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Mhd turbulent flow in presence of inclined magnetic field past a rotating semi-infinite plate

R.C.Maswai, M.N. Kinyanjui, J.K. Kwanza

Abstract: The turbulent incompressible fluid flow past a semi-infinite vertical rotating plate has been investigated, we considered the flow to be in the presence of a strong inclined constant magnetic field. An induced electric current exists due to the presence of both electric field and magnetic field. In this study we determined the velocity distribution of the fluid flow past a semi-infinite vertical plate, determined the temperature profiles of the fluid flow past a semi-infinite vertical plate due to velocity variations. Finally, the effects of various parameters like non-dimensional numbers and the angle of inclination of the magnetic field on the flow variables were also determined. The equations governing this problem are solved numerically using finite difference method since these equations are highly non-linear and there exists no analytical method of solving them. A sample result of the velocity profiles and temperature profiles were then obtained followed by a graphical representation of the same. The results will have major application in designing of cooling systems with liquid metals and purification of crude oil.

Index Terms—**Hall current, incompressible flow, rotating plate, turbulent flow.**

I. INTRODUCTION

Magnetohydrodynamics (Mhd) is an academic discipline which studies the dynamics of electrically conducting fluids. Examples of such fluids include plasmas, liquid metals, and salt water or electrolytes. The fundamental concept behind MHD is that magnetic fields can induce currents in a moving conductive fluid, which in turn changes the magnetic field itself and creates forces on the fluid. Considerable progress has been made recently in the general theory of MHD flows due to its wide spread application on designing of cooling systems with liquid metals, petroleum industry, purification of crude oil, separation of matter from fluids and many other applications, Rotating fluids have its applications especially in the geological sciences. Katagiri[1] discussed the effects of hall current on the MHD boundary layer flow past a semi-infinite plate. Pop and Soundergekar [2] analysed the hall effect on the flow in rotating frame of reference. Gupta [3] discussed effect of Hall current and heat transfer on rotating flow on a second grade fluid through a porous medium. Soundalgekar et al [4] studied free convection effects on MHD stokes problem for a vertical plate and they discovered that skin friction increased owing to a greater heating of the plate. Chartuverdi [5] studied the finite difference of MHD stokes problem for a vertical infinite plate in a dissipative heat generating fluid with Hall and Ion-slip current. Takhar and Soundalgekar[6] studied the forced and free convective flow past a semi-infinite vertical plate also MHD and heat transfer over a semi-infinite plate under a transverse magnetic field. Kinyanjui and Uppal [7]studied the MHD stokes problem for a vertical infinite plate in a dissipative rotating fluid with Hall current and they later investigated the effect of both hall and Ion-slip currents on the flow of heat generating rotating fluid system. They observed that for an Eckert value of 0.02, there was a decrease in the primary velocity profile with an increase in rotational parameter but in the case of secondary velocity profiles, there was initially a decrease and as the distance from the plate increased, the secondary velocity profile increased. They also observed that an increase in Hall parameter has no effect on the temperature profile but an increase in time causes an increase in the temperature profiles. Kinyanjui *et al.*[8] studied the finite difference analysis of free convection effects on MHD problem for a vertical plate in a dissipative rotating fluid system with constant heat flux and Hall current they also did a finite difference analysis of MHD stokes problem for a vertical infinite plate in a dissipative fluid with constant heat and Hall current. Kinyanjui *et al*. [9] studied Magneto hydrodynamic free convection heat and mass transfer of a heat generating fluid past an impulsively started infinite vertical porous plate with hall current and radiation absorption. Chamkha [10] studied unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate with heat absorption. The presence of heat absorption (thermal sink) effects had the tendency to reduce the fluid temperature. This caused the thermal buoyancy effects to decrease resulting in a net reduction in the fluid velocity.

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An investigation of MHD effect on the flow structure and heat transfer characteristics was carried out [11]. This was studied numerically for a liquid-gas annular flow under a transverse magnetic field. The results showed that temperature distribution in the liquid film and the Nusselt number distribution in the angular direction were influenced by the flow structures with the side walls. In 2006 [12] studied computational challenges in fluid flow problems, a MHD Stokes problem of convective flow from a vertical infinite plate in a rotating fluid. Seth *et al*[13] presented their work on effects of Hall current and rotation on unsteady MHD Couette flow in the presence of an inclined magnetic field. Kinyajui *et al* [14] analysed the hydromagnetic turbulent flow of a rotating system past a semi-infinite vertical plate with hall current where the magnetic field was considered to be variable and transverse they observed that the parameters in the governing equations affects the velocity, temperature and concentration profiles. Consequently their effect alters the skin friction and the rate of mass transfer. An investigation on Stokes problem of a convective flow past a vertical infinite plate in a rotating system in presence of variable magnetic field was carried out[15], they observed that all of the parameters affect the primary velocity, secondary velocity and temperature. Consequently their effect alters the rate of heat transfer and skin friction along the x and y axes.

II. MATHEMATICAL ANALYSIS

Governing Equations

In the present study we considered a hydromagnetic turbulent fluid flow past a rotating semi-infinite plate. A strong constant magnetic field H_0 is applied in a direction inclined to the flow at an angle α. The plate is non-conducting and the fluid is electrically conducting. In the presence of a strong magnetic field, hall current significantly affect the flow. The induced magnetic field will be assumed to be negligible. The assumption is justified because the magnetic Reynolds number is very small.

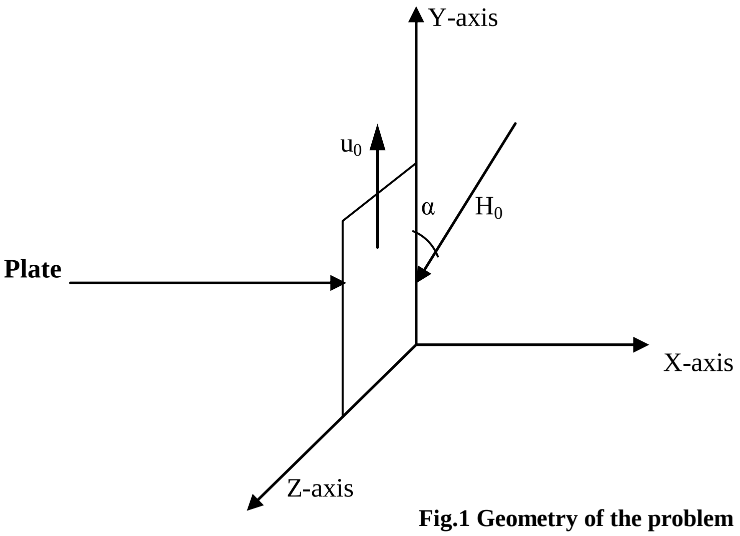

Fig.1 Geometry of the problem

The fluid and the plate are in a state of rigid rotation with uniform angular velocity about the X - axis taken normal to the plate. In this study the plate is taken to be semi- infinite in extent and the flow is unsteady therefore the physical variables are functions of x, y and t only.

