Effect of Hall Current and Rotation on MHD Free Convection Flow past a Vertical Infinite Plate under a Variable Transverse Magnetic Field

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***Abstract*—**In this study, the effect of Hall current and rotation on an electrically conducting fluid has been investigated. The fluid was considered to be flowing past an infinite vertical plate and under a strong variable transverse magnetic field. The flow was also turbulent due to the plate roughness and variation in physical properties. The entire system rotates about an axis normal to the plane of the plate with uniform angular velocity, Ω. The aim of the study was to find, the effects of Hall current and Rotation on velocity profile (both primary and secondary) and Temperature distribution of the fluid. The set of equations that describe the flow are a combination of the generalized ohm's law, Maxwell's equations, momentum equation and equation of energy. These equations are solved numerically using the methods of finite difference approximation. Then numerical results of velocity profile and temperature distribution are analyzed using tables and graphs for Hall current parameter, m and Rotational parameter, Er. It was observed that both Hall current and Rotation affect the Velocity profile and Temperature distribution of the fluid.

***Keywords*—**Free Convection; Hall Current; Magnetohydrodynamics (MHD); Rotation and Variable Magnetic Field.

***Abbreviations*—**Finite Difference Equation (FDE); Higher Order Terms (HOT); Magnetohydrodynamics (MHD).

I. INTRODUCTION

WHEN an electrically conducting fluid flow past an infinite vertical plate under a strong variable transverse magnetic field and the system is rotating, fluid motion is interfered with. This is because hall current is induced in the fluid, creating a magnetic field which interacts with the original field causing mechanical forces that interferes with the flow properties. This study is aimed at establishing the effect of Hall current and rotation on the temperature distribution and velocity profile of MHD free convection flow past an infinite vertical plate. Unlike most of the previous studies that considered a uniform magnetic field, in the present study the magnetic field is considered transverse to the flow and variable. The objectives of the study are:

- To determine the velocity profile and the temperature distribution of turbulent MHD free convection flow past an infinite vertical flat plate in a rotating system under a variable transverse magnetic field.
- Investigate how Hall current and Rotation affects temperature distribution and velocity profile of MHD free convectional flow.

The flow geometry in this study has applications in: nuclear engineering especially in the designing of cooling system of nuclear reactors, the study of the structures of the stars and planets. It also has Important Engineering applications in power generators, heat exchangers, Hall accelerators, construction of turbines, centrifugal machines among others.

II. LITERATURE REVIEW

The concept of MHD is largely perceived to have been initiated by Faraday [6] in his experiment to determine the current generated by the flow of River Thames in the earth's magnetic field. Because of the many applications of MHD including MHD power generators, MHD pumps, MHD accelerators, MHD flow-meters, Plasma jet engines, controlled thermo-nuclear reactors among others, the interest of many researchers have been drawn to this area. Hartmann [8] studied the effects of a conductor in an electrically conducting fluid; he engineered the Hartmann pump and described the theory of mercury dynamics. However, it was Alfvén [2] who established transverse waves in electrically conducting fluids and explained many astrophysical phenomena with it and therefore revolutionized the study of MHD.

Literatures on rotating unsteady MHD convection heat transfer with or without Hall currents are very extensive due to its technical importance in geophysics and astrophysics. In the recent years still a lot has been done in this area. Kinyanjui et al., [9] studied natural convection in hydro magnetic flow of a viscous incompressible rotating fluid, taking into account viscous dissipative heat and Hall current. Okelo [12] investigated unsteady free convection incompressible fluid past a semi-infinite vertical porous plate in the presence of a strong magnetic field inclined at an angle α to the plate with Hall and ion-slip current effect. Singh & Kumar [15] studied combined effects of Hall current and rotation on free convection MHD flow in a porous channel. They considered the flow to be oscillatory. Singh & Pathak [16] studied the effect of rotation and Hall current on mixed convection MHD flow through a porous medium filled in a vertical channel in the presence of thermal radiation.

