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Hydro-Magnetic Fluid Flow past a Rotating Semi-infinite Vertical Plate Considering Joule Heating

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Abstract: ***Stokes problem for a free convective flow past a vertical semi-infinite plate in a rotating system taking into account the effect of viscous dissipation and joule heating is investigated. The fluid considered is electrically conducting. The fluid is subjected to a variable magnetic field inclined at an angle α with positive direction of z axis in the $xy-$plane. The aim of the present investigation is to study the effects of variable magnetic field with joule heating on the flow variables. The central finite difference is used to discretisize space variables and Gauss Siedel iteration is used to advance time variable. Various parameters Magnetic parameter),Prandtl Number ,Hall parameters, Eckert Number, Rotational parameters, Joule Heating Parameter, appearing in dimensionless equations are varied and their effects on the flow variables are discussed in detail with the help of graphs and tables. The results obtained here are useful in applications on heat exchanger designs, wire and glass fiber drawing and in nuclear engineering in connection with the cooling of reactors.***

Index Terms: **Hall current, free convection, Inclined Magnetic field, Rotation.**

I. INTRODUCTION

The theoretical study of MHD flows has been a subject of great interest due to its widely spread application in designing of cooling systems with liquid metals, petroleum industry, purification of crude oil, separation of matter from fluids and many other applications. Rotation has important role in various phenomena like meteorology, geophysical fluids dynamics, gaseous and nuclear reactions. The study of rotating flow system problems is also important in the solar physics dealing with the sunspot development, the solar cycle and the structure of rotating magnetic stars. MHD flows with Hall current effect are encountered in power generators, Magneto hydrodynamics accelerators, refrigeration coils and electric transformers. Fluid flow involving rotation is observed in earth's atmosphere and in oceans. Meteorologist can use this study to understand dynamics of meteorology and air pollution.Ghosh *et. al*. [1] studied the Hall effects on steady Hydromagnetic flow in a rotating channel in the presence of an inclined magnetic field. In another study Ghosh *et. al.*[2] studied the Hydromagnetic flow in a rotating channel in the presence of inclined magnetic field. Ram [3] studied effects of Hall currents and wall temperature oscillations on convective flow in a rotating fluid through porous medium. Abdul [5] considered effects of Hall currents and viscous dissipation on MHD free convection fluid flow in a rotating system. Studies on MHD Stokes free convection flow past an infinite vertical porous plate subjected to constant heat flux with ion-slip current and radiation absorption was done by Kwanza J.K. *et. al.*[6].Debnath *et.al*. [7] Investigated the unsteady rotating flow of a viscous fluid in the presence of Hall Effect. Kwanza J,K, *et al*. [8] studied Hydromagnetic Free Convection Flow Past a Semi – Infinite Vertical. Porous Plate Subjected to Constant Heat Flux with Radiation Absorption. H.Sato [9] studied the Hall effects flow of ionized Gas between parallel Plates under Transverse Magnetic Field. Inspite of all these investigations, much has not been done on a convective flow past a semi- infinite vertical plate in a rotating system in presence of a variable inclined magnetic field with viscous dissipation and joule heating. The aim of this to study is to investigate effects of a variable inclined magnetic field taking into account the effect of viscous dissipation and joule heating is investigated. Magnetic parameter becomes significant and hence their consideration in the analysis has been important.

II. MATHEMATICAL FORMULATION

Consider a Hydromagnetic fluid flow past a rotating semi-infinite vertical plate taking into account joule heating. Let the x and z axes be parallel and normal, respectively, and let the y axis be coincident with the leading edge of the plate The fluid is subjected to a variable magnetic field inclined at an angle α with the positive direction of x axis in the x-z plane. The system rotates with uniform angular velocity Ω about the z axis

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perpendicular to the plane of flows (x z) in the presence of variable magnetic field, H_0. The regime is illustrated in Figure I below.

