Finite Element Solutions of MHD Natural Convective Fluid Flow Past a Vertical Plate in presence of Hall Current and Molecular Diffusivity

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Abstract: The present research aims to examine the joint effects of heat and mass transfer on MHD newtonian fluid towards a flat plate in presence of hall current. The newtonian fluid flow past a vertical flat plate is taken under the influence of Hall current. The flow of this newtonian fluid has been assumed in unsteady state. The rudimentary governing equations have been changed to a set of linear partial coupled differential using suitable non-dimensional variables. A most favorable technique called finite element method has been used to acquire the solution of the modelled problems. The impacts of various engineering parameters on velocity profiles, temperature profiles, concentration profiles as well as Skin-friction coefficient, Nusselt number coefficient and Sherwood number coefficient have been studied through graphs and tables.

Keywords: MHD; Hall current; Natural convection; Finite element method;

Nomenclature:

List of Variables:

C'_w	Concentration near the plate, *Kg/m*^{3}
C'	Concentration of the fluid, *Kg/m*^{3}
C'_∞	Concentration in the fluid far away from the plate, *Kg/m*^{3}
T'_w	Temperature of the plate, *K*
T'	Temperature of the fluid, *K*
T'_∞	Temperature of the fluid far away from the plate, *K*
m	Hall parameter
k_e	Mean absorption coefficient
x'	Spatial co-ordinate along the plate, *m*
y'	Spatial co-ordinate normal to the plate, *m*
C_p	Specific heat at constant Pressure, *J/kg-K*
u'	Velocity component in $x'-$direction, *m/s*
w'	Velocity component in $z'-$direction, *m/s*
$\bar{V}$	Velocity vector, *m/s*
$\Pr$	Prandtl number
Sc	Schmidt Number
g	Acceleration due to Gravity, 9.81 *m/s*^{2}
D	Chemical molecular diffusivity, *m*^{2}*/s*
e	Electron charge, *coulombs*
P_e	Electron Pressure, *N/ m*^{2}
Gr	Grashof Number
M	Hartmann number
Gc	Modified Grashof Number
n_e	Number density of the electron, *kg/m*^{3}
U_o	Reference velocity, *m/s*

Greek Symbols:

ϕ	Dimensionless concentration (*Kg/m*^{3})
θ	Dimensionless Temperature (*K*)
σ	Electrical conductivity, *mho/m*
κ	Thermal conductivity, *W/mK*
ν	Kinematics viscosity, *m*^{2}*/s*
ε	Porosity of the porous medium
α	Thermal Diffusivity
ρ	Density, *kg/m*^{3}
τ_e	Electron collision time, *Sec*

ω_e Electron frequency, *radian/sec*

μ_e Magnetic permeability, *Henry/meter*

μ Viscosity, Ns/m^2

β Volumetric co-efficient of thermal Expansion, K^{-1}

β^* Co-efficient of volume expansion with Species concentration, m^3/Kg

Superscripts:

$'$ Dimensionless Properties

Subscripts:

