EFFECT OF HEAT SOURCES ON MIXED CONVECTION SQUEEZING THREE-DIMENSIONAL FLOW IN A ROTATING CHANNEL WITH HALL CURRENTS AND THERMAL RADIATION

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Abstract

We investigate the effect of heat sources on MHD convective three-dimensional squeezing flow of a electrically conducting in rotating channel. The non-linear governing equations have been solved Runge-Kutta-Fehlberg fourth-fifth order method. Effect of pertinent parameters on velocity, temperature fields is examined through the plots. Skin-friction coefficients, Nusselt number for different variations are studied numerically. It is found that the normal, axial and transverse velocity components enhance in the flow region with increase in the strength of the heat generating source/ absorbing source.

Keywords : Heat Sources, Squeezing flow, Hall effect, rotating channel

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1. INTRODUCTION:

The investigation of heat generation or absorption impacts in moving fluids in imperative in perspective of a few physical issues, for example, fluids experiencing exothermic or endothermic chemical reactions. The volumetric heat era and been thought to be constant or an element of space variable. For example, a hypothetical core – disruptive accident in a liquid metal fast breeder reactor (LMFBR) could result in setting of fragmented fuel debris on horizontal surfaces below the core. The permeable debris could be saturated sodium coolant and heat era will result from the radioactive decay of the fuel particulate. Due to the fast growth of electronic technology, effective cooling of electronic equipment has become warranted and cooling of electronic equipment ranges from individual transistors to main frame computers and from energy suppliers to telephone switch boards.

The motion of rotation fluids enclosed with in a body or vice versa, was given by Greenspan [21], 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. Rao et.al. [38] 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 [45]. 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. [28]. 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. The problem of steady laminar micro polar fluid flow through porous walls of different permeability had been discussed by Agarwal and Dhanpal [5]. 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. [18] were discussed the rotating disk flow in the presence of strong magnetic field and weak magnetic field. Hazim Ali Attia [25] 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 [12] 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 [7] and Madhusudhana Reddy [30] have investigated convective heat and mass transfer flow in horizontal rotating fluid under different conditions. Singh and Mathew [52] have studied on oscillatory free convective MHD flow in a rotating vertical porous channel with heat sources. Madhavi et al[29] have investigated heat and mass transfer flow of a rotating fluid in a vertical channel with stretching and stationary walls. Sukanya et al[55] have studied the effect of non-uniform heat sources on convective heat and mass transfer flow in vertical channel bounded by Stretching walls. Watanabe and Pop [56] have discussed to Hall effects on magneto-hydrodynamic boundary layer flow over a continuous moving flat plate. Recently Sreenivasa Rao [53] has analysed the three dimensional convective squeezing flow in a rotating channel with Hall Effect and thermal radiation.

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 introduces by Stefan [54], 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 [23]. Domairry and Aziz [15] 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 [36], Hamza [22] 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 [35] 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 [24] have discussed an unsteady mixed convection three-dimensional squeezing flow of an incompressible Newtonian fluid

between two vertical parallel planes. Mahantesh et al[31] 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[31] have studied mixed MHD convection squeezing three-dimensional flow in a rotating channel filled with nanofluid.

The heat 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[46] was the first to study the effectiveness of MHD flows in fluids.

The effect of radiation on MHD flow and heat transfer problem have become more important industrially. At high operation temperature, radiation effect can be quite significant. Many processes in engineering areas occur at high temperature and a knowledge of radiation heat transfer becomes very important for the design of the pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering areas. Bestman [8] examined the natural convection boundary layer with suction and mass transfer in a porous medium. His results confirmed the hypothesis that suction stabilizes the boundary layer and affords the most efficient method in boundary layer control yet known. Abdul Sattar and Hamid Kalim [2] investigated the unsteady free convection interaction with thermal radiation in a boundary layer flow past a vertical porous plate. Mankinde [32] examined the transient free convection interaction with thermal radiation of an absorbing-emitting fluid along moving vertical permeable plate. Ibrahim et al. [26] have studied non classical thermal effects in Stokes second problem for micropolar fluids by used perturbation method.

