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Unsteady MHD Free Convective Heat flow and Mass Transfer Past an Infinite Vertical Porous Plate embedded in Porous Medium in Presence of Hall Current and Heat Source with Chemical Reaction.

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Abstract: An attempt has been made to study Hall effects on unsteady free convective flow and mass transfer over an infinite vertical porous plate which is embedded in porous medium with heat source.The Governing equations are transferred into a system of non-dimensional differential equations, which are then solved analytically by using perturbation techniques.The dimensionless velocity, temperature and concentration profiles are displayed graphically showing the effects in the flow domain for different values of the parameters involved in the problem.It is noted that increase of permeability parameter, Hall Parameter and Grashof Numbers for heat and mass transfer accelerates the velocity of fluid flow, but the reverse process happened if an increase of magnetic number.Further a growing Permeability Parameter enchances the skin friction at the wall.The effect of increasing heat source enchances the Heat Transfer at the wall. The same effect exists in mass transfer while increasing of Schmidt Number.

Keywords: Heat Transfer, Mass Transfer, Porous Medium, Hall Effects, Chemical Reaction.

1.Introduction

The Influence of Magnetic field on viscous incompressible flow of electrically conductor fluid has its important in many application such as extrustion of plastics in manufacture of rayon and nylon, purification of crude oil,paper industry, textile industry,etc.,. In Engineering in MHD pumps, MHD bearing etc., at high temperature attained in some Engineering devices, gas, for example can be ionized and so become an electrical conductor. However, in the presence of strong electric field, the electrical conductive is affected by magnetic field.Consequently, the conductivity parallel to electric field is reduced. Hence, the current is reduced to the direction normal to both electric and magnetic fields.This phenonmenon is known as Hall Effect. Gersten K. and Gross J.F.[1] analysis of flow and heat transfer along a plane wall with periodic suction effectively to obtain the solution. Cheng P and Minkowycz W.J.[2] discuss the nature of free Convection about a Vertical Plate embedded in a porous medium with application to Heat Transfer from a dike.Das U.N., Deka R and Soundalgekar V.M.[3] has analysis the effects of Mass Transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction .MD.Abdus Sattar and MD.Abdul Maleque[4] analyzed the Unsteady MHD natural convection flow along an accelerated porous plate with hall current and mass transfer in a rotating porous medium.

EM.Aboeldahab and EME.Elbarbary[5] analysis the effects of Hall current on Magneto-hydrodynamics free convection flow past a semi-infinite vertical plate with mass transfer. Pop I and Ingham D.B[6] were discuss the nature of Convective Heat Transfer. Mathematical and Computational Modeling of viscous fluid and porous media. Keeping the view of important of Heat Transfer, Elbashbeshy E.M.A and Bazid M.A.[7] analysis of Heat Transfer over an unsteady stretching surface with internal heat generation. Comprehensive reviews combined by KH.Abdul Maleque and MD.Abdus Sattar[8] presented the Effects of variable properties and Hall current on steady MHD laminar convective fluid flow due to a porous rotating disk. Govindarajan A,Ramamurthy V, and Sundarammal K[9] put the valuable contribution to analysis of 3D Couette flow of dusty fluid with transpiration cooling. Cortell R[10] deeply analysis of MHD flow and Heat Transfer of an Electrically Conducting fluid of second grade in a porous medium over a stretching sheet subject with chemically reactive species. IU.Mbeledogu and A.Ogulu [11] discuss the nature of Heat and mass transfer of an unsteady MHD natural convection flow of a rotating fluid past a vertical porous flat plate in the presence of radiative heat transfer. Cortell R[12] has discussed the nature of Viscous Flow and Heat Transfer over a non-linearly stretching Sheet. Hall Effect on MHD flow and heat transfer along a porous flat plate with mass transfer and source/sink were analyzed and discussed by K.Srihari, N.Krishnan and J.Ananad Rao[13]. Das S.S. [14] was analyzed the Effect of suction and injection on MHD three dimensional coquette flow and heat transfer through a porous medium.Das S.S and Panda J.P.[15] are well presented the Mass transfer effects on MHD flow and heat transfer past a vertical porous plate through a porous medium under oscillatory suction and heat source. Balamurugan K., Anuradha S.and Karthikeyan R [16] are deeply discussed the effects of Chemical reaction effects on Heat and Mass Transfer of Unsteady flow over an infinite vertical porous plate embedded in a porous medium with heat source.

In the view of all such studies, the present paper is to analyze the effects of hall current on unsteady MHD free convective heat and mass transfer flow past an infinite vertical porous plate embedded in porous medium with homogeneous chemical reaction and heat source. The Problem is governed by the system of coupled non-linear partial differential equations whose exact solutions are difficult to obtain, so we use Perturbation Techniques for obtained solution, which is more economical from computational point of view. The behavior of Velocity, temperature, Concentration, shearing stress, Nusselt Number and Sherwood Number has been discussed for variation in the govering parameters.

