Finite Element Results of Unsteady free convection flow Past a Vertical Permeable Moving Plate in Presence of Magnetic Field, Heat and Mass Transfer Effects

Mr.B.Jagan Mohan[1], Dr.Maddileti Pasupula[2] Mrs.Sudha S[3]

[1]Bharatiya Engineering Science and Technology Innovation University, Anantapur, Andhra Pradesh–515731, India[2]Department of Mathematics, University College of Science, Mahatma Gandhi University, Nalgonda-508 254[3] GFGc & PG Center ,Chintamani ,Chickballapur (D) ,Karnataka

Abstract: The problem of unsteady boundary layer flow of a viscous, incompressible, electrically conducting fluid along a semi-infinite vertical permeable moving plate in the presence of a uniform transverse magnetic field, heat and mass transfer effects are considered. The plate is assumed to move with a constant velocity in the direction of fluid flow while the free stream velocity is assumed to follow the exponentially increasing and time-dependent wall suction is assumed to occur at the permeable surface. The dimensionless governing equations for this investigation are solved numerically using finite element method. The evaluation of the numerical results is performed and some graphical results for the velocity, temperature and concentration profiles within the boundary layer and tabulated results for the skin-friction coefficient, Nusselt and the Sherwood numbers are presented and discussed.

Keywords: Heat and Mass transfer; Free Convection; MHD; Finite Element Method;

1. Introduction:

In recent years, the analysis of hydromagnetic convection flow involving heat and mass transfer in porous medium has attracted the attention of many scholars because of its possible applications in diverse fields of science and technology such as – soil sciences, astrophysics, geophysics, nuclear power reactors etc. In geophysics, it finds its applications in the design of MHD generators and accelerators, underground water energy storage system etc. It is worth-mentioning that MHD is now undergoing a stage of great enlargement and differentiation of subject matter. These new problems draw the attention of the researchers due to their varied significance, in liquid metals, electrolytes and ionized gases 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. [1]. Jithender Reddy and his co-workers ([2]-[9]) found the numerical solutions of heat and mass transfer fluid flow problems in presence of magnetic field using finite element technique. Anand Rao and Srinivasa Raju ([10]-[12]) 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. ([13]-[20]) 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. 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. Maddilety and Srinivasa Raju [26] found the numerical solutions of hall effect on an unsteady

MHD free convective Couette flow between two permeable plates using finite element technique. Ramya et al. ([27]-[29]) 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. [30]. 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. Rao et al. [34] studied the finite element analysis of thermal radiation and mass transfer flow past semi-infinite moving vertical plate with viscous dissipation. Dharmendar Reddy et al. ([35] and [36]) applied finite element technique on unsteady magnetohydrodynamic free convective flow past a vertical porous plate with hall current, chemical reaction, heat and mass transfer.

Motivated by the above reference work and the numerous possible industrial applications of the problem, it is of paramount interest in this study to investigate the effects of heat and mass transfer on an unsteady MHD flow along a porous flat plate. In this study, the effects of different flow parameters encountered in the equations are also studied. The problem is solved numerically using the finite element method, which is more economical from the computational view point.

2. Mathematical formulation:

Consider unsteady two-dimensional flow of a laminar, incompressible, viscous, electrically conducting fluid past a semi-infinite vertical permeable moving plate embedded in a uniform porous medium and subjected to a uniform transverse magnetic field in the presence of Soret and Dufour effects. It is assumed that there is no applied voltage which implies the absence of an electrical field. The transversely applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and the Hall effect are negligible. Similarly, in this work, Soret and Dufour effects are also negligible. A consequence of the small magnetic Reynolds number is the uncoupling of the Navier-Stokes equations from Maxwell's equations. The governing equations for this investigation are based on the balances of mass, linear momentum, energy and concentration species. The magnetic and viscous dissipations are neglected in this study. The third and fourth terms on the RHS of the momentum equation (2) denote the thermal and concentration buoyancy effects, respectively. It is assumed that the permeable plate moves with a constant velocity in the direction of fluid flow, and the free stream velocity follows the exponentially increasing. In addition, it is assumed that the temperature and the concentration at the wall as well as the suction velocity are exponentially varying with time. Taking into consideration the assumptions made above, these equations can be written in Cartesian frame of reference as follows:

Equation of Continuity:

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

(1)

Momentum Equation:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = -\frac{1}{\rho}\frac{\partial p'}{\partial x'} + \nu\frac{\partial^2 u'}{\partial y'^2} + g\beta_T\left(T' - T'_\infty\right) + g\beta_c\left(C' - C'_\infty\right) - \nu\frac{u'}{k'} - \frac{\sigma}{\rho}B^2{}_0 u'$$

(2)

Energy Equation:

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \alpha \frac{\partial^2 T'}{\partial y'^2}$$

(3)

Species Diffusion Equation:

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

(4)

The appropriate boundary conditions for the velocity, temperature and concentration fields are

$$\left.\begin{array}{l} u' = u'_p,\quad T' = T'_w + \varepsilon\left(T'_w - T'_\infty\right) e^{nt},\quad C' = C'_w + \varepsilon\left(C'_w - C'_\infty\right) e^{nt} \quad at \;\; y' = 0 \\ u' \to U'_\infty = U_0\left(1 + \varepsilon\, e^{nt}\right), \qquad T' \to T'_\infty, \qquad C' \to C'_\infty \;\; as \;\; y' \to \infty \end{array}\right\}$$

(5)

It is clear from equation (1) that the suction velocity at the plate surface is a function of time only. Assuming that it takes the following exponential form:

$$v' = -V_0\left(1 + \varepsilon\, A e^{nt}\right)$$

(6)

Where A is a real positive constant, ε and εA are small less than unity, and V_0 is a scale of suction velocity which has non-zero positive constant. Outside the boundary layer, equation (2) gives

$$-\frac{1}{\rho}\frac{dp'}{dx'} = \frac{dU'_\infty}{dt'} + \frac{v}{K'}U'_\infty + \frac{\sigma}{\rho}B_0^2 U'_\infty$$

(7)

It is convenient to employ the following dimensionless variables:

$$u = \frac{u'}{U_0},\quad v = \frac{v'}{V_0},\quad y = \frac{V_0 y'}{v},\quad U_\infty = \frac{U'_\infty}{U_0},\quad U_p = \frac{u'_p}{U_0}, t = \frac{t' V_0^2}{v},\quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\quad \phi = \frac{C' - C'_\infty}{C'_w - C'_\infty},\quad n = \frac{n' v}{V_0^2},\ K = \frac{K' V_0^2}{v^2},\ \mathrm{P}$$

$$M = \frac{\sigma B_0^2 v}{\rho V_0^2},\ Gr = \frac{v\beta_T g\left(T'_w - T'_\infty\right)}{U_0 V_0^2},\ Gc = \frac{v\beta_c g\left(C'_w - C'_\infty\right)}{U_0 V_0^2}$$

(8)

In view of equations (6)-(8) and equations (2)-(4) reduce to the following dimensionless form:

$$\frac{\partial u}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial u}{\partial y} = \frac{dU_\infty}{dt} + \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gc\phi + N\left(U_\infty - u\right)$$

(9)

$$\frac{\partial \theta}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2}$$

(10)

$$\frac{\partial \phi}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial \phi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2}$$

(11)

The dimensionless form of the boundary conditions (5) and (6) become

$$u = U_p,\ \theta = 1 + \varepsilon e^{nt},\ \phi = 1 + \varepsilon e^{nt}\ \ at\ \ y = 0\ \ \&\ u \to U_\infty,\ \theta \to 0,\ \phi \to 0\ \ as\ \ y \to \infty$$

(12)

The Skin-friction coefficient, the Nusselt number (Rate of heat transfer) and the Sherwood numbers (Rate of mass transfer) are important physical parameters for this type of boundary layer flow. These parameters can be defined and determined as follows:

$$\tau = \frac{\tau_w^*}{\rho U_o V_o} = \left(\frac{\partial u}{\partial y}\right)_{y=0}$$

(13)

$$Nu = x\frac{\left.\frac{\partial T'}{\partial y'}\right|_{y'=0}}{\left(T'_w - T'_\infty\right)} \Rightarrow Nu\,\mathrm{Re}_x^{-1} = \left.\frac{\partial \theta}{\partial y}\right|_{y=0}$$

(14)

$$Sh = x\frac{\left.\frac{\partial C'}{\partial y'}\right|_{y'=0}}{\left(C'_w - C'_\infty\right)} \Rightarrow Sh\,\mathrm{Re}_x^{-1} = \left.\frac{\partial \phi}{\partial y}\right|_{y=0}$$

(15)

Where $\mathrm{Re}_x = \frac{V_o x}{v}$ is the local Reynolds number.

