Numerical Solutions of Heat and Mass Transfer Effects on an Unsteady MHD Convective Flow past a Vertical Plate Embedded In Porous Medium through Finite Element Method

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Abstract*: The objective of this paper is to study the effects of heat and mass transfer on unsteady hydromagnetic free convective flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate in presence of constant suction. The fundamental governing equations of the flow field are solved using finite element method and the numerical solutions are obtained for velocity, temperature, concentration distributions. The effects of different physical flow parameters on these respective flow fields are discussed through graphs and results are physically interpreted. The problem has some relevance in the geophysical and astrophysical studies.

***Index Terms*: Heat and Mass transfer, Porous Medium, MHD, Finite Element Method.**

I. INTRODUCTION

The phenomenon of hydromagnetic flow with heat and mass transfer in an electrically conducting fluid past a porous plate embedded in a porous medium has attracted the attention of a good number of investigators because of its varied applications in many engineering problems such as MHD generators, plasma studies, nuclear reactors, oil exploration, geothermal energy extractions and in the boundary layer control in the field of aerodynamics. Heat transfer in laminar flow is important in problems dealing with chemical reactions and in dissociating fluids. Anand Rao and Srinivasa Raju ([1]-[3]) studied the effects of Soret, Dufour, Hall Current and viscous dissipation on an unsteady free convective fluid flow problems in presence of magnetic field, heat and mass transfer along a porous plate using finite element technique. Anand Rao et al. ([4]-[11]) found the numerical solutions of unsteady free convective along a vertical and oscillatory plate embedded in porous medium in presence of heat and mass transfer, magnetic field, thermal radiation, Soret, Dufour, Hall current, rotation, heat source, heat absorption etc. Combined effects of Soret and Dufour effects on unsteady hydromagnetic mixed convective flow in an accelerated vertical wavy plate through a porous medium investigated by Aruna et al. [12]. Jithender Reddy and his co-workers ([13]-[20])

Revised Version Manuscript Received on October 10, 2016.

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Found the numerical solutions of heat and mass transfer fluid flow problems in presence of magnetic field using finite element technique. Unsteady MHD free convection flow near on an infinite vertical plate embedded in a porous medium with Chemical reaction, Hall Current and Thermal radiation studied by Sarada et al. [21]. Sudhakar et al. ([22]-[24]) applied finite element technique on an unsteady magnetohydrodynamics free convective fluid flow along a vertical plate surrounded by porous medium in presence of chemical reaction, heat flux, Soret, Dufour, thermal radiation and viscous dissipation. Ramana Murthy et al. [25] studied heat and mass transfer effects on MHD natural convective flow past an infinite vertical porous plate with thermal radiation and Hall Current. Ramya et al. ([26]-[28]) studied the effects of velocity, thermal wall slips, chemical reaction, thermal radiation and heat generation/absorption on unsteady free convective nanofluid flow over a Nonlinearly Isothermal Stretching Sheet in presence of magnetic field, heat and mass transfer. Unsteady MHD mixed convection flow past a vertical porous plate in presence of radiation studied by Sivaiah et al. [29]. Maddilety and Srinivasa Raju [30] found the numerical solutions of hall effect on an unsteady MHD free convective Couette flow between two permeable plates using finite element technique. Sivaiah and Srinivasa Raju [31] found the numerical solutions of heat and mass transfer flow with hall current, heat source and viscous dissipation by applying finite element method. Simultaneous effects of thermal radiation and rotation effects on an unsteady MHD mixed convection flow through a porous medium with Hall current and Heat absorption investigated by Venkataramana et al. [32]. Sheri et al. [33] studied transient magnetohydrodynamic free convection flow past a porous vertical plate in presence of viscous dissipation. Dharmendar Reddy et al. ([34] and [35]) applied finite element technique on unsteady magnetohydrodynamic free convective flow past a vertical porous plate with hall current, chemical reaction, heat and mass transfer. Rao et al. [36] studied the finite element analysis of thermal radiation and mass transfer flow past semi-infinite moving vertical plate with viscous dissipation.

In the present study we therefore, propose to analyze the effect of mass transfer on unsteady free convective flow of a viscous incompressible electrically conducting fluid

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past an infinite vertical porous plate with constant suction and heat source in presence of a transverse magnetic field. This paper basically highlights the effects of heat and mass transfer on hydromagnetic flow in presence of suction and heat source.

