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Unsteady MHD free Convective Heat and Mass transfer flow Past an Infinite Vertical Porous Plate

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Abstract

Hall current and Chemical reaction in the existence of heat-source / absorption have been examined on unstable MHD open convective heat and mass transfer flow via an infinite vertical porous plate. The governing equations are transferred to a system of differential non-dimensional equations and then analytically solved by perturbation techniques. The dimensionless velocity, temperature and concentration profiles show the impacts on fluid properties for different flow limits in the flow domain. Tables measure the impact of different flow limits on the friction in skin the quantity of Nusselt and the quantity of Sherwood.

Keywords; *Heat Transfer, Mass Transfer, Porous Medium, Hall Impacts, Chemical Reaction.*

I. INTRODUCTION

In recent years, fluid flows through porous media have been of major importance as it is predominant in character. Due to its use in many fields of science and technology (e.g. agricultural) to explore the subsurface water supplies and water depletion in the river beds, oil technologies to research movement from natural gas, oil and water from petroleum reservoirs, chemical engineering for filtration and purifying, these flows have attracted the attention of a quantity of scholars. Free convection occurs with fluid when changes in temperature lead to a fluid density fluid impact. The freestanding example is the air flow driven by temperature differences. In some cases the flow is affected by concentration or material differences constitution. By temperature differences the free convection currents caused. This kind of flow is used in many fields of science and engineering. In view of its use in MHD generators, plasma experiments, nuclear reactors, geothermal energy extractions and boundary layer regulation in aerodynamics, the study of these flows under the influence of magnetic field has been of interest to many scientists. In the presence of free convection and radiation, instable fluid flow past a moveable plate was examined by [1,5,6,8-10]. All those studies were confined in a nonporous medium to instable flow. We observe in the previous literature survey that small papers were made in porous medium about unstable fluid flows.

Magnetic fields have an important influence on the viscous incompressible flow of electrically driving fluid in numerous applications, such as the plastics extrusion in the production of radius and nylon, crude oil purification, the paper industry, the textile industry, etc. For example, gas may be ionized in

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engineering in MHD pumps, MHD bearings and thus become an electric driver at high temperatures reached in certain engineering devices. But the electric conductor is affected by the magnetic field in the presence of a strong electrical field. Therefore, the conductivity is reduced parallel to the electric field. This reduces the current to both the electric and magnetic fields in the normal direction. It's called the Hall Impact. Das et al.[7] has studied how Mass Transfer impacts a stream past a vertical board with a constant flow of heat and chemical reaction. An analysis of the Unsteady MHD natural convection flow along with an accelerated porous plate including hall current and mass transfer in a rotating porous medium was carried out by Abdus Sattar and Abdul Malesque[2]. The results on the Mgneto-hydrodynamic free convector flow through an infinite vertical platform with mass transfer of Hall current studied by Aboeldahab and Elbarbary[3]. The impacts of chemical reactors on heat and mass transfer of unsteady flux on an infinite porous, vertical plate embedded into a heat-source porous medium are addressed deeply by Balamurugan et al[4].

In view of all such studies, the current study is to examine the impact of hall current and chemical reaction in the presence of the heat source / absorption on unstable MHD free convective heat, mass transfer and an infinite vertical porous surface. The problem is governed by the system of coupled, nonlinear partial differential equations, which have difficulty in exact solutions. Therefore we use perturbation techniques to find the solution which is more computationally economical. For changes in the governing limits the behavior of velocation, temperature, concentration, shear stress, Nusselt quantity and sherwood quantity have been addressed.

II. FORMULATION OF THE PROBLEM

In this issue, the flow of a viscous incompressible fluid in an uncontrolled natural mass transfer and convection fluid through an unending porous plate which is vertical packed with in a porous medium and heat source. The x'axis is taken upward vertically along with the plate and the y'axis is selected as usual. The control equations of the Flow area are written as follows, neglecting the Joulean heat dissipation and using Boussinesq approach as:

Continuity Equation

$$\frac{\partial v'}{\partial y'} = 0;\ v' = -v'_0 \quad \text{(constant)} \qquad (1)$$

MOMENTUM EQUATION:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_\infty)cos\alpha + g\beta^*(C'_w - C'_\infty)cos\alpha - \frac{\sigma B_0^2}{\rho(1+m^2)}u' - \frac{\nu}{k'}u' \qquad (2)$$

ENERGY EQUATIN:

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = k\frac{\partial^2 T'}{\partial y'^2} + \frac{\nu}{c_\rho}\left(\frac{\partial u'}{\partial y'}\right)^2 + \quad s'(T' - T'_\infty) + Q'(C' - C'_\infty) \qquad (3)$$