2.Formulation of the Problem

In the this problem, it can be considered that the flow is unsteady natural convection and mass transfer flow of a viscous incompressible fluid past an infinite vertical porous plate which is embedded in porous medium with heat source. The x' axis is taken in vertically upward direction along the plate and y' axis is chosen normal to it. Neglecting the

Joulean heat dissipation and applying Boussinesq's approximation the governing equations of the flow field are written as follows:

Continuity Equation:

$$\frac{\partial v'}{\partial y'} = 0\ ;\ \ v' = -v'_0(\text{Constant}) \tag{1}$$

Momentum Equation:

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\,\frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T_\infty{}') + g\beta^*\left(C' - C_\infty{}'\right) - \frac{\sigma B_0{}^2}{\rho(1+m^2)}u' - \frac{\nu}{K'}u' \tag{2}$$

Energy Equation:

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = k\,\frac{\partial^2 T'}{\partial y'^2} + \frac{\nu}{Cp}\left(\frac{\partial u'}{\partial y'}\right)^2 + S'(T' - T_\infty{}') \tag{3}$$

Concentration Equation

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

Boundary Conditions are:

$$u' = 0, v' = -v_0{}', T' = T_w{}' + \varepsilon(T_w{}' - T_\infty{}')e^{i\omega' t'}, C' = C_w{}' + \varepsilon(C_w{}' - C_\infty{}')e^{i\omega' t'}\ \ at\ y' = 0$$

$$u' \to 0, T' \to T_\infty{}', C' \to C_\infty{}'\ \ as\ y' \to \infty \tag{5}$$

Now, Introducing the following non- dimensional variables and parameters.

$$y = \frac{y' v'_0}{\nu},\ t = \frac{t' v'_0{}^2}{4\nu},\ \ \omega = \frac{4\nu\,\omega'}{v'_0{}^2},\ \ u = \frac{u'}{v'_0},\ \ \nu = \frac{\eta_0}{\rho}, K_p = \frac{v'_0{}^2 K'}{\nu^2}, T = \frac{T' - T_\infty{}'}{T'_w - T_\infty{}'}, C = \frac{C' - C_\infty{}'}{C_w{}' - C_\infty{}'}$$

$$P_r = \frac{\nu}{k}, Gr = \frac{\nu\, g\beta(T'_w - T_\infty{}')}{v'_0{}^3},\ Gc = \frac{\nu\, g\beta(T'_w - T_\infty{}')}{v'_0{}^3}, Sc = \frac{\nu}{D}, S = \frac{4S'\nu}{v'_0{}^2},\ Ec = \frac{v'_0{}^2}{Cp(T'_w - T_\infty{}')},$$

$$Kr = \frac{Kr'\nu}{v'_0{}^2}, M_1 = \frac{M}{1+m^2} \tag{6}$$

Where

$g, \rho, \vartheta, \beta, \beta^*, \omega, \eta_0, k, T', T'_w, T'_\infty, C', C_w{}', C_\infty{}', Cp, D, Pr, Sc, Gr, Gc, S, Kp, Ec$ and K_r are respectively the acceleration due to gravity, density, coefficient of kinematic viscosity, volumetric coefficient of expansions for heat transfer,volumetric coefficient of expansions for mass transfer, angular frequency,Coefficient of viscosity, thermal diffusivity, temperature, temperature at the plate, temperature at infinity,Concentration, Concentration at the plate, concentration at infinity, specific heat at constant pressure,molecular mass diffusivity,Prandtl number,Schmidt number, Grashof number for heat transfer, Grahof number for mass transfer, heat source parameter, permeability parameter, Eckert number and Chemical reaction parameter.

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

$$\frac{1}{4}\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=\frac{\partial^2 u}{\partial y^2}+GrT+Gc-(M_1+\frac{1}{Kp})u \quad (7)$$

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

$$\frac{1}{4}\frac{\partial C}{\partial t}-\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-Krc \quad (9)$$

The Corresponding boundary conditions are:

$$u=0, T=1+\varepsilon e^{i\omega t}, C=1+\varepsilon e^{i\omega t} \ \ at \ \ y=0$$

$$u\to 0, T\to 0, C\to 0 \ \ as\ y\ \to\infty \quad (10)$$

3.Method of Solution

To solve equations (7), (8) and (9) , we assume ε to be small and the velocity,temperature and concentration distribution of the flow field in the near of the plate as

$$u(y,t)=u_0(y)+\varepsilon e^{i\omega t}u_1(y) \quad (11)$$

$$T(y,t)=T_0(y)+\varepsilon e^{i\omega t}T_1(y) \quad (12)$$

$$C(y,t)=C_0(y)+\varepsilon e^{i\omega t}C_1(y) \quad (13)$$

Substituting equations (11) – (13) in equations (7) –(9) respectively, equating harmonic and nonharmonic terms and the neglecting the coefficients of ε^2 then we get

$$u_0''+u_0'-(M_1+\frac{1}{Kp})u_0=-GrT_0-GcC_0 \quad (14)$$

$$T_0''+PrT_0'+\frac{PrS}{4}T_0=-PrEc\left(\frac{\partial u_0}{\partial y}\right)^2 \quad (15)$$

$$C_0''+ScC_0'-ScKrC_0=0 \quad (16)$$

First Order:

$$u_1''+u_1'-\left(\frac{i\omega}{4}+M_1+\frac{1}{Kp}\right)u_1=-GrT_1-GcC_1 \quad (17)$$

$$T_1''+PrT_1'-\frac{Pr}{4}(i\omega-S)T_1=-2PrEc\left(\frac{\partial u_0}{\partial y}\right)\left(\frac{\partial u_1}{\partial y}\right) \quad (18)$$

$$C_1''+ScC_1'-Sc\left(\frac{i\omega}{4}+Kr\right)C_1=0 \quad (19)$$

The Corresponding boundary conditions are

$$y = 0: u_0 = 0, T_0 = 1, C_0 = 1, u_1 = 0, T_1 = 1, C_1 = 1$$

$$y \to \infty: u_0 = 0, T_0 = 0, C_0 = 0, u_1 = 0, T_1 = 0, C_1 = 0 \quad (20)$$