II. MATHEMATICAL FORMULATION

Consider the unsteady free convective mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate in presence of constant suction and heat source and transverse magnetic field. In Cartesian coordinate system, let $x'-$ axis is taken to be along the plate and the $y'-$ axis normal to the plate. Since the plate is considered infinite in $x'-$ direction, hence all physical quantities will be independent of $x'-$ direction. The wall is maintained at constant temperature (T'_w) and concentration (C'_w) higher than the ambient temperature (T'_∞) and concentration (C'_∞) respectively. A uniform magnetic field of magnitude B_o is applied normal to the plate. The transverse applied magnetic field and magnetic Reynold's number are assumed to be very small, so that the induced magnetic field is negligible. The homogeneous chemical reaction is of first order with rate constant $\overline{K}$ between the diffusing species and the fluid is neglected. It is assumed that there is no applied voltage which implies the absence of an electric field. The fluid has constant kinematic viscosity and constant thermal conductivity and the Boussinesq's approximation have been adopted for the flow. The concentration of the diffusing species in the binary mixture is assumed to be very small in comparison with the other chemical species, which are present and hence Soret and Dufour effects are negligible. The magnetohydrodynamic unsteady mixed convective boundary layer equations under the Boussinesq's approximations are:

Continuity Equation:

$$\frac{\partial v'}{\partial y'} = 0 \Rightarrow v' = -v_o \text{ (Constant)} \tag{1}$$

Momentum Equation:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_o^2}{\rho}u' - \frac{\nu}{K'}u' \tag{2}$$

Energy Equation:

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \kappa\frac{\partial^2 T'}{\partial y'^2} \tag{3}$$

Concentration Equation:

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{4}$$

The boundary conditions of the problem are:

$$\begin{aligned} &u' = 0,\ v' = -v_o,\ T' = T'_w + \varepsilon(T'_w - T'_\infty)e^{i\omega' t'}, \\ &C' = C'_w + \varepsilon(C'_w - C'_\infty)e^{i\omega' t'} \ \ at\ \ y' = 0 \\ &\&\ u' \to 0,\ T' \to T'_\infty,\ C' \to C'_\infty \ \ as\ \ y' \to \infty \end{aligned} \tag{5}$$

Introducing the following non-dimensional variables and parameters,

$$\left.\begin{aligned} &y = \frac{y' v'_o}{\nu},\ t = \frac{t' v_o'^2}{4\nu},\ \omega = \frac{4\nu\omega'}{v_o'^2},\ u = \frac{u'}{v'_o}, \\ &M = \left(\frac{\sigma B_o^2}{\rho}\right)\frac{\nu}{v_o'^2},\ K = \frac{v_o'^2 K'}{\nu^2},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \\ &\phi = \frac{C' - C'_\infty}{C'_w - C'_\infty},\ \Pr = \frac{\nu}{k},\ Gr = \frac{\nu g\beta(T'_w - T'_\infty)}{v_o'^3}, \\ &Gc = \frac{\nu g\beta^*(C'_w - C'_\infty)}{v_o'^3},\ Sc = \frac{\nu}{D} \end{aligned}\right\} \tag{6}$$

Substituting (6) in equations (2), (3) and (4) under boundary conditions (5), we get:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = (Gr)\theta + (Gc)\phi + \frac{\partial^2 u}{\partial y^2} - \left(M + \frac{1}{K}\right)u \tag{7}$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} \tag{8}$$

$$\frac{1}{4}\frac{\partial \phi}{\partial t} - \frac{\partial \phi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} \tag{9}$$

The corresponding boundary conditions are:

$$\begin{aligned} &u = 0,\ \theta = 1 + \varepsilon e^{i\omega t},\ \phi = 1 + \varepsilon e^{i\omega t} \ \ at\ \ y = 0 \\ &\&\ u \to 0,\ \theta \to 0,\ \phi \to 0 \ as\ y \to \infty \end{aligned} \tag{10}$$

III. METHOD OF SOLUTION

Finite Element Technique: The finite element procedure (FEM) is a numerical and computer based method of solving a collection of practical engineering problems that happen in different fields such as, in heat transfer, fluid mechanics ([37]-[54]) 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 ([55] and [56]) 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 (10) 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 is varied from to , where represents infinity external to the momentum, energy and concentration edge layers.

In one-dimensional space, linear and quadratic elements, or element of higher order can be taken. The entire flow province is divided into 11000 quadratic elements of equal size. Each element is three-noded, and therefore the whole domain contains 21001 nodes. At each node, three functions are to be evaluated; hence, after assembly of the element equations, we acquire a system of 81004 equations which are nonlinear. 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.