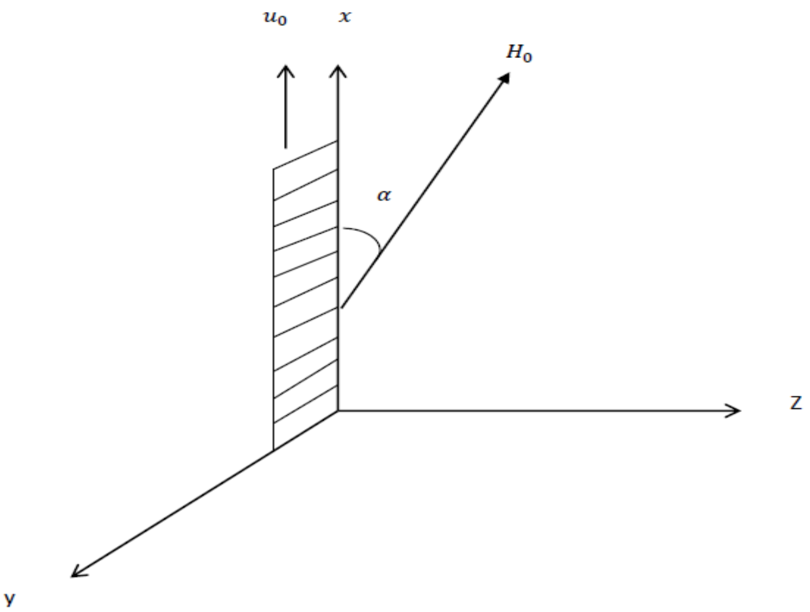

Fig 1: Flow Configuration

The applied magnetic field H_0 is strong enough to generate Hall currents as discussed by Sato[9] and a secondary flow is thereby introduced in the regime. Magnetic Reynolds number is also of sufficient magnitude that magnetic induction effects become important. The plate is semi-infinite in extent and the flow is unsteady therefore the physical variables are functions of and x, z and t. Following Cramer and Pai [10] and Shercliff [11] we take the following vectorial field equations,

$$\mathbf{q}=\left(u,v,0\right)\ \mathbf{H}=\left(H_x+H_0\cos\theta,0,H_z+H_0\sin\theta\right),\mathbf{E}=\left(E_x,E_y,E_z\right)\text{and }\mathbf{J}=\left(J_x,J_y,J_z\right) \quad (1)$$

Ohm's law for a moving conductor incorporating Hall current takes the form:

$$\mathbf{J}+\frac{\omega_e\tau_e}{\mathbf{H}_0}\left[\mathbf{J}\times\mathbf{H}\right]=\sigma\left[\mathbf{E}+\mu_e\mathbf{q}\times\mathbf{H}+\frac{1}{e\eta_e}\nabla\cdot\rho_e\right] \quad (2)$$

Neglecting ion-slip and thermoelectric effect equation (2) in components form becomes

$$J_x=\frac{\sigma\mu_e H_0\left(H_z+H_0\sin\alpha\right)\left(m\left(H_z+H_0\sin\alpha\right)u+H_0 v\right)}{H_0^{\,2}+m^2\left(H_z+H_0\sin\alpha\right)^2} \quad (3)$$

$$J_y=\frac{\sigma\mu_e H_0\left(H_z+H_0\sin\alpha\right)\left(m\left(H_z+H_0\sin\alpha\right)v-H_0 u\right)}{H_0^{\,2}+m^2\left(H_z+H_0\sin\alpha\right)^2}$$

(4)

In a rotating frame the governing boundary layer equations of mass, momentum and energy for free convection flows with the Boussinesq approximation are as follows

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \quad (5)$$

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$$\frac{\partial u}{\partial t}-u_0\frac{\partial u}{\partial z}+u\frac{\partial u}{\partial x}-2\Omega v=g\beta\left(T-T_\infty\right)+\upsilon\left(\frac{\partial^2 u}{\partial z^2}+\frac{\partial^2 u}{\partial x^2}\right)+\frac{\sigma\mu_e\left(H_z+H_0\sin\alpha\right)^2\left(m\left(H_z+H_0\sin\alpha\right)v-H_0u\right)}{\rho\left(H_0^{\,2}+m^2\left(H_z+H_0\sin\alpha\right)^2\right)} \tag{6}$$

$$\frac{\partial v}{\partial t}-u_0\frac{\partial v}{\partial z}+u\frac{\partial v}{\partial x}+2\Omega u=+\upsilon\left(\frac{\partial^2 v}{\partial z^2}+\frac{\partial^2 v}{\partial x^2}\right)+\frac{\sigma\mu_e\left(H_z+H_0\sin\alpha\right)^2\left(m\left(H_z+H_0\sin\alpha\right)u+H_0v\right)}{\rho\left(H_0^{\,2}+m^2\left(H_z+H_0\sin\alpha\right)^2\right)} \tag{7}$$

