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Radiation and Mass Transfer Effects on MHD Mixed Convection Flow from a Vertical Surface with Ohmic heating in the Presence of Chemical reaction

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ABSTRACT: The study sought to investigate the radiation and mass transfer effects in MHD mixed convection flow and mass transfer past an infinite vertical plate with Ohmic heating and viscous dissipation in the presence of chemical reaction have been discussed. The dimensionless governing equations are coupled and non-linear. These equations for this investigation are solved analytically using two-term harmonic and non-harmonic functions by perturbation technique. Approximate solutions have been derived for the velocity, temperature field, concentration profiles, skin - friction and rate heat transfer. The obtained results are discussed with the help of graphs to observe that the effect of various parameter like Grashof Number, Schmidt number, Prandtl number, Magnetic parameter, Radiation parameter and Chemical reaction parameter taking two cases viz. Case(I): when $Gr > 0$, (i.e. flow on cooled plate) and Case(II): $Gr < 0$ (i.e. flow on heated plate).

Keywords: MHD mixed convection, vertical moving surface, radiation, viscous dissipation and chemical reaction

I. INTRODUCTION

For many mixed flows of practical importance in nature as well as in many engineering devices, the environment is thermally stratified. The discharge of hot fluid into enclosed regions often results in a stable thermal stratification with lighter fluid overlying denser fluid. The thermal stratification effects of heat transfer over a porous wedge are of interest in polymer extrusion processes, where the object, after passing through a die, enters the fluid for cooling below a certain temperature. Transport processes in porous media play a significant role in various applications, such as geothermal engineering, thermal insulation, energy conservation, petroleum industries, solid matrix heat exchangers, chemical catalytic reactors, and underground disposal of nuclear waste materials. In many transport processes in nature and in industrial applications, the heat and mass transfer with variable viscosity is a consequence of buoyancy effects caused by the diffusion of heat and chemical species. The study of such processes is useful for improving a number of chemical technologies, such as polymer production and food processing. In nature, the presence of pure air or water is impossible. Some foreign mass may be presented either naturally or mixed with air or water. A large amount of research work has been reported in this field. Particularly, the study of heat and mass transfer with chemical reactions is of considerable importance in the chemical and hydrometallurgical industries.

Many researchers considered the effect of constant viscosity on boundary layers developed by continuously moving surface. The chemical equation is applicable to transformations of elementary particles as well as nuclear reaction. Numerous applications of chemical reaction are experiment in chemical engineering, in polymer production and manufacturing of ceramics etc. The importance of thermal radiation becomes intensified at high absolute-temperature levels due to basic difference between radiation and the convection and conduction energy-exchange mechanisms, some devices for space applications are designed to operate at high temperature levels in order to achieve high thermal efficiency. Hence, radiation must often be considered when calculating thermal effects in devices such as a rocket nozzle, a nuclear power plant, or a gaseous - core nuclear rocket. Consider the emission of NO_2 from automobiles and other smoke-stacks. This

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NO_2 reacts chemically in the atmosphere with unburned hydrocarbons (aided by sunlight) and produces peroxyacetylnitrate, which forms an envelop termed as the photochemical smog. It is known that the fluid viscosity changes with temperature. Ali [2] the effect of variable viscosity on a mixed convection heat transfer along a vertical moving surface was studied. Naveent Joshi and Manoj Kumar [21] The Combined effect of chemical reaction, radiation, MHD on mixed convection heat and mass transfer along a vertical moving surface.

Convection flow driven by temperature and concentration differences has been the objective of extensive research because such processes exists in nature and has engineering applications. The process occurring in nature includes photo-synthetic mechanism, calm-day evaporation and vaporization of mist and fog, while the engineering application includes the chemical reaction in a reactor chamber consisting of rectangular ducts, chemical vapor deposition on surfaces and cooling of electronic equipment. Heat and mass transfer on flow past a vertical plate have been studied by several authors; viz. Somess [24], Khair and Bejan [17] in numerous ways to include various physical aspects. Magnetohydrodynamics flows has applications in meteorology, solar physics, cosmic fluid dynamics, astrophysics, geophysics and in the motion of earthes core. In addition to the technological point of view, MHD free convection flows have significant applications in the field of stellar and planetary magnetospheres, aeronautics, chemical engineering and electronics. On account of their varied importance, this flow has been studied by several authors. Al-Odat et al. [3] investigated the influences of radiation on mixed convection flow of an optically dense viscous fluid along an isothermal wedge embedded in non-Darcy porous medium. Chamkha *et al*. [4] investigated on the steady-state, hydromagnetic forced convective boundary-layer flow of an incompressible Newtonian, electrically conducting and heat-generating/absorbing fluid over a non-isothermal wedge in the presence of thermal radiation effects. Duwairi [10] studied the radiation and magnetic effects on the skin friction and heat transfer for forced convection conditions.