3. Numerical Solutions By Finite Element Method:

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 (12) 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 is varied from 0 to $y_{max} = 9$, where y_{max} represents infinity $i.e.,$ 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, four 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.

4. Results and Discussions:

The similarity equations (9), (10) and (11) were solved numerically subject to the boundary conditions given by (12). Graphical representations of the numerical results are illustrated in Figure (1) through Figure (8) to show the influences of different numbers on the boundary layer flow. In this study, we investigate the influence of the effects of material parameters such as Prandtl number, Schmidt number, Hartmann number, Grashof number, Modified Grashof number and Permeability parameter separately in order to clearly observe their respective effects on the velocity, temperature and concentration profiles of the flow. Also Skin-friction coefficient, Rate of heat and mass transfer coefficients in terms of Nusselt number and Sherwood number respectively have been observed through graphically. During the course of numerical calculations of the velocity, temperature and concentration, the values of the Prandtl number are chosen for Mercury ($\Pr$ = 0.025), Air at 25°C and one atmospheric pressure ($\Pr$ = 0.71), Water ($\Pr$ = 7.00) and Methanol ($\Pr$ = 11.62). To focus out attention on numerical values of the results obtained in the study the values of Sc are chosen for the gases representing diffusing chemical species of most common interest in air namely Hydrogen (Sc = 0.22), Helium (Sc = 0.30), Water-vapour (Sc = 0.60) and Oxygen (Sc = 0.66). For the physical significance, the numerical discussions in the problem and at t = 1.0, stable values for velocity, temperature and concentration fields are obtained. To examine the effect of parameters related to the problem on the velocity field and Skin-friction numerical computations are carried out at $\Pr = 0.71$. To find solution of this problem, we have placed an infinite vertical plate in a finite length in the flow. Hence, we solve the entire problem in a finite boundary. However, in the graphs, the y values vary from 0 to 9, and the velocity, temperature, and concentration tend to zero as y tend to 9. This is true for any value of y. Thus, we have considered finite length.

