $Rd$  and  $\beta$ . An increase in chemical reaction parameter ( $\gamma > 0$ ) reduces  $Sh$  at  $\eta = 0$  and enhances at  $\eta = +1$  while a reversed effect is noticed in  $Sh$  with increase in  $\gamma < 0$ .

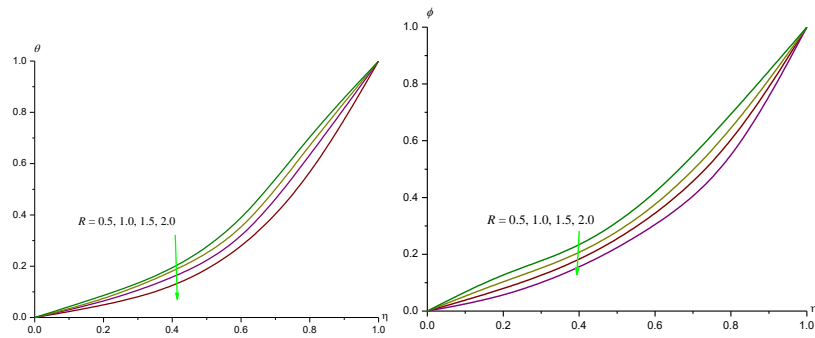


**Fig2a.** effect of  $R$  on  $f'(\eta)$  profiles  
 $Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



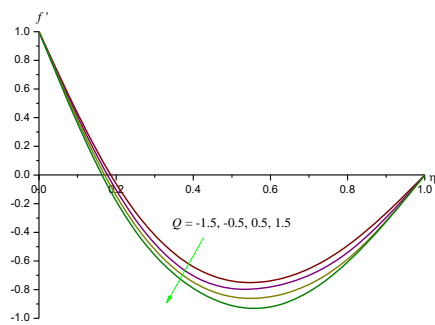
**Fig2b.** Effect of  $R$  on  $g(\eta)$  profiles  
 $Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



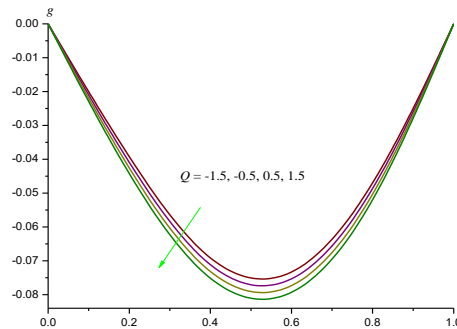


**Fig2c.** Effect of  $R$  on temperature  $\theta(\eta)$  profiles  
 $Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$

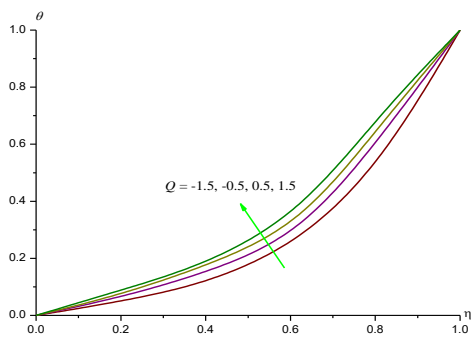
**Fig2d.** Effect of  $R$  on Concentration  $\phi(\eta)$  profiles  
 $Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



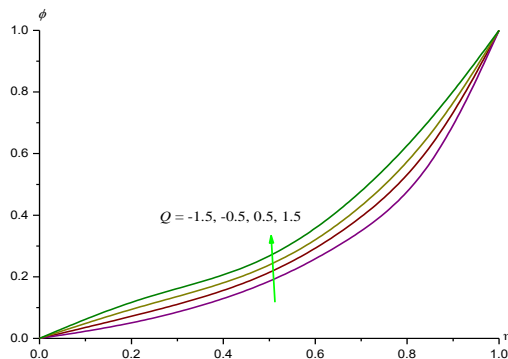
**Fig3a.** Effect of  $Q$  on  $f'(\eta)$  profiles  
 $R=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