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

$$C_0 = e^{M_2 y} \quad (21)$$

$$C_1 = e^{M_4 y} \quad (22)$$

Using Multi parameter perturbation technique and assuming Ec≪ 1, we take

$$u_0(y) = u_{00}(y) + Ecu_{01} \quad (23)$$

$$T_0 = T_{00} + EcT_{01} \quad (24)$$

$$u_1 = u_{10} + Ecu_{11} \quad (25)$$

$$T_1 = T_{10} + EcT_{11} \quad (26)$$

Now using equations (23) –(26) in equations (14),(15),(17) and (18) and equating the coefficients of like powers of Ec neglecting of Ec^2, we get the following set of differential equations

Zeroth Order:

$$u_{00}'' + u_{00}' - (M_1 + \frac{1}{Kp})u_{00} = -GrT_{00} - GcC_0 \quad (27)$$

$$u_{10}'' + u_{10}' - \left(\frac{i\omega}{4} + M_1 + \frac{1}{Kp}\right) u_{10} = -GrT_{10} - GcC_1 \quad (28)$$

$$T_{00}'' + PrT_{00}' + \frac{PrS}{4} T_{00} = 0 \quad (29)$$

$$T_{10}'' + PrT_{10}' - \frac{Pr}{4}(i\omega - S)T_{10} = 0 \quad (30)$$

The Corresponding boundary conditions are

$$y = 0: u_{00} = 0, T_{00} = 1, U_{10} = 0, T_{10} = 1$$

$$y \to \infty: u_{00} = 0, T_{00} = 0, U_{10} = 0, T_{10} = 0 \quad (31)$$

First Order:

$$u_{01}{}'' + u_{01}{}' - (M_1 + \frac{1}{Kp})u_{01} = -GrT_{01} \tag{32}$$

$$u_{11}{}'' + u_{11}{}' - \left(\frac{i\omega}{4} + M_1 + \frac{1}{Kp}\right)u_{11} = -GrT_{11} \tag{33}$$

$$T_{01}{}'' + PrT_{01}{}' + \frac{PrS}{4}T_{01} = -Pr(u_{00}{}')^2 \tag{34}$$

$$T_{11}{}'' + PrT_{11}{}' - \frac{Pr}{4}(i\omega - S)T_{11} = -2Pr\left(\frac{\partial u_{00}}{\partial y}\right)\left(\frac{\partial u_{10}}{\partial y}\right) \tag{35}$$

The Corresponding boundary conditions become,

$$y = 0: u_{01} = 0, T_{01} = 0, u_{11} = 0, T_{11} = 0$$

$$y \to \infty: u_{01} = 0, T_{01} = 0, u_{11} = 0, T_{11} = 0 \tag{36}$$

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

$$u_{00} = A_{10}e^{M_{10}y} + A_{11}e^{M_6y} + A_{12}e^{M_2y} \tag{37}$$

$$T_{00} = e^{M_6y} \tag{38}$$

$$u_{10} = A_{14}e^{M_{12}y} + A_{15}e^{M_8y} + A_{16}e^{M_4y} \tag{39}$$

$$T_{10} = e^{M_8y} \tag{40}$$

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

$$T_{01} = A_{18}e^{M_{14}y} + B_1e^{2M_{10}y} + B_2e^{2M_6y} + B_3e^{2M_2y} + B_4e^{(M_6+M_{10})y} + B_5e^{(M_1+M_6)}y + B_6e^{(M_2+M_{10})}y \tag{41}$$

$$T_{11} = A_{20}e^{M_{16}y} + C_1e^{(M_{10}+M_{12})y} + C_2e^{(M_8+M_{10})y} + C_3e^{(M_4+M_{10})y} + C_4e^{(M_6+M_{12})y} + C_5e^{(M_6+M_8)y} + C_6e^{(M_4+M_6)y} + C_7e^{(M_2+M_{12})y} + C_8e^{(M_2+M_8)y} + C_9e^{(M_2+M_4)y} \tag{42}$$

$$u_{10} = A_{22}e^{M_{18}y} + D_1e^{M_{14}y} + D_2e^{2M_{10}y} + D_3e^{2M_2y} + D_4e^{(M_6+M_{10})y} + D_5e^{(M_2+M_6)y} + D_6e^{(M_2+M_{10})y} + D_7e^{2M_6y} \tag{43}$$

$$u_{11} = A_{24}e^{M_{20}y} + E1e^{M_{16}y} + E2e^{(M_{10}+M_{12})y} + E3e^{(M_8+M_{10})y} + E4e^{(M_4+M_{10})y} + E5e^{(M_6+M_{12})y} + E6e^{(M_6+M_8)y} + E7e^{(M_4+M_6)y} + E8e^{(M_2+M_{12})y} + E9e^{(M_2+M_8)y} + E10e^{(M_2+M_4)y} \tag{44}$$