Raptis [41] analyzed the thermal radiation and free convection flow through a porous medium by using perturbation technique. Bakier and Gorla [6] investigated the effect of thermal radiation on mixed convection from horizontal surfaces in saturated porous media. Satapathy et al [47] studied the natural convection heat transfer in a Darcian porous regime with Rosseland radiative flux effects. With regard to thermal radiation heat transfer flows in porous media, Chamkha [9] studied the solar radiation effects on porous media supported by a vertical plate. Forest fire spread also constitutes an important application of radiative convective heat transfer. More recently Chitrapiromsri and Kuznetsov [11] have studied the influence of high-intensity radiation in unsteady thermo fluid transport in porous wet fabrics as a model of fire fighter protective clothing under intensive flash fires. Impulsive flows with thermal radiation effects and in porous media are important in chemical engineering systems, aerodynamic blowing processes and geophysical energy modeling. Such flows are transient and therefore temporal velocity and temperature gradients have to be included in the analysis. Raptis and Singh [42] studied numerically the natural convection boundary layer flow past an impulsively started vertical plate in a Darcian porous medium. The thermal radiation effects on heat transfer in magneto – aerodynamic boundary layers has also received some attention, owing to astronomical re-entry, plasma flows in astrophysics, the planetary magneto-boundary layer and MHD propulsion systems. Mosa [34] discussed one of the first models for combined radiative hydromagnetic heat transfer, considered the case of free convective channel flows with an axial temperature gradient. Nath et al [37] obtained a set of similarity solutions for radiative – MHD stellar point explosion dynamics using shooting methods. Abd-El-Naby et al [1] presented a finite difference solution of radiation effects on MHD unsteady free convection flow over a vertical porous plate. Shateyi et al [49] have analyzed the Thermal Radiation and Buoyancy Effects on Heat and Mass Transfer over a Semi-Infinite stretching Surface with Suction and Blowing. Dulal Pal et al [16] have discussed Heat and Mass transfer in MHD non-Darcian flow of a micropolar fluid over a stretching sheet embedded in a porous media with non-uniform heat source and thermal radiation. Dulal Pal

et al [17] have analyzed unsteady magnetohydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Rajesh et al [39] have considered the radiation effects on MHD flow through a porous medium with variable temperature or variable mass diffusion. Soret & Dufour effect, Rawat et al [43] have discussed the finite element study of natural convection heat and mass transfer in a micropolar fluid-saturated porous regime with. Ganesam and Loganathan [19] studied the effect of the radiation and mass transfer effects on flow past a moving vertical cylinder using Rosseland approximation by the crank – Nicolsan finite difference method. Seddeek.M.A et al [48] have discussed the effects of chemical reaction and variable viscosity on hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media with radiation. Devikarani et al [14] have considered oscillatory mixed convection in horizontal channel with heat sources and radiation effect.

With the fuel emergency extending everywhere throughout the world, there is an awesome worry to use the gigantic power underneath the world's outside layer in the geothermal region. Fluid in the geothermal area is an electrically conducting liquid because of high temperature. Hence the study of interaction of the geomagnetic field with the fluid in the geothermal region is of awesome interest, in this way prompting enthusiasm for the investigation of MHD convection courses through permeable medium. Keeping these applications in view the MHD convective heat and mass flow of a electrically conducting fluid past a stretching sheet has been considered by a few analysts [4,13,27,44].

Hall currents are essential and they have a marked effect on the magnitude and direction of the current density and subsequently on the magnetic forceterm. The issue of MHD free convection flow with Hall currents has many important engineering applications, for example, in control generators, MHD accelerators, refrigeration coils, transmission lines, electric transformers, warming components and so on., several authors [3,10,40,51,50,56] have studied hall current effects on MHD convective heat transfer in different configurations.