$$\rho c_p\left[\frac{\partial T}{\partial t}+u_0\frac{\partial T}{\partial z}+u\frac{\partial T}{\partial x}\right]=k\left[\frac{\partial^2 T}{\partial z^2}+\frac{\partial^2 T}{\partial x^2}\right]+\mu\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial x}\right)^2\right]+\sigma\mu^2{}_e\left(H_z+H_0\sin\alpha\right)^2\left(v^2+u^2\right) \tag{8}$$

The initial and boundary conditions are:

$$\begin{aligned}
&t\le 0 \quad u(x,z,t)=0,\quad v(x,z,t)=0,\quad T(x,z,t)=0\\
&t>0 \quad u(x,z,t)=u_0,\ v(0,z,t)=0 \quad T(0,z,t)=T_w\\
&\qquad\quad u(\infty,z,t)=0,\ v(\infty,z,t)=0 \quad T(\infty,z,t)=0
\end{aligned} \tag{9}$$

Where u, v and w are the x, y and z components of velocity vector respectively. Introducing the following non-dimensional quantities:

$$u^*=\frac{u}{u_0},\qquad v^*=\frac{v}{u_0},\qquad t^*=\frac{u_0^{\,2}t}{\upsilon}$$

$$x^*=\frac{xu_0}{\upsilon},\qquad z^*=\frac{zu_0}{\upsilon},\qquad H_x^*=\frac{H_x}{H_0},\qquad H_z^*=\frac{H_z}{H_0},\qquad \theta=\frac{T-T_\infty}{T_w-T_\infty} \tag{10}$$

Substituting (10) in equations (5),(6) , (7) and (8) we get

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial w^*}{\partial z^*}=0 \tag{11}$$

$$\frac{\partial u^*}{\partial t^*}-u_0\frac{\partial u^*}{\partial z^*}+u^*\frac{\partial u^*}{\partial x^*}-2Erv=Gr\theta+\left(\frac{\partial^2 u^*}{\partial z^{*2}}+\frac{\partial^2 u^*}{\partial x^{*2}}\right)+M\left(H^*{}_z+\sin\alpha\right)^2\left[\frac{m\left(H^*{}_z+\sin\alpha\right)v^*-u^*}{1+m^2(H^*{}_z+\sin\alpha)^2}\right] \tag{12}$$

$$\frac{\partial v^*}{\partial t^*}-u_0\frac{\partial v^*}{\partial z^*}+u^*\frac{\partial v^*}{\partial x^*}+2Eru=\left(\frac{\partial^2 v^*}{\partial z^{*2}}+\frac{\partial^2 v^*}{\partial z^{*2}}\right)-M\left(H^*{}_z+\sin\alpha\right)^2\left[\frac{m\left(H^*{}_z+\sin\alpha\right)u^*+v^*}{1+m^2(H^*{}_z+\sin\alpha)^2}\right] \tag{13}$$

$$\frac{\partial\theta}{\partial t^*}-u_0\frac{\partial\theta}{\partial z^*}+u^*\frac{\partial\theta}{\partial x^*}=\frac{1}{\Pr}\left(\frac{\partial^2\theta}{\partial z^{*2}}+\frac{\partial^2\theta}{\partial x^{*2}}\right)+Ec\left(\left(\frac{\partial u^*}{\partial z^*}\right)^2+\left(\frac{\partial v^*}{\partial z^*}\right)^2\right)+R\left(H_z^*+\sin\alpha\right)^2\left(v^{*2}+u^{*2}\right) \tag{14}$$

The initial and boundary conditions (9) in non-dimensional form are

$$t\le 0 \quad u(x,z,t)=0,\quad v(x,z,t)=0,\quad T(x,z,t)=0$$

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$$t>0 \quad u(x,z,t)=1, \quad v(0,z,t)=0 \quad T(0,z,t)=1$$
$$u(\infty,z,t)=0, \quad v(\infty,z,t)=0 \quad T(\infty,z,t)=0 \tag{15}$$