The effects of mass transfer on free convection flow past a vertical isothermal plate was first studied by Gebhart and Pera [12]. Hosain and Takhar [16] studied the radiation effect on mixed convection along a vertical plate with uniform surface temperature. Muthucumaraswamy and Kumar Senthil [20] Heat and Mass transfer effect on moving vertical plate in the presence of thermal radiation. Das et. al. [9] considered the case of radiation effects on flow past an impulsively started vertical plate. Choudary et. al. [5] radiation effect with simultaneous thermal and mass diffusion in magnetohydrodynamics (MHD) mixed convection flow from a vertical surface with ohmic heating. Muhaimin et.al [19] Numerical investigation of variable viscosities and thermal stratification effects on MHD mixed convective heat and mass transfer past a porous wedge in the presence of a chemical reaction.

The study of Magnotohydrodynamics (MHD) plays an important role in agriculture, engineering and petroleum industries. The problem of free convection under the influence of a magnetic field has attracted the interest of many researchers in view of its applications in geophysics and astrophysics. Magnetohydrodynamics has its own practical applications. For instance, it may be used to deal with problems such as cooling of nuclear reactors by liquid sodium and induction flow meter, which depends on the potential difference in the fluid in the direction perpendicular to the motion and go the magnetic field. Soundalgekar *et al.* [25] analyzed the problem of free convection effects on Stokes problem for a vertical plate under the action of transversely applied magnetic field. Elbashbeshy [11] studied the heat and mass transfer along a vertical plate under the combined buoyancy effects of thermal and species diffusion, in the presence of magnetic field. Helmy [15] presented an unsteady two-dimensional laminar free convection flow of an incompressible, electrically conducting (Newtonian or polar) fluid through a porous medium bounded by infinite vertical plane surface of constant temperature. Satya Narayana and Venkataramana [23] Hall current effects on free-convection MHD flow fast a porous plate. Gireesh Kumar and Satyanarayana [13] Mass transfer effects on MHD unsteady free convective Walter's memory flow with constant suction and heat sink. Saritha and Satya Narayana [22] Thermal diffusion and chemical reaction effects on unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate. Damala Ch Kesavaiah et.al [8] Radiation absorption, chemical reaction and magnetic field effects on the free convection and mass transfer flow through porous medium with constant suction and constant heat flux. Gireesh Kumar and Satyanarayana [14] Mass transfer effects on MHD unsteady free convective Walter's memory flow with constant suction and heat sink.

The effects of radiation on temperature have become more important industrially. Many processes in engineering areas occur at high temperature and acknowledge radiation heat transfer become very important for the design of pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for air craft, missiles, satellites and space vehicles are example of such engineering areas. For the problem of coupled heat and mass transfer in MHD free convection, the effect of both viscous dissipation and Ohmic heating are not studied in the above investigations. However, it is more realistic to include these two effects to explore the impact of the magnetic field on the thermal transport in the boundary layer. With this awareness, Chien-Hsin-Chen [6] studied the problem of combined heat and mass transfer of an electrically conducting fluid in MHD natural convection, adjacent to a vertical surface with Ohmic heating. Sri Hari Babu and Ramana Reddy [26] Mass transfer effects on

MHD mixed convective flow from a vertical surface with ohmic heating and viscous dissipation. In the context of space technology and in processes involving high temperatures the effects of radiation are of vital importance. Recent developments in hypersonic flights, missile reentry, rocket combustion chambers, power plants for inter planetary flight and gas cooled nuclear reactors, have focused attention on thermal radiation as a mode of energy transfer, and emphasize the need for improved understanding of radiative transfer in these process. The propagation of thermal energy through mercury and electrolytic solution in the presence of magnetic field and radiation has wide range of applications. Aboeldahab Emad [1] Radiation effect on heat transfer in an electrically conducting fluid at a stretching surface with uniform free stream, Ghaly and Elbarbary [13] Radiation effect on MHD free convection flow of a gas at a stretching surface with uniform free stream. Mazumdar and Deka [18] MHD flow past an impulsively started infinite vertical plate in presence of thermal radiation.

