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MODELING AND ANALYSIS OF MAGNETOHYDRODYNAMIC FREE CONVECTION TURBULENT FLUID FLOW PAST A VERTICAL INFINITE POROUS PLATE

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Abstract: A mathematical model of a two-dimension magnetohydrodynamic (MHD) free convection fluid flow that is turbulent and past a vertical infinite porous plate is developed. The fluid flow is impulsively started to in x-direction. Flow problem modeled using conservation of momentum, and conservation of energy equations. The arising partial differential equations, which are nonlinear, are solved numerically using explicit finite difference scheme. Simulation of the discretized equations is done using MATLAB. The impacts of flow parameters on velocities and temperature profiles such as Magnetic parameter (M), Hall parameter (m), and Prandtl number (Pr) were examined. It is evident from the results that during the cooling of the plate ($Gr > 0$), the primary velocity decreases with decrease in Hall parameter, m, and increase in magnetic parameter, M. It also decreases as the prandtl number, Pr, is increased. The secondary velocity decreases with decrease in Hall parameter, m, and increase in magnetic parameter, M. It also decreases as the prandtl number, Pr is increased.The results also shows that there is no significant effect on temperature profile as the Hall parameter is decreased. There is also no significant change as the magnetic parameter is increased. It is also evident that there is a decrease in temperature profile when the Prandtl number is increased.

Key words: Porous plate, Free Convection, Magnetohydrodynamic, Turbulent, Finite difference

LIST OF SYMBOL

H	Magnetic field intensity, (Wb/m^2)
B	Magnetic flux density, (Wb/m^2)
J	Current density vector
E	Electric field (Vm^1)
H_0	Constant magnetic field intensity, Wb/m^2
u, v, w	Velocity components in the x,y, and z direction respectively, m/s
u', v', w'	Fluctuating components of velocity
$\overline{u}, \overline{v}, \overline{w}$	Mean velocities
a	Acceleration, (m/s^2)
Q	Heat, (J)
W	Work, (J)
p	Fluid pressure, N/m^2
g	Acceleration due to gravity, m/s^2
t	Time, s
T	Absolute temperature, K
C_p	Specific heat at constant pressure of the fluid, $J/kg/K$
Re	Reynolds number
L	Characteristic length, m
M	Magnetic parameter
Pr	Prandtl number
Gr	Grashoff number
Ec	Eckert number

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Rt	Time parameter
μ	Coefficient of viscosity, *kg/ms*
ρ	Fluid density, *kg/m³*
α	Coefficient of thermal diffusivity, m^2/s
υ	Coefficient of kinematic viscosity, m^2/s
σ	Electrical conductivity, $\Omega^{-1}m^{-1}s$
β	Coefficient of thermal expansion, K^{-1}

I. INTRODUCTION

Many researchers have done investigations on magnetohydrodynamics which of great interest to scientists and engineers. Several investigations both theoretical and experimental have been done in the past in relation to this. Mukuna *et al.* (2020) modeled a Hydromagnetic free convection turbulent fluid flow over a vertical infinite plate using turbulent Prandtl number. Vijayalakshmi *et al.* (2018) did a research on the unsteady electrically transmitting fluid past an oscillating semi- infinite vertical plate with uniform temperature and mass diffusion under chemical reactions. Odekeye and Akinrinmade (2017) did a MHD research on mixed convective heat and mass transfer flow from vertical surfaces in porous media with Soret and Dufour effects. Loganathan and Eswari (2017) did a research on natural convective flow over moving vertical cylinder with temperature oscillation in the presence of porous medium. They used the iterative tridiagonal semi-implicit finite difference method. Mukuna *et al.* (2017b) analyzed heat and mass transfer rates of hydromagnetic turbulent fluid flow over an immersed cylinder with Hall current.

They modeled the flow using conservation equations and solved the arising partial differential equations using finite difference scheme. Mukuna *et al.* (2017a) researched on hydromagnetic turbulent free convection fluid flow over an immersed infinite vertical cylinder, modeled their problem using conservation equations and later solved the arising partial differential equations using finite difference scheme. Kiprop (2017) did a research on an unsteady MHD flow with mass and heat transfer in an incompressible, viscous, Newtonian and electrically conducting fluid past a vertical porous plate with consideration of chemical reaction, thermal radiation and induced magnetic field. Solution of governing equations were done using finite difference scheme, that is the Crank- Nicholson method. Seth *et al.* (2016) studied on the effects of an unsteady free convection flow past an impulsively moving porous vertical plate with Newtonian heating. Chebos *et al.* (2016) investigated an unsteady MHD free convection flow past an oscillating vertical porous plate with oscillatory heat flux. It is worth noting that despite of all these, MHD turbulent fluid flow has received little attention as expected.