∞ Free stream condition

p Plate

w Wall condition

1. Introduction:

Electric current in ionized gases is generally carried by electrons that subsequently collide with other charged or neutral particles. The electric current is very weak. However, in the presence of a strong electric field, it is explicitly affected by the magnetic field. As a result, the conductivity to the electric field is reduced. Therefore, the current is reduced to the direction of normal electric and magnetic fields. This phenomenon is known as the Hall effect. Several researchers have investigated the impact of Hall current on MHD flows due to the application of such studies to the problems of MHD generators and Hall accelerators. It plays an important role in determining the flow characteristics of fluid flow problems. It can be observed that Hall current induces secondary flow in the fluid, which is also characteristic of Coriolis force. Half-effects on fluid flow find application in the production of MHD, nuclear reactors and underground energy storage systems, and in many fields of astrophysics and geophysics. Therefore, it is necessary to investigate the combined effects of walking current and rotation on MHD fluid flow problems. Edwin Hall [1] was the first to give the concept of current Hall. It is important and attractive to investigate hydrodynamic problems. Hydrodynamic problems improve with the influence of the Hall currents. Pop and Soundalgekar [2] have studied the Hall effect on the viscous hydromagnetic fluid independent of time. Ahmed and Zueco [3] have investigated the flow of influence of heat and mass transmission with rotating permeable channel by captivating the Hall effects, and have obtained an exact solution of the modeled problem. Abdel Aziz [4] studied the effects of Hal on the nanofluid flow of the viscid flow with heat transmission through a stretch sheet. Awais et al. [5] have studied the impact of viscous dissipation on the convective flow of Jeffery liquids with current effects and ionic slips. Sulochana [6] has studied the unstable flow through a permeable medium in a rotating parallel plate with the Hall effect. Kholshchevnikova [7] considered two pairs of electrodes in MHD generator for analyzing the impact of Hall current mid of nineteenth century. Hall effect in superconducting films is investigated by Michaeli et al. [8]. In recent times, Sarojamma et al. [9] examined the effect of Hall current on flow over a stretching surface. Hall-magnetohydrodynamics (Hall-MHD) system is investigated by He et al. [10]. They proved that velocity has no increasing effects in finite time. Makinde et al. [11] observed Hall effects in MHD flow of nanofluid with variable viscosity in a rotating permeable channel. Some of the authors ([12]-[16]) studied hall effect on MHD, heat and mass transfer fluid flows in different flow regimes in presence of different fields.

With the above discussions in mind, the purpose of the current investigation is to analyze the influence of hall current on heat and mass transfer newtonian fluid flow under the influence of magnetic field. The governing flow problem is solved with the help of momentum, energy and concentration equations are solved using finite element method. The influence of magnetic field and Hall Effect are also taken into account with the help of Ohm's law. The impact of all the physical parameters of interest is taken into consideration with the help of graphs.

2. Mathematical formulation:

The effect of hall current on natural convective newtonian fluid flow of viscous, incompressible, electrically conducting with heat and mass transfer along a flat plate has been considered. For this research work, the following assumptions are made:

i. In Cartesian coordinate system, let $x'-$axis is taken to be along the plate and the $y'-$axis normal to the plate.

ii. Since the plate is considered infinite in $x'-$direction, hence all physical quantities will be independent of $x'-$direction.

iii. Let the components of velocity along x' and y' axes be u' and v' which are chosen in the upward direction along the plate and normal to the plate respectively.

iv. A uniform magnetic field of magnitude B_o is applied normal to the plate.

v. The transverse applied magnetic field and magnetic Reynold's number are assumed to be very small, so that the induced magnetic field is negligible.

vi. Initially, for time $t' \le 0$, the plate and the fluid are maintained at the same constant temperature (T'_∞) in a stationary condition with the same species concentration (C'_∞) at all points so that, the Soret and Dufour effects are neglected.

vii. When $t' > 0$, The wall is maintained at constant temperature (T'_w) and concentration (C'_w) higher than the ambient temperature (T'_∞) and concentration (C'_∞) respectively.

viii. Using the relation $\nabla.\overline{H} = 0$ for the magnetic field $\overline{H} = (H_x, H_y, H_z)$, we obtain H_y = constant = H_o (say) where H_o is the externally applied transverse magnetic field so that $\overline{H} = (0, H_o, 0)$.

ix. The equation of conservation of electric charge $\nabla.\bar{J} = 0$ gives j_y = constant, where $\bar{J} = (j_{x,}\ j_{y,}\ j_z)$. We further assume that the plate is non-conducting. This implies $j_y = 0$ at the plate and hence zero everywhere.