Ohmic heating and viscous heating play significant roles in the thermal transport of a fluid past a heated surface, and it is also further realistic to incorporate the impact of both the effects on the thermal transport in the boundary layer. In the case of electrolytic refining of mixtures or electrolysis, Ohmic heating plays a vital role. Ohmic heating or Joule heating is the generation of excess heat in the fluid either due to direct current or applied magnetic fields. Ganesan et.al. [27] Viscous and Ohmic heating effects in doubly stratified free convective flow over vertical plate with radiation and chemical reaction. Khaled et.al [28] Combined Effects of Hall and Ion-Slip Currents and Ohmic Heating on MHD of Non-Newtonian Power-Law Fluid with Diffusion and Chemical Reaction over a moving cylinder. ABakr and Raizah [29] Unsteady MHD mixed convection flow of a viscous dissipating micropolar fluid in a boundary layer slip flow regime with Joule heating. Pal and Talukdar [30] Buoyancy and chemical reaction effects on MHD mixed convection heat and mass transfer in a porous medium with thermal radiation and Ohmic heating. Chien [31] Combined heat and mass transfer in MHD free convection from a vertical surface with Ohmic heating and viscous dissipation.

The aim of the present paper is the propagation of thermal energy through air and water solution in the presence of magnetic field and radiation has wide range of applications. Hence, the object is to study the effect of the radiation and chemical reaction on magnetohydrodynamics (MHD) heat and mass transfer in air (Pr = 0.71) and water solution $\left(\mathrm{Pr}=7.0\right)$ past an infinite porous hot vertical plate in the presence of Ohmic heating and transverse magnetic field.

II. FORMULATION OF THE PROBLEM

We consider the mixed convection flow of an incompressible, electrically conducting viscous fluid radiating and chemically reacting fluid, such that x^*-axis is taken along the plate in upwards direction and y^*-axis is normal to it. A transverse constant magnetic field is applied i.e. in the direction of y^*- axis. Since the motion is two dimensional and length of the plate is large therefore all the physical variables are independent of x^*. Let u^* and v^* be the components of velocity in x^* and y^* directions, respectively, taken along and perpendicular to the plate. The governing equations of continuity, momentum and energy for a flow of an electrically conducting fluid along a hot, non-conducting porous vertical plate in the presence of concentration and radiation is given by

$$\frac{dv^*}{dy^*}=0 \tag{1}$$

$$v^*=-v_0 \text{ (Constant)} \tag{2}$$

$$\frac{dp^*}{dy^*}=0\Rightarrow p^* \text{ is independent of } y^* \tag{3}$$

$$\begin{aligned}\rho\left(v^*\frac{du^*}{dy^*}\right)&=\mu\frac{d^2u^*}{dy^{*2}}+\rho g\,\beta(T^*-T_\infty)\\&\quad-\sigma B_0^2u^*+\rho g\beta^*(C^*-C_\infty)\end{aligned} \tag{4}$$

$$\begin{aligned}\rho C_p\left(v^*\frac{dT^*}{dy^*}\right)&=k\frac{d^2T^*}{dy^{*2}}+\mu\left(\frac{du^*}{dy^*}\right)^2\\&\quad-\frac{\partial q_r^*}{\partial y^*}+\sigma B_0{}^2u^{*2}\end{aligned} \tag{5}$$

$$v^*\frac{dC^*}{dy^*}=D\frac{d^2C^*}{dy^{*2}}-Kr^*\left(C^*-C_\infty\right) \tag{6}$$

Here, g is the acceleration due to gravity, T^* the temperature of the fluid near the plate, T_∞ the free stream temperature, C^* concentration, β the coefficient of thermal expansion, k the thermal conductivity, P^* the pressure, C_p the specific heat of constant pressure, B_0 the magnetic field coefficient, μ viscosity of the fluid, q^* the radiative heat flux, ρ the density, σ the magnetic permeability of fluid V_0 constant suction velocity, ν the kinematic viscosity and D molecular diffusivity.

The radiative heat flux $q_r{}^*$ is given by equation (5) in the sprit of Cogly et.al [7]

$$\frac{\partial q_r^*}{\partial y^*} = 4(T^* - T_\infty) I \qquad (7)$$

where $I = \int_0^\infty K_{\lambda w} \frac{\partial e_{b\lambda}}{\partial T^*} d\lambda,$

$K_{\lambda w} -$ is the absorption coefficient at the wall and $e_{b\lambda} -$ is Planck's function, I is absorption coefficient
The boundary conditions are

$$\begin{aligned} &y^* = 0: \quad u^* = 0, \quad T^* = T_w, \quad C_\infty = C \\ &y^* \to \infty : u^* \to 0, \; T^* \to T_\infty, \; C^* \to C_\infty \end{aligned} \qquad (8)$$