The main objective of the present research is to study a two-dimensional hydro magnetic free convective flow of an incompressible viscous and electrically conducting fluid flow that is turbulent and past a vertical infinite porous plate using a mathematical model. It is evident from the results that during both the cooling and Heating of the plate ($Gr > 0$ and $Gr < 0$), the primary velocity decreases with decrease in Hall parameter, m, and increase in magnetic parameter, M. It also decreases during cooling of the plate as the prandtl number, Pr, is increased and even during the heating of the plate as the prandtl number, Pr, is decreased. For $Gr > 0$ and $Gr < 0$, the secondary velocity decreases with decrease in Hall parameter, m, and increase in magnetic parameter, M. It also decreases during cooling of the plate as the prandtl number, Pr is increased and also during heating of the plate as the prandtl number, Pr is decreased. The results also shows that there is NO significant effect on temperature profile during both cooling and heating of the plate as the Hall parameter is decreased. There is also NO significant change during the cooling of the plate as the magnetic parameter is increased and even during the heating of the plate as the magnetic parameter is decreased. It is also evident that there is a decrease in temperature profile when the Prandtl number is increased in both the cooling and Heating of the plate.

II. MATHEMATICAL MODEL

A two-dimensional flow is considered in this study. The infinite vertical porous plate is taken to be along the x-axis and the y-axis taken to be on the horizontal whereas the z-axis normal to the plate. The fluid being considered is incompressible and viscous. A magnetic field of a high magnitude H_0 is applied perpendicularly to the direction of flow of the fluid. It is assumed that the induced magnetic field is negligible therefore $H = (0,0,H_0)$ as indicated in the diagram below. At time t*>0, the fluid is stationary and the plate starts to move impulsively in its plane with velocity

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U_0 and the temperature of the plate raised instantly to T_w^* and maintained constant later on. The schematic diagram for the fluid flow is as given below:

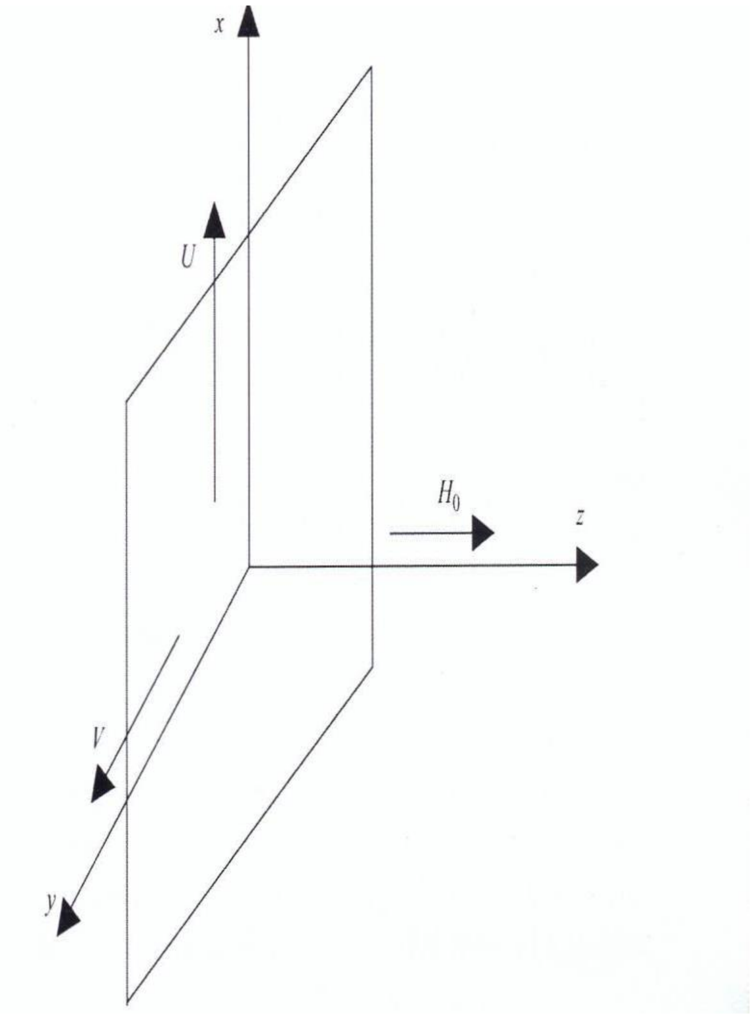

Figure 1: Schematic diagram for the fluid flow.