The combined effects of Hall currents and radiation on MHD free convection couette flow in a rotating system were studied by Chandra et al., [4]. Mariga et al (2012) studied Hydrodynamic turbulent flow of a rotating system past a semi infinite vertical plate with Hall current. It was observed that the Hall current, rotation, Eckert number, injection and Schmidt number affect the velocity, temperature and concentration profiles. The MHD free convection flow past a vertical infinite porous plate in the presence of transverse magnetic field with constant heat flux was done by Amenya et al., [3]. Seth et al., [14] looked at Effects of Hall current and rotation on MHD natural convection flow past an impulsively moving vertical plate with ramped temperature in the presence of thermal diffusion with heat absorption. The noted that Rotation tends to retard primary velocity whereas it has reverse effect on secondary velocity in the boundary layer region. Harisingh et al., [7] studied the effect of Hall current on an unsteady MHD free convective couette flow between two permeable plates in the presence of thermal radiation. It was noted that applied magnetic field retards the primary flow along the plate and supports the secondary flow; Hall current promotes the flow along the plate and the presence of radiation effects causes reductions in the fluid temperature [Sundernath & Muthucumarswamy, 18].

Hall effects on unsteady MHD three Dimensional flow through a porous medium in a rotating parallel plate channel with effect of inclined magnetic field [Sulochana, 17]. Okongo et al., [13] studied Hall current effects on a flow in a variable magnetic field past an infinite vertical porous flat plate. They considered the flow to be steady and restricted to laminar domain. It was noted that increase in hall current parameter has no effect on secondary velocity but decreases the primary velocity. This is as a result of increase in cyclotron frequency. The effect of hall current and rotational parameter on dissipative fluid flow past a vertical semi infinite plate was studied by Abuga et al., [1]. They considered the magnetic field to be transverse and uniform. It was noted that an increase in hall parameter for both cooling and heating of the plate by free convection currents leads to an increase in the velocity profiles and an increase in rotational parameter led to a decrease in velocity profiles. Musundi et al., [11] studied magnetic field and Hall current effect on MHD free convection flow past a vertical rotating flat plate. They considered a case where a strong magnetic field is applied at an angle α to both the electric field and the direction of flow of the fluid. They noted that an increase in Hall current does not affect the temperature profile though it produces a slight increase in primary velocity profile and a significant decrease in secondary velocity profiles far from the plate.

III. GEOMETRY OF THE PROBLEM

The vertical plate is along the x- y plane and the fluid flow along it, the variable magnetic field is transverse to the plate and flow and the entire system rotates about the z- axis.

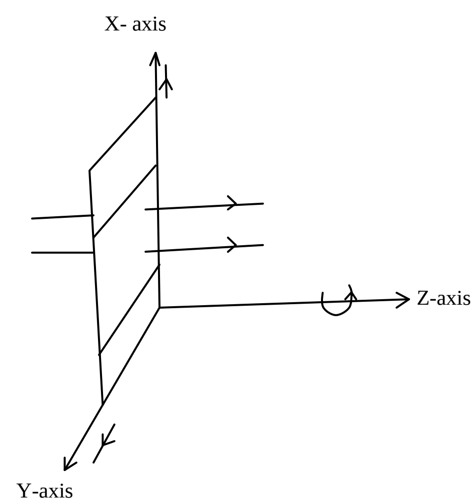

Figure 1: The Flow Geometry

IV. Governing Equations

The equations governing the flow of electrically incompressible fluid under a strong variable transverse magnetic field are Maxwell's equations, Ohm's law equation, momentum equations and energy equation.

4.1. Assumptions

The following assumptions are made to enable us simplify and solve the flow governing equations.

i) The flow is considered turbulent or unsteady.
ii) The external electric field is zero.
iii) Thermal conductivity and viscosity are assumed to be constant.
iv) The fluid is incompressible (density is assumed to be constant).