Introducing the following non-dimensional quantities

$$u = \frac{u^*}{v_0}, \quad y = \frac{v_0 y^*}{\nu}, \quad \theta = \frac{T^* - T_\infty}{T_w - T_\infty}$$

$$C = \frac{C^* - C_\infty}{C_w - C_\infty}, \qquad E = \frac{v_0^2}{C_p (T_w - T_\infty)}$$

$$F = \frac{4\nu I}{\rho C_p v_0^2}, M^2 = \frac{B_0^2 \nu^2 \sigma}{v_0^2 \mu}, Sc = \frac{\nu}{D}$$

$$Gr = \frac{\rho \beta g \nu^2 (T_w - T_\infty)}{v_0^3 \mu}, \; Kr = \frac{Kr^* \nu}{v_0^2} \qquad (9)$$

$$Gm = \frac{\rho \beta^* g (C - C_\infty)}{v_0^3}, \qquad \Pr = \frac{\mu C_p}{k}$$

III. SOLUTION OF THE PROBLEM

In the equations (4), (5), (6) and (8), we get

$$\frac{d^2 u}{dy^2} + \frac{du}{dy} - M^2 u = -Gr\theta - GmC \qquad (10)$$

$$\frac{d^2\theta}{dy^2} + \Pr \frac{d\theta}{dy} - F \Pr \theta + \Pr \left(\frac{du}{dy} \right)^2 + \Pr EM^2 u^2 = 0 \qquad (11)$$

$$\frac{d^2 C}{dy^2} + Sc \frac{dC}{dy} - ScKrC = 0 \qquad (12)$$

where Gr is Grashoff number, $\Pr$ is Prandtl number, M is Magnetic parameter, F is Radiation parameter, Sc is Schmidt number, E is Eckert number, Kr is Chemical reaction parameter.

The corresponding boundary condition in dimensionless form are reduced to

$$\begin{aligned} &y = 0: \quad u = 0, \quad \theta = 1, \quad C = 1 \\ &y \to \infty : u \to 0, \; \theta \to 0, C \to 0 \end{aligned} \qquad (13)$$

The physical variables u, θ *and* C can be expanded in the power of Eckert number (E). This can be possible physically as E for the flow of an incompressible fluid is always less than unity. It can be interpreted physically as the flow due to the Joules dissipation is super imposed on the main flow. Hence we can assume

$$\begin{aligned} &u(y) = u_0(y) + E u_1(y) + 0\left(E^2\right) \\ &\theta(y) = \theta_0(y) + E\,\theta_1(y) + 0\left(E^2\right) \\ &C(y) = C_0(y) + E\,C_1(y) + 0\left(E^2\right) \end{aligned} \qquad (14)$$

Using equation (14) in equations (10) – (12) and equating the coefficient of like powers of E, we have

$$u_0'' + u_0' - M^2 u_0 = -Gr\,\theta_0 - Gm C_0 \qquad (15)$$

$$\theta_0'' + \Pr \; \theta_0' - F \Pr \theta_0 = 0 \qquad (16)$$

$$C_0'' + Sc\, C_0' - Kr C_0 = 0 \qquad (17)$$

$$u_1'' + u_1' - M^2 u_1 = -Gr\,\theta_1 - Gm C_1 \qquad (18)$$

$$\theta_1'' + \Pr \theta_{01}' - F \Pr \theta_1 + \Pr u_0'^2 + \Pr M^2 u_0^2 u_{01}'^2 \qquad (19)$$

$$C_1'' + Sc\, C_1' - Kr C_1 = 0 \qquad (20)$$

and the corresponding boundary conditions are

$$\left.\begin{aligned} &u_0 = 0, \quad \theta_0 = 1, \; C_0 = 1 \\ &u_1 = 0, \quad \theta_1 = 0, \; C_1 = 0 \end{aligned}\right\} \quad y = 0$$

$$\left.\begin{aligned} &u_0 \to 0, C_0 \to 0, \; \theta_0 \to 0 \\ &u_1 \to 0, \; \theta_1 \to 0, C_1 \to 0 \end{aligned}\right\} \quad y \to \infty \qquad (21)$$

Solving equations (15) to (20) with the help of (21), we get

$$u_0 = A_1 e^{m_2 y} + A_2 e^{m_1 y} + A_3 e^{m_3 y}$$

$$\theta_0 = e^{m_2 y}; C_0 = e^{m_1 y}$$

$$\begin{aligned} u_1 = {} & A_{17} e^{m_3 y} + A_5 e^{2m_3 y} + A_1 e^{m_2 y} + A_6 e^{2m_2 y} \\ & + A_7 e^{2m_1 y} + A_8 e^{(m_2+m_3)y} + A_9 e^{(m_1+m_2)y} \\ & + A_{10} e^{(m_1+m_3)y} + A_{12} e^{2m_2 y} + A_{13} e^{2m_1 y} \\ & + A_{14} e^{(m_2+m_3)y} + A_{15} e^{(m_1+m_2)y} + A_{16} e^{(m_1+m_3)y} \end{aligned}$$