CONCENTRATION EQUATION:

$$\frac{\partial c'}{\partial t'} + v'\frac{\partial c'}{\partial y'} = D\frac{\partial^2 c'}{\partial y'^2} - Kr'(C' - C'_\infty) \qquad (4)$$

BOUNDARY CONDITIONS ARE:

$$\begin{aligned} &u' = 0,\ v' = -v'_0,\ T' = T'_w + \varepsilon(T'_w - T'_\infty)e^{i\omega' t'}, \\ &C' = C'_w + \varepsilon(C'_w - C'_\infty)e^{i\omega' t'}\ at\ y' = 0 \qquad (5) \\ &u' \to 0,\ T' \to T'_\infty,\ C' \to C'_\infty\ as\ y' \to \infty \end{aligned}$$

Now, introducing the following non-dimensional variables and limits

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$$y=\frac{y'u'_0}{v},\quad t=\frac{t'v_0'^2}{4v},\quad \omega=\frac{4v\omega'}{v_0'^2},$$
$$u=\frac{u'}{v_0'^2},\quad v=\frac{\eta_0}{\rho},\ K_p=\frac{v_0'^2K'}{v^2},$$
$$T=\frac{T'-T'_\infty}{T'_w-T'_\infty},\ C=\frac{C'-C'_\infty}{C'_w-C'_\infty},\ P_r=\frac{v}{k},$$
$$Gr=\frac{vg\beta(T'_w-T'_\infty)}{v_0'^3},\quad Gc=\frac{vg\beta(C'_w-C'_\infty)}{v_0'^3},$$
$$Sc=\frac{v}{D},\ S=\frac{4s'v}{v_0'^2},\quad Ec=\frac{v_0'^2}{c_p(T'_w-T'_\infty)},$$
$$Kr=\frac{Kr'v}{v_0'^2},\quad M_1=(\frac{M}{1+m^2}+\frac{1}{k_p}),$$
$$M=\frac{\sigma\beta_0^2v}{\rho v_0^2},\ Q=\frac{v^2Q'(C'_w-C'_\infty)}{uv_0^2(T'_w-T'_\infty)}\qquad(6)$$

Where □,g, v, β, β*, □, □0, k, T’, T’w, T’□, C’, C’w, C’□, cp, D, Pr, Sc, Gr, Gc, S, Q, Kp, Ec and Kr are weight , acceleration due to gravity, kinematic VC co-efficient, volumetric thermal density expantion co-efficient, volumetric mass transfer expansion coefficient, angular frequency, Viscosity coefficient, thermal diffusivity coefficient, temperature, surface temperature, infinity temperature, concentration at plate, infinity concentration, basic acceleration.

We get the following equations if we apply equation(6) in equations from (2) to (4) and under the boundary condition in equation (5)

$$\frac{1}{4}\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=\frac{\partial^2u}{\partial y^2}+\cos\alpha\,G_rT+\cos\alpha\,G_CC-M_1u\qquad(7)$$

$$\frac{1}{4}\frac{\partial T}{\partial t}-\frac{\partial T}{\partial y}=\frac{1}{\Pr}\frac{\partial^2T}{\partial y^2}+\frac{1}{4}ST+QC+EC\left(\frac{\partial u}{\partial y}\right)^2\qquad(8)$$

$$\frac{1}{4}\frac{\partial c}{\partial t}-\frac{\partial c}{\partial y}=\frac{1}{Sc}\frac{\partial^2c}{\partial y^2}-KrC\qquad(9)$$

The conditions of corresponding boundaries are:

$$\begin{aligned}&u=0,\ T=1+\varepsilon e^{i\omega't'},\ C=1+\varepsilon e^{i\omega't'}\ at\ y'=0\\&u\to0,\ T\to0,\ \ C\to0\ as\ y\to\infty\end{aligned}\qquad(10)$$

