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Research Article

FINITE DIFFERENCE SOLUTIONS OF NATURAL CONVECTIVE MHD HEAT AND MASS TRANSFER FLUID FLOW PAST VERTICALLY INCLINED POROUS PLATE WITH THERMAL RADIATION AND CHEMICAL REACTION

Bandham Saidulu*

Princeton Degree & PG College, Ramanthapur, Hyderabad, 5000013, Telangana State, India

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ABSTRACT

The aim of this numerical investigation is to study the combined effects of thermal radiation and chemical reaction effects on unsteady MHD natural convective on a viscous, incompressible, electrically conducting fluid flow past a vertically inclined plate embedded in porous medium in presence of viscous heat and mass transfer. The chemical reaction has been assumed to be homogeneous of first-order. The basic non-linear coupled partial differential equations governing the flow have been solved numerically using an efficient, flexible finite difference method. Graphical results for velocity, temperature and concentration profiles have been obtained, to show the effects of different parameters entering in the problem. Such flow problems are important in many processes, in which there is combined heat and mass transfer with chemical reaction, such as drying, evaporation at the surface of water body etc.

INTRODUCTION

In several problems related to demanding of efficient transfer of mass over inclined beds related to geophysical, petroleum, chemical, bio-mechanical, chemical technology and in situations the viscous drainage over an inclined porous plane is a subject of considerable interest to both theoretical and experimental investigators. Especially, in the flow of oil through porous rock, the extraction of geo-thermal energy from the deep interior of the earth to the shallow layers, the evaluation of the capability of heat removal from particulate nuclear fuel debris that may result from hypothetical accident in a nuclear reactor, the filtration of solids from liquids, flow of liquids through ion exchange beds, drug permeation through human glands, chemical reactor for economical separation or purification of mixtures flow through porous medium has been the subject of considerable research activity in recent years due to its notable applications. An important application in the petroleum industry where crude oil is trapped from natural underground reservoirs in which oil is entrapped since the flow behavior of fluids in petroleum reservoir rock depends to a large extent on the properties of the rock, techniques that yield new or additional information on the characteristics of the rock would enhance the performance of petroleum reservoirs. An important bio-medical application is the flow of fluids in lungs, blood vessels, arteries and so on, where the fluid is bounded by two layers which are held together by a set of fairly regularly spaced tissues. Slurry adheres to the reactor vessel and gets consolidated in many chemical processing industries, as a result of which chemical compounds within the reactor vessels percolates through the boundaries. Thus adhered substance within the reactor vessel acts as a porous boundary. The problem assumes greater importance in all such situations. The thin film adhering to the surfaces of the container must be taken into account for the purpose of precise chemical calculations in all such situations wherein hear and mass transfer occurs. Failure to do so leads to severe experimental errors. Hence, there is a need for such an analysis in detail. A mathematical model related to such a situation has been studied in detail. Dharmendar Reddy *et al.* ([1] and [2]) studied hall current effect on an unsteady MHD free convection flow past a vertical porous plate with chemical reaction, heat and mass transfer. Srinivasa Rao [3] studied finite element analysis of radiation and mass transfer flow past semi-infinite moving vertical plate with viscous dissipation. Sheri *et al.* ([4]-[7]) discussed transient approach to heat absorption and radiative heat transfer past an impulsively moving plate with ramped temperature. Venkataramana *et al.* [8] studied thermal radiation and rotation effect on an unsteady MHD mixed convection flow through a porous medium with Hall current and Heat absorption. Sailaja *et al.* ([9]-[12]) discussed finite element solutions of non-newtonian dissipative Casson fluid flow past a vertically inclined surface surrounded by porous medium including constant heat flux, thermal