$$\theta_1 = B_{13}e^{m_2 y} + B_1 e^{2m_3 y} + B_2 e^{2m_2 y} + B_3 e^{2m_1 y} + B_4 e^{(m_2+m_3)y} + B_5 e^{(m_1+m_2)y} + B_6 e^{(m_1+m_3)y} + B_7 e^{2m_3 y} + B_8 e^{2m_2 y} + B_9 e^{2m_1 y} + B_{10} e^{(m_2+m_3)y} + B_{11} e^{(m_1+m_2)y} + B_{12} e^{(m_1+m_3)y}$$

$$C_1 = 0$$

$$u = A_1 e^{m_2 y} + A_2 e^{m_1 y} + A_3 e^{m_3 y} + E\{A_{17} e^{m_3 y} + A_5 e^{2m_3 y} + A_6 e^{2m_2 y} + A_7 e^{2m_1 y} + A_8 e^{(m_2+m_3)y} + A_9 e^{(m_1+m_2)y} + A_{10} e^{(m_1+m_3)y} + A_{11} e^{2m_3 y} + A_{12} e^{2m_2 y} + A_{13} e^{2m_1 y} + A_{14} e^{(m_2+m_3)y} + A_{15} e^{(m_1+m_2)y} + A_{16} e^{(m_1+m_3)y}\}$$

$$\theta = e^{m_2 y} + E\{B_{13} e^{m_2 y} + B_1 e^{2m_3 y} + B_2 e^{2m_2 y} + B_3 e^{2m_1 y} + B_4 e^{(m_2+m_3)y} + B_5 e^{(m_1+m_2)y} + B_6 e^{(m_1+m_3)y} + B_7 e^{2m_3 y} + B_8 e^{2m_2 y} + B_9 e^{2m_1 y} + B_{10} e^{(m_2+m_3)y} + B_{11} e^{(m_1+m_2)y} + B_{12} e^{(m_1+m_3)y}\}$$

$$C = e^{m_1 y}$$

Skin – friction:

The skin-friction coefficient at the plate is given by

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = m_2 A_1 e + m_1 A_2 + m_3 A_3 + E\{m_3 A_{17} + 2m_3 A_5 + m_2 A_1 + 2m_2 A_6 + 2m_1 A_7 + (m_2+m_3) A_8 + (m_1+m_2) A_9 + (m_1+m_3) A_{10} + 2m_3 A_{11} + 2m_2 A_{12} + 2m_1 A_{13} + (m_2+m_3) A_{14} + (m_1+m_2) A_{15} + (m_1+m_3) A_{16}\}$$

Heat Transfer:

The rate of heat transfer in terms of Nusselt number at the plate is given by

$$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = m_2 + E\{m_2 B_{13} + 2m_3 B_1 + 2m_2 B_2 + 2m_1 B_3 + (m_2+m_3) B_4 + (m_1+m_2) B_5 + (m_1+m_3) B_6 + 2m_3 B_7 + 2m_2 B_8 + 2m_1 B_9 + (m_2+m_3) B_{10} + (m_1+m_2) B_{11} + (m_1+m_3) B_{12}\}$$

IV. RESULTS AND DISCUSSION

A study of velocity field, temperature field, heat transfer, mass transfer and skin friction of the MHD mixed convection flow of a viscous incompressible electrically conducting fluid over an infinite vertical porous plate in the presence of magnetic field with Ohmic heat has been carried out in the preceding sections, taking radiation effect and chemical reaction into account. We have computed the numerical values of velocity, temperature, skin friction, heat and mass transfer for two cases viz. (i) for cooling of the plate $(Gr > 0)$ and (ii) for heating of the plate $(Gr < 0)$. The values of Prandtl number (Pr) are taken 0.71 which represent air. The value of Eckert number (E) is taken 0.01 for the cooling of the plate and $E = -0.01$ is taken for the heating of the plate respectively. The obtained results are illustrated in Figures (1) to (14).

Case (1): $Gr > 0$ (i.e. cooling of the plate):

Velocity profiles:

Figure (1) depicts velocity profiles (u) versus y for the various values of Prandtl number $\Pr$ as $Kr = 1.0$ $Sc = 0.65,$ $Gr = 5.0,$ $M = 5.0,$ $E = 0.01,$ $F = 3.0$. It is observed that an increasing Pr the velocity decreases. Effect of radiation parameter F for fixed values $Kr = 1.0,$ $Sc = 0.65,$ $Pr = 0.71$ $M = 5.0,$ $E = 0.01,$ $Gr = 5.0$ is presented in figure (2) from which it is clear that increases F lead to the decrease the boundary layer thickness and to enhance the heat transfer rate in the presence of thermal and solutal buoyancy force. Figure (3) shows the influence of the thermal buoyancy force parameter Gr. As seen from this figure that maximum peak value attains for $Gr = 4.0$ and minimum peak value is observed in the absence of buoyancy force. This is due to the fact that buoyancy forces enhance fluid velocity and increase the boundary layer thickness with increase in the value of Gr. Figure (4) shows the variation of u (the component of velocity in the direction of motion of the plate) with y for different values of the chemical reaction parameter Kr. It can be seen that the axial velocity at any given instant and at a given height from the plate decreases with an increase in Kr. The velocity profiles are shown in Figure (5) for air $\Pr = 0.71$. It is observed that the velocity decreases with increasing M. To illustrate the effects of Schmidt number Sc on velocity distribution near the plate is presented in Figure (6). The velocity gradient for air Pr (0.71) is always greater than the water Pr (7.0). Physically, this is true because the increase in the Schmidt number is due to increase in the viscosity of the fluid which makes the fluid thick and hence causes a decrease in the velocity of the fluid. An increase in Sc leads to a fall in the velocity.

Temperature profiles:

Figure (7) temperature decreases with the increasing value of the Prandtl number Pr. Prandtl number is very important for temperature profiles. It is clear that increasing Pr increases θ and the thickness of the thermal boundary layer. An increase Pr leads to a fall in the temperature. This emphasizes the influence of the injected flow in the cooling process. Figure (8) shows the effect of M on temperature distribution. Temperature decreases as M increases. From figure (9) we observed that an increasing Kr the temperature profiles decreases.

Spices Concentration profiles:

Concentration profiles for different values of Kr shown in Figure (10). The species concentration decreases as Kr increases. In turn, this causes the concentration buoyancy effects to decrease as Kr increases. Consequently, less flow is induced along the cylinder resulting in decreases in the fluid velocity in the boundary layer. Schmidt number very important in concentration. From figure (11), we conclude that the concentration decreases as Sc increases. As expected concentration is lower for system with larger values of Sc. These behaviours are clearly depicted in figures (10) – (11).

Case (2): $Gr < 0$ (i.e. Ohmic heating of the plate):

Velocity profiles:

Figure (12) illustrates the velocity profiles for the same set of governing parameters as that applied in Figure (12). At a particular value of F, the velocity and the thermal boundary layer thickness increase by increasing the angle of inclination, with an accompanying decrease in the wall velocity gradient. This is because of the reduction in the buoyancy force as the plate is inclined from the vertical to a large angular position. Figure (13) shows the velocity profiles (u) versus y for the various values of chemical reaction parameter Kr for fixed values of $\Pr = 0.71$ $Sc = 0.65$, $Gr = -5.0$, $M = 5.0$, $E = -0.01$, $F = 3.0$. It is observed that an increasing Kr the velocity also increases. For a specific angle of inclination, it is seen from Figure (14) that the Ohmic heating effect due to the electromagnetic work is found to produce an increase in the fluid velocity, accompanied by a decrease in the velocity gradient at the wall. This behavior implies that the applied that the velocity profiles increases as $\Pr$ increases.

Table shows that the effect for different values of Prandtl number on the skin-friction and Nusselt number of the fluid under consideration. As the Prandtl number increases the both behaviors ski-friction and Nusselt number is found to be increasing.

APPENDIX

$$m_1 = -\left(\frac{Sc + \sqrt{Sc^2 + 4KrSc}}{2}\right)$$

$$m_2 = -\left(\frac{\Pr + \sqrt{\Pr^2 + 4F\Pr}}{2}\right)$$

$$m_3 = -\left(\frac{1 + \sqrt{1 + 4M^2}}{2}\right) \quad A_1 = -\frac{Gr}{m_2^2 + m_2 - M^2}$$

$$A_2 = -\frac{Gr}{m_1^2 + m_1 - M^2},\ A_3 = -(A_1 + A_2)$$

The other constants are not given here to save space.

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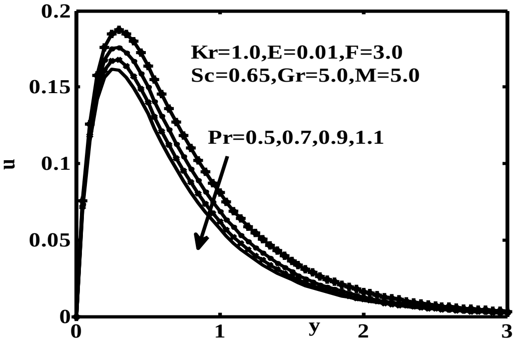