III. METHOD OF SOLUTION

The set of non-linear and coupled partial differential equations (11) to (14) under the initial and boundary conditions (15) are solved using the central difference scheme to discretisize space variables and Gauss-Siedel to advance in time. In the spatial discretization, we make the centre values the subject i.e. u_{ij}^k, v_{ij}^k .

$$\left[\frac{2}{(\Delta z)^2}+\frac{2}{(\Delta x)^2}+\frac{M^2\left(H_z^*+\sin\alpha\right)^2}{1+m^2\left(H_z^*+\sin\alpha\right)^2}\right]u_{ij}^k=\frac{1}{2\Delta z}\left[-\left(u_0u\right)_{ij+1}^k+\left(u_0u\right)_{ij-1}^k\right]+\frac{1}{(\Delta z)^2}\left[(u)_{ij+1}^k+(u)_{ij-1}^k\right]$$
$$+\frac{1}{(\Delta x)^2}\left[(u)_{i+1j}^k+(u)_{i-1j}^k\right]-\frac{1}{2\Delta x}\left[\left(u^2\right)_{i+1j}^k-\left(u^2\right)_{i-1j}^k\right]$$
$$+Gr\theta+2Erv_{ij}^k+M^2\left(H_z^*+\sin\alpha\right)^2\left[\frac{m\left(H_z^*\sin\alpha\right)v_{ij}^k}{1+m^2\left(H_z^*+\sin\alpha\right)^2}\right] \tag{16}$$

$$\left[\frac{2}{(\Delta z)^2}+\frac{2}{(\Delta x)^2}+\frac{M^2\left(H_z^*+\sin\alpha\right)^2}{1+m^2\left(H_z^*+\sin\alpha\right)^2}\right]v_{ij}^k=\frac{1}{2\Delta z}\left[-\left(u_0v\right)_{ij+1}^k+\left(u_0v\right)_{ij-1}^k\right]+\frac{1}{(\Delta z)^2}\left[(u)_{ij+1}^k+(u)_{ij-1}^k\right]$$
$$+\frac{1}{(\Delta x)^2}\left[(v)_{i+1j}^k+(v)_{i-1j}^k\right]-\frac{1}{2\Delta x}\left[(uv)_{i+1j}^k-(uv)_{i-1j}^k\right]$$
$$-2Eru_{ij}^k-M^2\left(H_z^*+\sin\alpha\right)^2\left[\frac{m\left(H_z^*+\sin\alpha\right)u_{ij}^k}{1+m^2\left(H_z^*+\sin\alpha\right)^2}\right] \tag{17}$$

The time advancement is done by invoking Gauss-Siedel iteration technique as below

$$u_{ij}^k=\frac{1}{A}F\left[u_{ij-1}^k,u_{ij-1}^k,u_{i-1j}^k,v_{ij}^k,v_{i+1j}^k,v_{i-1j}^k\right] \tag{18}$$

$$v_{ij}^k=\frac{1}{A}G\left[v_{ij-1}^k,v_{ij-1}^k,v_{i-1j}^k,u_{ij}^k,u_{i+1j}^k,u_{i-1j}^k\right] \tag{19}$$

For all i in [1,n-1] and j in [1,m-1] where

$$A=\left[\frac{2}{(\Delta z)^2}+\frac{2}{(\Delta x)^2}\pm\frac{M^2\left(H_z^*+\sin\alpha\right)^2}{1+m^2\left(H_z^*+\sin\alpha\right)^2}\right] \tag{20}$$

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For the energy equation we make θ_{ij}^{k} the subject

$$\left[\frac{2}{\Pr(\Delta z)^2}+\frac{2}{\Pr(\Delta x)^2}\right]\theta_{ij}^{k}=-\frac{1}{2\Delta z}\left[(u_0\theta)_{ij+1}^{k}-(u_0\theta)_{ij-1}^{k}\right]-\frac{1}{2\Delta x}\left[(u\theta)_{i+1j}^{k}-(u\theta)_{i-1j}^{k}\right]$$
$$+\frac{Ec}{4(\Delta z)^2}\left[\left(u_{ij+1}^{k}+u_{ij-1}^{k}\right)^2+\left(v_{ij+1}^{k}+v_{ij-1}^{k}\right)^2\right]$$
$$+\frac{1}{\Pr(\Delta z)^2}\left[\theta_{ij+1}^{k}+\theta_{ij-1}^{k}\right]+\frac{1}{\Pr(\Delta x)^2}\left[\theta_{i+1j}^{k}+\theta_{i-1j}^{k}\right] \quad (21)$$