III. METHOD OF SOLUTION

In order to calculate eq (7) to (9), we consider □ which is to be small and the velocity, temperature and disbursement concentration of the flow field into near of the plate

$$u(y,t)=u_0(y)+\varepsilon e^{i\omega't'}u_1(y)\qquad(11)$$

$$T(y,t)=T_0(y)+\varepsilon e^{i\omega't'}T_1(y)\qquad(12)$$

$$C(y,t)=C_0(y)+\varepsilon e^{i\omega't'}C_1(y)\qquad(13)$$

Apply equations (11) to (13) in equations (7) to (9) accordingly, equating non-harmonic and harmonic terms and avoiding the co-efficient of □2 then we get

$$u_0''+u_1'-M_1u_0=-\cos\alpha\,G_rT_0-\cos\alpha\,G_CC_0\quad(14)$$

$$T_0''+\Pr T_0'+\frac{\Pr s}{4}T_0=-\Pr QC_0-\Pr Ec\left(u'_0\right)^2\qquad(15)$$

$$C_0''+ScC_0'-Kr\,ScC_0=0\qquad(16)$$

First order:

$$u_0''+u_1'-K_1u_1=-\cos\alpha\,G_rT_1-\cos\alpha\,G_CC_1\qquad(17)$$

$$T_1''+\Pr T_1'-\frac{\Pr}{4}K_2T_1=-\Pr Ecu'_0u'_1-QC_1\qquad(18)$$

$$C_1''+ScC_1'-ScK_3\ C_1=0\qquad(19)$$

$$Where\ K_1=\left(\frac{iw}{4}+M_1\right),\ K_2=(iw-S),\ K_3=\left(\frac{iw}{4}+K_r\right)$$

The corresponding boundary conditions are

$$\begin{aligned}&y=0,\ u_0=0,\ T_0=1,\ u_1=0,\ T_1=1,\ C_1=1\\&y\to\infty,\ u_0=0,\ T_0=0,\ C_0=0,\ u_1=0,\ T_1=0,\ C_1=0\end{aligned}\qquad(20)$$

Solving equations (16) and (19) under the boundary condition (20), then we get

$$C_0=e^{-m_1y}\qquad(21)$$

$$C_1=e^{-m_2y}\qquad(22)$$

Using Multi limit perturbation technique and assuming Ec << 1, we take

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$$u_0(y) = u_{00}(y) + Ec\, u_{01}(y) \qquad (23)$$

$$T(y)_0 = T_{00}(y) + Ec\, T_{01}(y) \qquad (24)$$

$$u_1(y) = u_{10}(y) + Ec\, u_{11}(y) \qquad (25)$$

$$T_1(y) = T_{10}(y) + Ec\, T_{11}(y) \qquad (26)$$

We can get the following differential equations if we apply equations (23) to (26) in equations (14),(15),(17) & (18) and equating the co-efficients of like powers of Ec ,neglecting 〖Ec〗^2

Zeroth order:

$$u_{00}'' + u_{00}' - M_1 u_{00} = -\cos\alpha\, G_r T_{00} - \cos\alpha\, G_C C_0 \qquad (27)$$
$$u_{10}'' + u_{10}' - K_1 u_{10} = -\cos\alpha\, G_r T_{10} - \cos\alpha\, G_C C_1 \qquad (28)$$
$$T_{00}'' + \Pr T_{00}' + \frac{\Pr s}{4} T_{00} = -\Pr Q\, C_0 \qquad (29)$$
$$T_{10}'' + \Pr T_{10}' - \frac{\Pr}{4} K_2 T_{10} = -\Pr Q\, C_1 \qquad (30)$$

The conditions corresponding to the boundaries are

$$\begin{aligned} &y = 0,\ u_{00} = 0,\ T_{00} = 1,\ U_{10} = 0,\ T_{10} = 1 \\ &y \to \infty,\ u_{00} = 0,\ T_{00} = 0,\ U_{10} = 0,\ T_{10} = 0 \end{aligned} \qquad (31)$$

First Order:

$$u_{01}'' + u_{01}' - M_1 u_{01} = -cos\alpha G_r T_{01} \qquad (32)$$
$$u_{11}'' + u_{11}' - K_1 u_{11} = -\cos\alpha\, G_r T_{11} \qquad (33)$$
$$T_{01}'' + \Pr T_{01}' + \frac{\Pr s}{4} T_{01} = -\Pr (u_{00}')^2 \qquad (34)$$
$$T_{11}'' + \Pr T_{11}' - \frac{\Pr}{4} K_2 T_{11} = -2\Pr u_{00}'\, u_{10}' \qquad (35)$$

The conditions corresponding to the boundaries are,

$$\begin{aligned} &y = 0, u_{01} = 0, T_{01} = 1, U_{11} = 0, T_{11} = 0 \\ &y \to \infty, u_{01} = 0, T_{01} = 0, U_{11} = 0, T_{11} = 0 \end{aligned} \qquad (36)$$