At $t < 0$ the temperature of the fluid and the plate are assumed to be the same. At time t >O, the plate starts moving impulsively in its own plane with velocity u_0 .Fluid flow is assumed incompressible, Newtonian and electrically conducting. The plate is maintained at a constant temperature and its temperature is instantaneously raised or lowered to which is maintained constant. We let the superscript (*) star denotes the dimensional form of the equations. The continuity equation is given by Kinyanjui *et al*[14] as

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$$\frac{\partial \rho^*}{\partial t^*} + \rho\left(\frac{\partial u*}{\partial x*} + \frac{\partial v*}{\partial y*} + \frac{\partial w*}{\partial z*}\right) = 0 \quad (1)$$

For an incompressible two-dimensional fluid flow, w=0 and $\frac{\partial \rho}{\partial t} = 0$ hence (1) reduces to

$$\frac{\partial u*}{\partial x*} + \frac{\partial v*}{\partial y*} = 0 \quad (2)$$

The momentum Equation in free convectional fluid flow including the magnetic field and using the Reynolds Rule of averaging, is given by Kinyanjui *et al*[14] as

$$\rho\left(\frac{\partial \bar{u}^*{}_i}{\partial t^*} + \bar{u}^*{}_j \frac{\partial \bar{u}^*{}_i}{\partial x^*{}_j}\right) = -\frac{\partial \bar{p}^*}{\partial x^*{}_i} + \mu \nabla^2 \bar{u}^*{}_i - \rho \frac{\overline{\partial u^{*'}{}_i u^{*'}{}_j}}{\partial x^*{}_i} + \bar{F}^*{}_i + (\vec{J} \times \vec{B}) \quad (3)$$

In free convectional fluid flow, the body force is given by $F_{ig} = \rho g$ .The pressure gradient $\left(\frac{\partial \rho}{\partial x}\right)$ in the y-direction results from the change in elevation up the plate thus $\frac{\partial \rho}{\partial y} = -\rho_\infty g$.

$$\rho\left(\frac{\partial \bar{u}^*}{\partial t^*} + u_0{}^* \frac{\partial \bar{u}^*}{\partial x^*} + v^* \frac{\partial \bar{v}^*}{\partial y^*}\right) = \rho_\infty g - \rho g + \mu\left(\frac{\partial^2 \bar{u}^*}{\partial x^{*2}} + \frac{\partial^2 \bar{u}^*}{\partial y^{*2}}\right) - \rho \frac{\overline{\partial u^{*'}{}_i u^{*'}{}_j}}{\partial x^*{}_i} + (J \times B)$$

Expressing the density difference terms $\rho_\infty - \rho$ of the volume coefficient of expansion

β , where $\beta = \frac{\rho - \rho_\infty}{\rho(T^* - T^*{}_\infty)}$

therefore, the equation of momentum in component form is given by;

$$\frac{\partial \bar{v}^*{}_i}{\partial t^*} + \bar{u}^* \frac{\partial \bar{v}^*}{\partial x^*} + \bar{v}^* \frac{\partial \bar{v}^*}{\partial y^*} = g\beta(T^* - T^*{}_\infty) + \nu\left(\frac{\partial^2 \bar{v}^*}{\partial \bar{x}^{*2}} + \frac{\partial^2 \bar{v}^*}{\partial \bar{y}^{*2}}\right) - \frac{\partial}{\partial x^*}\overline{u^* v^*} + \frac{(\hat{J} \times \hat{B})_{y^*}}{\rho} \quad (4)$$

$$\frac{\partial \bar{w}^*{}_i}{\partial t^*} + \bar{u}^* \frac{\partial \bar{w}^*}{\partial x^*} + \bar{v}^* \frac{\partial \bar{w}^*}{\partial y^*} = \nu\left(\frac{\partial^2 \bar{w}^*}{\partial \bar{x}^{*2}} + \frac{\partial^2 \bar{w}^*}{\partial \bar{y}^{*2}}\right) - \frac{\partial}{\partial x^*}\overline{u^* w^*} + \frac{(\hat{J} \times \hat{B})_{z^*}}{\rho} \quad (5)$$

The generalized Ohms Law neglecting Hall effect is given by,

$$\hat{J} = \sigma(\hat{E} + \hat{q} \times \hat{B}) \quad (6)$$

Neglecting polarization effect, the electric potential E becomes $\hat{E} = 0$, therefore equation (6) reduces to $\hat{J} = \sigma(\hat{q} \times \hat{B})$ and the components for $\boldsymbol{J}$ the electric current density, $\boldsymbol{B}$ the magnetic induction and $\boldsymbol{q}$ velocity are given as

$J = (0, J_y, J_z)$, $B = (B_x, B_y, 0)$, $q = (0, v, w)$

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The term $\hat{q}\times\hat{B}$ in Equation yields

$$\hat{q}\times\hat{B}=\begin{vmatrix}\hat{i} & \hat{j} & \hat{k}\\ 0 & v & w\\ B_x & B_y & 0\end{vmatrix}=wB_x\hat{j}-vB_x\hat{k}$$

Thus from equation

$$\vec{J}_y=\sigma wB_x \qquad \vec{J}_z=-\sigma vB_x$$

The Lorentz force becomes

$$J\times B=\begin{vmatrix}\hat{i} & \hat{j} & \hat{k}\\ 0 & J_y & J_z\\ B_x & B_y & 0\end{vmatrix}=B_xJ_z\hat{j}-B_xJ_y\hat{k}$$

but $B_x=\mu_e H_0\sin\alpha$

The momentum equation is therefore given by;

$$\frac{\partial\bar{v}^*}{\partial t^*}+\bar{u}_0{}^*\frac{\partial\bar{v}^*}{\partial x^*}+\bar{v}^*\frac{\partial\bar{v}^*}{\partial y^*}=g\beta(T^*-T^*{}_\infty)+\nu\left(\frac{\partial^2\bar{v}^*}{\partial\bar{x}^{*2}}+\frac{\partial^2\bar{v}^*}{\partial\bar{y}^{*2}}\right)-\frac{\partial}{\partial x^*}\overline{u^*v^*}+\frac{\mu_e H_0\sin\alpha}{\rho}J_z \quad (7)$$

where g is the acceleration due to gravity, β^* is the volumetric coefficient of thermal expansion T^*, T^*_∞ are the temperature in the boundary layer and free- stream respectively , ρ the fluid density , ν is the kinematic viscosity, J_y , J_z are the current density components and v^*, w^* are the components in the Y and Z direction.