The flow is therefore governed by the following equations:

$$\frac{\partial U^*}{\partial t^*} + V^*\frac{\partial U^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x} + \upsilon\left(\frac{\partial^2 U^*}{\partial z^{*2}}\right) - \frac{\partial(\overline{uw})}{\partial z^*} + \rho g + JxB \quad (1)$$

$$\frac{\partial V^*}{\partial t^*} + V^*\frac{\partial V^*}{\partial y^*} = \upsilon\left(\frac{\partial^2 V^*}{\partial z^{*2}}\right) - \frac{\partial(\overline{u\,w})}{\partial z^{*2}} + JxB \quad (2)$$

$$\frac{\partial T^*}{\partial t^*} + V^*\frac{\partial \overline{T}}{\partial y} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T^*}{\partial z^{*2}}\right) - \frac{\partial(\overline{w T})}{\partial z^*} \quad (3)$$

Where $\upsilon = \frac{\mu}{\rho}$ is the kinematic viscosity

ρ is the fluid density

The initial and boundary conditions will be as follows:

$t^* > 0 : U^* = 0, V^* = 0, T^* = T_\infty^*$ everywhere (4a)

$t^* \geq 0 : U^* = 0, V^* = 0, T^* = T_w^*$ at z= 0; (4b)

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$U^* \to U_0,\ V^* \to 0, T^* \to T_\infty^*$ as z→ ∞ (4c)

On introducing non dimensional quantities:

$$t = \frac{t^* U_0^2}{\upsilon}, = \frac{z^* U_0}{\upsilon}, y = \frac{y^* U_0}{\upsilon}\ U = \frac{U^*}{U_0}, V = \frac{V^*}{U_0}, \theta = \frac{T^* - T_W^*}{T_W^* - T_\infty^*},$$
$$Gr = \frac{\upsilon g\beta(T_W^* - T_\infty^*)}{U_0^3}, \theta = \frac{T^* - T_W^*}{T_W^* - T_\infty^*}, M^2 = \frac{\sigma\mu_e^2 H_0^2 \upsilon}{U_0^2},$$

The above governing equations and boundary conditions becomes:

$$\frac{\partial U}{\partial t} + V\frac{\partial U}{\partial y} = \left(\frac{\partial^2 U}{\partial z^2}\right) - \frac{\partial \overline{uw}}{\partial z} - Gr\theta + \frac{M^2(mV - U)}{(1 + m^2)} \quad (5)$$
$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial y} = \left(\frac{\partial^2 V}{\partial z^2}\right) - \frac{\partial \overline{vw}}{\partial z} - \frac{M^2(mU + V)}{1 + m^2} \quad (6)$$
$$Pr\left(\frac{\partial \theta}{\partial t} + V\frac{\partial \theta}{\partial y}\right) = \left(\frac{\partial^2 \theta}{\partial z^2}\right) - \Pr\frac{\partial \overline{wT}}{\partial z} \quad (7)$$

t< 0 , U= 0, V= 0, $\theta = 0$, everywhere (8a)

$t \geq 0, U = 0, V = 0, \theta = 0$, at $z \to \infty$ (8b)

$U = 1, V = 0, \theta = 1$, at $z = 0$ (8c)

III. PRANDTL MIXING LENGTH HYPOTHESIS

It is not possible to solve these equations due to the existence of the Reynolds stresses $\overline{uw}$ and $\overline{vw}$ in equations (5) and (6) respectively, therefore the need to adopt the Boussinesque approximation

$$\tau_t = -\rho\overline{uv} = A_{\tau}\frac{dU}{dy} \quad (9)$$

It is worth noting that A_τ is not a fluid property as μ but depends on mean velocity$U$. On the other hand, $\rho\overline{uv}$ stands for flux of x- momentum in the y-direction, which is assumed that this momentum was transported by eddies which moved in the y-direction over a given distance say $\mathfrak{l}$ with no interaction and then mixed with the existing fluid at the new location i.e momentum is taken to be conserved over distance $\mathfrak{l}$, (McComb, 1990).