x. When the strength of magnetic field is very large, the generalized Ohm's law in the absence of electric field takes the following form:

$$\bar{J} + \frac{\omega_e \tau_e}{B_o} \bar{J} \times \overline{H} = \sigma \left(\mu_e \overline{V} \times \overline{H} + \frac{1}{e n_e} \nabla P_e \right) \tag{1}$$

xi. Under the assumption that the electron pressure (for weakly ionized gas), the thermo-electric pressure and ion-slip conditions are negligible, equation (1) becomes:

$$j_x = \frac{\sigma\mu_e H_o}{1+m^2}(mu' - w') \text{ and } j_z = \frac{\sigma\mu_e H_o}{1+m^2}(mw' + u') \tag{2}$$

Where u' is the x' – component of $\overline{V}$, w' is the z' – component of $\overline{V}$ and $m \ (= \omega_e \tau_e)$ is the hall parameter.

Within the above framework, the equations which govern the flow under the usual Boussinesq's approximation are as follows:

Equation of Continuity:

$$\frac{\partial v'}{\partial y'} = 0 \tag{3}$$

Momentum Equations:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma\mu^2{}_e H_o^2}{\rho(1+m^2)}(u' + mw') + g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) \tag{4}$$

$$\frac{\partial w'}{\partial t'} + v'\frac{\partial w'}{\partial y'} = \nu\frac{\partial^2 w'}{\partial y'^2} - \frac{\sigma\mu^2{}_e H_o^2}{\rho(1+m^2)}(w' - mu') \tag{5}$$

Energy Equation:

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} \tag{6}$$

Species Diffusion Equation:

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{7}$$

The corresponding initial and boundary conditions are:

$$\left.\begin{array}{l} t' \le 0: \ u' = 0, \quad w' = 0, \ T' = T'_{\infty,} \ C' = C'_\infty \quad \text{for all} \quad y' \\ t' > 0: \begin{cases} u' = 0, \quad w' = 0, \ T' = T'_{w,} \ C' = C'_w \quad \text{at} \quad y' = 0 \\ u' = 0, \quad w' = 0, \ T' = T'_{\infty,} \ C' = C'_\infty \quad \text{as} \quad y' \to \infty \end{cases} \end{array}\right\} \tag{8}$$

The non-dimensional quantities introduced in the equations (3)-(7) are:

$$\left.\begin{array}{l} t = \frac{t' U_o^2}{\nu}, \ y = \frac{y' U_o^2}{\nu}, (u, v, w) = \frac{(u', v', w')}{U_o}, \ \theta = \frac{(T' - T'_\infty)}{(T'_w - T'_\infty)}, \phi = \frac{(C' - C'_\infty)}{(C'_w - C'_\infty)}, M = \frac{\sigma\mu_e^2 H_0^2 \nu}{\rho U_o^2}, \\ Sc = \frac{\nu}{D}, \ Gr = \frac{\nu g\beta(T'_w - T'_\infty)}{U_o^3}, \ Gc = \frac{\nu g\beta^*(C'_w - C'_\infty)}{U_o^3}, \Pr = \frac{\mu C_p}{\kappa} \end{array}\right\} \tag{9}$$

The governing equations can be obtained in the dimensionless form as:

Momentum Equations:

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} - \frac{M}{(1+m^2)}(u + mw) + (Gr)\theta + (Gc)\phi \tag{10}$$

$$\frac{\partial w}{\partial t} + v\frac{\partial w}{\partial y} = \frac{\partial^2 w}{\partial y^2} - \frac{M}{(1+m^2)}(w - mu) \tag{11}$$

Energy Equation:

$$\frac{\partial\theta}{\partial t}+v\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2} \tag{12}$$

Species Diffusion Equation:

$$\frac{\partial\phi}{\partial t}+v\frac{\partial\phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2} \tag{13}$$

The initial and boundary conditions (8) in the non-dimensional form are:

$$\left.\begin{array}{l} t\le 0: u=0,\ w=0,\ \theta=0,\ \ \phi=0 \quad for\,all\ \ y \\ t>0:\begin{cases} u=0,\ w=0,\ \theta=1,\ \phi=1 & at\ y=0 \\ u=0,\ w=0,\ \theta=0,\ \phi=0 & as\ y\to\infty \end{cases} \end{array}\right\} \tag{14}$$