The Coriolis effect is the apparent deflection of moving objects from a straight path when they are viewed from a rotating frame of reference. The Coriolis effect is caused by the Coriolis force, which appears in the equation of motion in a rotating frame of reference(Persson 1998).Initially both the plates and the fluid are in a state of solid rotation with constant angular velocity Ω about the x-axis. The vector formula for the magnitude and direction of the Coriolis acceleration is given by

$$2\Omega\times q=\begin{vmatrix}\hat{i} & \hat{j} & \hat{k}\\ -2\Omega & 0 & 0\\ u_0 & v & w\end{vmatrix}=2\Omega w\hat{j}-2\Omega v\hat{k} \quad (8)$$

Therefore, the momentum equation appears as follows;

$$\frac{\partial\bar{v}^*}{\partial t^*}+\bar{u}_0{}^*\frac{\partial\bar{v}^*}{\partial x^*}+\bar{v}^*\frac{\partial\bar{v}^*}{\partial y^*}+2\Omega w^*=g\beta(T^*-T^*{}_\infty)+\nu\left(\frac{\partial^2\bar{v}^*}{\partial\bar{x}^{*2}}+\frac{\partial^2\bar{v}^*}{\partial\bar{y}^{*2}}\right)-\frac{\partial}{\partial x^*}\overline{u^*v^*}+\frac{\mu_e H_0\sin\alpha}{\rho}J_z \quad (9)$$

$$\frac{\partial\bar{w}^*}{\partial t^*}+\bar{u}_0{}^*\frac{\partial\bar{w}^*}{\partial x^*}+\bar{v}^*\frac{\partial\bar{w}^*}{\partial y^*}-2\Omega v^*=\nu\left(\frac{\partial^2\bar{w}^*}{\partial\bar{x}^{*2}}+\frac{\partial^2\bar{w}^*}{\partial\bar{y}^{*2}}\right)-\frac{\partial}{\partial x^*}\overline{u^*w^*}-\frac{\mu_e H_0\sin\alpha}{\rho}J_y \quad (10)$$

Ohm's law for a moving conductor taking Hall current into account given by [14] and [15] is

$$\vec{J}+\frac{\omega_e\tau_e}{H_0}\vec{J}\times\vec{H}=\sigma\left(\vec{E}+\mu_e\vec{q}\times\vec{H}+\frac{1}{e\eta_e}\nabla.p_e\right) \quad (11)$$

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Where $\sigma, \mu_e, \omega_e, \tau_e, e, \eta_e, p_e$ are the electrical conductivity, the magnetic permeability, the cyclotron frequency, the collision time, the electric charge, the number density of electron, the electron pressure respectively.

For partially ionized fluids the electron pressure gradient may be neglected. In this case we consider a short circuit problem in which the applied electric field=0.Thus neglecting pressure, the y and z components become;

$$\hat{j} + \frac{\omega_e \tau_e}{H}\left(\hat{j} \times \hat{H}\right) = \sigma\mu_e\left(\hat{q} \times \hat{H}\right)$$

$$\left(\hat{j}_y, \hat{j}_z\right) + \frac{m}{H_0}\begin{vmatrix} i & j & k \\ 0 & j_y & j_z \\ H_0 \sin\alpha & H_0 \cos\alpha & 0 \end{vmatrix} = \sigma\mu_e \begin{vmatrix} i & j & k \\ 0 & v & w \\ H_0 \sin\alpha & H_0 \cos\alpha & 0 \end{vmatrix}$$

solving and equating the y and z components yields

$$j_y + m(j_z \sin\alpha) = \sigma\mu_e(wH_0 \sin\alpha)$$

$$j_z - m(j_y \sin\alpha) = -\sigma\mu_e(vH_0 \sin\alpha)$$

calculating j_{y^+} and j_{z^+} we have;

$$j_y = \frac{\sigma\mu_e H_0 \sin\alpha(w + mv\sin\alpha)}{1 + m^2 \sin^2\alpha} \qquad (12)$$

$$j_z = \frac{\sigma\mu_e H_0 \sin\alpha(mw\sin\alpha - v)}{1 + m^2 \sin^2\alpha} \qquad (13)$$

where $m = \varpi_e \tau_e$ is the hall current

$$\tau = -\rho\overline{vw} = A\frac{\partial\overline{v}}{\partial z}$$ Adopting the Boussinesque approxiamation

Prandlt deduced that

$$\rho\overline{vw} = -\rho l^2\left(\frac{\partial\overline{v}}{\partial z}\right)^2$$

Taking that $l = kz$ where k is the von Karman constant so we have

$$\rho\overline{vw} = -\rho k^2 z^2\left(\frac{\partial\overline{v}}{\partial z}\right)^2$$

Hence

$$\overline{vw} = -k^2 z^2\left(\frac{\partial\overline{v}}{\partial z}\right)^2$$

Similarly we deduce

$$\overline{uv} = -k^2 x^2\left(\frac{\partial\overline{v}}{\partial x}\right)^2$$

$$\overline{uw} = -k^2 x^2\left(\frac{\partial\overline{w}}{\partial x}\right)^2$$

The final set of governing equations in dimensional form are;

$$\frac{\partial v^*}{\partial t^*} + u_0^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*} + 2\Omega w^* = g\beta(T^* - T^*_\infty) + v\left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}}\right) + 2k^2 x\left(\frac{\partial v}{\partial x}\right)^2 + 2k^2 x^2\left(\frac{\partial^2 v}{\partial x^2}\right)\left(\frac{\partial v}{\partial x}\right) + M^2(\sin\alpha)^2\left[\frac{(mw\sin\alpha - v)}{1 + m^2(\sin\alpha)^2}\right]$$

(14) (14)

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$$\frac{\partial w^*}{\partial t^*}+u_0{}^*\frac{\partial w^*}{\partial x^*}+v^*\frac{\partial w^*}{\partial y^*}-2\Omega v^*=\nu\left(\frac{\partial^2 w^*}{\partial x^{*2}}+\frac{\partial^2 w^*}{\partial y^{*2}}\right)^2+2k^2x\left(\frac{\partial w}{\partial x}\right)^2+2k^2x^2\left(\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial w}{\partial x}\right)-M^2(\sin\alpha)^2\left[\frac{(w+mv\sin\alpha)}{1+m^2(\sin\alpha)^2}\right]$$

(15)

$$\rho c_p\left(\frac{\partial T}{\partial t}+\frac{\partial T}{\partial x_i}\right)=\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)+\frac{J^2}{\sigma}+\phi \qquad (16)$$

$\frac{\sigma B_0{}^2}{\rho}\frac{\nu}{U^3}$ is the magnetic parameter which is M^2.

In this study non- dimensionalization is based on the following non- dimensional quantities

$$\left.\begin{aligned} &t=\frac{t^*U^2}{\nu} \quad x=\frac{x^*U}{\nu} \quad y=\frac{y^*U}{\nu} \quad u_0=\frac{u_0{}^*}{U} \quad v=\frac{v^*}{U} \quad w=\frac{w^*}{U} \quad u=\frac{u^*}{U}\\ &\Pr=\frac{\mu c_p}{k} \quad Gr=\frac{\upsilon g\beta\left(q^*\upsilon/kU\right)}{U^3} \quad E_c=\frac{U^2}{c_p\left(q^*\upsilon/kU\right)} \quad \theta=\frac{T^*-T_\infty}{T_w-T_\infty}\\ &E_r=\frac{\Omega\upsilon}{U^2} \end{aligned}\right\} \qquad (17)$$