Prandtl was able to deduce experimentally that:

$$\rho\overline{uv} = -\rho\mathfrak{l}^2\left(\frac{\partial U}{\partial y}\right)^2 \quad (10)$$

At this level, more assumptions are taken as follows:

i) $y^+ > 5$, viscous term in shear stress is neglected.

ii) $\mathfrak{l} = ky$, where k is the karman constant given as $k = 0.4$, McComb, (1990).

On substituting$\mathfrak{l}^2$, it yields

$\rho\overline{uv} = \rho k^2 y^2\left(\frac{\partial U}{\partial y}\right)^2$ This reduces to

$$\overline{uv} = -k^2 y^2\left(\frac{\partial U}{\partial y}\right)^2 \quad (11)$$

Equation 4.46 can be deduced further to give

$$\overline{uw} = -k^2 z^2\left(\frac{\partial U}{\partial z}\right)^2 \quad (12)$$

And

$$\overline{vw} = -k^2 z^2\left(\frac{\partial V}{\partial z}\right)^2 \quad (13)$$

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Considering the turbulent Prandtl number also given by

$Pr_t = \frac{\varepsilon_M}{\varepsilon_H}$ where $\varepsilon_M = -2k^2z^2\frac{\partial \bar{u}}{\partial z}$

Thus,

It can be deduced from (11) that $\overline{WT} = \frac{-2k^2z^2}{\varepsilon_M}\frac{\partial \bar{u}}{\partial z}\frac{\partial \theta}{\partial z}$ (14)

It can now be shown that equations (11),(12), (13) and (14) can yield the following set of differential equations as:

$$\frac{\partial U}{\partial t} + V\frac{\partial U}{\partial y} = \left(\frac{\partial^2 U}{\partial z^2}\right) + 2k^2 z\left(\frac{\partial U}{\partial z}\right)^2 + 2k^2z^2\left(\frac{\partial^2 U}{\partial z^2}\right)\left(\frac{\partial U}{\partial z}\right) + Gr\theta + \frac{M^2(mU+V)}{(1+m^2)} \quad (15)$$

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial y} = \left(\frac{\partial^2 V}{\partial z^2}\right) + 2k^2 z\left(\frac{\partial V}{\partial z}\right)^2 + 2k^2z^2\left(\frac{\partial^2 V}{\partial z^2}\right)\left(\frac{\partial V}{\partial z}\right) - \frac{M^2(mV-U)}{1+m^2} \quad (16)$$

$$Pr\left(\frac{\partial \theta}{\partial t} + V\frac{\partial \theta}{\partial y}\right) = \left(\frac{\partial^2 \theta}{\partial z^2}\right) + Pr\left(\frac{2k^2z^2}{Pr_t}\frac{\partial \bar{u}}{\partial z}\frac{\partial \theta}{\partial z}\right) \quad (17)$$

IV. EXPLICIT FINITE DIFFERENCE SCHEME

The explicit finite difference scheme is employed in the solution of these governing equations (15), (16) and (17) since they are highly non-linear. The approximations of these governing equations using the Finite difference Scheme are respectively given where

In this case, $k = 0.4, z = \acute{\imath}\Delta z$ and ί and j refer to z and t respectively.
The initial and boundary conditions will now take the form given as:

$U_{\acute{\imath},j} = 0;\ V_{\acute{\imath},j} = O;\ \theta_{\acute{\imath},j} = 0$ Everywhere for $\theta < 0$ (18a)

$\theta \geq 0;\ U_{\acute{\imath},j} = 0;\ V_{\acute{\imath},j} = 0;\ \theta_{\acute{\imath},j} = 1$ For $\acute{\imath} = 0$ (18b)

$U_{\acute{\imath},j} = 1;\ V_{\acute{\imath},j} = 0;\ \theta_{\acute{\imath},j} = 0$ For $\acute{\imath} = \infty$ (18c)