Solving equations (27) to (30) subject to the boundary conditions (31) we get

$$u_{00} = A_5 e^{-m_4 y} + A_4 e^{-m_3 y} + A_3 e^{-m_1 y} \qquad (37)$$

$$T_{00} = A_2 e^{-m_3 y} + A_1 e^{-m_1 y} \qquad (38)$$

$$u_{10} = A_{10} e^{-m_6 y} + A_9 e^{-m_5 y} + A_8 e^{-m_2 y} \qquad (39)$$

$$T_{10} = A_7 e^{-m_5 y} + A_6 e^{-m_2 y} \qquad (40)$$

Solving equations from (32) to (35) subject to boundary conditions (36), we get

$$T_{.01} = A_{17} e^{-m_7 y} + A_{16} e^{-m_{10} y} + A_{15} e^{-m_9 y} + A_{14} e^{-m_8 y} + A_{13} e^{-2m_4 y} + A_{12} e^{-2m_3 y} + A_{11} e^{-2m_1 y} \qquad (41)$$

$$\begin{aligned} T_{.11} = {} & A_{27} e^{-m_{11} y} + A_{26} e^{-m_{20} y} + A_{25} e^{-m_{19}} + A_{24} e^{-m_{18} y} + A_{23} e^{-m_{17} y} + A_{22} e^{-m_{16} y} + A_{21} e^{-m_{15} y} \\ & + A_{20} e^{-m_{14} y} + A_{19} e^{-m_{13} y} + A_{18} e^{-m_{12} y} \end{aligned} \qquad (42)$$

$$\begin{aligned} u_{.01} = {} & A_{35} e^{-m_{21} y} + A_{34} e^{-m_7 y} + A_{33} e^{-m_{10} y} + A_{32} e^{-m_9 y} + A_{31} e^{-m_8 y} + A_{30} e^{-2m_4 y} \\ & + A_{29} e^{-2m_3 y} + A_{28} e^{-2m_1 y} \end{aligned} \qquad (43)$$

$$\begin{aligned} u_{11} = {} & A_{46} e^{-m_{22} y} + A_{45} e^{-m_{11} y} + A_{44} e^{-m_{20} y} + A_{43}{}^{-m_{19} y} + A_{42} e^{-m_{18} y} \\ & + A_{41} e^{-m_{17} y} + A_{40} e^{-m_{16} y} + A_{39} e^{-m_{15} y} + A_{38} e^{-m_{14} y} \\ & + A_{37} e^{-m_{13} y} + A_{36} e^{-m_{12} y} \end{aligned} \qquad (44)$$

Substituting the values of C0 and C1 from equations (21) and (22) in equation (13) the solution for concentration distribution of the flow field is given by

$$C = e^{-m_1 y} + \in e^{i\omega t} (e^{-m_2 y}) \qquad (45)$$

3.1 Skin friction: The shear stress at wall given by

$$\left(\frac{\partial u}{\partial y}\right)_{y=0} = [u_{00}^1 + Ec\, u_{01}^1]_{y=0} + \in e^{i\omega t} [u_{10}^1 + Ec\, u_{11}^1]_{y=0} \qquad (46)$$

3.2 Heat flux: The heat flux at the wall is given by

$$\left(\frac{\partial T}{\partial y}\right)_{y=0} = [T_{00}^1 + Ec\, T_{01}^1]_{y=0} + \in e^{i\omega t} [T_{10}^1 + Ec\, T_{11}^1]_{y=0} \qquad (47)$$

3.3 Mass flux: The rate of Mass transfer i.e., mass flux at the wall in terms of Sherwood quantity Sh is given by

$$\left(\frac{\partial c}{\partial y}\right)_{y=0} = [c_0^1 + \in e^{i\omega t} c_1^1]_{y=0} = -(m_1 + \in e^{i\omega t} m_2) \qquad (48)$$

IV. RESULTS AND DISCUSSIONS

Transfer to an infinite vertical porous plate in porous medium with hall heat source was studied on instable flow from a viscous incompressible fluid past an infinite vertical porous plate. The results of fluid flow limits were carefully analyzed and described in a diagram which is easy to understand. Figures (1-8) display the velocity profile for the different Grashof heat transfer values: Gc, Grashof mass transfer value Gc, Prandtl quantity Pr, Magnetic limit M, Schmidt quantity Sc, Hall current