IV. RESULTS AND DISCUSSIONS

The effects of heat and mass transfer on an unsteady free convective flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate with constant suction and heat source in presence of a transverse magnetic field has been studied. The governing equations of the flow field are solved by applying finite element method and approximate solutions are obtained for velocity, temperature and concentration distributions. The effects of the pertinent parameters on the flow field are analyzed and discussed with the help of velocity profiles (figures (1)-(6)), temperature profiles (figures (7)) and concentration profiles (figure (8)). To be more realistic, during numerical calculations we have chosen the values of $\Pr = 0.71$ representing air at $20^o C$, Sc = 0.60 representing Water-vapour, $Gr > 0$ corresponding to cooling of the plate

4.1. Velocity field:

The velocity of the flow field is found to change more or less with the variation of the flow six parameters. The major factors affecting the velocity of the flow field are Hartmann number, Permeability parameter, Schmidt number, Grashof number for heat and mass transfer and Heat source parameter. The effects of these parameters on the velocity field have been analyzed with the help of figures (1)-(7). The effect of the Hartmann number is shown in figure (1). It is observed that the velocity of the fluid decreases with the increase of the magnetic field number values. The decrease in the 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 figure (1). Figure (2) shows the effect of the permeability of the porous medium parameter on the velocity distribution. As shown, the velocity is increasing with the increasing dimensionless porous medium parameter. The effect of the dimensionless porous medium K becomes smaller as K increase. Physically, this result can be achieved when the holes of the porous medium may be neglected. The temperature and the species concentration are coupled to the velocity via Grashof number and Modified Grashof number as seen in equation (7). For various values of Grashof number and Modified Grashof number, the velocity profiles u are plotted in figures (3) and (4). The Grashof number signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there is a rise in the velocity due to the enhancement of thermal buoyancy force. Also, as Gr increases, the peak values of the velocity increases rapidly near the porous plate and then decays smoothly to the free stream velocity. The Modified Grashof number defines the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases properly to approach

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the free stream value. It is noticed that the velocity increases with increasing values of the Modified Grashof number.