The skin-friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. The skin-friction coefficient at the wall along x' -axis is given by

$$\tau_1=\left(\frac{\partial u}{\partial y}\right)_{y=0} \tag{15}$$

The skin-friction coefficient at the wall along z' -axis is given by

$$\tau_2=\left(\frac{\partial w}{\partial y}\right)_{y=0} \tag{16}$$

The rate of heat transfer coefficient (Nusselt number) due to temperature profiles is given by

$$Nu=\left(\frac{\partial\theta}{\partial y}\right)_{y=0} \tag{17}$$

And the rate of mass transfer coefficient (Sherwood number) due to concentration profiles is given by

$$Sh=\left(\frac{\partial\phi}{\partial y}\right)_{y=0} \tag{18}$$

3. Numerical Solutions By Finite Element Technique:

The finite element procedure (FEM) is a numerical and computer based method ([17 and [18) of solving a collection of practical engineering problems that happen in different fields such as, in heat transfer, fluid mechanics and many other fields. It is recognized by developers and consumers as one of the most influential numerical analysis tools ever devised to analyze complex problems of engineering. The superiority of the method, its accuracy, simplicity, and computability all make it a widely used apparatus in the engineering modeling and design process. It has been applied to a number of substantial mathematical models, whose differential equations are solved by converting them into a matrix equation. The primary feature of FEM is its ability to describe the geometry or the media of the problem being analyzed with huge flexibility. This is because the discretization of the region of the problem is performed using highly flexible uniform or non uniform pieces or elements that can easily describe complex shapes. The method essentially consists in assuming the piecewise continuous function for the results and getting the parameters of the functions in a manner that reduces the fault in the solution. The steps occupied in the finite element analysis areas follows.

Step-1: Discretization of the Domain The fundamental concept of the FEM is to divide the region of the problem into small connected pieces, called finite elements. The group of elements is called the finite element mesh. These finite elements are associated in a non overlapping manner, such that they completely cover the entire space of the problem.

Step-2: Invention of the Element Equations

i) A representative element is secluded from the mesh and the variational formulation of the given problem is created over the typical element.

ii) Over an element, an approximate solution of the variational problem is invented, and by surrogating this in the system, the element equations are generated.

iii) The element matrix, which is also known as stiffness matrix, is erected by using the element interpolation functions.

Step-3: Assembly of the Element Equations The algebraic equations so achieved are assembled by imposing the inter element continuity conditions. This yields a large number of mathematical equations known as the global finite element model, which governs the whole domain.

Step-4: Imposition of the Boundary Conditions On the accumulated equations, the Dirichlet's and Neumann boundary conditions (14) are imposed.

Step-5: Solution of Assembled Equations The assembled equations so obtained can be solved by any of the numerical methods, namely, Gauss elimination technique, LU decomposition technique, and the final matrix equation can be solved by iterative technique. For computational purposes, the coordinate y varies from 0 to 9, where y_{max} represents infinity external to the momentum, energy and concentration edge layers.

In one-dimensional space, linear elements are taken. The entire flow province is divided into 11000 quadratic elements of equal size. Each element is two-noded, and therefore the whole domain contains 21001 nodes. At each node, four functions are to be evaluated; hence, after assembly of the element equations, we acquire a system of 81004 equations which are non-linear. Therefore, an iterative scheme must be developed in the solution. After striking the boundary conditions, a system of equations has been obtained which is solved mathematically by the Gauss elimination method while maintaining a correctness of 0.00001. A convergence criterion based on the relative difference between the present and preceding iterations is employed. When these differences satisfy the desired correctness, the solution is assumed to have been congregated and iterative process is terminated. The Gaussian quadrature is applied for solving the integrations. The computer cryptogram of the algorithm has been performed in MATLAB running on a PC. Excellent convergence was completed for all the results.