The final set of non-dimensional equations are;

$$\frac{\partial v}{\partial t}+u_0\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+2E_rw=\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+2k^2x\left(\frac{\partial v}{\partial x}\right)^2+2k^2x^2\left(\frac{\partial^2 v}{\partial x^2}\right)\left(\frac{\partial v}{\partial x}\right)+G_r\theta+M^2(\sin\alpha)^2\left[\frac{(mw\sin\alpha-v)}{1+m^2(\sin\alpha)^2}\right] \qquad (18)$$

$$\frac{\partial w}{\partial t}+u_0\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}-2E_rv=\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+2k^2x\left(\frac{\partial w}{\partial x}\right)^2+2k^2x^2\left(\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial w}{\partial x}\right)-M^2(\sin\alpha)^2\left[\frac{(w+mv\sin\alpha)}{1+m^2(\sin\alpha)^2}\right] \qquad (19)$$

$$\frac{\partial\theta}{\partial t}+u_0\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial x^2}\right)+\frac{\delta}{\Pr}\theta+E_c\left[\left(\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial w}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right] \qquad (20)$$

The initial and boundary conditions in non-dimensional form become

$$\left.\begin{aligned} &\text{at } t\le 0 \quad v(x,y,0)=0 \quad w\,(x,y,0)=0 \quad \theta(x,y,0)=0\\ &\text{at } t>0 \quad v(0,y,t)=1 \quad w(0,y,t)=0 \quad \theta\,(0,y,t)=1\\ &\qquad\qquad v(\infty,y,t)=0 \quad w(\infty,y,t)=0 \quad \theta(\infty,y,t)=0 \end{aligned}\right\} \qquad (21)$$

III. METHOD OF SOLUTION

Equations governing the flow are highly non-linear. Getting an exact analytical solution to them is not possible. We generate numerical solutions of the equations by using the finite difference method. The equations are solved subject to the initial and boundary conditions. In finite difference the equations [18],[19]and [20] are of the form

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$$
v_{i,j}^{k+1}=\left(\begin{array}{l}
v_{i,j}^{k}+u_{0}\,\Delta t\,\dfrac{v_{i+1,j}^{k+1}}{\Delta x}-v_{i,j}^{k}\Delta t\,\dfrac{v_{i,j+1}^{k+1}}{\Delta y}+2E_{r}w_{i,j}^{k}\Delta t\;+\\
\Delta t\left\{\begin{array}{l}
\dfrac{v_{i+1,j}^{k+1}}{(\Delta x)^{2}}+\dfrac{v_{i-1,j}^{k+1}}{(\Delta x)^{2}}+\dfrac{v_{i,j+1}^{k+1}}{(\Delta y)^{2}}+\dfrac{v_{i,j-1}^{k+1}}{(\Delta y)^{2}}+\dfrac{k^{2}x}{(\Delta x)^{2}}\\
\left[\left(v_{i+1,j}^{k+1}\right)^{2}-2v_{i+1,j}^{k+1}v_{i-1,j}^{k+1}+\left(v_{i-1,j}^{k+1}\right)^{2}\right]+\dfrac{k^{2}x^{2}}{(\Delta x)^{3}}\left(\left(v_{i+1,j}^{k+1}\right)^{2}-\left(v_{i-1,j}^{k+1}\right)^{2}\right)\\
+G_{r}\theta_{i,j}^{k}+M^{2}(\sin\alpha)^{2}\dfrac{(w_{i,j}^{k}+mv_{i,j}^{k}\sin\alpha)}{1+m^{2}\sin^{2}\alpha}
\end{array}\right\}
\end{array}\right)\div
$$

$$
\left(1+\frac{\Delta t u_{0}}{\Delta x}-\frac{\Delta t v_{i,j}^{k}}{\Delta y}+\Delta t\frac{2}{(\Delta x)^{2}}+\Delta t\frac{2}{(\Delta y)^{2}}\right) \qquad (22)
$$

$$
w_{i,j}^{k+1}=\left(\begin{array}{l}
w_{i,j}^{k}+u_{0}\,\Delta t\,\dfrac{w_{i+1,j}^{k+1}}{\Delta x}-v_{i,j}^{k}\Delta t\,\dfrac{w_{i,j+1}^{k+1}}{\Delta y}+2E_{r}v_{i,j}^{k}\Delta t\;+\\
\Delta t\left\{\begin{array}{l}
\dfrac{w_{i+1,j}^{k+1}}{(\Delta x)^{2}}+\dfrac{w_{i-1,j}^{k+1}}{(\Delta x)^{2}}+\dfrac{w_{i,j+1}^{k+1}}{(\Delta y)^{2}}+\dfrac{w_{i,j-1}^{k+1}}{(\Delta y)^{2}}+\dfrac{k^{2}x}{(\Delta x)^{2}}\\
\left[\left(w_{i+1,j}^{k+1}\right)^{2}-2w_{i+1,j}^{k+1}w_{i-1,j}^{k+1}+\left(w_{i-1,j}^{k+1}\right)^{2}\right]+\dfrac{k^{2}x^{2}}{(\Delta x)^{3}}\left(\left(w_{i+1,j}^{k+1}\right)^{2}-\left(w_{i-1,j}^{k+1}\right)^{2}\right)\\
-M^{2}(\sin\alpha)^{2}\dfrac{(mw_{i,j}^{k}\sin\alpha-v_{i,j}^{k})}{1+m^{2}\sin^{2}\alpha}
\end{array}\right\}
\end{array}\right)\div
$$

$$
\left(1+\frac{\Delta t u_{0}}{\Delta x}-\frac{\Delta t w_{i,j}^{k}}{\Delta y}+\Delta t\frac{2}{(\Delta x)^{2}}+\Delta t\frac{2}{(\Delta y)^{2}}\right) \qquad (23)
$$

$$
T_{i,j}^{k+1}=\left[\begin{array}{l}
T_{i,j}^{k}+u_{0}\Delta t\dfrac{T_{i+1,j}^{k+1}}{\Delta x}-v_{i,j}^{k}\,\Delta t\dfrac{T_{i,j+1}^{k+1}}{\Delta y}+\dfrac{1}{\Pr}\Delta t\left(\dfrac{T_{i+1,j}^{k+1}}{(\Delta x)^{2}}+\dfrac{T_{i-1,j}^{k+1}}{(\Delta x)^{2}}+\dfrac{T_{i,j+1}^{k+1}}{(\Delta y)^{2}}+\dfrac{T_{i,j-1}^{k+1}}{(\Delta y)^{2}}\right)-\\
\dfrac{\delta}{\Pr}(\Delta t)T_{i,j}^{k}+(\Delta t)E_{c}\left(\begin{array}{l}
\left(\dfrac{v_{i+1,j}^{k+1}-v_{i,j}^{k+1}}{\Delta x}\right)^{2}\left(\dfrac{w_{i+1,j}^{k+1}-w_{i,j}^{k+1}}{\Delta x}\right)^{2}+\left(\dfrac{v_{i,j+1}^{k+1}-v_{i,j}^{k+1}}{\Delta y}\right)^{2}+\\
\left(\dfrac{w_{i,j+1}^{k+1}-w_{i,j}^{k+1}}{\Delta y}\right)^{2}
\end{array}\right)
\end{array}\right]\div \qquad (24)
$$

$$
\left(1+\frac{2\Delta t}{\Pr}\left(\left(\frac{1}{(\Delta x)^{2}}+\frac{1}{(\Delta y)^{2}}\right)\right)+\frac{(\Delta t)u_{0}}{\Delta x}-\frac{(\Delta t)v_{i,j}^{k}}{\Delta y}\right)
$$