Substituting the values of C_0 and C_1 from equations(21) and (22) in equation(13) the solution for concentration distribution of the flow field is given by

$$\mathrm{C} = e^{M_2 y} + \epsilon e^{i\omega t + M_4 y} \tag{45}$$

3.1 Skin friction: The wall shear stress i.e. the skin friction at the wall is given by

$$\tau_w = \left(\frac{\partial u}{\partial y}\right)_{y=0} = \mathrm{A_{10}M_{10}+A_{11}M_6+A_{12}M_2+Ec(A_{22}M_{10}+D_1M_6+2D_2M_{10}+2D_3M_2+(M_6+M_{10})D_4+(M_6+M_2)D_5+(M_{10}+M_2)D_6+2M_6D_7)}$$

$$\epsilon \mathrm{Exp}[I\omega t]\mathrm{Ec}\big(\mathrm{A_{24}M_{12}+E1M_8+E2(M_{10}+M_{12})+E3(M_{10}+M_8)+E4(M_4+M_6)+E5(M_6+M_{12})+E6(M_8+M_6)+E7(M_6+M_4)+E8(M_2+}$$

3.2 Heat flux: The rate of heat transfer i.e heat flux at the wall in terms of Nusselt Number N_u is given by

$$N_u = \left(\frac{\partial T}{\partial y}\right)_{y=0} = \mathrm{M_6 + Ec(A_{18}M_6 + 2B_1M_{10} + 2B_2M_6 + 2B_3M_2 + B_4(M_6 + M_{10}) + B_5(M_6 + M_2) + B_6(M_2 + M_{10}))} + \epsilon \mathrm{Exp}[I\omega t](\mathrm{M_8Ec(A_{20}M_8 + C_1(M_{10} + M_{12}) + C_2(M_{10} + M_8) + C_3(M_4 + M_{10}) + C_4(M_6 + M_{12}) + C_5(M_6 + M_8) + C_6(M_6 + M_4) + C_7(M_2 + M_{12}) + C_8(M_2 + M_8) + C_9(M_2 + M_4)))} \tag{47}$$

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

$$S_h = \left(\frac{\partial C}{\partial y}\right)_{y=0} = M_2 + M_4 \epsilon \mathrm{Exp}[I\omega t] \tag{48}$$

4.Results and discussions:-

MHD Free Convective and Mass Transfer on on unsteady flow of a viscous incompressible fluid past an infinite vertical porous plate embedded in a porous medium with Hall heat and heat source has been studied. The effects of parameters in the fluid flow are thoroughly analyzed and given in the form of graph to easily understand. The figure 1-5 shown velocity profile, 6 to 8 shown temperature profile and 9 to 10 shown concentration profile.

Velocity field: The flow parameters affecting the velocity flow field are permeability parameter Kp., Grashof number for both heat and mass transfer Gr, Gc, accelerate the transient velocity of the flow field.As well as inverse effects exists in the transient velocity of the flow field while increasing Magnetic Parameter (M) (i.e shows decrease effects the velocity of the flow field).

Temperature Field:- Temperature profiles of the flow field with the effected parameters like Prandtl number, Grashof Number (Gr) and Magnetic Parameter (M) are graphically shown its effects on the flow field.

Concentration Field: Schmidt Number (Sc) and Chemical reaction parameter(K_r) plays important role in the concentration fluid flow field. The effects of these parameters on the fluid flow field graphically shown. While growing Schmidt number (Sc) decrease the concentration boundary layer thickness of the flow in similar way the effects of mass transfer are decrease while growing of Chemical reaction parameter (K_r).