Fig 1. Effect of Pr on velocity

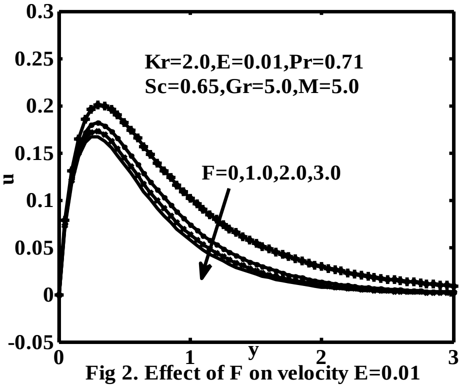

Fig 2. Effect of F on velocity E=0.01

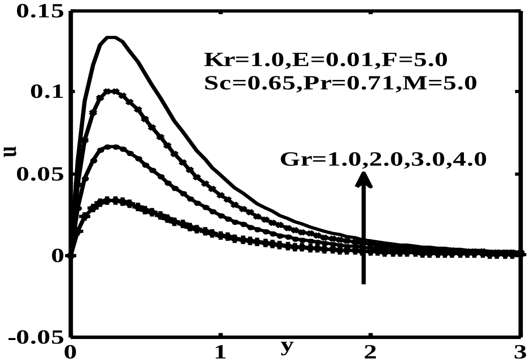

Fig 3. Effect of Gr on velocity, E=0.01

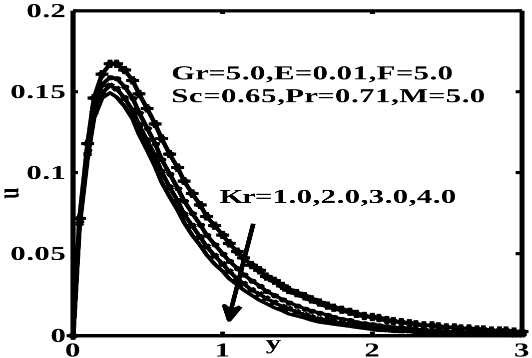

Fig 4. Effect of Kr on velocity, E=0.01

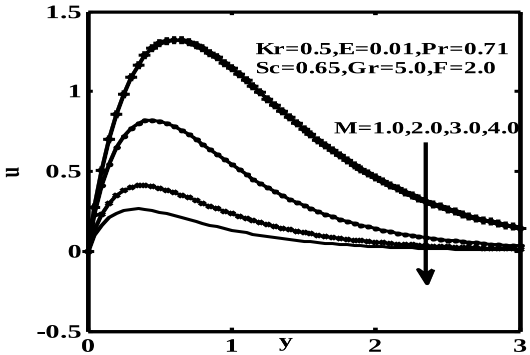

Fig 5.Effect of M on velocity E=0.01

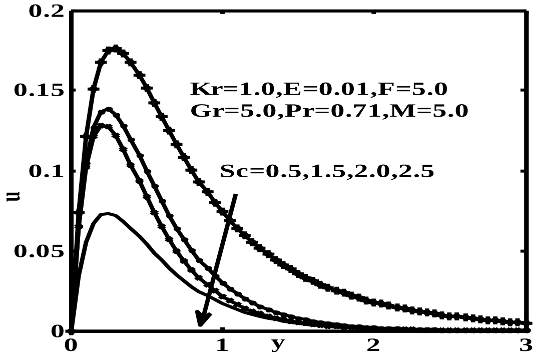

Fig 6. Effect of Sc on velocity, E=0.01

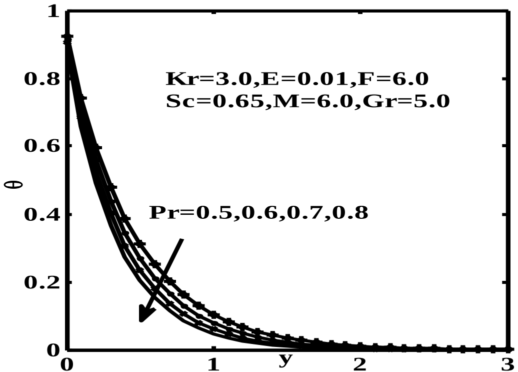

Fig 7. Effect of Pr on temperature, E=0.01

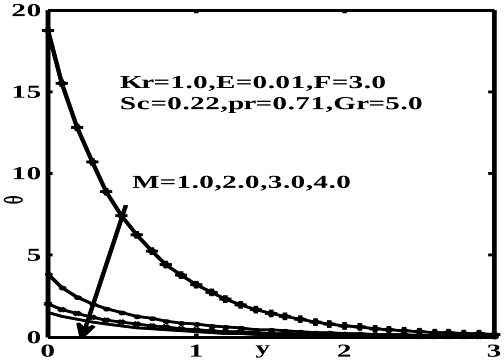

Fig 8. Effect of M on temperature, E=0.01

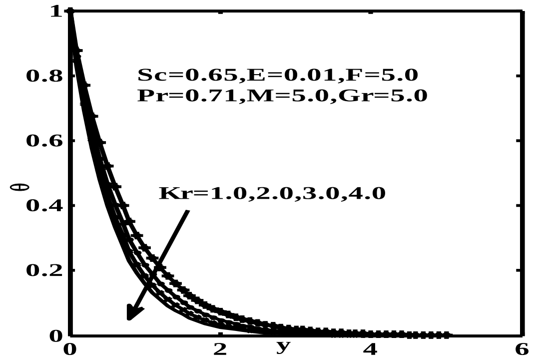