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limit m, Eckert quantity Ec, permeability limit Kp, chemistry response limit Kr, Heat origin limit S. Grashof's active heat transfer quantity Gr and Grashof for mass Gc transfer at speed distribution is shown in figures (1 & 2). We note that the speed rises with the increasing values of Grashof for thermal transmission Gr and Grashof for mass transmission Gc. This is because of the liquid particles' buoyancy due to gravitational forces that improve the fluid rate. Figure.3 shows the velocity distribution impact of Magnetic Limit M. With enhancing values of magnetic limit M, it is observed that the speed reduces. As it is well understood that the process passes the commonly used magnetic field to the flow leads to a stream resistive force called the Lorentz force which works in the other direction of the flow. This pressure causes the flow of the liquid to slow down. Figures (4, 5 & 6) show the impacts on velocity distributions of hall current limit m, heat source limit Q and Eckert quantity Ec. It can be seen that the speed improves with the hall current limit m, heat source limit Q and Eckert quantity Ec increasing. Figure.7 shows the velocity distribution impact of Kr chemical reaction limit. The rate reduces when the values of the chemical reaction limit Kr improved. The heat source limit S impact on the velocity distribution is shown in Figure.8. It is observed that the speed improves when heat source limit S values are improved.

The figures (9-15) show that temperature profiles for different heat transfer Gr, Gc, Eckert quantity Ec, time t, Prandtl quantity Pr, heat source limit S for thermal heat transfer quantity Gr. Figures (9, 11, 12, 13 & 14) show heat transfer quantitys Grashof, mass transfer quantity Gc Grashof, heat source limit Q, heat S and Eckert temperature distribution limit quantity Ec. The temperature rises with the increasing Grashof quantity’s for heat transfer Gr, Grashof quantitys for mass transfer Gc, and heat source limit Q, heat source limit S and Eckert quantitys Ec. The influence of Prandtl on temperature distribution is shown in Figure.10. The reduce in temperature is observed when prandtl quantitys improved. That is happened because the reduced rate implies the temperature of the ground is not conversed easily. The time t impact on the temperature distribution is shown in figure.15. For increasing time values t, temperature reduces.

In figures (16-18), the Schmidt quantitys (Sc) and the limits of chemical reaction Kr have different concentration profiles. Figures 16 and 18 show the quantity of Schmidt Sc and the impact on concentration distribution. The concentration improves with the increasing quantitys Sc and of Schmidt. Figure.17 shows the impact on concentration distribution of the chemical reaction limit Kr. The concentration reduces with improved values of chemical reaction limit Kr.

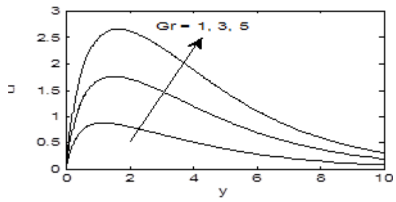

Fig. 1: Velocity Profile for Gr

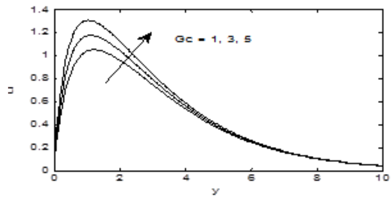

Fig. 2: Velocity Profile for Gc

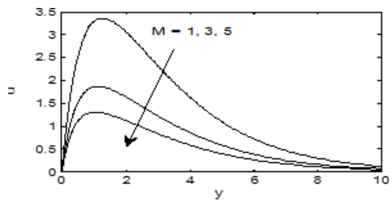

Fig. 3: Velocity Profile for M

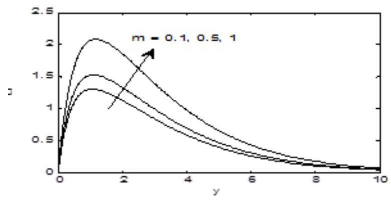

Fig. 4: Velocity Profile for m

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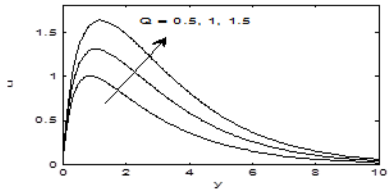