4.2. Ohm's Law

When a conductor move within a magnetic field the magnetic field induces a current in the conductor of magnitude $\vec{V}\times\vec{B}$, where $\vec{V}=ui+vj$.

From the Maxwell's equations, $\vec{B}=\alpha\mu_e\vec{H}$

The modified generalized Ohm's law that includes the Hall current effects according to Cowling [5] is given by:

$$\vec{J}+\frac{\omega_e\tau_e\alpha}{H_0}\left(\vec{J}\times\vec{H}\right)=\sigma\left(\vec{E}+\mu_e\alpha\vec{V}\times\vec{H}+\frac{1}{e\eta_e}\nabla P_e\right) \quad (1)$$

According to Meyer [10], there being no external electric field $\vec{E}=0$; Also neglecting pressure gradient P_e because the fluid is weakly ionized, equation 3 above becomes:

$$\vec{J}+\frac{\omega_e\tau_e\alpha}{H_0}\left(\vec{J}\times\vec{H}\right)=\sigma\mu_e\alpha\vec{V}\times\vec{H} \quad (2)$$

Note that the Hall current parameter $m=\omega_e\tau_e$.

Equation 2 in component form can be written as:

$$\begin{pmatrix} j_x \\ j_y \\ 0 \end{pmatrix}+\frac{m\alpha}{H_0}\begin{pmatrix} j_yH_0 \\ -j_xH_0 \\ 0 \end{pmatrix}=\sigma\mu_e\alpha\begin{pmatrix} vH_0 \\ -uH_0 \\ 0 \end{pmatrix} \quad (3)$$

Equating x and y components in the above Equation 3 yields:

$$j_x+mj_y\alpha=\sigma\mu_e v\alpha H_0 \quad (4)$$

$$j_y-mj_x\alpha=-\sigma\mu_e u\alpha H_0 \quad (5)$$

Solving equation 4 and 5 simultaneously yields:

$$j_x=\frac{\sigma\mu_e\alpha H_0\left(m\alpha u+v\right)}{\alpha^2m^2+1} \quad (6)$$

$$j_y=\frac{\sigma\mu_e\alpha H_0\left(m\alpha v-u\right)}{\alpha^2m^2+1} \quad (7)$$

4.3. Momentum Equation

These equations are based on Newton's second law of motion. The law states that the net rate of change of momentum must be equal to the net sum of forces acting on the fluid. Considering a rotating frame of reference with a uniform angular velocity Ω, the equation of momentum becomes:

$$\rho\left[\frac{\partial\vec{V}}{\partial t}+\vec{V}\left(\nabla.\vec{V}\right)+2\vec{\Omega}\times\vec{V}\right]=-\frac{\partial P}{\partial x}+\mu\nabla^2\vec{V}-\rho g+\mu_e\alpha\left(\vec{J}\times\vec{H}\right) \quad (8)$$

Note that the pressure gradient is given by $-\frac{\partial P}{\partial x}=\rho_\infty g$.

Combining the pressure term and the gravitational body force term then introduce the volumetric coefficient of thermal expansion, we have:

$$\frac{\partial V}{\partial t}+\left(u\frac{\partial V}{\partial x}+v\frac{\partial V}{\partial y}\right)=\upsilon\frac{\partial^2 V}{\partial z^2}-2\vec{\Omega}\times\vec{V}+g\beta\left(T-T_\infty\right)+\frac{1}{\rho}\mu_e\alpha\left(\vec{J}\times\vec{H}\right) \quad (9)$$