The initial and boundary conditions in finite take the form.

$$
\left.\begin{array}{l}
\text{At } x=0\quad v^{0}(0,j)=1\quad w^{0}(0,j)=0\quad \theta^{0}(0,j)=1\\
\text{At } y=0\quad v^{0}(i,j)=0\quad w^{0}(i,j)=0\quad \theta^{0}(i,j)=0\\
\text{At } x=0\quad v^{k}(0,j)=1\quad w^{k}(0,j)=0\quad \theta^{k}(0,j)=1\\
\text{At } y=0\quad v^{k}(i,j)=0\quad w^{k}(i,j)=0\quad \theta^{k}(i,j)=0
\end{array}\right\} \qquad (25)
$$

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The computations are performed using small values of Δt , in this research $\Delta t = 0.00125$ and $\Delta x = 0.05$ $\Delta y = 0.05$ .Fixing $x = 2.05$ that is $i = 41$ as corresponding to $i = \infty$ because *v, w and* θ tend to zero at around $x = 2.0$ .The velocities $v_{i,j}^{k+1}$, $w_{i,j}^{k+1}$ *and* $\theta_{i,j}^{k+1}$ are computed from equation (22), (23) and (24). This procedure is repeated until $k = 400$ that is $t = 0.5$ .In the calculations the Prandlt number is taken as 0.71 which corresponds to air, magnetic parameter $M^2=5.0$ which signifies a strong magnetic field. Two cases are considered,

a) When the Grashof number, $Gr > 0(5.0)$ corresponding to convective cooling of the plate.

b) When the Grashof number, $Gr > 0(-5.0)$ corresponding to convective heating of the plate.

To ensure stability and convergence, a program is run using smaller values of Δt = 0.0001, 0.000125, 0.0003. It is observed that there were no significant changes in the results, which ascertain that the finite difference method used in the problem will converge and is stable.

IV. RESULTS AND DISCUSSION

A program was run for various values of velocities and temperature profiles for the finite difference equations. The velocities v and w at the end of each time step is computed from equation (**22 and 23)** in terms of velocity and temperature at earlier time steps. Similarly, theta is computed from equation **(24).**

In order to get physical insight into the problem under study, the velocity field and temperature field are discussed by assigning numerical values to the parameters i.e. the angle of inclination and non-dimensional numbers (Hall parameter, Eckert number, Rotational parameter and heat parameter) encountered into the corresponding Equations. To be realistic, the value of Eckert number is Ec=0.02. The velocities are classified as primary (v) and secondary (w) along the y and z axes respectively.

Case 1: Cooling at the Plate

In this case, the Grashof number Gr>0. Hence the plate is at higher temperature than the surrounding and so Gr=5.0.

a) Primary Velocity

From fig. 2 we note that:

i. Increase in the rotational parameter Er leads to a decrease in the primary velocity. This is because the presence of the inclined magnetic field which creates a resistive force similar to the drag force that acts in the opposite direction of the fluid; thus causing the velocity of the fluid to decrease.

ii. Increase in the Hall parameter m leads to an increase in the primary velocity The Hall parameter increases with the magnetic field strength. Physically, the trajectories of electrons are curved by the Lorentz force. When the Hall parameter is low, their motion between the two encounters with heavy particles (neutral or ion) is almost linear. But if it is high, the electron movements are highly curved. Also, because effective conductivity decreases with an increase in Hall parameter which reduces magnetic damping force hence the increase in velocity.

iii. Increase in the heat parameter δ leads to a decrease in the primary velocity. This is due to an increase in the internal heat generation and because the plate is cooling, the rate of energy transfer is increased therefore the velocity of the fluid will reduce.

iv. Increase in the Eckert number Ec leads to a decrease in the primary velocity. Increase in Ec means the fluid absorbs more heat energy that is released from internal viscous forces. This will in turn increase the velocity of the convection current.

v. Increase in time t leads to a decrease in the primary velocity. With time the flow gets to the free stream and therefore its velocity increases.

vi. Increase in the angle α leads to an increase in the primary velocity.

b) Secondary Velocity

From fig. 3 we note that:

i. Increase in the rotational parameter Er leads to an increase in the secondary velocity. This is because the presence of the inclined magnetic field creates a resistive force similar to the drag force that acts in the opposite direction of the fluid; thus causing the velocity of the fluid to decrease.

ii. . Increase in the Hall parameter m leads to an increase in the secondary velocity , because effective conductivity decreases with an increase in Hall parameter which reduces magnetic damping force hence the increase in secondary velocity.

iii. Increase in the heat parameter δ leads to an increase in the secondary velocity. This is due to an increase in the internal heat generation and because the plate is cooling, the rate of energy transfer is increased therefore the velocity of the fluid will reduce.

iv. Increase in the Eckert number Ec leads to a decrease in the secondary velocity. Increase in Ec means the fluid absorbs more heat energy that is released from internal viscous forces. This will in turn increase the velocity of the convection current.

v. Increase in time t leads to a decrease in the secondary velocity. With time the flow in the free stream decreases.

vii. Increase in the angle α leads to a decrease in the secondary velocity, increasing the angle of the magnetic field causes an increase in the Magnetic strength which retards the fluid motion by affecting the velocity .

C) Temperature profile

From fig. 4 we note that:

i. Increase in the rotational parameter Er leads to an increase in the temperature profile. Frequency of oscillation increase thus increasing the temperature of the fluid.

ii. Increase in the Hall parameter m leads to a slight effect on the Temperature profiles, it tends to increase the temperature profile. This is due to the increase in the thermal boundary layer that is caused by an increase in Hall parameter. An increase in the thermal boundary layer decreases the temperature gradient and hence increases the temperature in the fluid.

iii. Increase in the heat parameter δ leads to a decrease in the temperature profile. This is due to an increase in the internal heat generation and because the plate is cooling, the rate of energy transfer is increased therefore the velocity of the fluid will reduce.

iv. Increase in the Eckert number Ec leads to an increase in the temperature profile. Increase in Ec means the fluid absorbs more heat energy that is released from internal viscous forces. This will in turn increase the temperature.

v. Increase in time t leads to an increase in the temperature profile. With time as the flow gets to the free stream the velocity is increased hence there is increased rate of energy transfer and therefore the temperature will increase.

vi. Increase in the angle α leads to a decrease in the temperature profile.

Case 2: Heating at the Plate

In this case, the Grashof number Gr < 0. Hence the plate is at a lower temperature than the surrounding and so Gr = -5.0.