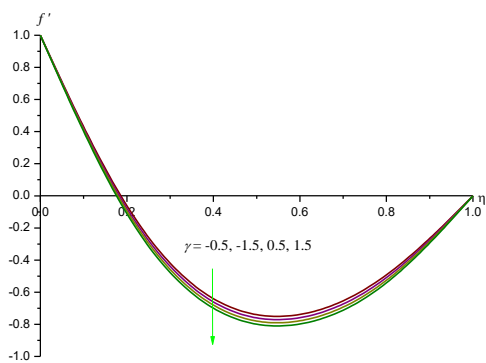
**Fig3b.** Effect of  $Q$  on  $g(\eta)$  profiles  
 $R=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



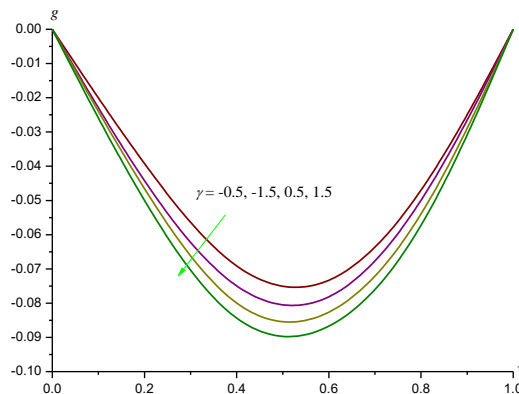
**Fig3c.** Effect of  $Q$  on temperature  $\theta(\eta)$  profiles  
 $R=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



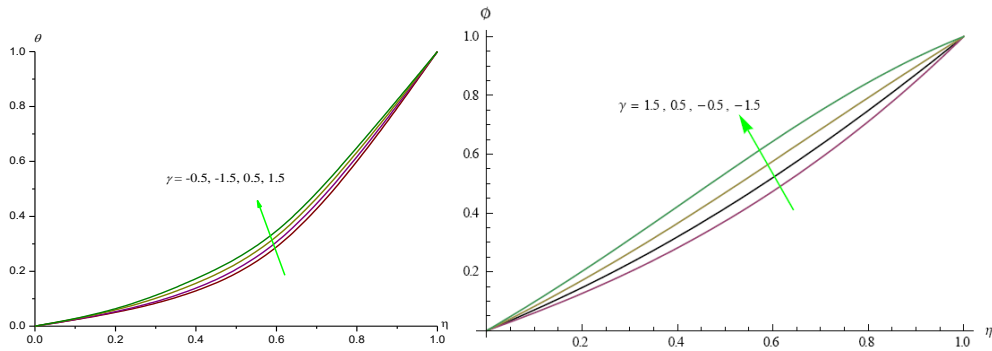
**Fig3d.** Effect of  $Q$  on Concentration  $\phi(\eta)$  profiles  
 $R=0.5, Sr=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