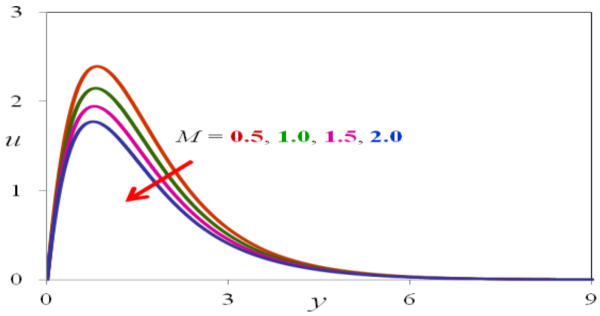

Figure 1. Influence of *M* on Velocity profiles

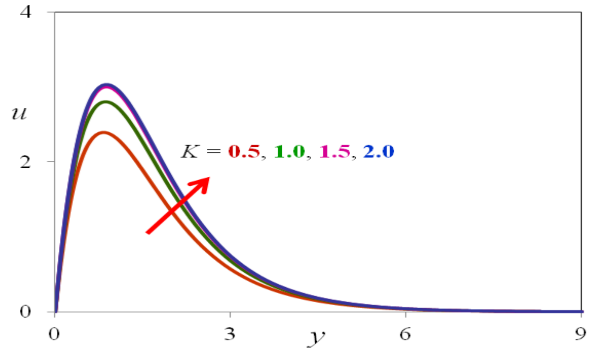

Figure 2. Influence of *K* on Velocity profiles

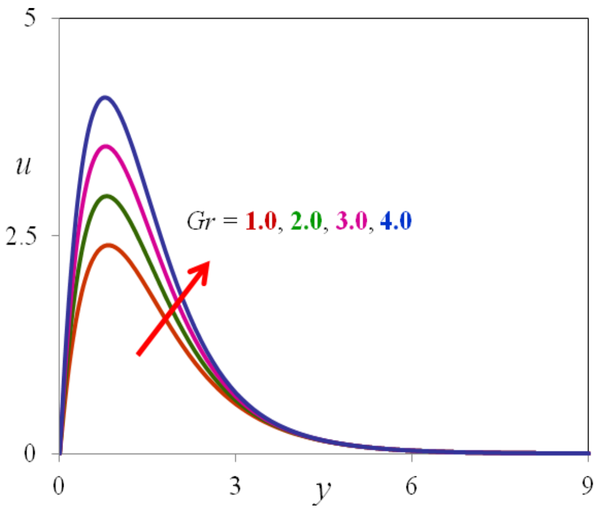

Figure 3. Influence of *Gr* on Velocity profiles

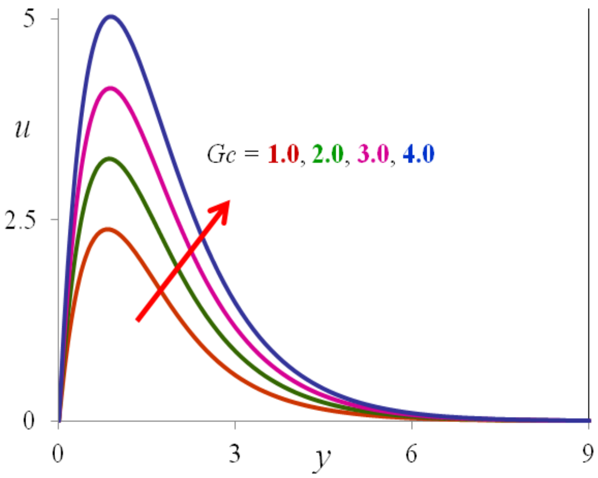

Figure 4. Influence of *Gc* on Velocity profiles

Figure (5) depicts the effect of Prandtl number on velocity profiles in presence of foreign species such as Mercury (Pr = 0.025), Air (Pr = 0.71), Water (Pr = 7.00) and Methanol (Pr = 11.62) are shown in figure (6). We observe that from figure (5) the velocity decreases with increasing of Prandtl number. The nature of velocity profiles in presence of foreign species such as Hydrogen (*Sc* = 0.22), Helium (*Sc* = 0.30), Water-vapour (*Sc* = 0.60) and Oxygen (*Sc* = 0.66) are shown in figure (6). The flow field suffers a decrease in velocity at all points in presence of heavier diffusing species.

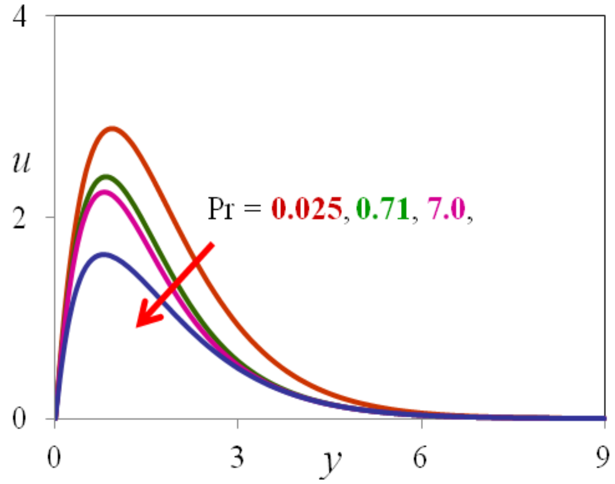

Figure 5. Influence of Pr on Velocity profiles

4.2. Temperature field:

The temperature of the flow field suffers a substantial change with the variation of the flow parameters such as Prandtl number. These variations are shown in figure (7). In figure (7) 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 conclude 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.