4. Results and Discussions:

The influence of Hall current on an unsteady MHD free convective flow of heat and mass transfer of an electrically conducting, incompressible, viscous newtonian fluid along an infinite vertical plate has been studied and solved by using finite element method. The effects of various material parameters on the primary velocity, secondary velocity, temperature and concentration profiles of the flow is studied. Also numerical values of skin-friction coefficients, Nusselt number due to temperature profiles and Sherwood number due to concentration profiles have been discussed in tables-1 and 2 respectively. For the physical significance, the numerical discussions in the problem and at t = 1.0, stable values for primary velocity, secondary velocity, temperature and concentration fields are obtained.

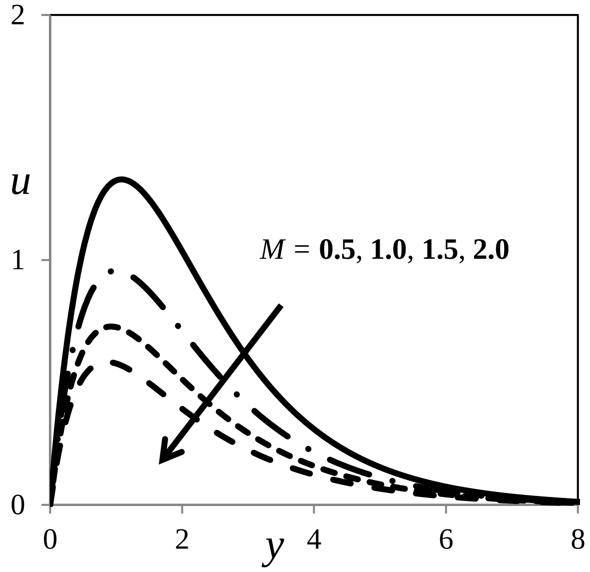

Fig. 1. Influence of M on u

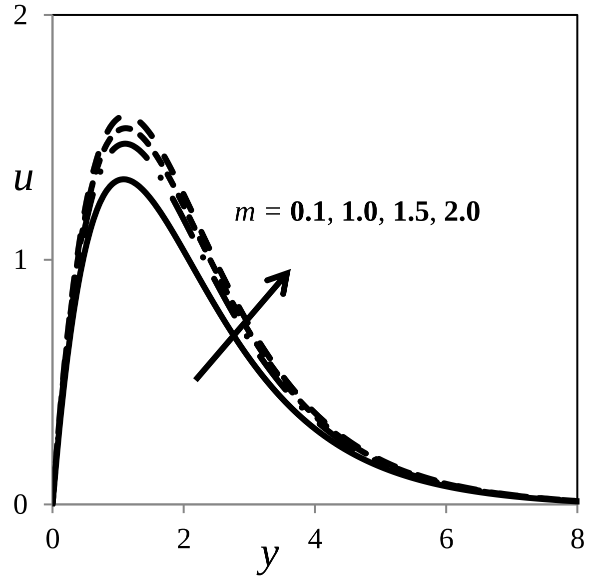

Fig. 2. Influence of m on u

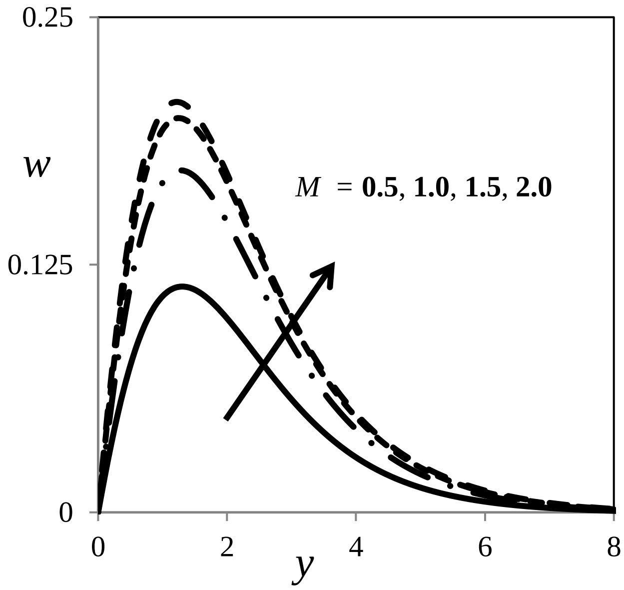

Fig. 3. Influence of M on w

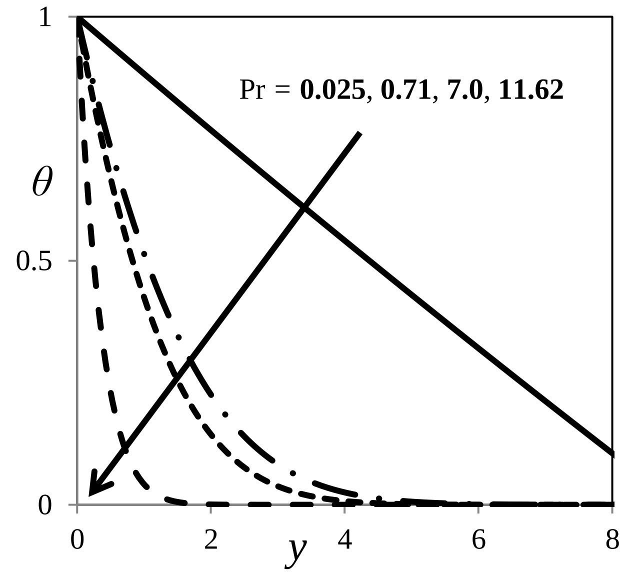

Fig. 4. Influence of Pr on θ

The effect of the Hartmann number is shown in Fig. 1. It is observed that, the primary velocity of the fluid decreases with the increasing of the magnetic field number values. The decrease in the primary velocity as the Hartmann number increases is because the presence of a magnetic field in an electrically conducting fluid introduces a force called the Lorentz force, which acts against the flow, if the magnetic field is applied in the normal direction, as in the present study. This resistive force slows down the fluid velocity component as shown in Fig. 1. Fig. 2 depicts the primary