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Corresponding author:* **Bandham Saidulu
Princeton Degree & PG College, Ramanthapur, Hyderabad, 5000013, Telangana State, India

diffusion and diffusion thermo. Sivaiah and Srinivasa Raju and their co-authors ([13]-[14]) studied finite element solution of heat and mass transfer flow with hall current, heat source and viscous dissipation. Ramya *et al.* ([15]-[18]) discussed boundary layer viscous flow of nanofluids and heat transfer over a nonlinearly isothermal stretching sheet in the presence of heat generation/absorption and slip boundary conditions. Srinivasa Raju ([19] and [20]) studied unsteady MHD boundary layer flow of casson fluid over an inclined surface embedded in a porous medium with thermal radiation and chemical reaction. Srinivasa Raju *et al.* ([21] and [22]) studied radiation effect on unsteady MHD free convection with Hall current near on an infinite vertical porous plate. Srinivasa Raju [23] studied numerical treatment of casson fluid free convection flow past an infinite vertical plate filled in magnetic field in presence of angle of inclination and thermal radiation using finite element technique. Srinivasa Raju *et al.* ([24]-[39]) discussed influence of transpiration on unsteady heat transfer MHD fluid flow over an infinite vertical plate in presence of hall current. Srinivasa Raju [40] studied effects of soret and Dufour on natural convective fluid flow past a vertical plate embedded in porous medium in the presence of thermal radiation via finite element method. Srinivasa Raju *et al.* [41] discussed magnetohydrodynamic chemically reacting flow past vertically inclined permeable plate filled in porous medium with convergence analysis of FEM. Combined influence of thermal diffusion and diffusion thermo on unsteady hydromagnetic free convective fluid flow past an infinite vertical porous plate in presence of chemical reaction studied by Srinivasa Raju [42]. Srinivasa Raju *et al.* ([43]-[46]) discussed the application of finite element method to unsteady MHD free convection flow past a vertically inclined porous plate including thermal diffusion and diffusion thermo effects. Application of finite element method to MHD mixed convection chemically reacting flow past a vertical porous plate with cross diffusion and Biot number effects studied by Srinivasa Raju [47]. Simultaneous effects of soret and Dufour on unsteady hydromagnetic free convective chemically reacting fluid flow past an infinite vertical plate filled in porous medium studied by Srinivasa Raju and Sarada [48]. Study of grid independence of finite element method on MHD free convective casson fluid flow with slip effect studied by Srinivasa Raju and Ramesh [49]. Manideep *et al.* ([50] and [51]) discussed MHD free convection heat transfer Couette flow in rotating system. Maddilety and Srinivasa Raju [52] studied hall effect on an unsteady MHD free convective Couette flow between two permeable plates. Heat and mass transfer effects on MHD natural convective flow past an infinite vertical porous plate with thermal radiation and hall current studied by Ramana Murthy *et al.* [53]. Sudhakar *et al.* ([54]-[56]) studied hall effect on an unsteady MHD flow past along a porous flat plate with thermal diffusion, diffusion thermo and chemical reaction. 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.* [57]. Anand Rao *et al.* ([58]-[67]) studied finite element analysis of unsteady MHD free convection flow past an infinite vertical plate with Soret, Dufour, thermal radiation and heat source. Anand Rao and Srinivasa Raju ([68]-[70]) studied hall effect on an unsteady MHD flow and heat transfer along a porous flat plate with mass transfer and viscous dissipation. Jitthender Reddy *et al.* ([71]-[79]) discussed chemical reaction and radiation effects on MHD free convection from an impulsively started infinite vertical plate with viscous dissipation. Aruna *et al.* [80] studied combined influence of Soret and Dufour effects on unsteady hydromagnetic mixed convective flow in an accelerated vertical wavy plate through a porous medium, Krishna Prasad *et al.* ([81]-[83]) discussed thermal radiation influence on MHD Flow of a rotating fluid with heat transfer through finite element and element free Galerkin solutions.

Hence, motivate by above reference work, the aim of the present work is to investigate the effect of thermal radiation on MHD natural convection flow past an impulsively started semi-infinite porous plate with variable temperature in the presence of chemical reaction by finite difference method which is more economical from computational view point. It is also assumed that temperature of the plate and concentration near the plate varies linearly with time.