**Fig4a.** Effect of  $\gamma$  on  $f'(\eta)$  profiles  
 $R=0.5, Q=0.5, Sr=0.5, \beta=0.5, Rd=0.5$

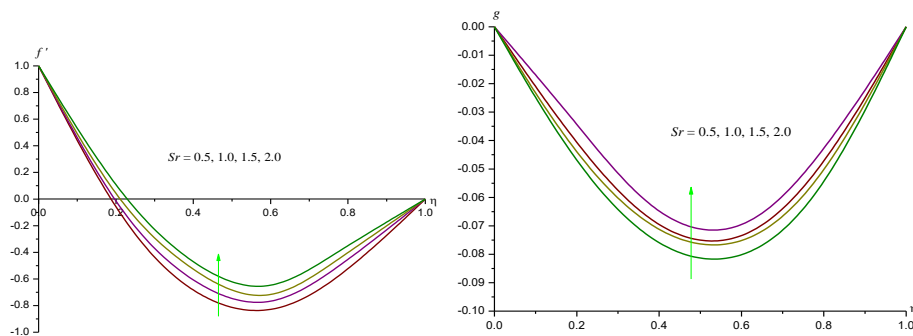


**Fig4b.** Effect of  $\gamma$  on  $g(\eta)$  profiles  
 $R=0.5, Q=0.5, Sr=0.5, \beta=0.5, Rd=0.5$



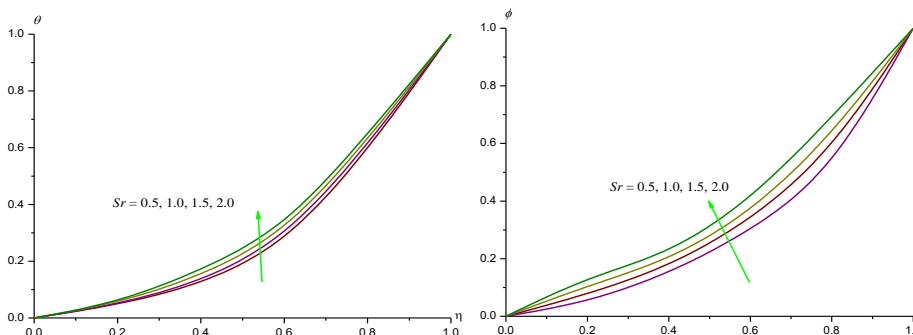
**Fig4c.** Effect of  $\gamma$  on temperature  $\theta(\eta)$  profiles  
 $R=0.5, Q=0.5, Sr=0.5, \beta=0.5, Rd=0.5$

**Fig4d.** Effect of  $\gamma$  on Concentration  $\phi(\eta)$  profiles  
 $R=0.5, Q=0.5, Sr=0.5, \beta=0.5, Rd=0.55$



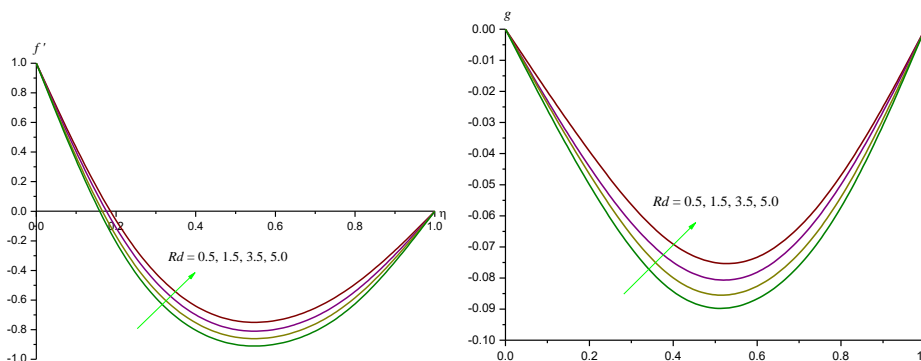
**Fig5a.** Effect of  $Sr$  on  $f'(\eta)$  profiles  
 $R=0.5, Q=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$

**Fig5b.** Effect of  $Sr$  on  $g(\eta)$  profiles  
 $R=0.5, Q=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



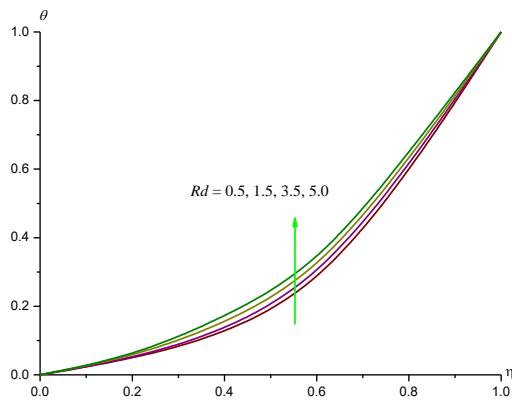
**Fig5c.** Effect of  $Sr$  on temperature  $\theta(\eta)$  profiles  
 $R=0.5, Q=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$