velocity profiles as the Hall parameter m increases. We see that u increases as m increases. It can also be observed that u profiles approach their classical values when Hall parameter m becomes large (m > 1). In Fig. 3, we have the influence of the Hartmann number on the secondary velocity. It can be seen that as the values of this parameter increases, the secondary velocity increases. In Fig. 4, we depict the effect of Prandtl number on the temperature field. It is observed that an increase in the Prandtl number leads to decrease in the temperature field. Also, temperature field falls more rapidly for water in comparison to air and the temperature curve is exactly linear for mercury, which is more sensible towards change in temperature. From this observation it is concluded that mercury is most effective for maintaining temperature differences and can be used efficiently in the laboratory. Air can replace mercury, the effectiveness of maintaining temperature changes are much less than mercury. However, air can be better and cheap replacement for industrial purpose. This is because, either increase of kinematic viscosity or decrease of thermal conductivity leads to increase in the value of Prandtl number. Hence temperature decreases with increasing of Prandtl number. Fig. 5 shows the concentration field due to variation in Schmidt number for the gasses Hydrogen, Helium, Water-vapour, Oxygen and Ammonia. It is observed that, the concentration field is steadily for Hydrogen and falls rapidly for Oxygen and Ammonia in comparison to Water-vapour. Thus Hydrogen can be used for maintaining effective concentration field and Water-vapour can be used for maintaining normal concentration field.