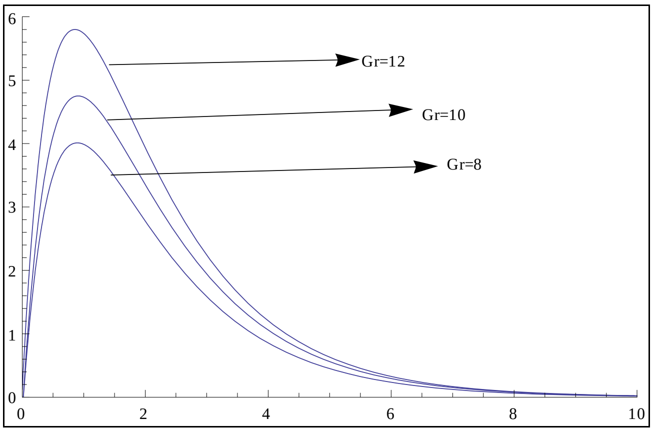

Fig.1Transient Velocity for various values of Gr

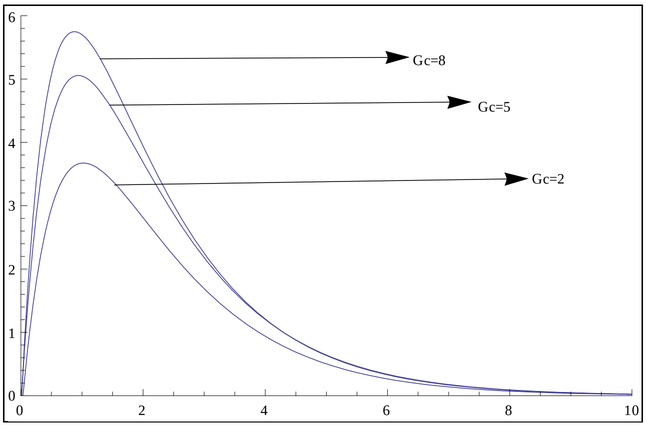

Fig.2 Transient Velocity for various values of Gc

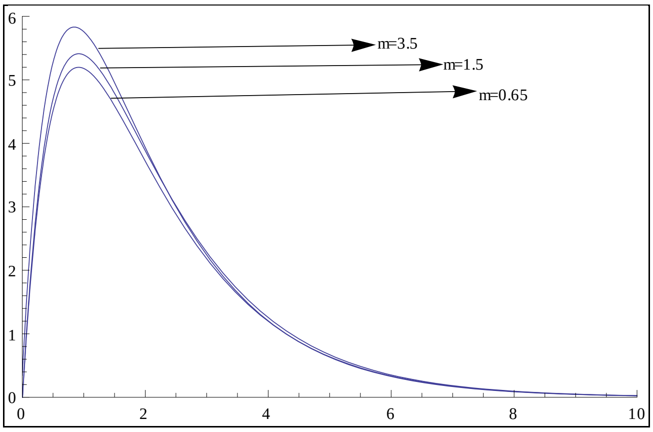

Fig.3 Transient Velocity for various values of m

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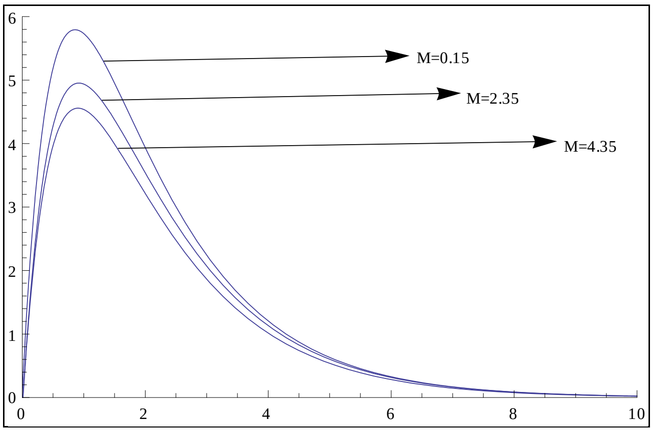