**Fig5d.** Effect of  $Sr$  on Concentration  $\phi(\eta)$  profiles  
 $R=0.5, Q=0.5, \gamma=0.5, \beta=0.5, Rd=0.5$



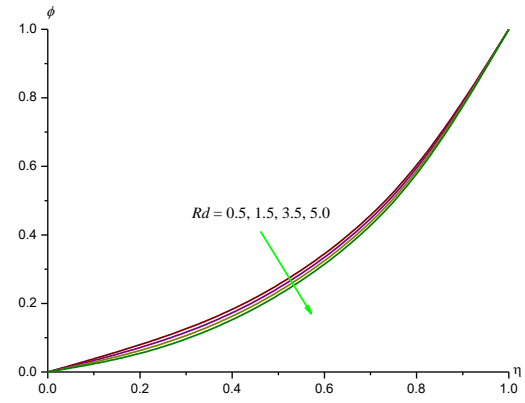
**Fig6a.** Effect of  $Rd$  on  $f'(\eta)$  profiles  
 $R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5$

**Fig6b.** Effect of  $Rd$  on  $g(\eta)$  profiles  
 $R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5$



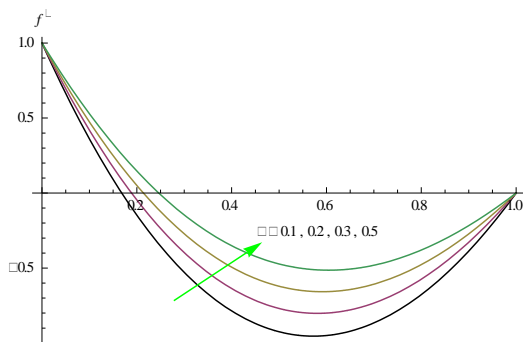
**Fig6c.** Effect of  $Rd$  on temperature  $\theta(\eta)$  profiles

$R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5$



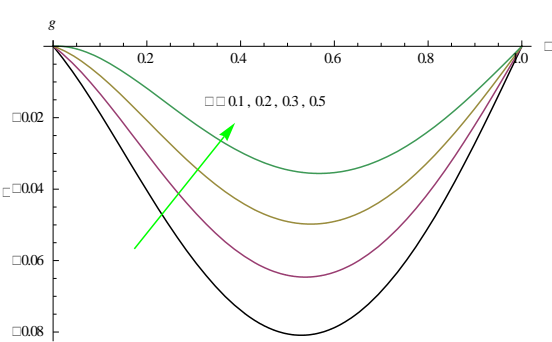
**Fig6d.** Effect of  $Rd$  on Concentration  $\phi(\eta)$  profiles

$R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, \beta=0.5$



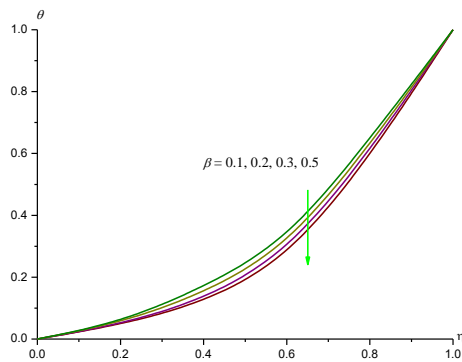
**Fig7a.** Effect  $\beta$  on  $f'(\eta)$  profiles

$R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, Rd=0.5$



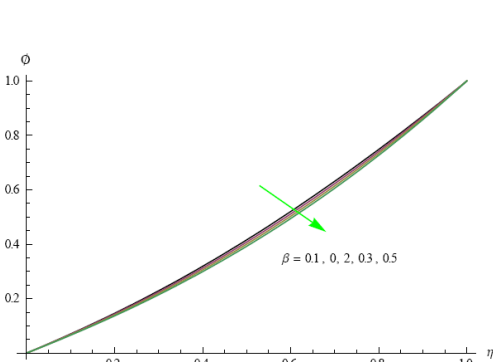
**Fig7b.** Effect of  $\beta$  on  $g(\eta)$  profiles