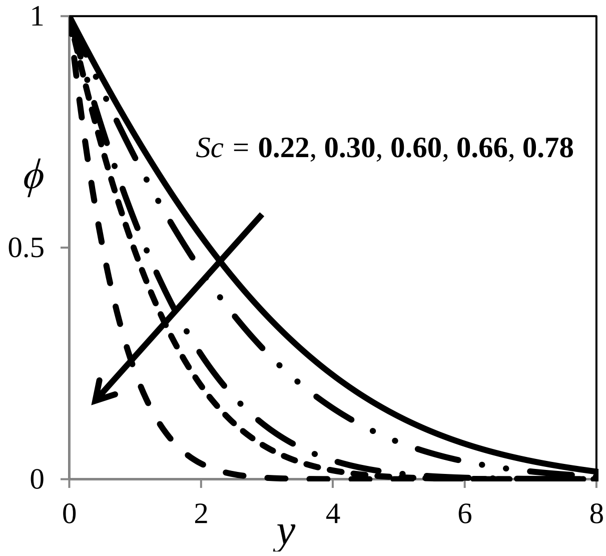

Fig. 5. Influence of *Sc* on ϕ

Table-1 shows the variation of shearing stresses $(\tau_1 \,\&\, \tau_2)$ different values *Gr*, *Gc*, *Sc*, Pr, *M* and *m*. From this table-1, it is concluded that the magnitude of shearing stress τ_1 and τ_2 increase as the value of *Gr*, *Gc*, *m* increase and this behavior is found just reverse with the increase of *Sc*, Pr and *M*. From this table-1, it is also concluded that the magnitude of shearing stress τ_1 and τ_2 increase as the value of *Gr*, *Gc*, *M*, *m* increase and this behavior is found just reverse with the increase of Pr and *Sc*. Table-2 shows the variation of Nusselt and Sherwood numbers $(Nu \,\&\, Sh)$ for different values of *Sc* and Pr. From this table-2, it is observed that the Nusselt number decreases with increasing values of Pr. From this table-2, it is also observed that, the Sherwood number decreases with increasing values of *Sc*.

Table-1: Variation of shearing stress (τ_1 and τ_2) for different values of *Gr*, *Gc*, Pr, *Sc*, *M* and *m*

Gr	*Gc*	Pr	*Sc*	*M*	*m*	τ_1	τ_2
2.0	2.0	0.71	0.22	0.5	0.5	1.1120111568	0.1866023989
4.0	2.0	0.71	0.22	0.5	0.5	1.2560031976	0.2966145365
2.0	**4.0**	0.71	0.22	0.5	0.5	1.3088402399	0.3566211489
2.0	2.0	**7.00**	0.22	0.5	0.5	1.0622744187	0.1154490231
2.0	2.0	0.71	**0.30**	0.5	0.5	1.0762300481	0.1355015447
2.0	2.0	0.71	0.22	**1.0**	0.5	1.1626619874	0.2366180456
2.0	2.0	0.71	0.22	0.5	**1.0**	1.1590132487	0.2623117484

Table-2: Variation of Nusselt and Sherwood numbers (*Nu* & *Sh*) for different values of Pr and *Sc*

Pr	*Nu*	*Sc*	*Sh*
0.71	1.8522359478	0.22	1.6922401865
7.00	1.6533015995	**0.30**	1.5560231487

5. Conclusions:

In this research work, the influence of Hall current on unsteady magnetohydrodynamic flow of an electrically conducting, incompressible, viscous fluid along a flat plate with heat and mass transfer is studied. The fundamental dimensionless equations are solved by using finite element method. This study concludes the following results.

1. It is observed that the primary velocity of the fluid increases with the increasing of Hall parameter and decreases with the increasing of Hartmann number.
2. It is observed that the secondary velocity of the fluid increases with the increasing of Hartmann number.
3. The fluid temperature decreases with the increasing of Prandtl number.
4. The Concentration of the fluid decreases with the increasing of Schmidt number.
5. From table-1, it is concluded that the magnitude of shearing stress increases as the increasing values of Grashof number for heat transfer, Grashof number for mass transfer, Hartmann number, Hall parameter and this behavior is found just reverse with the increasing of Prandtl number and Schmidt number.
6. From table-2, it is concluded that the Nusselt number due to temperature profiles are decreasing with increasing values of Prandtl number and the Sherwood number due to concentration profiles are decreasing with increasing values of Schmidt number.

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