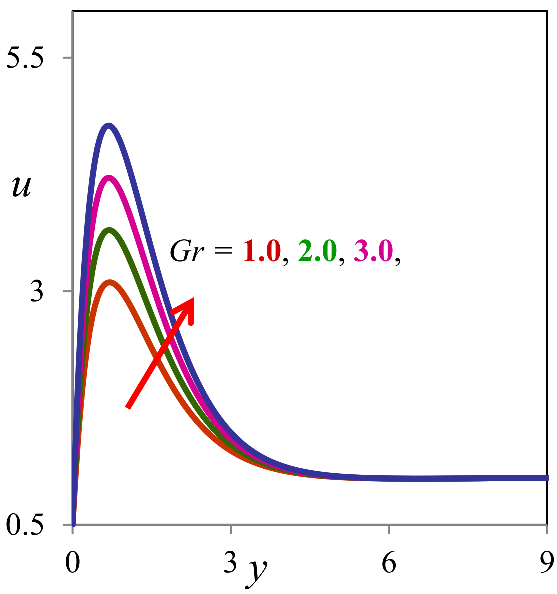

Fig. 1. Effect of *Gr* on Velocity profiles

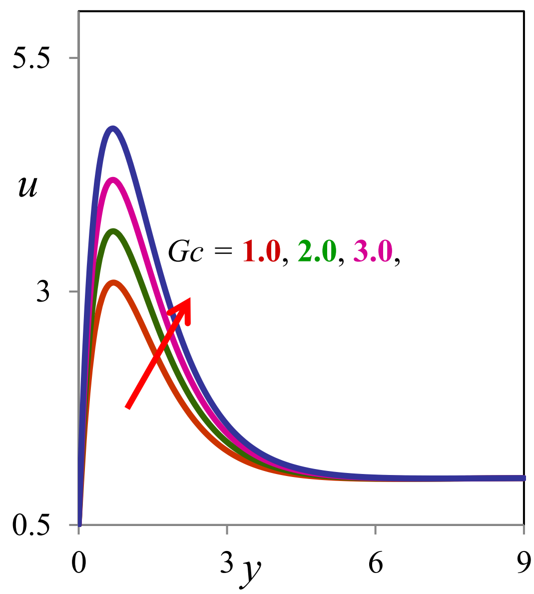

Fig. 2. Effect of *Gc* on Velocity profiles

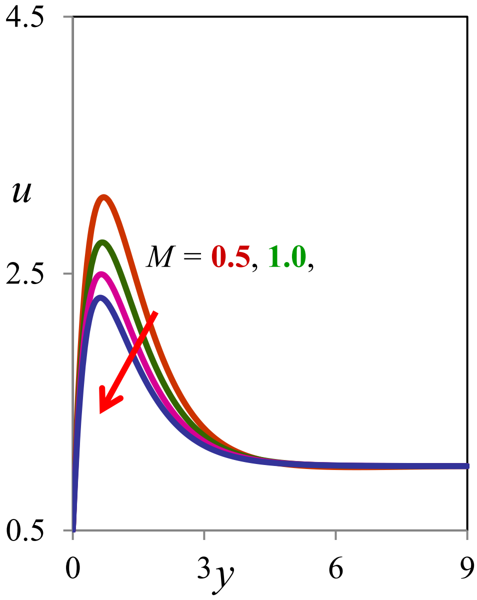

Fig. 3. Effect of *M* on Velocity profiles

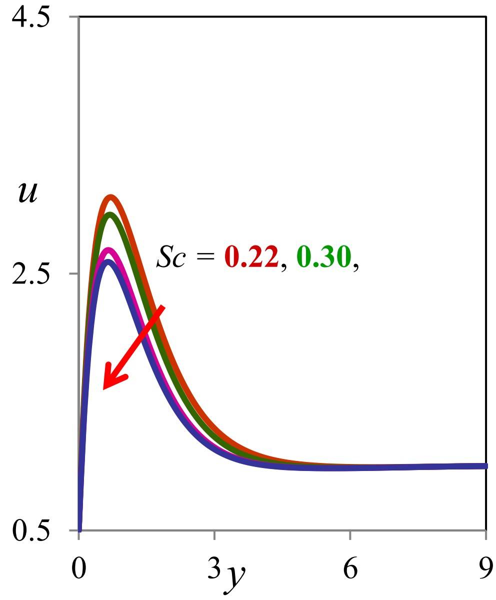

Fig. 4. Effect of *Sc* on Velocity profiles

4. 1. Results And Discussions of Velocity Profiles:

The temperature and the species concentration are coupled to the velocity via Grashof number and Modified Grashof number as seen in equation (9). Figures (1)-(6) display the effects of material parameters such as Gr, Gc, Sc, $\Pr$, M and K. For various values of Grashof number and Modified Grashof number, the velocity profiles u are plotted in figures (1) and (2). 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 the free stream value. It is noticed that the velocity increases with increasing values of the Modified Grashof number. The effect of the Hartmann number is shown in figure (3). 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 (3). 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 (4). The flow field suffers a decrease in velocity at all points in presence of heavier diffusing species. 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 (5). We observe that from figure (5) the velocity decreases with increasing of Prandtl number. In figure (6) we have the influence of the Permeability parameter on the velocity. It can be seen that as the values of this parameter increases, the velocity increases.