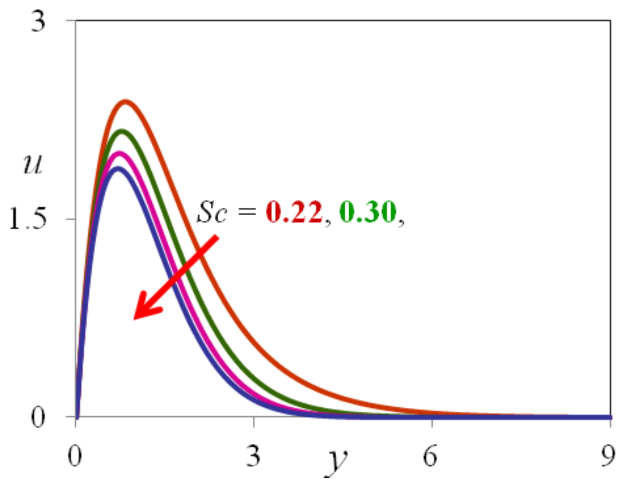

Figure 6. Influence of *Sc* on Velocity profiles

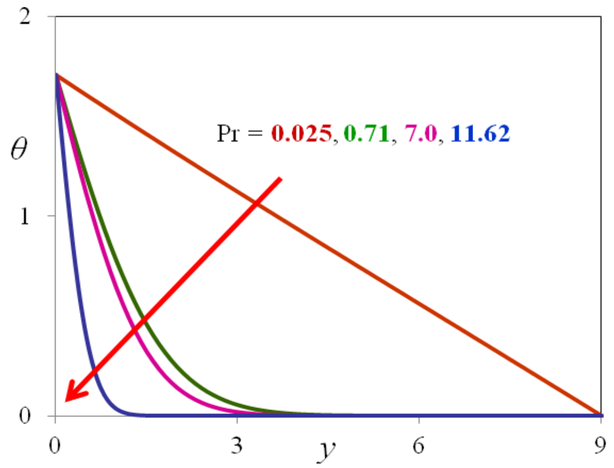

Figure 7. Influence of Pr on Temperature profiles

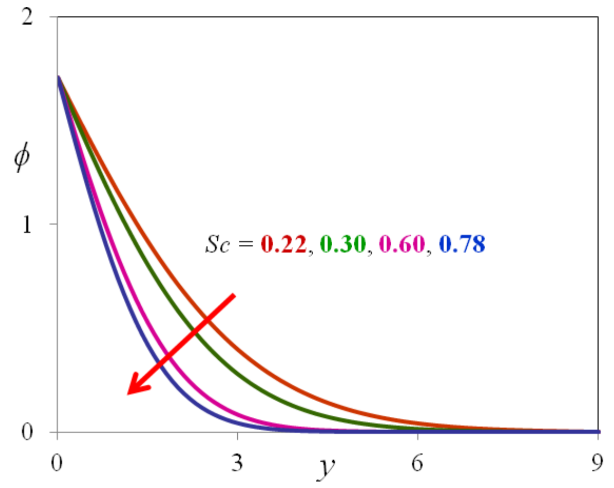

Figure 8. Influence of *Sc* on Concentration profiles

4.3. Concentration field:

The effect of Schmidt number on the concentration field is presented in figure (8). Figure (8) shows the concentration field due to variation in Schmidt number for the gasses Hydrogen, Helium, Water-vapour and Ammonia. It is observed that concentration field is steadily for Hydrogen and falls rapidly for 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.

V. CONCLUSIONS

The author summarize below the following results of physical interest on the velocity, temperature and the concentration distribution of the flow field and also on the wall shear stress and rate of heat transfer at the wall.

1. A growing Hartmann number retards the velocity of the flow field at all points.
2. The effect of increasing Grashof number for heat and mass transfer or heat source parameter is to accelerate velocity of the flow field at all points.
3. The velocity of the flow field increases with an increase in permeability parameter.
4. The Prandtl number increases the temperature of the flow field at all points
5. The effect of increasing Schmidt number is to reduce the concentration boundary layer thickness of the flow field at all points.

VI. NOMENCLATURE

List of Variables:

B_o	Magnetic field component along $y'-$ axis
C_p	Specific heat at constant pressure
g	Acceleration of gravity
Gr	Grashof number
M	Hartmann number
Gc	Modified Grashof number
$\Pr$	Prandtl number
Sc	Schmidt number
K'	The permeability of medium
K	The permeability parameter
D	Chemical molecular diffusivity
C'	Concentration of fluid near the plate
C	Concentration of the fluid
C'_∞	Concentration of the fluid at infinity
C'_w	Concentration of the fluid far away of the fluid from the plate
T'	Temperature of fluid near the plate
T'_∞	Temperature of the fluid at infinity
T'_w	Temperature of the fluid far away of the fluid from the plate
t'	Time in x', y' coordinate system
x', y'	Co-ordinate system
x, y	Dimensionless coordinates
u	Dimensionless velocity component in $x'-$ direction
v'_o	Dimensionless velocity component in $y'-$ direction

t Time in dimensionless co-ordinates
u' Velocity component in $x'-$ direction
v' Velocity component in $y'-$ direction

Greek symbols:

ω Angular frequency
β Coefficient of volume expansion for heat transfer
β^* Coefficient of volume expansion for mass transfer
ρ Density of the fluid
σ Electrical conductivity of the fluid
ν Kinematic viscosity
θ Non-dimensional temperature
ωt Phase angle
κ Thermal conductivity of the fluid

Superscripts:

$/$ Dimensionless Properties

Subscripts:

p Plate
w Wall condition
∞ Free stream condition

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