Fig.4 Transient Velocity for various values of M

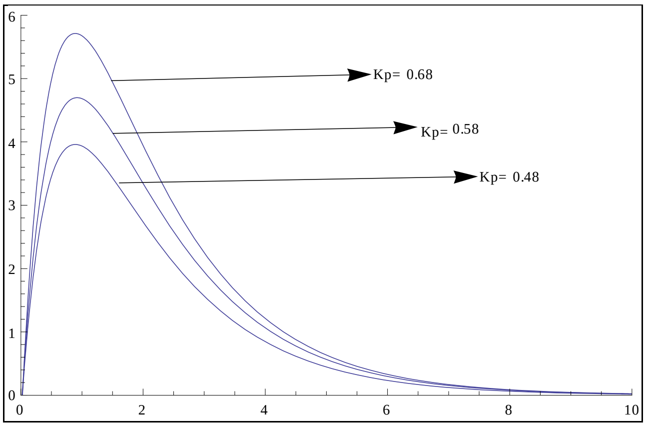

Fig.5 Transient Velocity for various values of Kp

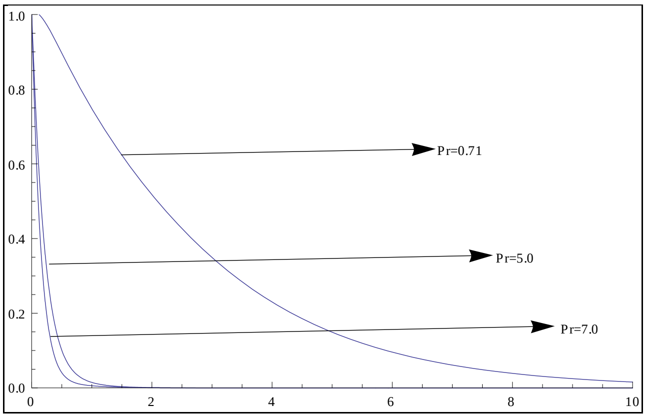

Fig.6 Temperature Profile for various values of Pr

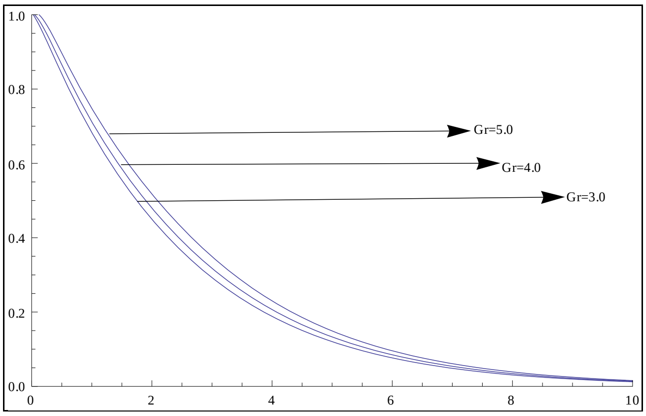

Fig.7 Temperature Profile for various values of Gr

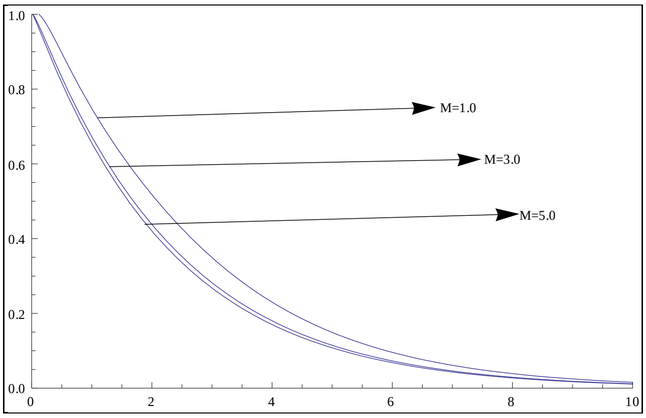

Fig.8 Temperature Profile for various values of M

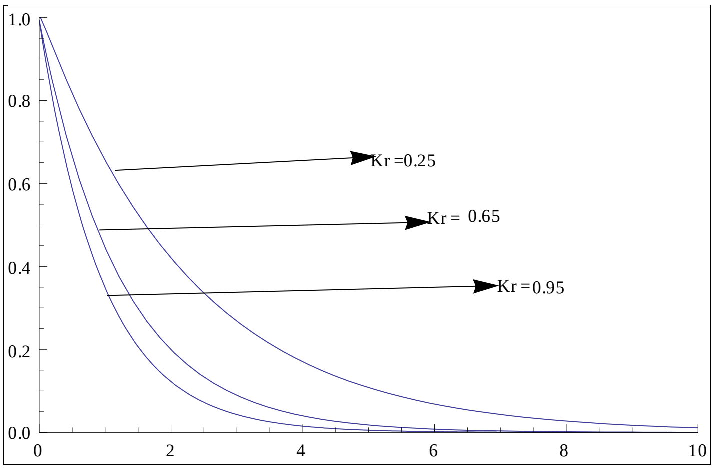

Fig.9 Concentration Profile for various values of Kr

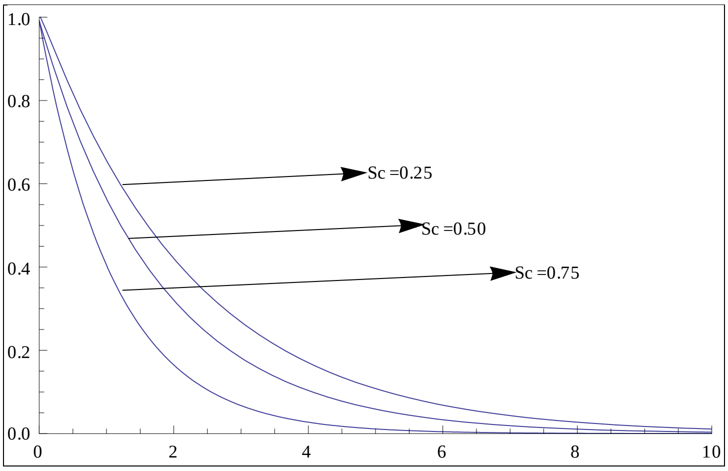

Fig.10 Concentration Profile for various values of Sc

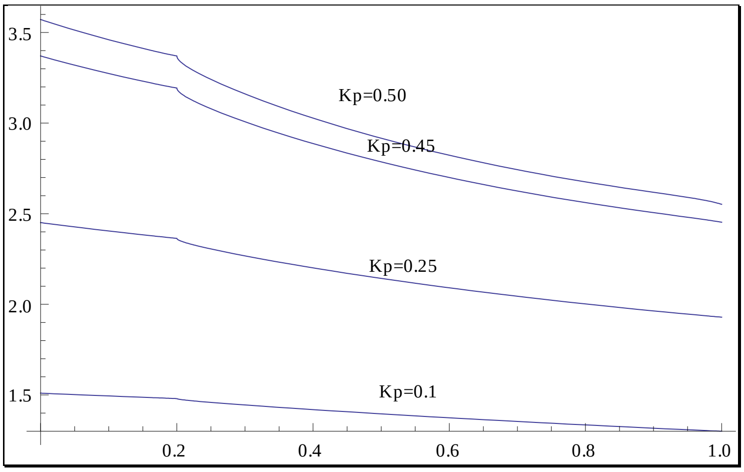

Fig.11 Skin friction for various values of Kp

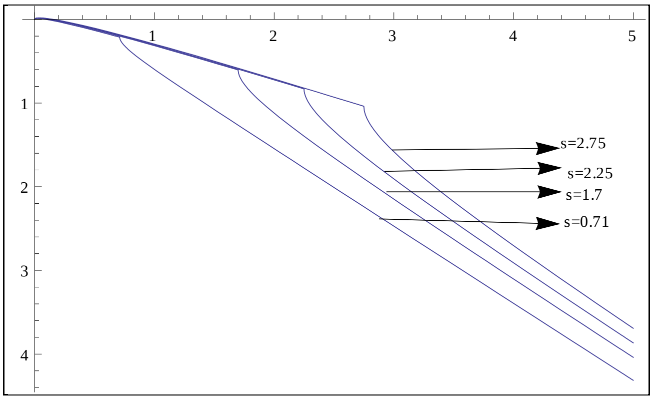

Fig.12 Heat flux for various values of s

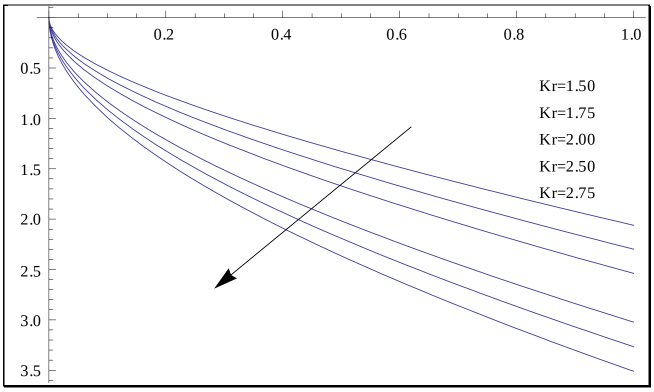

Fig.13 Mass Flux for various values of Kr

5.Conclusion:-

In this paper clearly shows effects of the parameters in the flow fluid. The velocity, temperature and concentration profiles are shown graphically with various values of parameters.

Permeability parameter (Kp) accelerates the transient velocity of the fluid flow.

Growing of Grashof Number (Gr) accelerates the transient velocity of the fluid flow but growing magnetic Parameter (M) retards the transient velocity.

Permeability parameter (Kp) and Grashof Number (Gc) accelerates the transient profile of the fluid flow.

Growing of Magnetic Parameter (M) and Prandtl retards the temperature of the fluid flow.

The Parameter of Grashof Number (Gr) accelerates the temperature of the fluid flow.