Fig. 5: Velocity Profile for Q

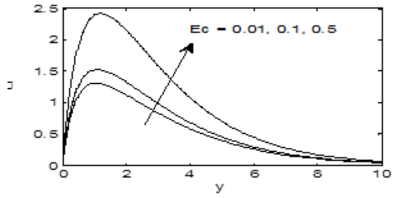

Fig. 6: Velocity Profile for Ec

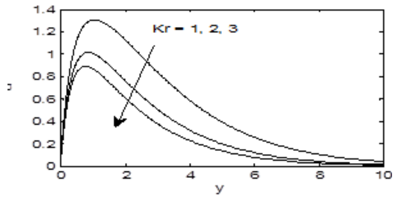

Fig. 7: Velocity Profile for Kr

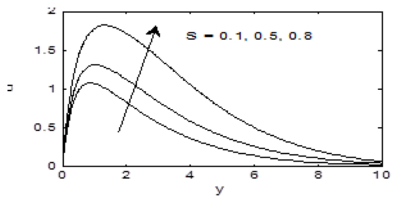

Fig. 8: Velocity Profile for S

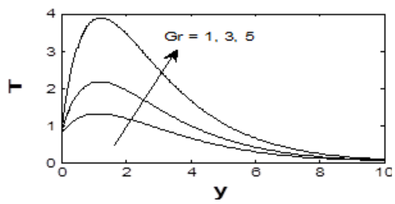

Fig. 9: Temperature Profile for Gr

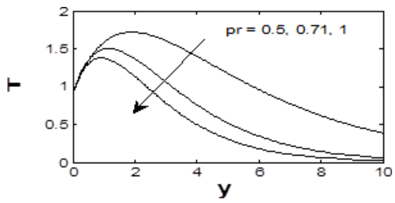

Fig. 10: Temperature Profile for Pr

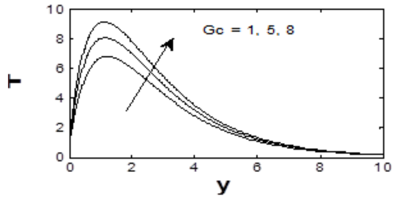

Fig. 11: Temperature Profile for Gc

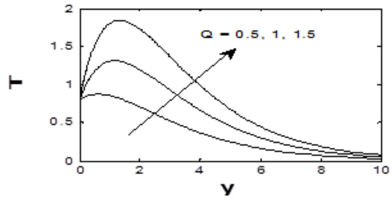

Fig. 12: Temperature Profile for Q

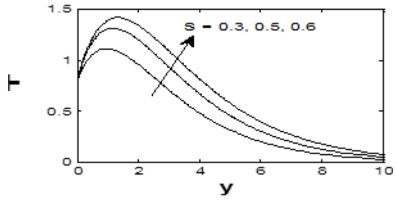

Fig. 13: Temperature Profile for S

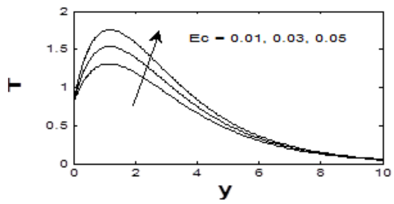

Fig. 14: Temperature Profile for Ec

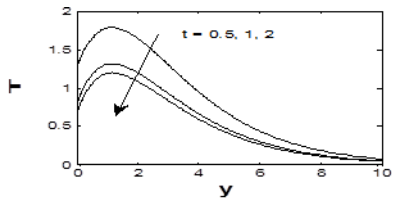

Fig. 15: Temperature Profile for t

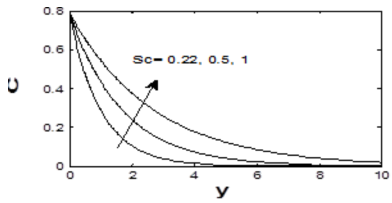

Fig. 16: Concentration Profile for Sc

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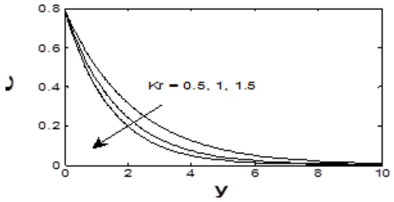

Fig. 17: Concentration Profile for Kr

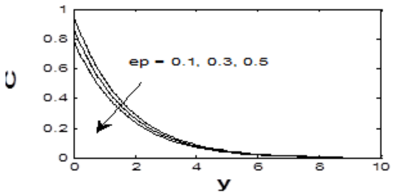

Fig. 18: Concentration Profile for ep

V. CONCLUSIONS

In this paper impacts of the limits are clearly shown in the flow fluid. The velocity, temperature and concentration profiles with different limit values are shown graphically.