Mathematical formulation

Consider a two-dimensional unsteady MHD free convection flow of a viscous, incompressible, electrically conducting fluid past a semi-infinite tilted porous plate with chemical reaction and thermal radiation. 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 of first order with rate constant $\overline{K}$ between the diffusing species and the fluid is assumed. 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 fluid is considered to be gray absorbing-emitting radiation but non-scattering medium and the Roseland's approximation is used to describe the radiative heat flux. It is considered to be negligible in $x'-$ direction as compared in $y'-$ direction. At time $t' > 0$ the plate is given an impulsive motion in the direction of flow i.e. along $x'-$ axis against the gravity with constant velocity U_o, it is assumed that the plate temperature and concentration at the plate are varying linearly with time. 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. Under these assumptions the equations governing the flow are:

Momentum Equation

$$\frac{\partial u'}{\partial t'} = g\beta(T' - T'_\infty)(\cos\alpha) + g\beta^*(C' - C'_\infty)(\cos\alpha) + \nu\frac{\partial^2 u'}{\partial y'^2} - \left(\frac{\sigma B_o^2}{\rho} + \frac{\nu}{K'}\right)u' \qquad (1)$$

Energy Equation

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa \frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} \qquad (2)$$

Species Diffusion Equation

$$\frac{\partial C'}{\partial t'} = D \frac{\partial^2 C'}{\partial y'^2} - K_r\left(C' - C'_\infty\right) \qquad (3)$$

With the following initial and boundary conditions

$$\left.\begin{array}{l} t' \le 0 : u' = 0,\ T' = T'_\infty,\ C' = C'_\infty \quad for \quad all \quad y' \\ t' > 0 : \begin{cases} u' = U_o,\ T' = T'_\infty + \left(T'_w - T'_\infty\right)At',\ C' = C'_\infty + \left(C'_w - C'_\infty\right)At',\ at\ \ y' = 0 \\ u' \to 0,\ T' \to 0,\ C' \to 0 \ \ as \ \ y' \to \infty \end{cases} \end{array}\right\} \qquad (4)$$

Where $A = \frac{U_o^2}{\nu}$. The radiative heat flux q_r, under Rosseland approximation has the form

$$q_r = -\frac{4\sigma_1}{3\kappa} \frac{\partial^2 T'^4}{\partial y'} \qquad (5)$$

It is assumed that, the temperature differences within the flow are sufficiently small such that T'^4 may be expressed as a linear function of the temperature T'_∞. This is obtained by expanding T'^4 in a Taylor series about T'_∞ and neglecting higher order terms. Thus, we get

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \qquad (6)$$

By using equations (5) and (6), equation (2) reduces to

$$\frac{\partial T'}{\partial t'} = \frac{\kappa}{\rho C_p} \frac{\partial^2 T'}{\partial y'^2} - \frac{16\sigma_1 T'^3_\infty}{3k_1 \rho C_p} \frac{\partial^2 T'}{\partial y'^2} \qquad (7)$$

Introducing the following non-dimensional parameters in equations (1), (2), (3) and (7) quantities

$$\left.\begin{array}{l} y = \frac{y'U_o}{\nu}, t = \frac{t'U_o}{\nu}, u = \frac{u'}{U_o},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\ \phi = \frac{C - C_\infty}{C_w - C_\infty},\ Gr = \frac{g\beta\nu\left(T'_w - T'_\infty\right)}{U_o^3},\ Gc = \frac{g\beta^*\nu\left(C_w - C_\infty\right)}{U_o^3},\ \Pr = \frac{\mu C_p}{\kappa}, M = \left(\frac{\sigma B_o^2}{\rho}\right)\frac{\nu}{U_o^2}, \\ Sc = \frac{\nu}{D}, K = \frac{K'U_o^2}{\nu^2},\ N = \frac{\kappa U_o^2}{4\nu^2\sigma_1 T'^3_\infty},\ \lambda = \frac{K_r\nu}{U_o^2} \end{array}\right\} \qquad (8)$$

In equations (1), (2), (3) and (7) reduces to

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - (M + \frac{1}{K})u + (Gr)\theta(\cos\alpha) + (Gc)\phi(\cos\alpha) \qquad (9)$$

$$(\Pr)\frac{\partial \theta}{\partial t} = \left(1 + \frac{4}{3N}\right)\frac{\partial^2 \theta}{\partial y^2} \qquad (10)$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - \lambda\phi \qquad (11)$$