A) Primary Velocity

From fig. 5 we note that:

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i. Increase in the rotational parameter *Er* leads to a decrease in the primary velocity. This is because the presence of the inclined magnetic field which creates a resistive force similar to the drag force that acts in the opposite direction of the fluid; thus causing the velocity of the fluid to decrease.

ii. Increase in the Hall parameter *m* leads to an increase in the primary velocity The Hall parameter increases with the magnetic field strength. Physically, the trajectories of electrons are curved by the Lorentz force. When the Hall parameter is low, their motion between the two encounters with heavy particles (neutral or ion) is almost linear. But if it is high, the electron movements are highly curved. Also, because effective conductivity decreases with an increase in Hall parameter which reduces magnetic damping force hence the increase in velocity.

iii. Increase in the heat parameter δ leads to an increase in the primary velocity. This is due to an increase in the internal heat generation and because the plate is heating, the rate of energy transfer is decreased therefore the velocity of the fluid will increase.

iv. Increase in the Eckert number *Ec* leads to a decrease in the primary velocity. Increase in Ec means the fluid absorbs more heat energy that is released from internal viscous forces. This will in turn increase the velocity of the convection current.

v. Increase in time *t* leads to a decrease in the primary velocity. With time the flow gets to the free stream and therefore its velocity increases.

vi. Increase in the angle α leads to an increase in the primary velocity.

b) Secondary Velocity

From fig. 6 we note that:

i. Increase in the rotational parameter *Er* leads to an increase in the secondary velocity. This is because the presence of the inclined magnetic field creates a resistive force similar to the drag force that acts in the opposite direction of the fluid; thus causing the velocity of the fluid to decrease.

ii. . Increase in the Hall parameter *m* leads to an increase in the secondary velocity , because effective conductivity decreases with an increase in Hall parameter which reduces magnetic damping force hence the increase in secondary velocity.

iii. Increase in the heat parameter δ leads to an increase in the secondary velocity. This is due to an increase in the internal heat generation and because the plate is heating, the rate of energy transfer is decreased therefore the velocity of the fluid will increase.

iv. Increase in the Eckert number *Ec* leads to a decrease in the secondary velocity. Increase in Ec means the fluid absorbs more heat energy that is released from internal viscous forces. This will in turn increase the velocity of the convection current.

v. Increase in time *t* leads to an increase in the secondary velocity. With time the flow in the free stream decreases.

vi. Increase in the angle α leads to a decrease in the secondary velocity, increasing the angle of the magnetic field causes an increase in the Magnetic strength which retards the fluid motion by affecting the velocity .

C) Temperature profile

From fig. 7 we note that:

i. Increase in the rotational parameter *Er* leads to an increase in the temperature profile. Frequency of oscillation increase thus increasing the temperature of the fluid.

ii. Increase in the Hall parameter *m* leads to a slight effect on the Temperature profiles, it tends to increase the temperature profile. This is due to the increase in the thermal boundary layer that is caused by an increase in

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Hall parameter. An increase in the thermal boundary layer decreases the temperature gradient and hence increases the temperature in the fluid.

iii. Increase in the heat parameter δ leads to a decrease in the temperature profile. This is due to an increase in the internal heat generation and because the plate is cooling, the rate of energy transfer is increased therefore the velocity of the fluid will reduce.

iv. Increase in the Eckert number *Ec* leads to an increase in the temperature profile. Increase in Ec means the fluid absorbs more heat energy that is released from internal viscous forces. This will in turn increase the temperature.

v. Increase in time *t* leads to an increase in the temperature profile. With time as the flow gets to the free stream the velocity is increased hence there is increased rate of energy transfer and therefore the temperature will increase.

vi. Increase in the angle α leads to a decrease in the temperature profile.

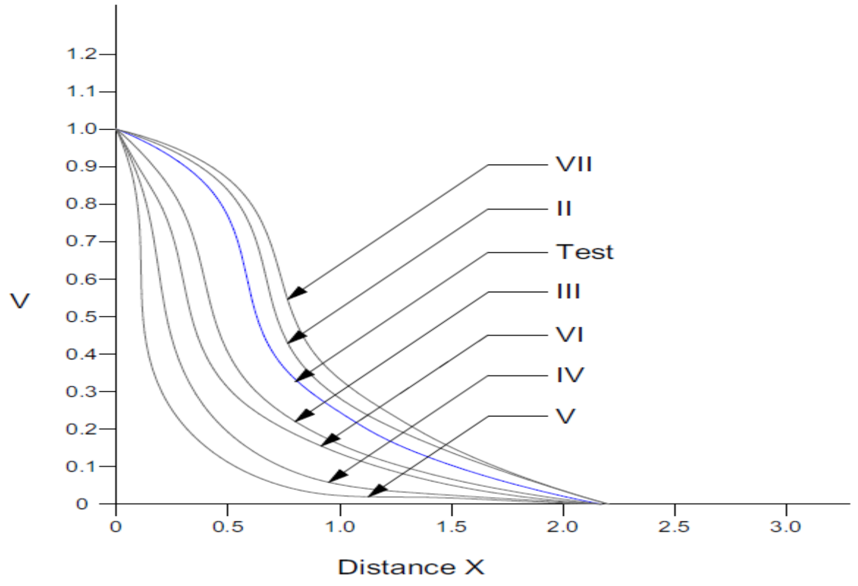

Fig 2: Primary Velocity Profile(Cooling at the plate)

	m	Er	Ec	δ	t	α
TEST	1.0	1.0	0.02	1.0	0.2	0.79
II	2.0	1.0`	0.02	1.0	0.2	0.79
III	1.0	2.0	0.02	1.0	0.2	0.79
IV	1.0	1.0	0.50	1.0	0.2	0.79
V	1.0	1.0	0.02	5.0	0.2	1.57
VI	1.0	1.0	0.02	1.0	0.15	0.79
VII	1.0	1.0	0.02	1.0	0.2	0.87