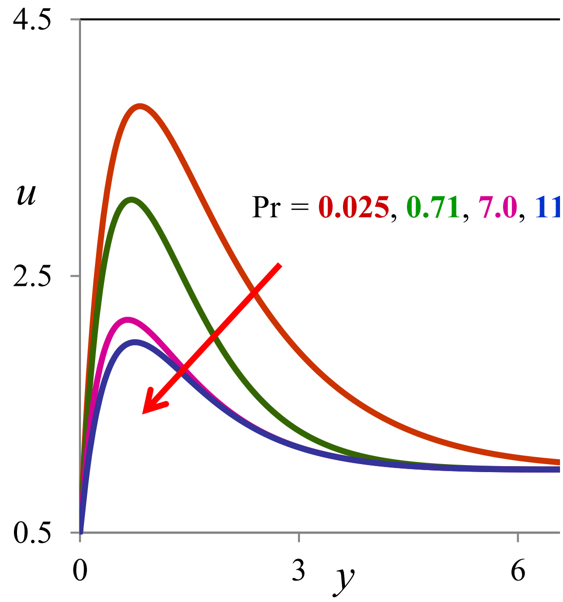

Fig. 5. Effect of Pr on Velocity profiles

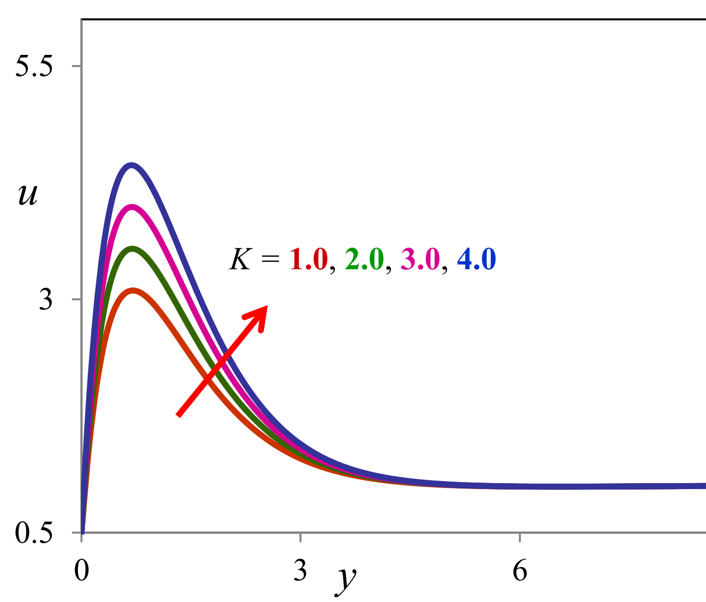

Fig. 6. Effect of *K* on Velocity profiles

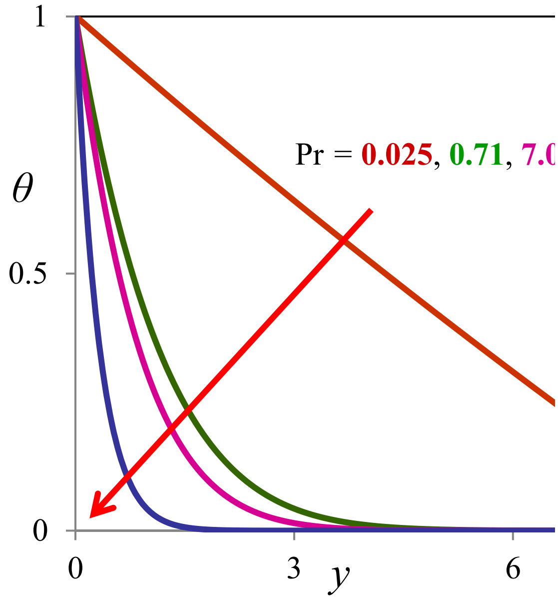

Fig. 7. Effect of Pr on Temperature profiles

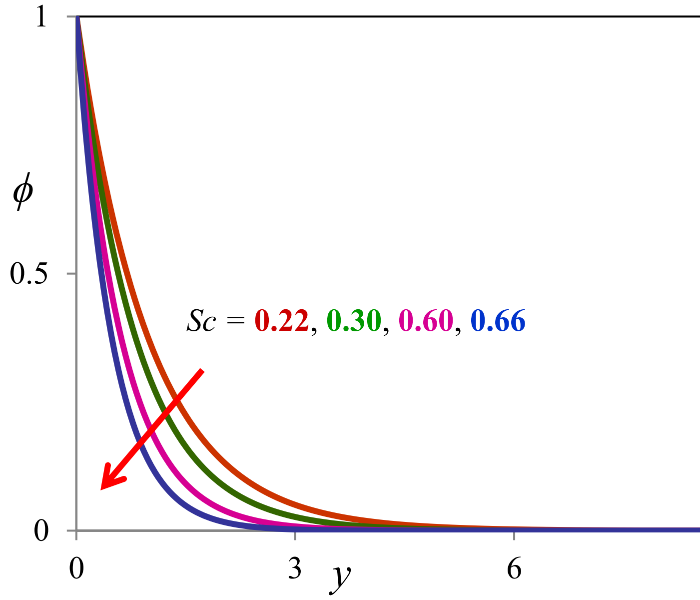

Fig. 8. Effect of *Sc* on Concentration profiles

4. 2. Results And Discussions of Temperature Profiles:

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.

4. 3. Results And Discussions of Concentration Profiles:

The effect of Schmidt number on the concentration field is presented in figures (8). Figure (8) shows the concentration field due to variation in Schmidt number for the gasses Hydrogen, Helium, Water-vapour and Oxygen. It is observed that concentration field is steadily for Hydrogen and falls rapidly for Water-vapour and Oxygen in comparison to Helium. Thus Hydrogen can be used for maintaining effective concentration field and Helium can be used for maintaining normal concentration field.

Table-1: Skin-friction coefficient (τ)

Gr	Gc	M	K	Pr	Sc	τ
1.0	1.0	1.0	1.0	0.71	0.22	0.2161
2.0	1.0	1.0	1.0	0.71	0.22	0.2314
1.0	2.0	1.0	1.0	0.71	0.22	0.2406
1.0	1.0	2.0	1.0	0.71	0.22	0.1513
1.0	1.0	1.0	2.0	0.71	0.22	0.2615
1.0	1.0	1.0	1.0	7.00	0.22	0.2148

1.0	1.0	1.0	1.0	0.71	0.30	0.2116

4. 4. Results And Discussions of Skin-friction Coefficient:

The profiles for Skin-friction due to velocity under the effects of Grashof number, Modified Grashof number, Hartmann number, Permeability parameter, Prandtl number and Schmidt number is presented in the table-1. We observe from the above table-1, the Skin-friction due to velocity increases under the effects of Grashof number, Modified Grashof number, Permeability parameter and decreases under the effects of Hartmann number, Prandtl number and Schmidt number.

4. 5. Results And Discussions of Nusselt & Sherwood Numbers:

The profiles for Nusselt number due to temperature profile under the effect Prandtl number is presented in the table-2. We see from this table-2 the Nusselt number due to temperature falls under the effect of Prandtl number. The profiles for Sherwood number due to concentration profiles under the effect of Schmidt number is presented in the table-2. We see from this table the Sherwood number due to concentration profile falls under the effect of Schmidt number.

Table-2: Nusselt number and Sherwood number

Pr	Nu	Sc	Sh
0.71	4.8586	0.22	7.5597
7.00	4.4782	0.30	7.3401
11.62	3.3719	0.78	6.3932

5. Conclusions:

This work investigated an unsteady MHD flow past a semi-infinite vertical moving permeable moving plate with heat transfer and mass transfer. The governing equations are approximated to a system of linear ordinary differential equations by using suitable similarity transformations. Numerical calculations are carried out for various values of the dimensionless numbers of the problem using an efficient and finite element method. The results are presented graphically and we can conclude that the flow field and the quantities of physical interest are significantly influenced by these numbers.

1. The velocity increases as the permeability parameter, heat and mass transfer increases. However, the velocity was found to decreases as the Hartmann number, Prandtl number and Schmidt number are increases.
2. The fluid temperature was found to decrease as the Prandtl number increases.
3. The concentration decreases as the Schmidt number increases.
4. The Skin-friction coefficient due to velocity profile increases under the effects of Grashof number, Modified Grashof number and Permeability parameter and decreases under the effects of Hartmann number, Prandtl number and Schmidt number.
5. Nusselt number due temperature profile falls under the effect of Prandtl number.
6. Sherwood number due concentration profile falls under the effect of Schmidt number.

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