The corresponding initial and boundary conditions in dimensionless form are

$$\left.\begin{array}{l} t \le 0 :\ u = 0,\ \theta = 0,\ \phi = 0 \quad for \quad all \quad y \\ t > 0 : \begin{cases} u = 1,\ \theta = t,\ \phi = t \ \ at \ \ y = 0 \\ u \to 0,\ \theta \to 0,\ \phi \to 0 \ \ as \ \ y \to \infty \end{cases} \end{array}\right\} \qquad (12)$$

RESULTS AND DISCUSSION

In order to get a physical insight in to the problem the effects of various governing parameters on the physical quantities are computed and represented in figures (1)-(14) and discussed in detail. Figures (1) and (2) exhibit the effect of Grashof number and Modified Grashof numbers on the velocity profile with other parameters are fixed. 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. Figure (3) 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 Water at $4^o C$ ($\Pr$ = 11.62) are shown in figure (3). It is observed that from figure (3), the velocity decreases with increasing of Prandtl number $(\Pr)$. The nature of velocity profiles in presence of foreign species such as Hydrogen (Sc = 0.22), Helium (Sc = 0.30), Oxygen (Sc = 0.60) and Water-vapour (Sc = 0.66) are shown in figure (4).

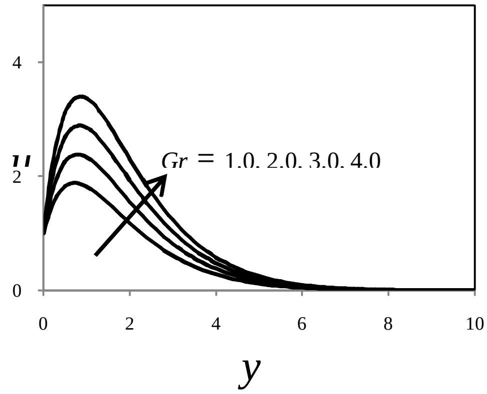

Figure 1 Effect of *Gr* on Velocity profiles

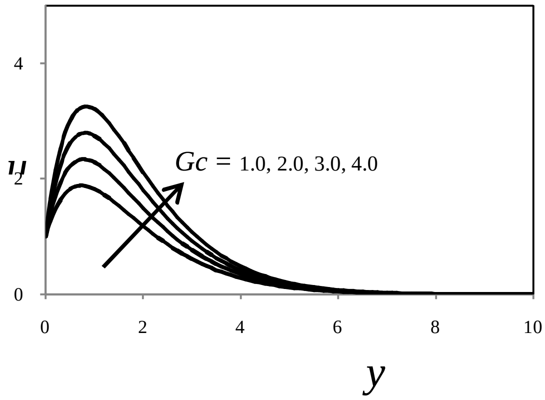

Figure 2 Effect of *Gc* on Velocity profiles

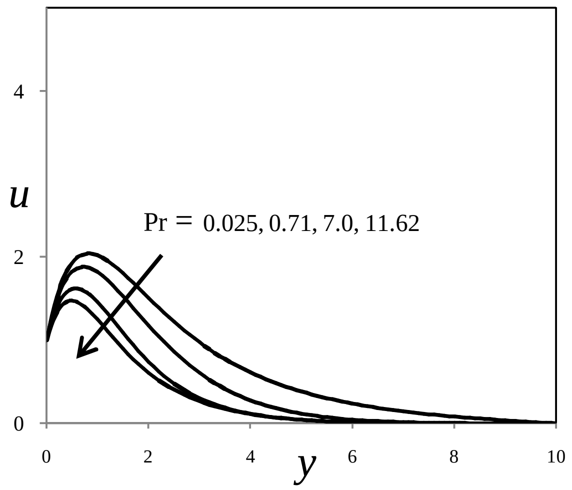

Figure 3 Effect of Pr on Velocity profiles

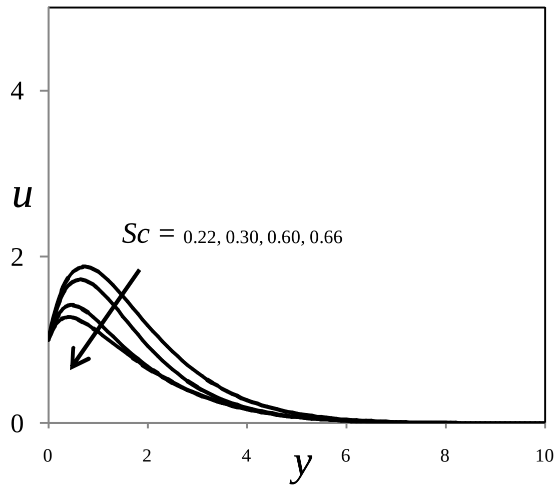

Figure 4 Effect of sc on Velocity profiles

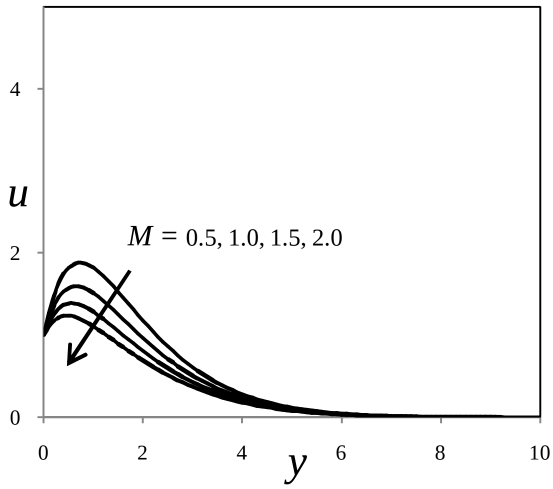

Figure 5 Effect of *M* on Velocity profiles

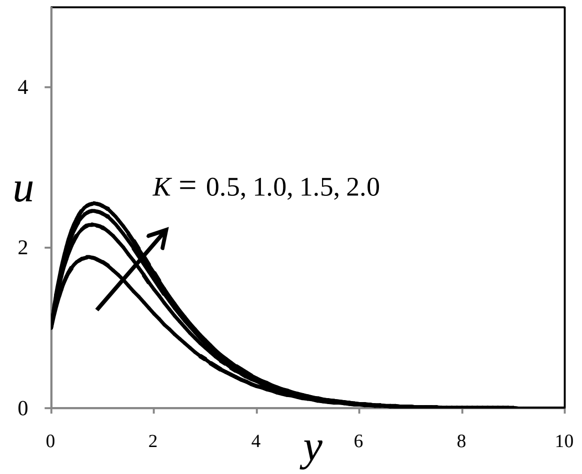

Figure 6 Effect of *K* on Velocity profiles

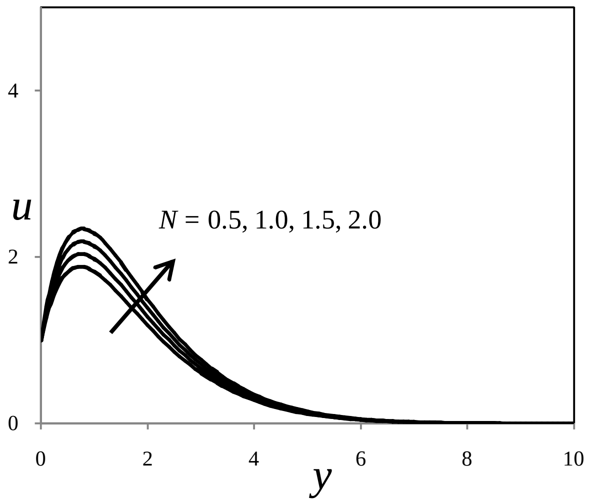

Figure 7 Effect of *N* on Velocity profiles