The Chemical reaction parameter (Kr) and Schmidt Number (Sc) both retards of the concentration of mass while both are grown.

The variation of skin friction at the wall against the different values of Permeability Parameter.It observed increase effects exists if the Permeability Parameter is increase.

The rate of heat transfer at the wall is increase for the different values heat source.

While the rate of mass transfer at the wall decrease while increase effects of Schmidt Number (S_c) and increase of Chemical reaction parameter (K_r)

Appendix:-

$$M_2 = \frac{-Sc - \sqrt{Sc^2 + 4ScK_r}}{2}$$

$$M_4 = \frac{-Sc - \sqrt{Sc^2 + Sc(4K_r + i\omega)}}{2}$$

$$M_6 = \frac{-Pr - \sqrt{Pr^2 - Prs}}{2}$$

$$M_8 = \frac{-Pr - \sqrt{Pr^2 + \mathrm{Pr}(i\omega - s)}}{2}$$

$$M_{12} \frac{= -1 - \sqrt{1 + \frac{4}{Kp} + I\omega + 4M_1}}{2}$$

$$M_{10} = \frac{-1-\sqrt{1+4M_1+\frac{4}{Kp}}}{2}$$

$$A_5 + A_6 = 1\,,$$

$$A_{11} = \frac{-Gr}{{M_6}^2 + M_6 - (M_1 + \frac{1}{Kp})}$$

$$A_{12} = \frac{-Gc}{{M_2}^2 + M_2 - (M_1 + \frac{1}{Kp})}$$

$$A_{10} = -(A_{11} + A_{12})$$

$$A_{15} = \frac{-Gr}{{M_8}^2 + M_8 - (\frac{1}{Kp} + \frac{i\omega}{4} + M_1)}$$

$$A_{16} = \frac{-Gc}{{M_4}^2 + M_4 - (\frac{1}{Kp} + \frac{i\omega}{4} + M_1)}$$

$$A_{14} = -(A_{15} + A_{16})$$

$$A_{18} = -(B_1 + B_2 + B_3 + B_4 + B_5 + B_6)$$

$$B_1 = \frac{-Pr{M_{10}}^2 {A_{10}}^2}{4{M_{10}}^2 + 2PrM_{10} + \frac{Prs}{4}}$$

$$B_2 = \frac{-PrM_6{}^2 A_{11}{}^2}{4M_6{}^2 + 2PrM_6 + \frac{Prs}{4}}$$

$$B_3 = \frac{-PrM_2{}^2 A_{12}{}^2}{4M_2{}^2 + 2PrM_2 + \frac{Prs}{4}}$$

$$B_4 = \frac{-2PrM_{10}A_{10}M_6A_{11}}{(M_6 + M_{10})^2 + Pr(M_6 + M_{10}) + \frac{Prs}{4}}$$