Equation 9 when simplified using vector analysis and substituting the Ohm's law equations 6 and 7 we have:

$$\frac{\partial u}{\partial t}=\upsilon\frac{\partial^2 u}{\partial z^2}+2\Omega v+g\beta(T-T_\infty)+\frac{1}{\rho}\sigma\mu_e^2\alpha^2{H_0}^2\frac{\left(m\alpha v-u\right)}{\alpha^2m^2+1} \quad (10)$$

$$\frac{\partial v}{\partial t}=\upsilon\frac{\partial^2 v}{\partial z^2}-2\Omega u-\frac{1}{\rho}\sigma\mu_e^2\alpha^2H_0^2\frac{\left(m\alpha u+v\right)}{\alpha^2m^2+1} \quad (11)$$

4.4. Energy Equations

The equation is based on conservation of energy which states that energy is neither created nor destroyed but can be transformed from one form to another. It is derived from the first law of thermodynamics which states that the amount of energy added to a system dQ equals to change of internal energy dE plus dW i.e

$$dQ=dE+dW \quad (12)$$

Therefore the energy equation becomes:

$$\rho c_p\frac{DT}{Dt}=k\nabla^2T+\mu\nabla^2\vec{V}+Q^* \quad (13)$$

According to the flow in consideration, Equation 13 can be written as:

$$\frac{\partial T}{\partial t}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial z^2}+\frac{\upsilon}{c_p}\left[(\frac{\partial u}{\partial z})^2+(\frac{\partial v}{\partial z})^2\right]+\frac{Q^*}{\rho c_p} \quad (14)$$

Equations 15, 16 and 20 are the equations to be solved to obtain the velocity and temperature profiles of the flow situation in consideration.

4.5. Non-dimensionalisation

The flow governing equations 10, 11 and 14 are first non-dimensionalised before solving. This process reduces the parameters and also makes it possible to apply the outcome or results of this study to other similar flow geometry under different conditions. Hence the flow governing equation in non-dimensional form are:

$$\frac{\partial u^*}{\partial t^*}=\frac{\partial^2 u^*}{\partial z^{*2}}+2Erv^*+Gr\theta+M^2\alpha^2\left(\frac{m\alpha v^*-u^*}{m^2\alpha^2+1}\right) \quad (15)$$

$$\frac{\partial v^*}{\partial t^*}=\frac{\partial^2 v^*}{\partial z^{*2}}-2Eru^*-M^2\alpha^2\left(\frac{m\alpha u^*+v^*}{m^2\alpha^2+1}\right) \quad (16)$$

$$\frac{\partial\theta}{\partial t^*}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial z^{*2}}+Ec\left|(\frac{\partial u^*}{\partial z^*})^2+(\frac{\partial v^*}{\partial z^*})^2\right|+\frac{1}{\Pr}\delta\theta \quad (17)$$

The non-dimensional equations 15, 16 and 17 are solved using the Finite difference method.

The initial and boundary condition in non-dimensional form becomes:

$t^* \le 0: \quad u^* = 0, v^* = 0, \theta = 1 \quad t^* > 0: \quad u^* = 1, v^* = 0, \theta = 1$ at $z = 0 \quad u^* \to 0, v^* \to 0, \theta \to 0$ as $z \to \infty$.

V. Method of Solution

In this study, the non-dimensionalised governing equations 15, 16 and 17 are solved using the Finite difference method. This method was preferred because it's stable (converges) and also flexible to use with initial and boundary conditions. A uniform mesh is used. Therefore using central finite difference for the first order time derivative and central finite difference for the first and second order partial derivatives, the governing equations 15, 16 and 17 can be written in the finite difference form as follows:

$$\frac{u^{*n+1}_{(k,i+1)} - u^{*n}_{(k,i-1)}}{2\Delta t^*} = \left[\frac{u^{*n}_{(k+1,i)} - 2u^{*n}_{(k,i)} + u^{*n}_{(k-1,i)}}{(\Delta z^*)^2}\right] + 2Erv^{*n}_{(k,i)} + Gr\theta^{n}_{(k,i)} + M^2\alpha^2\left(\frac{m\alpha v^{*n}_{(k,i)} - u^{*n}_{(k,i)}}{m^2\alpha^2 + 1}\right) \tag{18}$$