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 transfer characteristics with hall effect. 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 fields is examined through the plots. Skin-friction coefficients, Nusselt 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.

Fig. 1 : Flow configuration and coordinate

2. MATHEMATICAL FORMULATION

We analyse transient 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 $U_{w0} = ax/(1 - \alpha t)$ in x -direction and maintained at the constant temperature T_0 . 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 $Q = \frac{Q_0}{(1-\alpha t)}$. 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 taken into account.

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].

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (2.1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + 2 \frac{\omega}{1-\alpha t} w = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\ - \frac{\sigma B_0^2}{\rho(1-\alpha t)} (u + mw) + \frac{g\beta_T}{\rho} (T - T_0), \end{aligned} \quad (2.2)$$

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

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

$$\begin{aligned} \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k_f}{(\rho C_p)} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{Q_0}{(\rho C_p)(1-\alpha t)} (T - T_0) \\ - \frac{1}{(\rho C_p)} \frac{\partial(q_R)}{\partial y} + 2\mu \left(\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial y} \right)^2 \right) + \frac{\sigma B_0^2}{1+m^2} (u^2 + w^2) \end{aligned} \quad (2.5)$$

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, 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, k_f and (ρC_p) are thermal conductivity and heat capacity of the fluid respectively. ρ_f is the density of fluid, μ_f is the dynamic viscosity of the fluid, The approximate boundary conditions for the present problem are;

$$\left. \begin{aligned} u(x, y, t) = U_{w0}, \quad v(x, y, t) = V_{w0}, \\ w(x, y, t) = 0, \quad T(x, y, t) = T_0, \end{aligned} \right\} \quad \text{at } y = 0 \quad (2.6)$$

$$\left. \begin{aligned} u(x, y, t) = 0, \quad v(x, y, t) = V_h, \\ w(x, y, t) = 0, \quad T(x, y, t) = T_h \end{aligned} \right\} \quad \text{at } y = h(t) \quad (2.7)$$

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

$$\psi = \sqrt{\frac{\alpha \nu_f}{1 - \alpha t}} x f(\eta), \quad \eta = \frac{y}{h(t)}, T = T_0 + \frac{T_0}{1 - \alpha t} \theta(\eta), \quad (2.8)$$

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

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 (2.8), the equation (2.1) is automatically satisfied, while the equation (2.2) – (2.4) are respectively reduces to the following nonlinear ordinary differential equations;

$$f_{\eta\eta\eta} - \left[f f_{\eta\eta} - f_\eta^2 - \beta \left(f_\eta \frac{\eta}{2} f_{\eta\eta} \right) - 2Rg - \frac{M^2}{1+m^2} (f_\eta + m g) + G(\theta) \right] = \frac{(1-\alpha t)^2}{\rho a^2 x} \frac{\partial p}{\partial x}, \quad (2.9)$$

$$f_{\eta\eta} - \left[-f f_\eta + \frac{\beta}{2} (f + \eta f_\eta) \right] = -\frac{1-\alpha t}{\rho \nu_f a} p_\eta, \quad (2.10)$$

$$g_{\eta\eta} + \left[f g_\eta - f_\eta g - \beta \left(g \frac{\eta}{2} g_\eta \right) + 2Rf_\eta \right] - \frac{M^2}{1+m^2} (g - m f_\eta) = 0, \quad (2.11)$$

$$\left(1 + \frac{4Rd}{3} \right) \theta_{\eta\eta} + \text{Pr} \left[\left\{ \beta \left(\theta + \frac{\eta}{2} \theta_\eta \right) + f \theta_\eta \right\} - Q\theta \right] + \frac{\text{Pr} Ec M^2}{1+m^2} (f_\eta^2 + g^2) + \text{Pr} Ec (f_{\eta\eta}^2 + g_\eta^2) = 0 \quad (2.12)$$