$$B_5 = \frac{-2PrM_2A_{12}M_6A_{11}}{(M_6 + M_2)^2 + Pr(M_6 + M_2) + \frac{Prs}{4}}$$

$$B_6 = \frac{-2PrM_2A_{10}M_{10}A_{12}}{(M_{10} + M_2)^2 + Pr(M_{10} + M_2) + \frac{Prs}{4}}$$

$$A_{20} = -(C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9)$$

$$C_1 = \frac{-2PrM_{12}A_{10}M_{10}A_{14}}{(M_{10} + M_{12})^2 + Pr(M_{10} + M_{12}) - \frac{Pr}{4}(i\omega - s)}$$

$$C_2 = \frac{-2PrM_8A_{10}M_{10}A_{15}}{(M_{10} + M_8)^2 + Pr(M_{10} + M_8) - \frac{Pr}{4}(i\omega - s)}$$

$$C_3 = \frac{-2PrM_4A_{10}M_{10}A_{16}}{(M_{10} + M_4)^2 + Pr(M_{10} + M_4) - \frac{Pr}{4}(i\omega - s)}$$

$$C_4 = \frac{-2PrM_6A_{11}M_{12}A_{14}}{(M_6 + M_{12})^2 + Pr(M_6 + M_{12}) - \frac{Pr}{4}(i\omega - s)}$$

$$C_5 = \frac{-2PrM_6A_{11}M_8A_{15}}{(M_6 + M_8)^2 + Pr(M_6 + M_8) - \frac{Pr}{4}(i\omega - s)}$$

$$C_6 = \frac{-2PrM_6A_{11}M_4A_{16}}{(M_6 + M_4)^2 + Pr(M_6 + M_4) - \frac{Pr}{4}(i\omega - s)}$$

$$C_7 = \frac{-2PrM_2A_{12}M_{12}A_{14}}{(M_2 + M_{12})^2 + Pr(M_2 + M_{12}) - \frac{Pr}{4}(i\omega - s)}$$

$$C_8 = \frac{-2PrM_2A_{12}M_8A_{15}}{(M_2 + M_8)^2 + Pr(M_2 + M_8) - \frac{Pr}{4}(i\omega - s)}$$

$$C_9 = \frac{-2PrM_2A_{12}M_4A_{16}}{(M_2+M_4)^2+Pr(M_2+M_4)-\frac{Pr}{4}(i\omega - s)}$$

$$A_{22} = -(D_1+D_2+D_3+D_4+D_5+D_6+D_7)$$

$$D_1 = \frac{-GrA_{18}}{{M_6}^2+M_6-(M_1+\frac{1}{Kp})}$$

$$D_2 = \frac{-GrB_1}{4{M_{10}}^2+2M_{10}-(M_1+\frac{1}{Kp})}$$

$$D_3 = \frac{-GrB_2}{4{M_6}^2+2M_6-(M_1+\frac{1}{Kp})}$$

$$D_4 = \frac{-GrB_3}{4{M_2}^2+M_2-(M_1+\frac{1}{Kp})}$$

$$D_5 = \frac{-GrB_4}{(M_6+M_{10})^2+(M_6+M_{10})-(M_1+\frac{1}{Kp})}$$

$$D_6 = \frac{-GrB_5}{(M_6+M_2)^2+(M_6+M_2)-(M_1+\frac{1}{Kp})}$$

$$D_7 = \frac{-GrB_6}{(M_{10}+M_2)^2+(M_{10}+M_2)-(M_1+\frac{1}{Kp})}$$

$$A_{24} = -(D_8+D_9+D_{10}+D_{11}+D_{12}+D_{13}+D_{14}+D_{15}+D_{16}+D_{17})$$

$$E1 = \frac{-GrA_{20}}{{M_8}^2+M_8-\left(\frac{1}{Kp}+\frac{i\omega}{4}+M_1\right)}$$

$$E2 = \frac{-GrC_1}{(M_{10+}M_{12})^2+(M_{10+}M_{12})-\left(\frac{1}{Kp}+\frac{i\omega}{4}+M_1\right)}$$

$$E3 = \frac{-GrC_2}{(M_{10+}M_8)^2+(M_{10+}M_8)-\left(\frac{1}{Kp}+\frac{i\omega}{4}+M_1\right)}$$

$$E4 = \frac{-GrC_3}{(M_{10+}M_4)^2 + (M_{10+}M_4) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

$$E5 = \frac{-GrC_4}{(M_{12+}M_6)^2 + (M_{12+}M_6) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

$$E6 = \frac{-GrC_5}{(M_{6+}M_8)^2 + (M_{6+}M_8) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

$$E7 = \frac{-GrC_6}{(M_{4+}M_6)^2 + (M_{4+}M_6) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

$$E8 = \frac{-GrC_7}{(M_{12+}M_2)^2 + (M_{12+}M_2) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

$$E9 = \frac{-GrC_8}{(M_{2+}M_8)^2 + (M_{2+}M_8) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

$$E10 = \frac{-GrC_9}{(M_{2+}M_4)^2 + (M_{2+}M_4) - \left(\frac{1}{Kp} + \frac{i\omega}{4} + M_1\right)}$$

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