$$\frac{v^{*n+1}_{(k,i+1)} - v^{*n}_{(k,i-1)}}{2\Delta t^*} = \left[\frac{v^{*n}_{(k+1,i)} - 2v^{*n}_{(k,i)} + v^{*n}_{(k-1,i)}}{(\Delta z^*)^2}\right] - 2Eru^{*n+1}_{(k,i)} - M^2\alpha^2\left(\frac{m\alpha u^{*n+1}_{(k,i)} + v^{*n}_{(k,i)}}{m^2\alpha^2 + 1}\right) \tag{19}$$

$$\frac{\theta^{n+1}_{(k,i+1)} - \theta^{n}_{(k,i-1)}}{2\Delta t^*} = \frac{1}{\Pr}\left[\frac{\theta^{n}_{(k+1,i)} - 2\theta^{n}_{(k,i)} + \theta^{n}_{(k-1,i)}}{(\Delta z^*)^2}\right] + Ec\left[\frac{u^{*n+1}_{(k+1,i)} - u^{*n+1}_{(k-1,i)}}{2\Delta z^*}\right]^2 + Ec\left[\frac{v^{*n+1}_{(k+1,i)} - v^{*n+1}_{(k-1,i)}}{2\Delta z^*}\right]^2 + \frac{1}{\Pr}\delta\theta^{n}_{(k,i)} \tag{20}$$

These finite difference equations 18, 19 and 20 that govern the flow are solved using a computer program called Matlab that takes care of their non-linear properties.

5.1. Boundary and Initial Conditions

The initial condition when $t^* = 0$ takes the form At $z^* = 0$, $u^{*0}_{(0,i)} = 1$, $v^{*0}_{(0,i)} = 0$, $\theta^{*0}_{(0,i)} = 1$

At $z^* > 0$, $u^{*0}_{(k,i)} = 0$, $v^{*0}_{(k,i)} = 0$ and $\theta^{0}_{(k,i)} = 0$ At k>0 and all i, the boundary conditions take the form

$z^* = 0$, $u^{*n}_{(0,i)} = 1$, $v^{*n}_{(0,i)} = 0$, and $\theta^{n}_{(0,i)} = 1$ At $x^* = 0$, $u^{*n}_{(k,0)} = 1$, $v^{*n}_{(k,0)} = 0$ and $\theta^{n}_{(k,0)} = 1$

In order to get physical insight into the problem under study, the velocity field and temperature distribution are discussed by assigning numerical values to the parameters encountered into the corresponding equations. The computations are done when Δt^* is small. Set $\Delta t^* = 0.0025$ We set $k = 120$ to correspond to $z^* = \infty$ and $\Delta x^* = \Delta z^* = 1$. Therefore $u^{*n}_{(120,i)} = v^{*n}_{(120,i)} = \theta^{n}_{(120,i)} = 0$. The Prandtl number is taken as 0.71 which corresponds to air. Magnetic parameter $M^2 = 10$ which signifies a strong variable magnetic field. Grashof number, $Gr > 0(0.4)$ corresponding to convective cooling of the plate. Eckert number is 0.6. $\alpha = 0.8$ Because applied magnetic field is strong throughout despite being variable.

VI. Numerical Results and Discussion

6.1. Primary Velocity $u(z^*, t)$

Solving equation 18 while varying m as 0.5, 1.0, 1.5 and also varying Er as 0.1, 0.3, 0.6 using Matlab software, we get the solutions $u^*(z^*, t^*)$ in Table 1 that are graphically represented as shown in Figure 2 and Figure 3.