The modified boundary conditions are;

$$\begin{aligned} f_\eta = 1, f = fw, \quad g = 0, \quad \theta = 0, \quad \text{at} \quad \eta = 0 \\ f_\eta = 0, f = \frac{\beta}{2}, \quad g = 0, \quad \theta = 1, \quad \text{at} \quad \eta = 1 \end{aligned} \quad (2.13)$$

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, $G = g\beta_T T_0 x^3 / \nu_f^2 (1 - \alpha t)$ is Grashof number, $Re = xU_{w0} / \nu_f$ is Reynolds number, $Pr = (\mu c_p)_f / k_f$ is the Prandtl number, $Q = Q_0 / \alpha(\rho C_p)_f$ 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 (2.9)-(2.12) takes the following form;

$$f_{\eta\eta\eta} - \left[\frac{\beta}{2} (3 f_{\eta\eta} + \eta f_{\eta\eta\eta}) f_\eta f_{\eta\eta} - f f_{\eta\eta\eta} + 2Rg_\eta \right] - \frac{M^2}{1+m^2} (f_{\eta\eta} + m g_\eta) + G(\theta_\eta) = 0 \quad (2.14)$$

$$g_{\eta\eta} + \left[f g_{\eta} - f_{\eta} g - \beta \left(g + \frac{\eta}{2} g_{\eta} \right) + 2R f_{\eta} \right] - \frac{M^2}{1+m^2} (g - m f_{\eta}) = 0 \quad (2.15)$$

$$\begin{aligned} (1 + \frac{4Rd}{3}) \theta_{\eta\eta} - \Pr \left(\left\{ \beta \left(\theta + \frac{\eta}{2} \theta_{\eta} \right) + f \theta_{\eta} \right\} - Q \theta \right) \\ + \frac{\Pr Ec M^2}{1+m^2} (f_{\eta}^2 + g^2) + \Pr Ec (f_{\eta\eta}^2 + g_{\eta}^2) = 0 \end{aligned} \quad (2.16)$$

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;

$$C_{f, \text{ at } y=0}^* = \frac{(\tau_{xy})_{y=0}}{\rho_{\eta f} U_{w0}^2}, \quad C_{f, \text{ at } y=h(t)}^* = \frac{(\tau_{xy})_{y=h(t)}}{\rho_{\eta f} U_{w0}^2}, \quad (2.17)$$

$$Nu_{\text{ at } y=0}^* = \sqrt{\frac{v_f}{a}} \frac{(q_{xy})_{y=0}}{k_f T_0}, \quad Nu_{\text{ at } y=h(t)}^* = \sqrt{\frac{v_f}{a}} \frac{(q_{xy})_{y=h(t)}}{k_f T_0}, \quad (2.18)$$

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

$$\tau_{xt} = \mu_{\eta f} \left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right), \quad q_{xt} = -k_{\eta f} \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} \right) \quad (2.19)$$

In view of equation (2.19) and similarity transformations (2.8); equations (2.17)-(2.18) will takes the following form;

$$\begin{aligned} C_{f, \text{ at } y=0}^* &= \sqrt{\text{Re}} C_{f, \text{ at } y=0}^* = f_{\eta\eta}(0), \\ C_{f, \text{ at } y=h(t)}^* &= \sqrt{\text{Re}} C_{f, \text{ at } y=h(t)}^* = f_{\eta\eta}(1), \\ Nu_{\text{ at } y=0}^* &= (1 - \alpha t)^{1.5} Nu_{\text{ at } y=0}^* = -\theta_{\eta}(0), \\ Nu_{\text{ at } y=h(t)}^* &= (1 - \alpha t)^{1.5} Nu_{\text{ at } y=h(t)}^* = -\theta_{\eta}(1) \end{aligned} \quad (2.20)$$

3. NUMERICAL METHOD AND VALIDATION

A set of non-similar equations (2.14)-(2.16) 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 (2.13) 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.