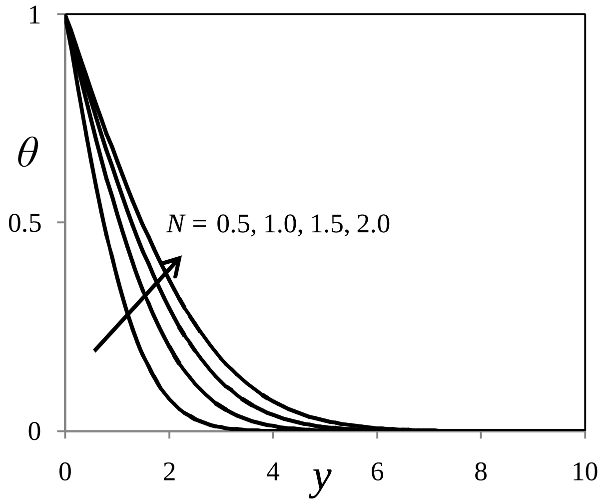

Figure 8 Effect of *N* on Temperature profiles

The flow field suffers a decrease in velocity at all points in presence of heavier diffusing species. The effect of the Hartmann number is shown in figure (5). 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 (5). The effect of Permeability parameter is presented in the figure (6). From this figure it observe that, the velocity is increases with increasing values of *K*. The effects of the thermal radiation parameter on the velocity and temperature profiles in the boundary layer are illustrated in figures (7) and (8) respectively. Increasing the thermal radiation parameter produces significant increase in the thermal condition of the fluid and its thermal boundary layer. This increase in the fluid temperature induces more flow in the boundary layer causing the velocity of the fluid there to increase. Figures (9) and (10) display the effects of the chemical reaction parameter on the velocity and concentration profiles, respectively. As expected, the presence of the chemical reaction significantly affects the concentration profiles as well as the velocity profiles. It should be mentioned that the studied case is for a destructive chemical reaction. In fact, as chemical reaction increases, the considerable reduction in the velocity profiles is predicted, and the presence of the peak indicates that the maximum value of the velocity occurs in the body of the fluid close to the surface but not at the surface. Also, with an increase in the chemical reaction parameter, the concentration decreases. It is evident that the increase in the chemical reaction significantly alters the concentration boundary layer thickness but does not alter the momentum boundary layers.