Table 1: Values of Primary Velocity $u^*(z^*, t)$

z^*	$Er = 0.5$	$Er = 0.75$	$Er = 0.5$	$m = 0.5$	$m = 1.0$	$m = 1.5$
0	112166.3	105162.4	100159.8	10587.19	7915.556	6506.341
1	207076.3	200069.1	196064.3	19527.48	14613.33	12011.71
2	284729.9	277720.0	273713.4	26820.88	20093.33	16516.10
3	345127.2	338115.2	334107.2	32467.38	24355.55	20019.51
4	388268.1	381254.6	379245.6	36466.98	27400.00	22521.95
5	414152.6	407138.3	403128.6	38819.69	29226.67	24023.41
6	422780.8	415766.1	411756.3	39525.50	29835.55	24523.90
7	414152.6	410738.3	406128.6	38584.42	29226.67	24023.41
8	388268.1	381254.6	379245.6	35996.44	27400.00	22521.95

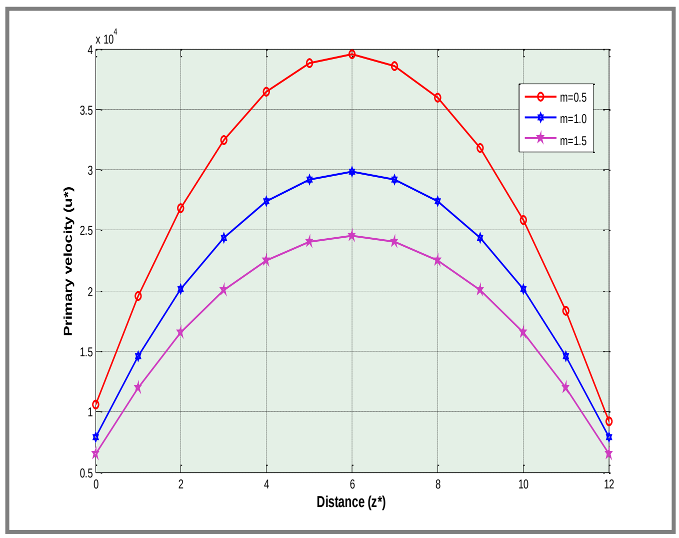

Figure 2: Graph of Primary Velocity, u^* against Distance, z^* at varying Hall Parameter m

From Figure 2, it is observed that the velocity increases gradually near the plate and decreases slowly away from the plate. This is due to first the heat energy gained by the molecules which in turn increases their kinetic energy then away from the plate, there is the cooling effect that results in reduction in kinetic energy that causes a decline in the velocity. An increase in hall parameter causes a significant decrease in the primary velocity; this is due to the established fact that the application of a magnetic field to an electrically conducting fluid gives rise to a force, known as Lorentz force, which tends to resist the fluid motion.

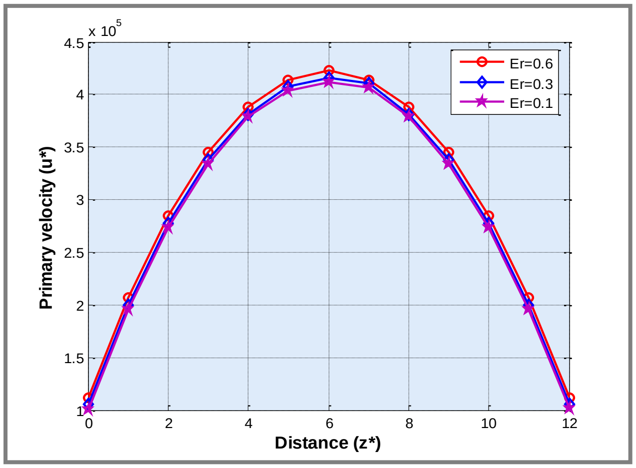

Figure 3: Graph of Primary Velocity, u^* against Distance, z^* at varying Rotational Parameter, Er

The graph in Figure 3 is parabolic due to the heating followed by the cooling effects on the fluid molecules. This affects the kinetic energy of the molecules which in turn affects their velocity. It is noted that an increase in the rotation parameter, Er leads to a slight increase in the primary velocity profile. This implies that Rotation accelerates fluid velocity in the primary fluid flow direction.