The computation for the consecutive grid points for primary and secondary velocitie and temperature can now be done using the initial and boundary conditions i.e:

$U_{(i,j+1)}$; $V_{(i,j+1)}$And $\theta_{(i,j+1)}$

$$U_{(i,j+1)} = U_{(i,j)} + \Delta t\left\{-V_{(i,j)}\frac{U_{(i+1,j)}-U_{(i,j)}}{\Delta y} + \left(\frac{U_{(i+1,j)}-2U_{(i,j)}+U_{(i-1,j)}}{(\Delta z)^2}\right) + 0.32\acute{\imath}\Delta z\left(\frac{U_{(i+1,j)}-U_{(i,j)}}{\Delta z}\right)^2 + 0.32(\acute{\imath}\Delta z)^2\left(\frac{U_{(i+1,j)}-2U_{(i,j)}+U_{(i-1,j)}}{(\Delta z)^2}\right)\left(\frac{U_{(i+1,j)}-U_{(i,j)}}{\Delta z}\right) + Gr\theta_{\acute{\imath},j} + M^2\left(\frac{mV_{(i,j)}-U_{(i,j)}}{1+m^2}\right)\right\} \quad (19)$$

$$V_{(i,j+1)} = V_{(i,j)} + \Delta t\{-V_{(i,j)}\frac{V_{(i+1,j)}-V_{(i,j)}}{\Delta y} + \left(\frac{V_{(i+1,j)}-2V_{(i,j)}+V_{(i-1,j)}}{(\Delta z)^2}\right) + 0.32\acute{\imath}\Delta z\left(\frac{V_{(i+1,j)}-V_{(i,j)}}{\Delta z}\right)^2 + 0.32(\acute{\imath}\Delta z)^2\left(\frac{V_{(i+1,j)}-2V_{(i,j)}+V_{(i-1,j)}}{(\Delta z)^2}\right)\left(\frac{V_{(i+1,j)}-V_{(i,j)}}{\Delta z}\right) + Gr\theta_{\acute{\imath},j} + M^2\left(\frac{mU_{(i,j)}+V_{(i,j)}}{1+m^2}\right)\} \quad (20)$$

$$\theta_{i,j+1} = \theta_{(i,j)} + \Delta t\left\{-V_{i,j}\frac{\theta_{i+1,j}-\theta_{i,j}}{\Delta y} + \frac{1}{Pr}\left[\left(\frac{\theta_{(i+1,j)}-2\theta_{(i,j)}+\theta_{(i-1,j)}}{\Delta z^2}\right) + 0.32(\acute{\imath}\Delta z)^2\frac{Pr}{Pr_t}\left\{\left(\frac{U_{(i+1,j)}-U_{(i,j)}}{\Delta z}\right)\left(\frac{\theta_{(i+1,j)}-\theta_{(i,j)}}{\Delta z}\right)\right\}\right]\right\}$$
(21)

V. DISCUSSION OF RESULTS

For physical understanding of the problem and discussion of results, numerical simulation has been run for velocity and temperature profiles. Graphical presentation of the numerical results of the discretized governing equations from MATLAB is given. Various fluid parameters were varied on primary velocity,U, secondary velocity, V, and temperature,θ, profiles and then discussed. The effects of flow parameters including Grashoff numbers,Gr, Prandtl number,Pr, magnetic parameter, M, and Hall parameter, m, on mean primary velocity, U, secondary velocity, V, and temperature profile, θ, obtained. In each case, $P_{r_t} = 0.85$, and $K = 0.4$.

From figure 2, it can be shown that Hall current has little significance to primary velocity. However, primary velocity decreases with decrease in Hall parameter. This may be attributed to the fact that for a small value of m, the term $\frac{1}{1+m}$ will in turn increases the resistive force of the applied magnetic parameter thus reducing the primary velocity.

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Figure 3 clearly shows that primary velocity decreases with increase in magnetic parameter. Magnetic parameter, M, refers to the ratio of the magnetic force to inertial force therefore higher M means higher magnetic force acting perpendicularly on an electrically conducting fluid hence developing Lorentz force which is an opposing force to fluid motion thus decreasing the primary velocity.

Considering figure 4, primary velocity decreases with increase in Prandtl number, Pr, though in a smaller extent. This is because increased Prandtl number leads to increase in viscosity making the fluid more thick thus leading to a decrease in primary velocity.