- With an improvement in Prandtl's quantity and time t, the temperature reduces. Nevertheless, the temperature rises as the heat transferred in figure for Grashof, the mass transfer figure Grashof, the heat source limit and the Eckert quantity are improved.
- With an improve in chemical reaction limits, the concentration reduces. But with the rise of the Schmidt quantity and the concentration is automatically increasing.
- Prandtl, Grashof quantity for mass transfer, magnetic limit, Schmidt quantity, heat source limit, chemical reaction limit and inclination angle improve the friction in the body. But with an improvement in Grashof quantitys for heat transfer, heat source limit and Eckert quantitys the skin friction is decreasing.
- The quantity of Grashof, the Grashof quantity for mass transmission, the heat source factor and an Eckert quantity will be improved in Nusselt. Nevertheless, the quantity of Nusselt reduces improve in the quantity of Prandtl, magnetism, Schmidt, chemistry reaction factor, and inclination angle.
- The quantity Sherwood improves the quantity of Schmidt and the limit of chemical reaction. Nevertheless, with changes in time t the Sherwood quantity reduces.

VI. APPENDIX

$M_1 = \frac{M}{1+m^2} + \frac{1}{K}$, $\quad K_1 = \frac{i\omega}{4} + M_1$

$K_2 = (i\omega - S)$, $\quad K_3 = \frac{i\omega}{4} + Kr$

$m_1 = \frac{Sc + \sqrt{Sc^2 + 4Sc\,Kr}}{2}$, $\quad m_2 = \frac{Sc + \sqrt{Sc^2 + 4Sc\,K_3}}{2}$

$m_3 = m_7 = \frac{\Pr + \sqrt{\Pr^2 - \Pr S}}{2}$, $\quad m_4 = \frac{1 + \sqrt{1 + 4m_1}}{2}$

$m_5 = \frac{\Pr + \sqrt{\Pr^2 + \Pr K_2}}{2}$, $\quad m_6 = \frac{1 + \sqrt{1 + 4K_1}}{2}$

$m_7 = m_3 = \frac{\Pr + \sqrt{\Pr^2 - \Pr S}}{2}$, $\quad m_8 = (m_3 + m_4)$

$m_9 = (m_1 + m_3)$, $\quad m_{10} = (m_1 + m_4)$

$m_{11} = m_5 = \frac{\Pr + \sqrt{\Pr^2 + \Pr K_2}}{2}$, $m_{12} = (m_6 + m_4)$

$m_{13} = (m_5 + m_4)$, $\quad m_{14} = (m_2 + m_4)$

$m_{15} = (m_3 + m_6)$ $\quad m_{16} = (m_3 + m_5)$

$m_{17} = (m_3 + m_2)$ $\quad m_{18} = (m_1 + m_6)$

$m_{19} = (m_1 + m_5)$

$m_{20} = (m_1 + m_2)$ $\quad m_{21} = m_4 = \frac{1 + \sqrt{1 + 4m_1}}{2}$

$m_{22} = m_6 = \frac{1 + \sqrt{1 + 4K_1}}{2}$ $\quad A_1 = -\frac{\Pr Q_0}{m_1^2 - \Pr m_1 + \frac{\Pr S}{4}}$

$A_2 = 1 - A_1$, $\quad A_3 = -\frac{(A_1 Gr + Gc)\cos\alpha}{m_1^2 - m_1 - M_1}$

$A_4 = -\frac{A_2 Gr\ \cos\alpha}{m_3^2 - m_3 - M_1}$, $\quad A_6 = -\frac{\Pr Q_0}{m_2^2 - \Pr m_2 + \frac{\Pr K_2}{4}}$

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$A_7 = 1 - A_6$, $A_8 = -\frac{(A_6 Gr + Gc) Cos\alpha}{m_2^2 - m_2 - K_1}$

$A_9 = -\frac{A_7 Gr\ Cos\alpha}{m_5^2 - m_5 - K_1}$, $A_{10} = -(A_8 + A_9)$

$A_{11} = -\frac{\Pr A_3^2\ m_1^2}{4\ m_1^2 - 2\Pr m_1 + \frac{\Pr S}{4}}$, $A_{12} = -\frac{\Pr A_4^2\ m_3^2}{4\ m_3^2 - 2\Pr m_3 + \frac{\Pr S}{4}}$

$A_{13} = -\frac{\Pr A_5^2\ m_4^2}{4\ m_4^2 - 2\Pr m_4 + \frac{\Pr S}{4}}$, $A_{14} = -\frac{2\Pr A_4 A_5\ m_3 m_4}{m_8^2 - \Pr m_8 + \frac{\Pr S}{4}}$

$A_{15} = -\frac{2\Pr A_4 A_3\ m_3 m_1}{m_9^2 - \Pr m_9 + \frac{\Pr S}{4}}$, $A_{16} = -\frac{2\Pr A_3 A_5\ m_1 m_4}{m_{10}^2 - \Pr m_{10} + \frac{\Pr S}{4}}$