4. COMPARISON

Table 1 : In the absence of heat sources ($Q=0$) the results are in good agreement with Sreenivasa Rao [53].

Parameter		Sreenivas Rao [53] results		Present Results ($Q=0$)	
		Nu(0)	Nu(1)	Nu(0)	Nu(1)
m	0.5	-0.999841	-1.00005	-0.999831	-1.00006
	1.0	-0.998857	-1.00032	-0.998851	-1.00029
	1.5	-0.99939	-1.00045	-0.99937	-1.00042
	2.0	-0.998316	-1.00055	-0.998314	-1.00053
R	0.5	-0.999841	-1.00005	-0.999838	-1.00006
	1.0	-0.998858	-1.00031	-0.998850	-1.00032
	1.5	-0.999392	-1.00045	-0.999389	-1.00042
	2.0	-0.998316	-1.00055	-0.998312	-1.00059
Rd	0.5	-0.999841	-1.00005	-0.999837	-1.00003
	1.5	-0.997252	-1.00139	-0.997249	-1.00132
	3.5	-0.996392	-1.00295	-0.996389	-1.00296
	5.0	-0.991122	-1.00519	-0.991120	-1.00512
β	0.2	-0.999165	-1.00108	-0.999159	-1.00106
	0.4	-0.998989	-1.00145	-0.998982	-1.00142
	0.6	-0.998813	-1.00182	-0.998811	-1.00184
	0.8	-0.998637	-1.00218	-0.998632	-1.00216
Pr	0.71	-1.00012	-0.999896	-1.00009	-0.999895
	1.71	-1.00029	-0.999749	-1.00031	-0.999742
	3.71	-1.00047	-0.999603	-1.00042	-0.999605
	7.0	-1.00064	-0.999456	-1.00069	-0.999457

5. RESULTS AND DISCUSSIONS

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: $S=0.4$, $M^2=0.5$, $Q=0.5$, $R=0.5$, $\beta=0.5$, $Pr=0.71$. In order to analyse the effects of various pertinent parameters on velocity, temperature profiles, several graphs are plotted.

Figure.2a-2d are plotted for f, f', g, θ profiles against η for different values of G by fixing other parameters. It can seen from the profiles that the temperature decreases in the region $(0,0.5)$ and enhances in the remaining region with increase in Grashof number G , the normal velocity(f) reduces, the axial velocity(f') enhances and the transverse velocity(g) reduces in the region $(0,0.5)$ and a reversed effect is noticed in the remaining region with increase in G . This may be attributed to the fact that an increase in G reduces the thickness of the momentum boundary layer and increases the thickness of the thermal boundary layer.

Fig.3a-3d represent the effect of magnetic field on f, f', g, θ . It can be found from the profiles that the normal velocity(f) reduces and the transverse velocity(g) enhances with increasing M (figs.3a,3c). 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.3b). The thickness of the thermal boundary layers enhance with increase in M which results in a rise in the temperature and concentration in the flow region(figs.3d).

Fig.4a-4d represent the effect of Hall current on f, f', g, θ . It can be found from the profiles that the normal velocity(f), axial velocity (f'), the transverse velocity(g) enhances with increasing Hall parameter(m)(figs.3a-3c). The thickness of the thermal boundary layers

reduces with increase in m which results in a fall in the temperature in the flow region (figs.4d).

The influence of rotation parameter (R) on f, f', g, θ can be observed from the figs.5a-5d. The normal velocity (f) and transverse velocity (g) enhances with increase in R . The axial velocity (f') enhances in the left half (0,0.5) and reduces in the right half (0.5,1.0) of the channel. The temperature 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 boundary layers increase with R .

Figs.6a-6d show the influence of thermal radiation on f, f', g, θ . It can be seen from the profiles (figs.6a-6d) that there is a significant depreciation in the magnitude of the velocity components f, f' and g in the presence of thermal radiation throughout the flow region. 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 R_d (fig.6d).