Figure 5 shows a significant decrease in secondary velocity with decrase in Hall parameter,m. Considering the model equation, and the fact that for any value of m, in the term $\frac{1}{1+m^2}$ will decrease the negative value of M^2 which will in turn decrease the secondary velocity.

It can also be clearly shown From figure 6 that secondary velocity was increased first at the beginning but later was decrease with an increase in magnetic parameter, M. This is because at the beginning, Lorentz force decelerated the primary velocity but increased the lateral flow which in this case is the secondaey velocity. The secondary velocity later decreased with increase in magnetic parameter because of the reduction of the magnetic force by the Hall current. Clearly, figure 7 depicts a decrease in secondary velocity with an increase in Prandtl number. This is due to increased viscosity of the fluid hence decreasing the secondary velocity.

Figure 8 clearly shows that there is no significant change in temperature as the Hall parameter is varied. However, the small change shows that the temperature, θ, of the fluid flow decreases with decrease in Hall parameter.

From figure 9, it shows there is no significant temperature change with variation in magnetic parameter. However, the small change indicates that there is a decrease in temperature profile with increase in magnetic parameter.

Figure 10 shows that there is a decrease in temperature profile with an increase in prandtl number . since prandtl number is the ratio of momentum diffusivity to thermal diffusivity, thus increased prandtl number means lower thermal diffusivity in comparison to momentum diffusivity hence decreasing thermal boundary layer which will in turn decreases the temperature distribution of the fluid.

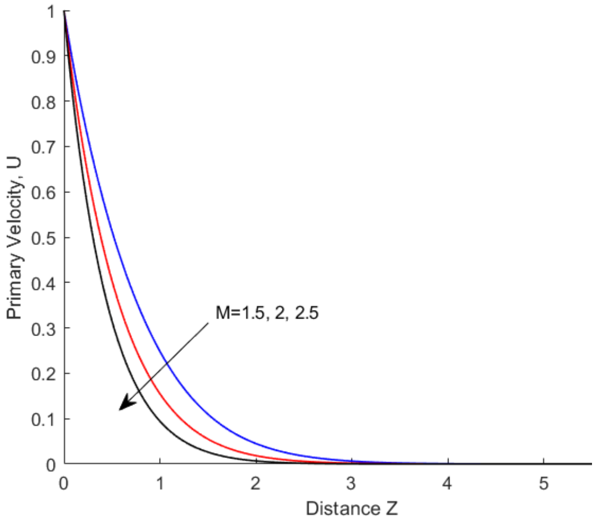

Figure 2: Variation of M on Primary Veloity Profiles

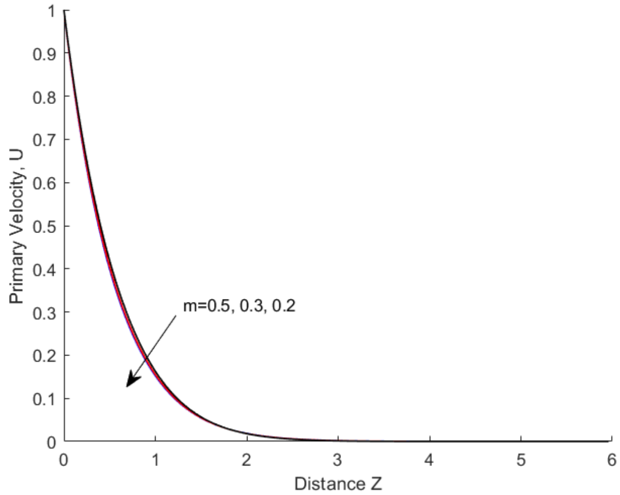

Figure 3 Variation of m on Primary Veloity Profiles

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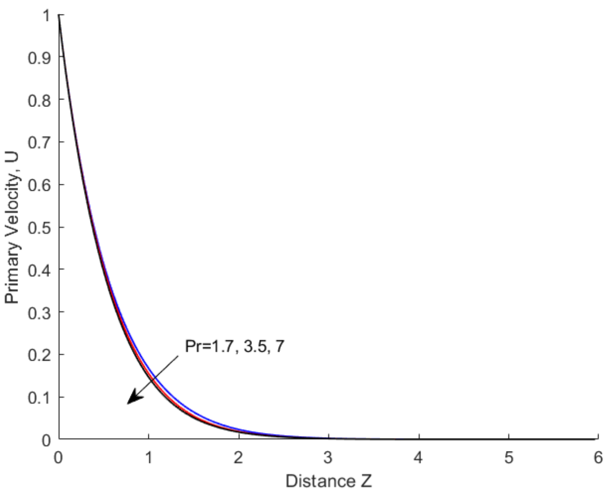