$R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, Rd=0.5$



**Fig7c.** Effect of  $\beta$  on temperature  $\theta(\eta)$  profiles

$R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, Rd=0.5$



**Fig7d.** Effect of  $\beta$  on Concentration  $\phi(\eta)$  profiles

$R=0.5, Q=0.5, Sr=0.5, \gamma=0.5, Rd=0.5$

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

Parameter	$\tau_x(0)$	$\tau_x(1)$	$\tau_z(0)$	$\tau_z(1)$	$Nu(0)$	$Nu(1)$	$Sh(0)$	$Sh(1)$	
<b>R</b>	0.5	-7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.0	-7.00169	4.30684	-0.46061	0.833542	-0.999983	-1.00001	-0.678729	-1.31305
	1.5	-6.89933	4.23431	-0.76616	1.39106	-0.999983	-1.00001	-0.67845	-1.31311
	2.0	-6.74424	4.12494	-1.06935	1.9514	-0.999983	-1.00001	-0.678024	-1.31322
<b><math>\gamma</math></b>	0.5	-7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302

	1.5	- 7.04199	4.33981	-0.153604	0.277757	-0.999983	-1.00001	-0.58319	-1.59163
	-0.5	- 7.06493	4.34739	-0.153777	0.27757	-0.999983	-1.00001	-0.797585	-1.0005
	-1.5	- 7.07971	4.35347	-0.153874	0.277464	-0.999983	-1.00001	-0.947508	- 0.643519
<b>Sr</b>	0.5	- 7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.0	- 7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678887	-1.31301
	1.5	- 7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678906	-1.313
	2.0	- 7.05256	4.343	-0.153687	0.277668	-0.999983	-1.00001	-0.678926	-1.31298
<b>Q</b>	0.5	- 7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	1.5	- 7.05256	4.34299	-0.153687	0.277668	-0.999986	-1	-0.678865	-1.31302
	-0.5	- 7.05255	4.34299	-0.153687	0.277668	-0.999979	-1.00002	-0.678869	-1.31301
	-1.5	- 7.05255	4.34299	-0.153687	0.277668	-0.999975	-1.00002	-0.678871	-1.31301
<b>Rd</b>	0.5	- 7.05256	4.34299	-0.153687	0.277668	-0.999983	- 0.678867	-0.678867	-1.31302
	1.5	- 7.05261	4.34302	-0.153687	0.277667	-1.0004	-0.67867	-0.67867	-1.31368
	3.5	- 7.05267	4.34305	-0.153688	0.277667	-1.00088	- 0.678429	-0.678429	-1.31431
	5.0	- 7.05281	4.34313	-0.153688	0.277666	-1.00219	- 0.677777	-0.677777	-1.31595
<b><math>\beta</math></b>	0.1	- 7.05256	4.34299	-0.153687	0.277668	-0.999983	-1.00001	-0.678867	-1.31302
	0.2	- 6.39337	3.67161	- 0.0958119	0.225586	-0.999977	-1.00002	-0.663103	-1.36765
	0.3	- 5.77256	3.03904	-0.04295	0.177955	-0.999972	-1.00003	-0.648176	-1.42139
	0.5	- 5.15864	2.41319	0.0078338	0.132139	-0.999968	-1.00004	-0.633338	-1.47682

#### 4. CONCLUSIONS

The effect of rotation, thermo-diffusion, squeezing, thermal radiation and heat source on convective heat and mass transfer of an electrically conducting fluid in a vertical channel has been analysed .It is found that an increase in Rd, Sr, reduces  $f'$  & g, while squeezing parameter( $\beta$ ) enhances  $f'$  and reduces g. The temperature and concentration enhances with Rotation and soret parameter, reduces with squeezing parameter( $\beta$ ). Higher the thermal radiation larger the temperature and smaller the concentration in the flow region. The Nusselt number enhances with R, Sr,  $\beta$  and reduces with Rd, while the Sherwood number reduces with R, Sr and enhances with Rd, $\beta$  on  $\eta=+1$ .

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