$A_{17} = -(A_{16} + A_{15} + A_{14} + A_{13} + A_{12} + A_{11})$

$A_{18} = -\frac{2\Pr A_{10} A_5\ m_6 m_4}{m_{12}^2 - \Pr m_{12} - \frac{\Pr K_2}{4}}$, $A_{19} = -\frac{2\Pr A_9 A_5\ m_9 m_4}{m_{13}^2 - \Pr m_{13} - \frac{\Pr K_2}{4}}$

$A_{20} = -\frac{2\Pr A_8 A_5\ m_2 m_4}{m_{14}^2 - \Pr m_{14} - \frac{\Pr K_2}{4}}$ $A_{21} = -\frac{2\Pr A_4 A_{10}\ m_3 m_6}{m_{15}^2 - \Pr m_{15} - \frac{\Pr K_2}{4}}$

$A_{22} = -\frac{2\Pr A_4 A_9\ m_3 m_5}{m_{16}^2 - \Pr m_{16} - \frac{\Pr K_2}{4}}$ $A_{23} = -\frac{2\Pr A_4 A_8\ m_3 m_2}{m_{17}^2 - \Pr m_{17} - \frac{\Pr K_2}{4}}$

$A_{24} = -\frac{2\Pr A_3 A_{10}\ m_1 m_6}{m_{18}^2 - \Pr m_{18} - \frac{\Pr K_2}{4}}$ $A_{25} = -\frac{2\Pr A_3 A_9\ m_1 m_5}{m_{19}^2 - \Pr m_{19} - \frac{\Pr K_2}{4}}$

$A_{26} = -\frac{2\Pr A_3 A_8\ m_1 m_2}{m_{20}^2 - \Pr m_{20} - \frac{\Pr K_2}{4}}$

$A_{27} = -(A_{26} + A_{25} + A_{24} + A_{23} + A_{22} + A_{21} + A_{20} + A_{19} + A_{18})$

$A_{28} = -\frac{A_{11} Gr\ Cos\alpha}{4\ m_1^2 - 2\ m_1 - M_1}$, $A_{28} = -\frac{A_{11} Gr\ Cos\alpha}{4\ m_1^2 - 2\ m_1 - M_1}$

$A_{29} = -\frac{A_{12} Gr\ Cos\alpha}{4\ m_3^2 - 2\ m_3 - M_1}$, $A_{30} = -\frac{A_{13} Gr\ Cos\alpha}{4\ m_4^2 - 2\ m_4 - M_1}$

$A_{31} = -\frac{A_{14} Gr\ Cos\alpha}{m_8^2 - m_8 - M_1}$, $A_{32} = -\frac{A_{15} Gr\ Cos\alpha}{m_9^2 - m_9 - M_1}$

$A_{33} = -\frac{A_{16} Gr\ Cos\alpha}{m_{10}^2 - m_{10} - M_1}$, $A_{34} = -\frac{A_{17} Gr\ Cos\alpha}{m_7^2 - m_7 - M_1}$

$A_{35} = -(A_{34} + A_{33} + A_{32} + A_{31} + A_{30} + A_{29} + A_{28})$

$A_{36} = -\frac{A_{18} Gr\ Cos\alpha}{m_{12}^2 - m_{12} - K_1}$, $A_{37} = -\frac{A_{19} Gr\ Cos\alpha}{m_{13}^2 - m_{13} - K_1}$

$A_{38} = -\frac{A_{20} Gr\ Cos\alpha}{m_{14}^2 - m_{14} - K_1}$ $A_{39} = -\frac{A_{21} Gr\ Cos\alpha}{m_{15}^2 - m_{15} - K_1}$

$A_{40} = -\frac{A_{22} Gr\ Cos\alpha}{m_{16}^2 - m_{16} - K_1}$, $A_{43} = -\frac{A_{25} Gr\ Cos\alpha}{m_{19}^2 - m_{19} - K_1}$

$A_{41} = -\frac{A_{23} Gr\ Cos\alpha}{m_{17}^2 - m_{17} - K_1}$ $A_{44} = -\frac{A_{26} Gr\ Cos\alpha}{m_{20}^2 - m_{20} - K_1}$

$A_{42} = -\frac{A_{24} Gr\ Cos\alpha}{m_{18}^2 - m_{18} - K_1}$ $A_{45} = -\frac{A_{27} Gr\ Cos\alpha}{m_{11}^2 - m_{11} - K_1}$

$A_{46} = -(A_{45} + A_{44} + A_{43} + A_{42} + A_{41} + A_{40} + A_{39} + A_{38} + A_{37} + A_{36})$

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