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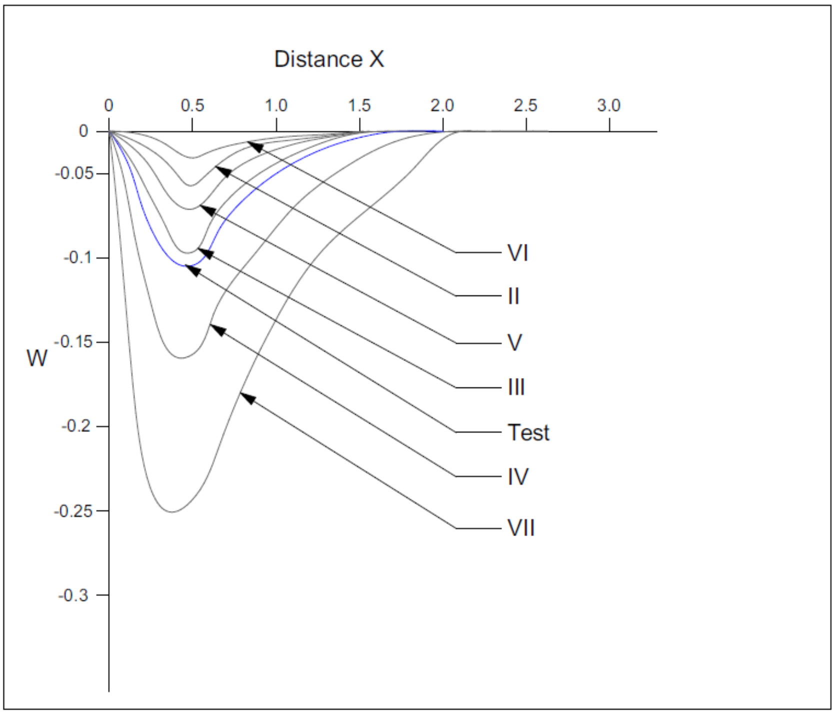
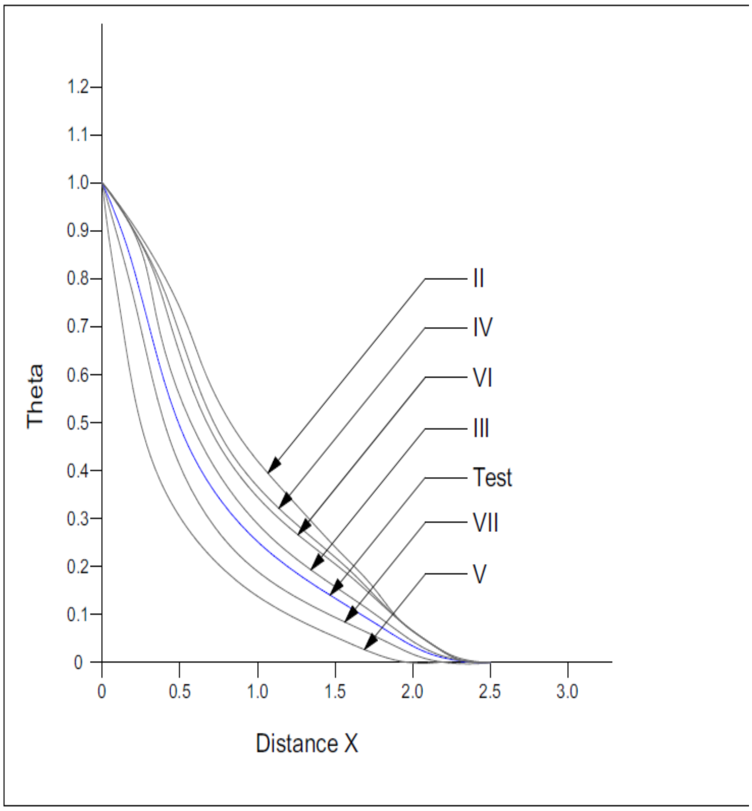


	m	Er	Ec	δ	t	α
TEST	1.0	1.0	0.02	1.0	0.2	0.79
II	2.0	1.0`	0.02	1.0	0.2	0.79
III	1.0	2.0	0.02	1.0	0.2	0.79
IV	1.0	1.0	0.50	1.0	0.2	0.79
V	1.0	1.0	0.02	5.0	0.2	1.57
VI	1.0	1.0	0.02	1.0	0.15	0.79
VII	1.0	1.0	0.02	1.0	0.2	0.87

Fig 3: Secondary Velocity Profile (Cooling at the plate)



	m	Er	Ec	δ	t	α
TEST	1.0	1.0	0.02	1.0	0.2	0.79
II	2.0	1.0`	0.02	1.0	0.2	0.79
III	1.0	2.0	0.02	1.0	0.2	0.79
IV	1.0	1.0	0.50	1.0	0.2	0.79
V	1.0	1.0	0.02	5.0	0.2	1.57
VI	1.0	1.0	0.02	1.0	0.15	0.79
VII	1.0	1.0	0.02	1.0	0.2	0.87

Fig 4:Temparature Profile(Cooling at the plate)

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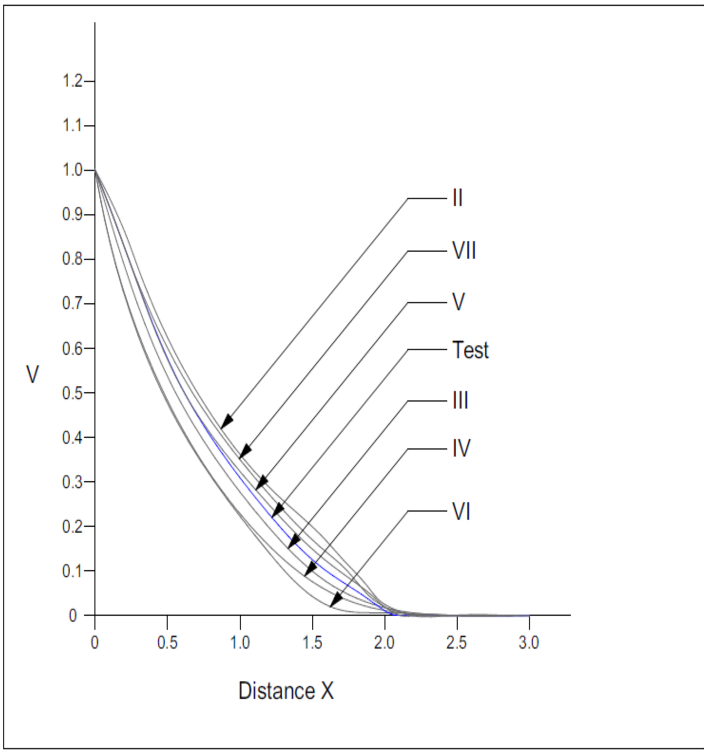
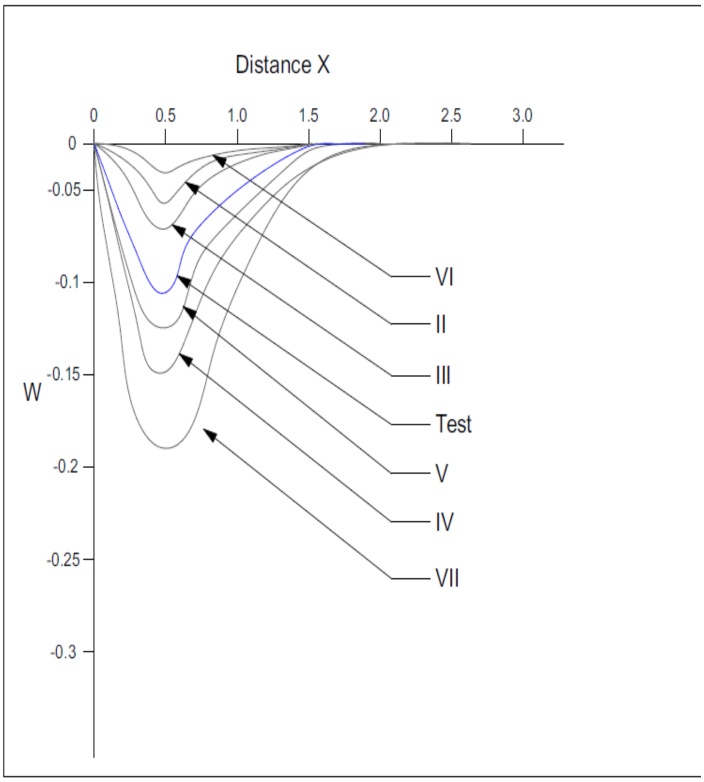


	m	Er	Ec	δ	t	α
TEST	1.0	1.0	0.02	1.0	0.2	0.79
II	2.0	1.0`	0.02	1.0	0.2	0.79
III	1.0	2.0	0.02	1.0	0.2	0.79
IV	1.0	1.0	0.50	1.0	0.2	0.79
V	1.0	1.0	0.02	5.0	0.2	1.57
VI	1.0	1.0	0.02	1.0	0.15	0.79
VII	1.0	1.0	0.02	1.0	0.2	0.87