6.2. *Secondary Velocity* $v(z^*,t)$

Solving equation 19 while varying m as 0.5, 1.0, 1.5 and also varying Er as 0.1, 0.3, 0.6 using Matlab software, we get the solutions $v^*(z^*,t)$ in Table 2 that are graphically represented as shown in Figure 4 and Figure 5.

Table 2: Values of Secondary Velocity $v^*(z^*,t^*)$

z^*	$m=0.5$	$m=1.0$	$m=1.5$	$Er=0.6$	$Er=0.3$	$Er=0.1$
0	2579.155	2547.041	2495.041	17173	19760	21901.18
1	4761.518	4702.229	4606.229	33893	36480	40432.95
2	6547.086	6465.564	6333.564	47573	50160	55595.30
3	7935.862	7837.048	7677.048	58213	60800	67388.24
4	8927.845	8816.679	8636.679	64773	68400	75811.77
5	9523.035	9404.458	9212.458	68293	72960	80865.89
6	9721.432	9600.384	9404.384	70813	74480	82550.59
7	9523.035	9404.458	9212.458	68293	72960	80865.89
8	8927.845	8816.679	8636.679	64773	68400	75811.77

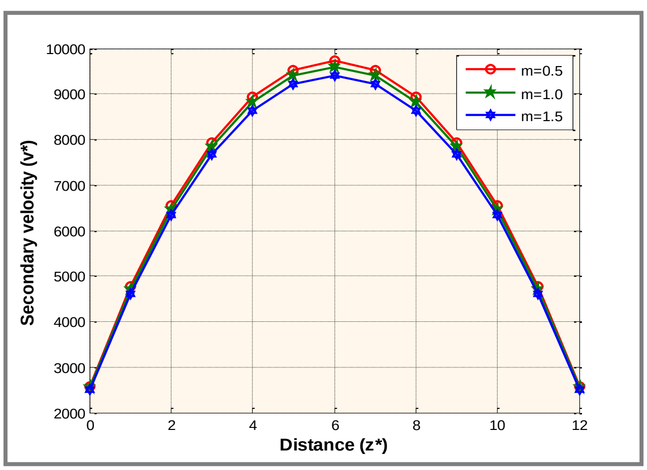

Figure 4: Graph of Secondary Velocity, v^* against Distance, z^* at varying Hall Parameter m

It is observed from graph in Figure 4 that the velocity increases gradually near the plate and then decreases slowly far away from the plate. This is due to the heating followed by the cooling effect the fluid molecules experience. An increase in Hall parameter m leads to a slight drop in the secondary velocity profile. This is due to the minimal retarding force along the y-direction created between the interaction of the applied magnetic field and the field due to the hall current.

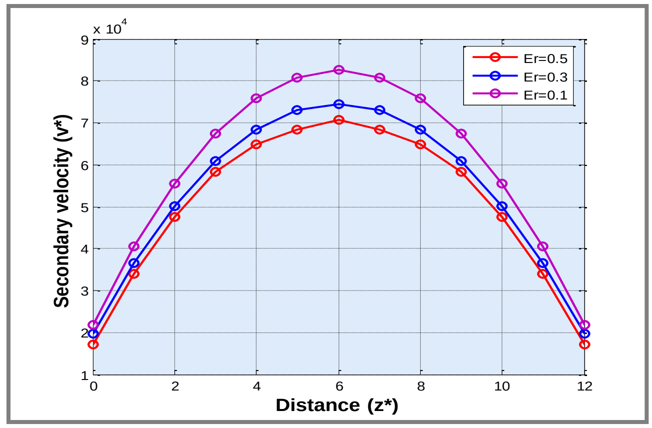

Figure 5: Graph of Secondary Velocity, v^* against Distance, z^* at varying Rotational Parameter, Er

From graph in figure 5, an increase in the rotation parameter Er leads to a significant decrease in the secondary velocity profile. This implies that rotation has a retarding influence on the fluid flow in the secondary flow direction.