The time advancement is done by invoking Gauss-Siedel iteration technique as below

$$\theta_{ij}^{k+1}=\frac{1}{B}H\left[\theta_{ij+1}^{k},\theta_{ij-1}^{k},\theta_{i+1j}^{k},u_{ij+1}^{k},u_{ij+1}^{k},v_{ij+1}^{k},v_{ij-1}^{k}\right] \quad (22)$$

For all I in [1,n-1] and j in [1,m-1] where

$$B=\left[\frac{2}{\Pr(\Delta z)^2}+\frac{2}{\Pr(\Delta x)^2}\right] \quad (23)$$

For these equations, a solution domain of 50 by 50 grid points is used. The equations were solved using four loops. The first and second loops solved for the velocity, the third for temperature while the fourth incorporated time advancement.

IV. RESULTS AND DISCUSSION

To investigate the practical situation of the problem, the numerical values of the dimensionless primary velocity(u),the secondary velocity(v) and the temperature (θ) for the given flow have been obtained. Because of the great importance of cooling problem in nuclear engineering in connection with the cooling of reactors the values of the Grashof number for heat transfer is taken positive. Since most important fluids are atmospheric air, salt water and water so the results are limited to Pr=0.71(Prandtl number for air at $20^0 C$),Pr=1.0(Prandtl for salt water at $20^0 C$) and Pr=7.0(Prandtl number for air at $20^0 C$).

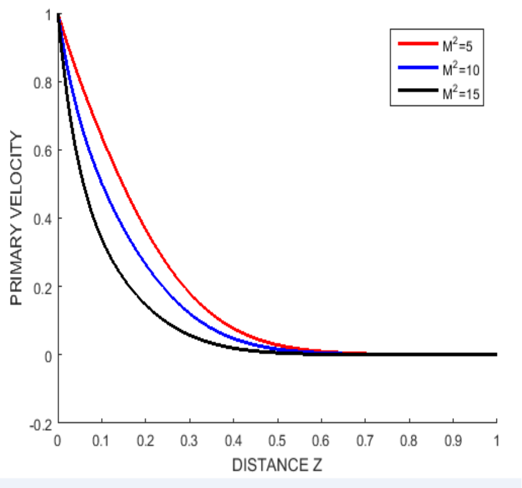

Fig 2: Variation of primary velocity(u)for various values of magnetic parameter M^2 with m=0.5,Ec=0.02,R=10.

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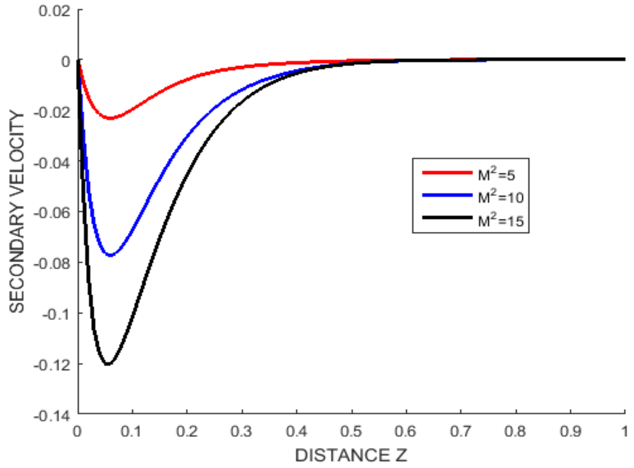

Fig 3: Variation of secondary velocity (v) for various values of Magnetic field parameter M^2 with m=0.5,Ec=0.02,R=10