Figs.7a-7d are plotted to illustrate the effect of heat source parameter (Q) on the flow variables. It can be seen from the profiles that the normal, axial and transverse velocity components enhance in the flow region with increase in the strength of the heat generating source/ absorbing source. This may be attributed to the fact that in the presence of heat generating/absorbing source, energy is generated in the flow region (figs.7a-7c). From figs.7d we find that in the presence of heat generating source, energy is generated in the flow region, which results in an enhancement in the temperature while in the presence of heat absorbing source, energy is absorbed which leads to a depreciation in the temperature.

Figs.8a-8d represents the effect of Eckert number (Ec) on f, f', g, θ from the velocity profile we find that the normal velocity (f) enhances while axial and transverse velocity component depreciate in magnitude in the flow region (figs.8a-8c). From fig.8d we notice an enhancement in temperature in entire flow region. It may be attributed to the fact that higher dissipation larger the thickness of the thermal boundary layer.

Figs.9a-9d present the typical profiles namely, f, f', g, θ respectively for different values of the squeezing parameter (β). From figs.9a&9b show that the magnitude of the normal 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. The axial velocity (f') reduces in the left half (0,0.3) and enhances in the right half (0.32,1.0) of the channel. with increase in β . An increase in β leads to a reduction in the temperature (figs.9d).

Figs.10a-10d 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 normal, axial and transverse velocity components (figs.10a-10c). From figs.10d we find that the temperature increases with increase in suction /injection parameters. This may be attributed to the fact that the thickness of the thermal boundary layer increases with increase in fw .

The effect of Prandtl number (Pr) on f, f', g, θ can be seen from figs.11a-11d. From the profiles we find that all the velocity components experience an enhancement with increase in Pr . Also lesser the thermal diffusivity larger the thickness of the thermal boundary layer in the entire flow region (figs.11d).

Fig.2a Variation of f with G
 $M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.2b Variation of f' with G
 $M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.2c Variation of g with G
 $M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.2d Variation of θ with G
 $M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.3a Variation of f with M
 $G=2, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.3b Variation of f' with M
 $G=2, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.3c Variation of g with M
 $G=2, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.3d Variation of θ with M
 $G=2, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.4a Variation of f with m
 $G=2, M=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.4b Variation of f' with m
 $G=2, M=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.4c Variation of g with m
 $G=2, M=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.4d Variation of θ with m
 $G=2, M=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.5a Variation of f with R
 $G=2, M=0.5, m=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.5b Variation of f' with R
 $G=2, M=0.5, m=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.5c Variation of g with R
 $G=2, M=0.5, m=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.5d Variation of θ with R
 $G=2, M=0.5, m=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.6a Variation of f with Rd
 $G=2, M=0.5, m=0.5, R=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.6b Variation of f' with Rd
 $G=2, M=0.5, m=0.5, R=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.6c Variation of g with Rd
 $G=2, M=0.5, m=0.5, R=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.6d Variation of θ with Rd
 $G=2, M=0.5, m=0.5, R=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.7a Variation of f with Q
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.7b Variation of f' with Q
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.7c Variation of g with Q
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.7d Variation of θ with Q
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2, Pr=0.71$

Fig.8a Variation of f with Ec
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $\beta=0.2, fw=0.2, Pr=0.71$

Fig.8b Variation of f' with Ec
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $\beta=0.2, fw=0.2, Pr=0.71$

Fig.8c Variation of g with Ec
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $\beta=0.2, fw=0.2, Pr=0.71$

Fig.8d Variation of θ with Ec
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $\beta=0.2, fw=0.2, Pr=0.71$

Fig.9a Variation of f with β
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, fw=0.2, Pr=0.71$

Fig.9b Variation of f' with β
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, fw=0.2, Pr=0.71$

Fig.9c Variation of g with β
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, fw=0.2, Pr=0.71$