Figure 4 Variation of Pr on Primary Veloity Profiles

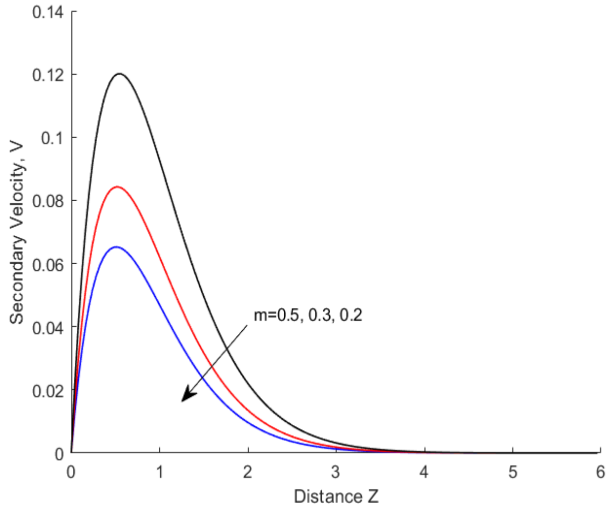

Figure 5 Variation of m on Secondary Veloity Profiles

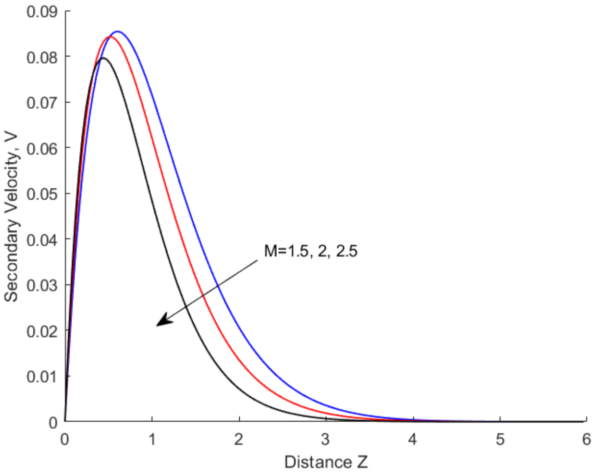

Figure 6 Variation of M on Secondary Velocity Profiles

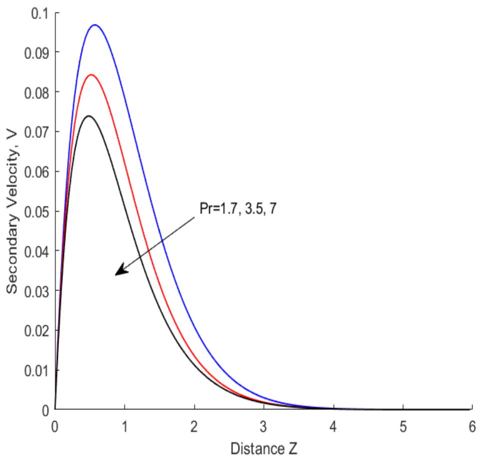

Figure 7 Variation of Pr on Secondary Veloity Profiles

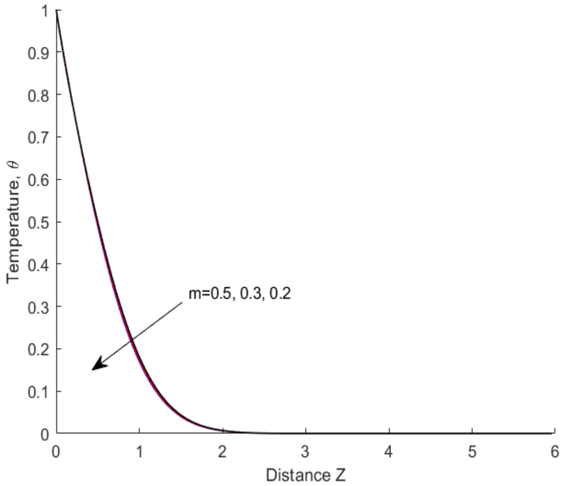

Figure 8: Variation of m on Temperature Profiles

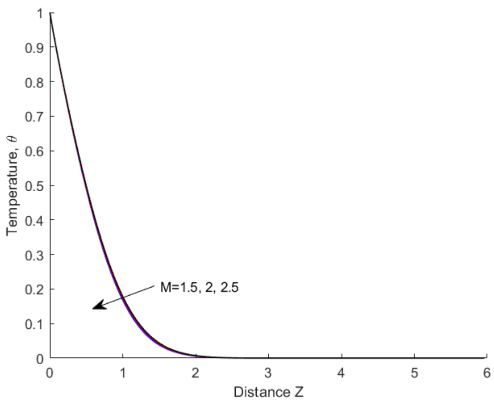

Figure 9: Variation of M on Temperature Profiles

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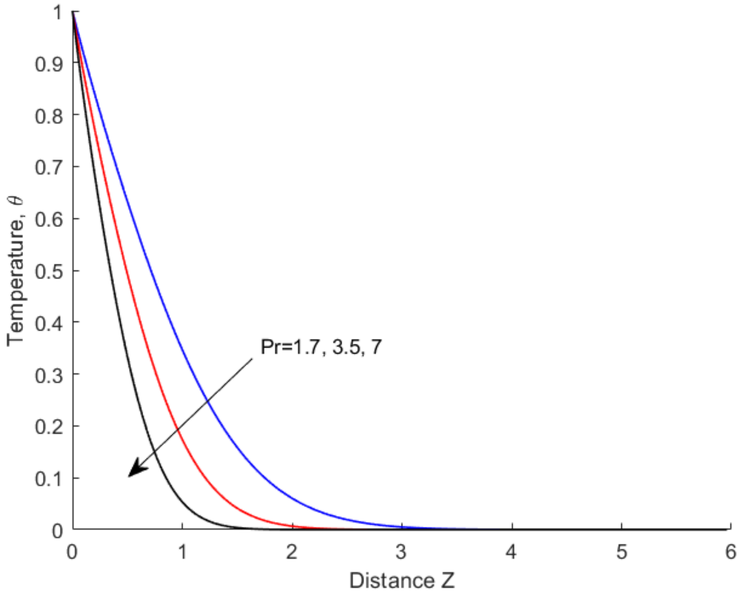

Figure 10: Variation of Pr on Temperature Profiles

VI. VALIDATION OF RESULTS

Our results when compared with those of Kwanza *et.al* (2010) who developed a mathematical model of turbulent convective fluid flow past an infinite vertical plate with Hall current in a dissipative fluid and found out that an increase in hall current leads to an increase in velocity profiles. These results are in agreement with our results. Comparison also with Mukuna $et\ al.$ (2020) who modeled a Hydromagnetic free convection turbulent fluid flow over a vertical infinite plate using turbulent Prandtl number. They found out that there is an increase in primary velocity whenever magnetic parameter(M) is decreased, Hall parameter increased and when Grashoff number is increased.

It was also evident that secondary velocity increases when magnetic parameter (M) is decreased and decreases when Hall parameter is increased. They also found out that temperature profile decreases when magnetic parameter (M) is decreased, decreases when Hall parameter is increased and also increases when Prandtl number decreases. These results also agree with the findings of this paper.

VII. CONCLUSION

The method of solution used in this paper which is explicit finite difference scheme has made it possible to approximate the solution to the highly non linear partial differential equations. The simulation was done using MATLAB and the discussed results are summarised as:

i) During the cooling of the plate ($Gr > 0$,), the primary velocity decreases with decrease in Hall parameter,m, and increase in magnetic parameter, M. It also decreases as the Prandtl number, Pr, is increased.
ii) During the cooling of the plate ($Gr > 0$,), the secondary velocity decreases with decrease in Hall parameter, m, and increase in magnetic parameter M. It also decreases as the Prandtl number, Pr, is increased.
iii) There is no significant effect on temperature profile, θ, during the cooling of the plate as the Hall parameter, m, is decreased. There is also no significant change as the magnetic parameter, M, is increased. There is decrease in temperature profile when Prandtl number, Pr, is increased.

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