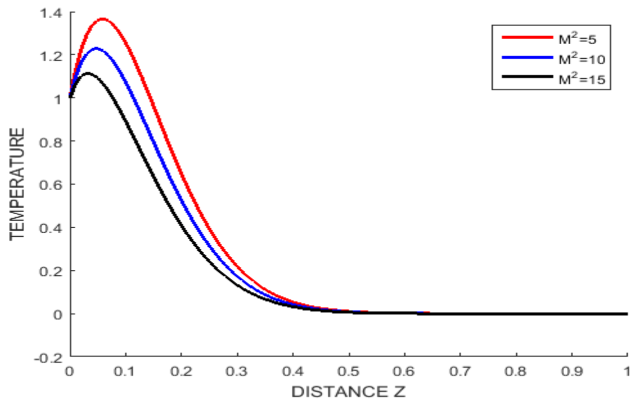

Fig 4: Variation of dimensionless temperature (θ) for various values of Magnetic field Parameter with m=0.5,Ec=0.02,R=10

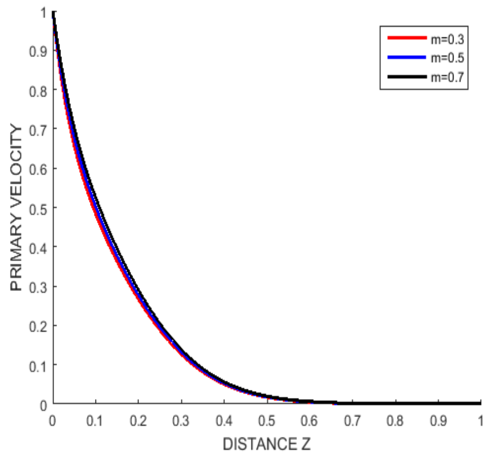

Fig 5: Variation of primary velocity (u) for various values of Hall parameter with M^2 =10,Ec=0.02,R=10

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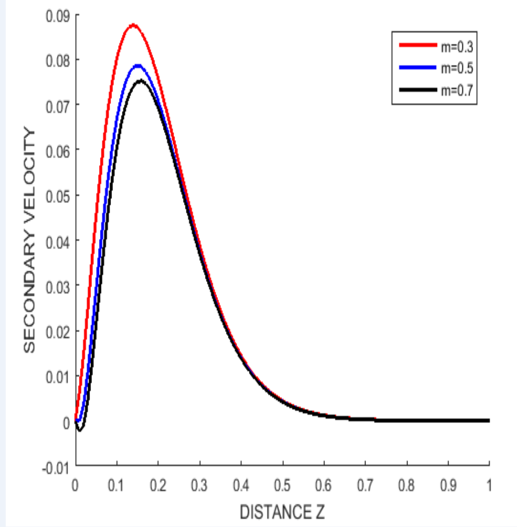

Fig 6: Variation of secondary velocity (v) for various values of Hall parameter with M^2 =10,Ec=0.02 ,R=10

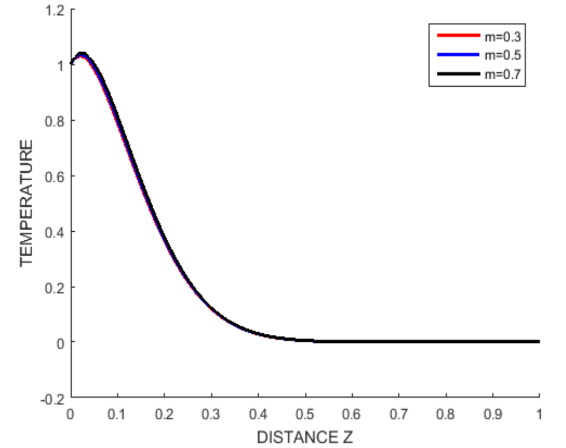

Fig 7: Variation of dimensionless temperature (θ) for various values of Hall parameter with M^2 =10,Ec=0.02 ,R=10

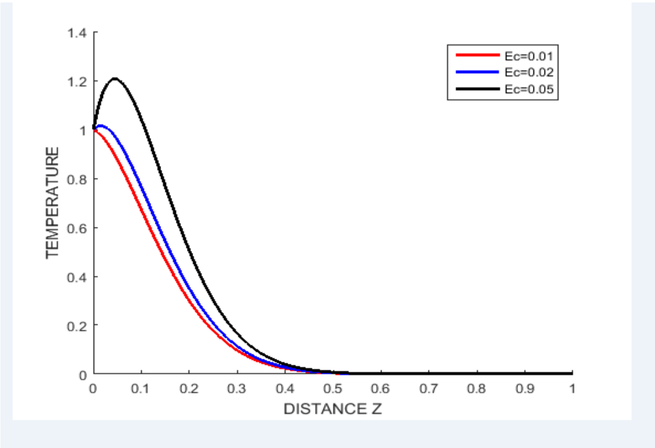

Fig 8: Variation of dimensionless temperature (θ) for various values of Eckert number Ec with M^2 =10,m=0.5,R=10