Fig.9d Variation of θ with β
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, fw=0.2, Pr=0.71$

Fig.10a Variation of f with fw
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, Pr=0.71$

Fig.10b Variation of f' with fw
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, Pr=0.71$

Fig.10c Variation of g with fw
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, Pr=0.71$

Fig.10d Variation of θ with fw
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, Pr=0.7$

Fig.11a Variation of f with Pr
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2$

Fig.11b Variation of f' with Pr
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2$

Fig.11c Variation of g with Pr
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2$

Fig.11d Variation of θ with Pr
 $G=2, M=0.5, m=0.5, R=0.5, Rd=0.5, Q=0.5,$
 $Ec=0.1, \beta=0.2, fw=0.2$

Table – 2 : Skin friction (τ_x, τ_z), Nusselt number(Nu) at $\eta = 0$

Parameter		$\tau_x(0)$	$\tau_x(1)$	$\tau_z(0)$	$\tau_z(1)$	$Nu(0)$	$Nu(1)$
G	2	-6.83728	4.55659	-0.217414	0.400461	-1.00012	-0.999896
	4	-7.0333	4.34982	-0.221933	0.395779	-1.01258	-0.989815
	6	-7.22839	4.14182	-0.226464	0.391099	-1.00013	-0.999901
	10	-7.61989	3.72742	-0.235542	0.38176	-1.00014	-0.999905
M	0.5	-6.83728	4.55659	-0.217414	0.400461	-1.00012	-0.999896
	1.0	-7.24151	4.57113	-0.283278	0.610635	-1.01371	-0.988573
	1.5	-7.88362	4.60213	-0.296643	0.832418	-1.00016	-0.999869
	2.0	-8.71913	4.66448	-0.242126	1.01315	-1.0002	-0.999847
m	0.5	-6.47851	4.9276	-0.209246	0.408959	-0.999831	-1.00006
	1.0	-6.39218	4.92528	-0.23684	0.446722	-0.998851	-1.00029
	1.5	-6.3614	4.92403	-0.224203	0.417741	-0.99937	-1.00042
	2.0	-6.34991	4.92353	-0.212981	0.39505	-0.998314	-1.00053
R	0.5	-6.47851	4.9276	-0.209246	0.408959	-0.999838	-1.00006
	1.0	-6.46107	4.91611	-0.343623	0.672034	-0.998850	-1.00032
	1.5	-6.42502	4.89233	-0.50754	0.99397	-0.999389	-1.00042
	2.0	-6.31734	4.82159	-0.804064	1.58119	-0.998312	-1.00059
Rd	0.5	-6.47851	4.9276	-0.209246	0.408959	-0.999837	-1.00003
	1.5	-6.47848	4.92784	-0.209242	0.40896	-0.997249	-1.00132
	3.5	-6.47851	4.92806	-0.209238	0.408959	-0.996389	-1.00296
	5.0	-6.4784	4.92871	-0.209234	0.408961	-0.991120	-1.00512
Q	0.5	-6.47851	4.9276	-0.209246	0.408959	-0.999837	-1.00004