6.3. *Temperature Distribution* θ

Solving equation 20 while varying Ec as 0.6, 1.0, 1.5 using Matlab software, we get Temperature solutions $\theta(z^*,t^*)$ in Table 3 that are graphically represented as shown in Figure 6.

Table 3: Values of Temperature $\theta(z^*,t^*)$ for varying Eckert Number, Ec

z^*	$Ec=0.6$	$Ec=1.0$	$Ec=1.5$	z^*	$Ec=0.6$	$Ec=1.0$	$Ec=1.5$
0	3.737769	3.686236	3.646236	4	3.250750	3.237463	3.227463
1	3.524989	3.487092	3.457092	5	3.245708	3.237103	3.227103
2	3.368499	3.339742	3.309742	6	3.245766	3.237160	3.227160
3	3.283748	3.265172	3.245172	7	3.245756	3.237150	3.227150

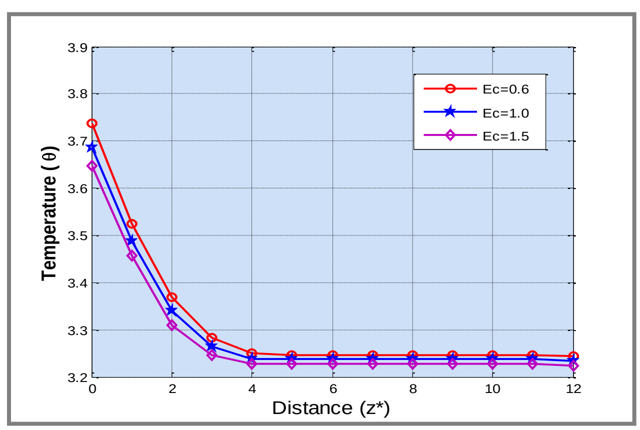

Figure 6: Graph of Temperature, θ against Distance, z^* at varying Eckert Number, Ec

From Figure 6, it is observed that Temperature profiles decreases gradually near the plate and remains constant away from the plate. Increase in Eckert number leads to a slight decrease in Temperature distribution. Because the Eckert number depends on primary velocity, increase in hall parameter causes a slight increase in Temperature distribution while increase of rotational parameter leads to a slight decrease in Temperature distribution.

VII. Conclusion

This study considered the flow of an electrically conductive fluid past a vertical infinite plate in the presence of a variable transverse magnetic field and the system rotating about the z-axis. We employed the Finite difference method to solve the flow governing equations using matlab software. Numerical results of velocity (primary and secondary) and Temperature distribution were determined. By carrying out graphical analysis of the results, the effects of Hall parameter and Rotational parameter on the primary velocity, secondary velocity and temperature distribution of the flow geometry was established. It is noted that an increase in Hall parameter causes a significant decrease in primary velocity profile, a slight decrease in the secondary velocity profile and a slight increase in the Temperature distribution. It is also noted that an increase in Rotational parameter produces a slight increase in Primary velocity profile, a significant decrease in secondary velocity profile and a slight decrease in the Temperature distribution.

It is hoped that the results will be useful for applications including nuclear engineering especially in designing more efficient cooling system of nuclear reactors and that they can also be used for comparison with other problems dealing with Hall current and rotational parameter which might be more complicated. It is also hoped that the results can serve as a complement to other studies.

VIII. Recommendation

From this study, there are areas that arise for further analysis and development. These may be theoretical or experimental and specific areas of study include:

- Flow of fluids when the variable magnetic field is at an angle to the plate.
- Analysis of the overall computation error in the results obtained.
- Flow of fluid which is compressible.
- A more practical approach in Engineering would reduce theoretical assumptions made in this study.

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