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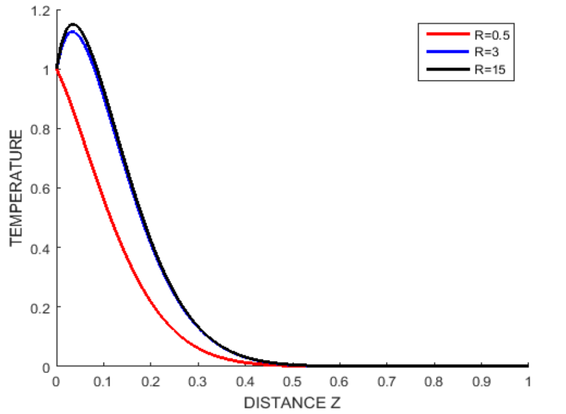

Fig 9: Variation of dimensionless temperature (θ) for various values of Joule heating parameter (R) with $M^2 = 10$,m=0.5,Ec=0.02.

From Figures 2 and 3 we observe that increase in Magnetic field parameter M^2 causes a decrease in the magnitude of both the primary and the secondary velocity profiles respectively. Also in Figure 4 shows that an increase in M^2 causes a decrease in the temperature profiles. The reduced velocity by the frictional drag due to the Lorentz force is responsible for reducing thermal viscous dissipation in the fluid leading to a thinner thermal boundary layer. Magnetic field can therefore be employed to control the velocity and temperature boundary layer characteristics of fluid. Figure 5 shows that increase in Hall parameter (m) causes an in increase in primary velocity profiles. The fluid velocity increases with increasing m due to the fact that the effective conductivity of the fluid decreases with increase in the Hall parameter m, since the magnetic damping force is reduced. However secondary velocity reduces as the hall parameter increases as shown in Figure 6. Figure 7 shows the effect of Hall parameter (m) on the dimensionless temperature. An increase in the hall parameter leads to a slight increase in the temperature profiles. Increase in the hall parameter increases the thermal boundary layer hence increase the temperature of the fluid. The effect of Eckert number on the dimensionless temperature is shown in Figure 8. An increase in Eckert number (Ec) leads to an increase in temperature profiles. This is because for an increase in Eckert number, it implies that the kinetic energy is large and hence the velocities are higher hence when these particles attain higher velocities, the vibration also increases and this leads to increased collision of particles. This increased collision of particles brings about dissipation of heat in the boundary layer region hence an increase in temperature profile. From figure 9, we note that an increase in the joule heating parameter(R) leads to an increase in the temperature profiles. Increase in joule heating parameter leads to the heating of the fluid thereby boasting the velocity of the convection currents.

V. CONCLUSION

From the results, we have seen that the parameters under investigation arising from the governing equations affect the velocity and temperature profiles. First we see that the Magnetic parameter has retarding effect on both primary and secondary velocity profiles. Secondly, the temperature reduces due to reduction in temperature. On the other hand, an increase in Eckert number causes an increase in temperature profiles and Hall parameter has slight effect in the temperature profiles. Hence magnetic field can therefore be employed to control the velocity and temperature boundary layer characteristics of a fluid flow. The Authors recommend that the same problem can be studied incorporating mass transfer.

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NOMENCLATURE

u, v, w: Velocity components in x, y, z directions respectively

Ec :Eckert number

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Pr: Prandtl number

C_p : Specific heat at constant pressure

R: Joule heating parameter

k: Thermal conductivity

Nu: Nusselt number

T: Temperature

J: Joule heating parameter

M: Magnetic number

m: Hall parameter

Er: Rotational Parameter

ν: Kinematical viscosity, m^2 / s

θ: Dimensionless temperature,K

μ : Dynamic Viscosity

ω :Cycloton frequency,m/s

μ_e :Magnetic permeability,H/m

Ω : Angular velocity m/s

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