	1.5	-6.47858	4.9272	-0.209249	0.408962	-0.999292	-0.999432
	-0.5	-6.47849	4.92762	-0.209246	0.408959	-0.998699	-1.00116
	-1.5	-6.47845	4.92767	-0.209245	0.40896	-0.996432	-1.00412
Ec	0.1	-6.59453	4.82922	-0.14758	0.29702	-0.999745	-1.00015
	0.3	-6.52816	4.82644	-0.164443	0.322076	-0.998231	-1.00104
	0.5	-6.49453	4.82422	-0.17758	0.349702	-0.99756	-1.00214
	0.7	-6.46594	4.82374	-0.195063	0.38502	-0.996221	-1.00305
β	0.2	-3.90753	1.9897	0.0283874	0.0269731	-0.999159	-1.00106
	0.4	-2.42315	0.488939	0.0686951	-0.0105308	-0.998982	-1.00142
	0.6	-0.97046	-0.980832	0.106272	-0.0455559	-0.998811	-1.00184
	0.8	-0.449969	-2.41911	0.141369	-0.0783278	-0.998632	-1.00216
fw	0.2	-3.90751	1.98968	0.0283874	0.0269731	-0.998408	-1.0016
	0.4	-9.11561	8.59556	-0.160448	0.185456	-0.998022	-1.00177
	-0.2	1.98063	-3.96617	0.172401	-0.124842	-0.998787	-1.00144
	-0.4	8.71439	-9.26322	0.27959	-0.268523	-0.999159	-1.00128
Pr	0.71	-6.83728	4.55659	-0.217414	0.400461	-1.00009	-0.999895
	1.71	-6.83733	4.5569	-0.217404	0.400561	-1.00031	-0.999742
	3.71	-6.83739	4.5576	-0.2173814	0.400661	-1.00042	-0.999605
	7.0	-6.83749	4.55861	-0.2173414	0.400761	-1.00069	-0.999457

The Skin friction components τ_x, τ_z , Nusselt number(Nu) on the walls ($\eta=0,1$) are exhibited in tables.2 for different parametric variations. The skin friction component τ_x and τ_z enhance with increase on the left wall ($\eta=0$) and reduce on the right wall($\eta=+1$) with increase in G. An increase in magnetic parameter(M) leads to a n enhancement in both the skin friction component τ_x and τ_z enhance on both the walls. An increase in Hall parameter(m) or rotation parameter (R) reduces τ_x and enhances τ_z on the both the walls. Higher the radiative heat flux larger the skin friction component(τ_x) on right wall and smaller on then left wall, while τ_z reduces with Rd on both the walls. The variation of skin friction components with heat source parameter(Q) shows that τ_x enhances with increase in the strength of the heat generating source and depreciates with that of heat absorption source at $\eta=0$ while on $\eta=1$,it a reversed effect is noticed in its behaviour. τ_z enhances on $\eta=\pm 1$ with $Q>0$ and with $Q<0$, τ_z reduces at $\eta=0$ and enhances at $\eta=1$. Higher the dissipation (Ec) smaller the skin friction component (τ_x) and larger the skin friction (τ_z) and both the walls. An increase in the squeezing parameter(β) smaller τ_x and larger τ_z 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 τ_x, τ_z enhance with increase in suction/injection parameter at both the walls.Lesser the thermal diffusivity larger the skin friction component τ_x at both the walls while larger τ_z at $\eta=1$ and smaller at $\eta=0$.

The rate of heat transfer(Nu) at $\eta=0,1$ are shown in table.2.The rate heat transfer enhances at the left wall and reduces at the right wall with increase in G and M. An increase in Hall parameter (m) or R or Rd reduces Nu at the left wall and enhances at the right wall. Higher the dissipation (Ec)or squeezing parameter(β) smaller Nu at $\eta=0$ and larger at $\eta=1$.The rate of heat transfer reduces at the left wall and enhances at the right wall with increase in R or β or Pr .An increase in $Q>0$,reduces Nu at $\eta=\pm 1$ and increases with $Q<0$ at $\eta=\pm 1$. 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 Prandtl number reduces Nu at $\eta=1$ and enhances at $\eta=0$.

6. CONCLUSIONS:

The effect of rotation, Hall currents, 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 Hall parameter(m) increases f, f' and g while squeezing parameter(β) enhances f and reduces f' & g . The temperature enhances with Rotation and Hall parameter, reduces with squeezing parameter(β). Higher the thermal radiation/dissipation larger the temperature in the flow region. The Nusselt number enhances at $\eta=1$ and reduces at $\eta=0$, with increase in m, R, Rd, Ec, β . It is found that the normal, axial and transverse velocity components enhance in the flow region with increase in the strength of the heat generating source/ absorbing source(Q).

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