Fig 5:Primary velocity(Heating at the plate)



	m	Er	Ec	δ	t	α
TEST	1.0	1.0	0.02	1.0	0.2	0.79
II	2.0	1.0`	0.02	1.0	0.2	0.79
III	1.0	2.0	0.02	1.0	0.2	0.79
IV	1.0	1.0	0.50	1.0	0.2	0.79
V	1.0	1.0	0.02	5.0	0.2	1.57
VI	1.0	1.0	0.02	1.0	0.15	0.79
VII	1.0	1.0	0.02	1.0	0.2	0.87

Fig 6:Secondary velocity(Heating at the plate)

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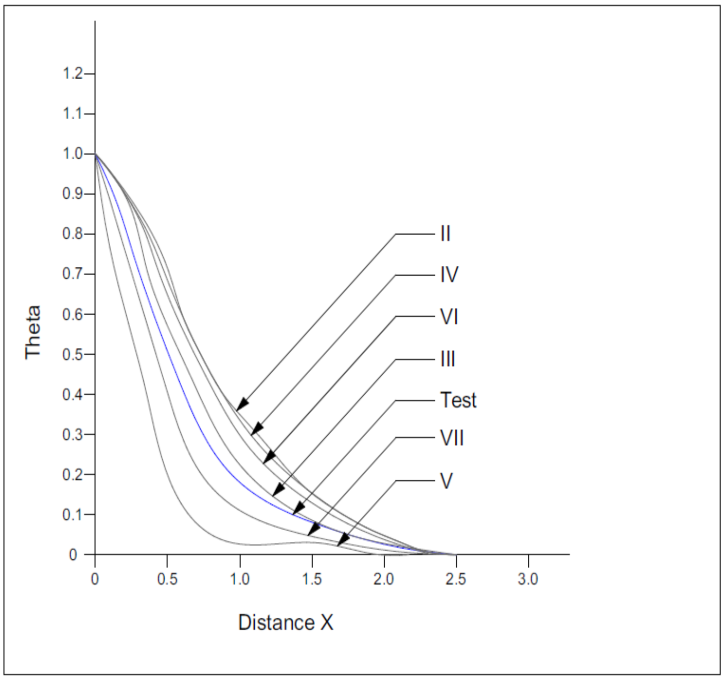

	m	Er	Ec	δ	t	α
TEST	1.0	1.0	0.02	1.0	0.2	0.79
II	2.0	1.0`	0.02	1.0	0.2	0.79
III	1.0	2.0	0.02	1.0	0.2	0.79
IV	1.0	1.0	0.50	1.0	0.2	0.79
V	1.0	1.0	0.02	5.0	0.2	1.57
VI	1.0	1.0	0.02	1.0	0.15	0.79
VII	1.0	1.0	0.02	1.0	0.2	0.87

Fig 7: Temperature profile (Heating at the plate)

IV.CONCLUSION

Some or all of the parameters affect the primary velocity, secondary velocity and temperature. In all cases considered, the applied magnetic field was resolved into components and our flow is considered turbulent .The equations governing the flows considered in our study are non-linear therefore in order to obtain their solutions, an efficient finite difference scheme has been developed.

Increase in m and α leads to an increase in the primary velocity profiles for both free convection cooling and heating at the plate while an increase in Er, Ec and t leads to a decrease in the primary velocity profiles for both free convection cooling and heating at the plate. δ leads to a decrease in the primary velocity profiles for the cooling of the plate and an increase at the heating of the plate ,which is in agreement with [13], [14] and [15].

Increasing Er, m and t leads to an increase in the secondary velocity for both cooling and heating of the plate while, Ec and α leads to a decrease in the secondary velocity profile. δ leads to a decrease in the secondary velocity profiles for the cooling of the plate and an increase at the heating of the plate .

Increase in Er, Ec ,t and m leads to an increase in the temperature profiles for both free convection cooling and free convection heating. The effect of the magnetic field inclined at an angle is to retard the fluid motion by affecting the velocity and temperature profiles.

From this results, it's clear that the parameters in the governing equations affect the primary, secondary and temperature profile. It's recommended that this work be extended by considering; variable inclined magnetic field and also the effects of the parameters in the governing equations on skin friction and rate of mass transfer.

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NOMENCLATURE

ROMAN SYMBOLS

Symbol	Meaning
B	Magnetic flux density,Wb/m^2
C_p	Specific heat J/kg K
D	Diffusion coefficient, m^2/s
e	Electric charge Coulombs/m^3
E	Electric field strength,V/m
g	Acceleration due to gravity, m/s^2
H	Magnetic field strength
H_x, H_y, H_z	Components of magnetic field strength
J	Electric current density, A/m^2
J_x, J_y, J_z	Components of the current density
k	Thermal conductivity, w/m. K
L	Characteristic length,m
P_e	The electric pressure, N/m^2
q	Velocity of the fluid, m/s
u, v, w	Components of velocity
t	Dimensional time,s
T	Dimensional temperature K
T_w	Temperature of the fluid at the plate, K
T_∞	Temperature of the fluid in the free stream, K
u_0	Dimensional injection velocity,m/s
x, y, z	Cartesian coordinates

GREEK SYMBOLS

Symbol	Meaning
β	Coefficient of volumetric expansion
α	Electrical conductivity, α/m
ρ	Fluid density kg/m3
μ_e	Magnetic permiability,H/m
υ	Kinematic viscosity m^2/s
σ_{ij}	Stress tensor
δ_{ij}	Kronector delta
η	Dynamic viscosity
Ω	Angular velocity,m/s

Abbreviations

MHD-Magnetohydrodynamics

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AUTHOR BIOGRAPHY

Miss. Rency Chebet Maswai obtained her BSc. in Applied Mathematics and Computer Science from Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya in 2012. Presently she is working as a Part-Time Lecturer at JKUAT (Karen) and at Gresta University. She is an MSc. student at JKUAT. Her area of research is in MHD and Fluid Dynamics.

Professor Mathew Ngugi Kinyanjui Obtained his MSc. In Applied Mathematics from Kenyatta University, Kenya in 1989 and a PhD in Applied Mathematics from Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya in 1998. Presently he is working as a professor of Mathematics at JKUAT where is also the director of Post Graduate Studies. He has published over fifty papers in international Journals. He has also guided many students in **Masters** and **PhD** courses. His Research area is in MHD and Fluid Dynamics.

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Professor Jackson Kioko Kwanza Obtained his MSc. In Applied Mathematics from Kenyatta University, Kenya in 1992 and a PhD in Applied Mathematics from Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya in 2002. Presently he is working as a professor of Mathematics at JKUAT and the Principle at JKUAT Karen. He has published over twenty papers in international Journals. He has also guided many students in **Masters** and **PhD** courses. His Research area is in Fluid Dynamics.