Fig 9. Effect of Kr on temperature, E=0.01

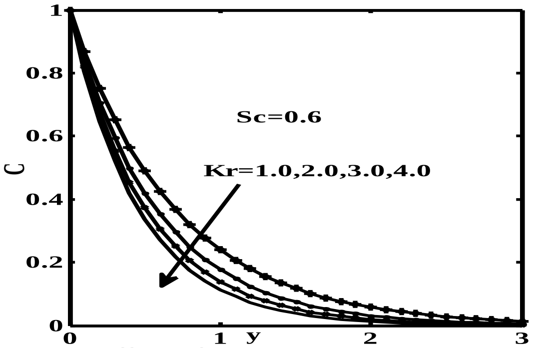

Fig 10.Effect of Kr on species concentration

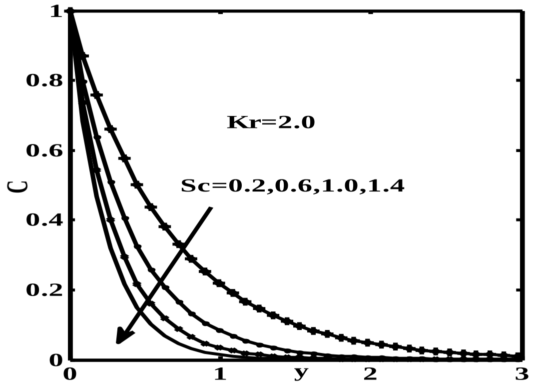

Fig 11.Effect of Sc on species concentration

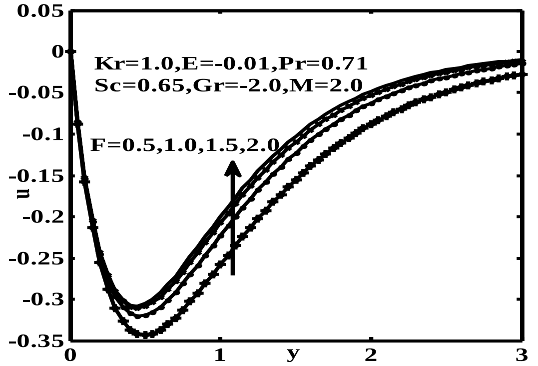

Fig 12. Effect of F on ohmic heating plate G= - 5.0

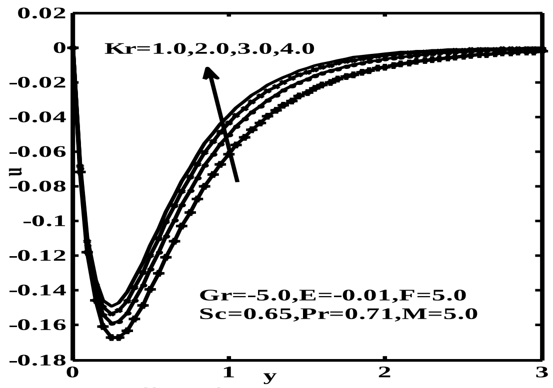

Fig 13. Effect of Kr on velocity, G = - 5.0

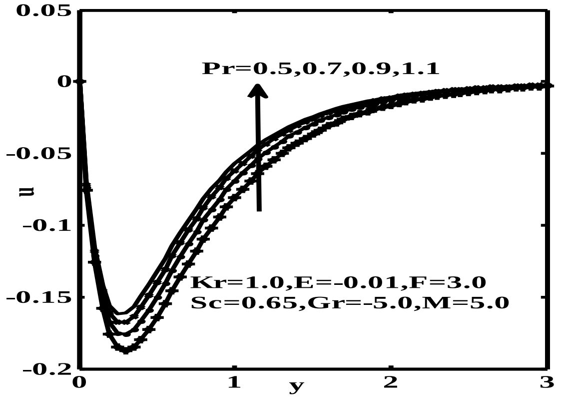

Fig 14. Effect of Pr on velocity G = -5.0

Table: Skin friction and Nusselt number for Pr

Pr	τ	Nu
0.025	4.195	0.026
0.050	4.394	0.034
0.075	4.567	0.057
0.100	4.705	0.150

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