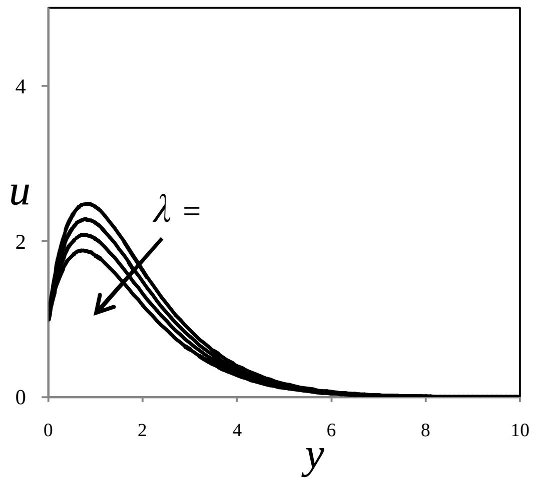

Figure 9 Effect of *λ* on Velocity profiles

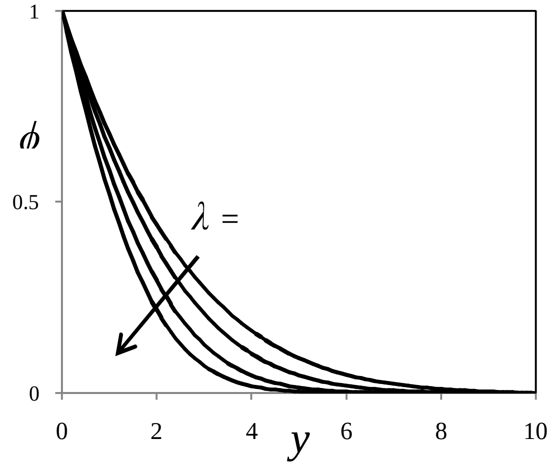

Figure 10 Effect of *λ* on Concentration profiles

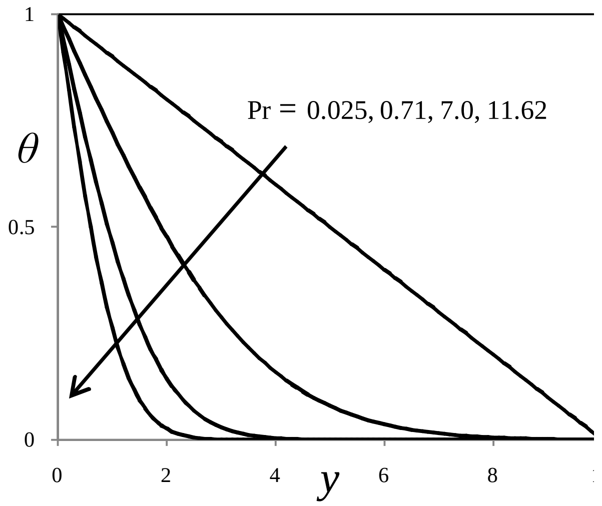

Figure 11 Effect of Pr on Temperature profiles

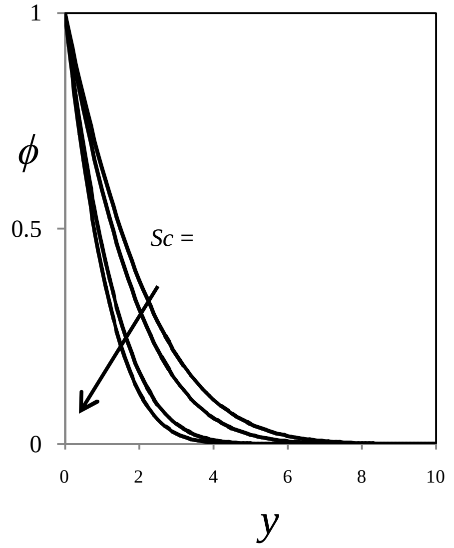

Figure 12 Effect of *Sc* on Concentration profiles

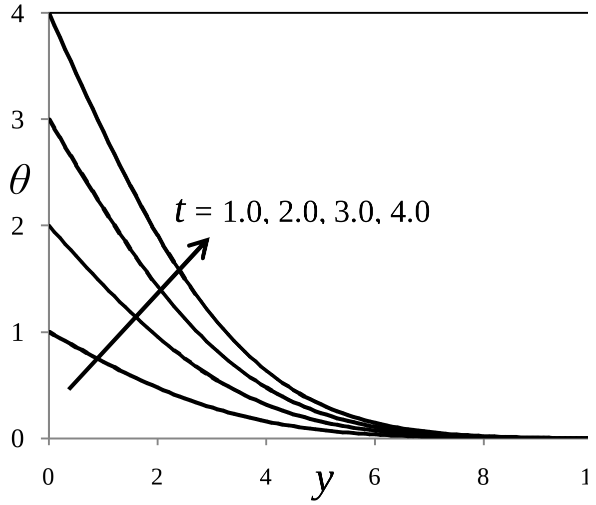

Figure 13 Effect of *t* on Temperature profiles

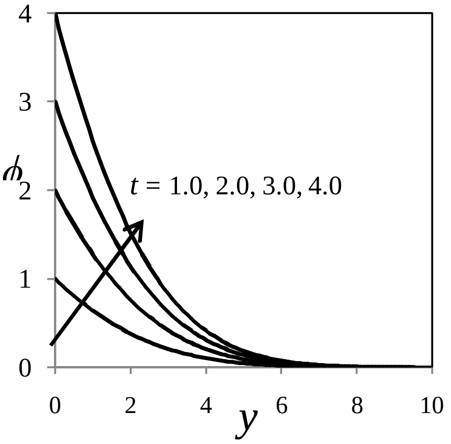

Figure 14 Effect of *t* on Concentration profiles

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 (12) illustrates the effect of Schmidt number on the concentration field. It is noticed that as the Schmidt number increases, the concentration of the fluid medium decreases significantly in the boundary layer region and thereafter not much of variation is noticed. Figures (13) and (14) display the effect of the time on temperature and concentration profiles respectively. From these two figures it observed that, both temperature and concentration are increasing with increasing values of time.

CONCLUSIONS

The author summarize below the following results of physical interest on the velocity, temperature and concentration distributions of the flow field and also on the skin-friction, rate of heat and mass transfer at the wall.

1 A growing Hartmann number or Prandtl number or Schmidt number or Chemical reaction parameter retards the velocity of the flow field at all points.
2 The effect of increasing Grashof number or Modified Grashof number or Permeability parameter or Thermal radiation parameter is to accelerate velocity of the flow field at all points.
3 A growing Prandtl number decreases temperature of the flow field at all points and increases with increasing of Time or Thermal radiation parameter.
4 The Schmidt number and Chemical reaction parameter decreases the concentration of the flow field at all points.

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