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Research Article

Hall current effect on MHD free Convective flow past a moving Inclined Porous Plate in presence of Chemical **Reaction with Ohmic heating, Radiation, Viscous** dissipation, Heat Source and Soret effect

K.Balamurugan and V.Amuthavalli^{*}

Department of Mathematics, Government Arts College, Tiruvannamalai, Tamilnadu, India.

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Abstract: The present article discusses with the analysis of hall current effect on heat and mass transfer in MHD free convection flow of an incompressible and electrically conducting viscous fluid through a moving inclined heated porous plate with ohmic heating, radiation, viscous dissipation, heat source and Soret effect in presence of chemical reaction. The governing non-linear partial differential equations of the problem are reduced to a set of ordinary differential equations which are then solved analytically by using perturbation technique. The effect of different parameters like Magnetic parameter(M), Porosity parameter(K), Hall parameter(m), Soret effect(So), Grashof number(Gr), Modified Grashof number(Gm), Heat source parameter(H), Prandtl number(Pr), Radiation parameter(F), Schmidt number(Sc) and Chemical reaction parameter(R) on velocity, temperature, concentration profiles and skin friction are displayed with the help of numerical values and the graphs.

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Keywords: Heat and mass transfer, ohmic heating, viscous dissipation, inclined porous plate, heat source, chemical reaction and Soret effect.

INTRODUCTION

The study of free convective mass transfer flow has become the object of extensive research as the effects of heat transfer along with mass transfer effects are dominant features in many engineering applications such as rocket nozzles, cooling of nuclear reactors, high sinks in turbine blades, high speed aircrafts and their atmospheric re-entry, chemical devices and process equipments. Radiation convective flows have gained attention of many researchers in recent years. Radiation plays a vital role in many engineering, environment and industrial processes e.g. heating and cooling chambers, fossil fuel combustion energy processes astrophysical flow and space vehicle re-entry. Hall current has important contribution in the study of magnetohydrodynamic viscous flows. It has many applications in problems of the Hall accelerators as well as in the flight magnetohydrodynamics. The current trend is on the application of magnetohydrodynamics is towards a strong magnetic field and a low density of gas. For this reason, the hall current and ion slip become important. Several researchers have investigated the Soret and chemical reaction effect on MHD free convective flow of an inclined porous plate in the presence of radiation and hall current. Hossain¹ discussed the viscous and Joule heating effects on MHD free convection flow with variable plate temperature while the thermo diffusion and chemical effects with simultaneous thermal and mass diffusion in MHD mixed convection flow with Ohmic heating have been studied by Reddy et. al.,². Kumar et. al.,³ investigated the effects of the chemical reaction and mass transfer on MHD unsteady free convection flow past an infinite vertical plate with constant suction and heat sink. Sibanda and Makinde⁴ examined the steady MHD flow and heat transfer past a rotating disk in a porous medium with Ohmic heating and viscous dissipation. The radiation and Dufour effects on chemically reacting MHD mixed convective slip flow in an irregular channel have been reported by Rushi Kumar and Sivarai⁵ while Das et. al.,⁶ analyzed the combined natural convection and mass transfer effects on unsteady flow past an infinite vertical porous plate embedded in a porous medium with heat source. AlamgirKabir and Abdullah⁷ discussed the effects of thermophoresis on unsteady MHD free convective heat and mass transfer along an inclined plate with heat generation in presence of magnetic field while the heat and mass transfer in MHD free convection flow over an inclined plate with Hall current have been studied by Mohammad Shah Alamet. al.,⁸. Sandeep and Sugunamma⁹ investigated the effects of inclined magnetic field on unsteady free convective flow of dissipative fluid past a vertical plate while Mohanty and Das¹⁰ examined the effect of chemical reaction on unsteady hydromagnetic mass transfer flow past a semiinfinite vertical porous moving plate with time dependent suction and radiative heat source.

The MHD free convective flow through porous medium in the presence of hall current, radiation and thermal diffusion have been studied by Aarti Manglesh and Gorla¹¹. The effects of radiation and free convection currents on unsteady couette flow between two vertical parallel plates with constant heat flux and heat source through porous medium have been examined by Kesavaiah *et. al.*,¹² while Choudhury and

⁹⁰⁷ J. Chem. Bio. Phy. Sci. Sec. C, August 2017 – October, 2017, Vol. 7, No. 4; 906-920. [DDl: 10.24214/jcbps.C.7.4.90620.]

Das¹³ reported the mixed convection visco elastic MHD flow with Ohmic heating. Hossain and Gorla¹⁴ analyzed the Joule heating effect on magnetohydrodynamic mixed convection boundary layer flow with variable electrical conductivity while the steady MHD boundary free convective heat and mass transfer flow over an inclined porous plate with variable suction and Soret effect in presence of hall current have been investigated by Alam et. al.,¹⁵. Daniel Simon¹⁶ discussed the effect of heat of transfer on unsteady MHD couette flow between two infinite parallel porous plates in an inclined magnetic field while Balamuruganet. al.,¹⁷ studied the 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. Veeresh et. al.,¹⁸ reported the heat and mass transfer in MHD free convection chemically reactive and radiative flow in a moving inclined porous plate with temperature dependent heat source and joule heating. Balamurugan and Karthikeyan¹⁹ investigated the radiation effects of MHD oscillatory rotation flow through a porous medium bounded by two vertical porous plates in the presence of hall current and Dufour effect with chemical reaction while the Balamurugan and Gopikrishnan²⁰ analyzed the radiation effects of MHD oscillatory flow along a porous medium bounded by two vertical porous plates in presence of hall current and Dufour effect with chemical reaction. Balamurugan and Amuthavalli²¹ examined the radiation and hall effects on unsteady free MHD convection flow past a vertical porous plate with heat absorption, thermo diffusion and chemical reaction in slip flow regime.

The objective of the present study is to discuss the MHD free convective flow past a moving inclined porous plate in presence of chemical reaction and hall current with radiation, viscous dissipation, ohmic heating, heat source and Soret effect.

MATHEMATICAL FORMULATION

Consider an unsteady MHD convective flow of a viscous incompressible and electrically conducting fluid past a semi-infinite moving permeable plate inclined at an angle α in vertical direction embedded in a uniform porous medium with temperature and concentration. Choose x^* - axis is taken along the leading edge of the inclined plate and y^* - axis along normal to it and extends parallel to x^* - axis. Let u^* and v^* be the velocity components of fluid flow along x^* and y^* directions respectively. Under the above assumptions and usual boundary layer approximation, the dimensional governing equations of continuity, momentum, energy and concentration respectively are given by

$$\frac{\partial v^*}{\partial y^*} = 0 \Longrightarrow v^* = -v_0 \tag{1}$$

$$\rho v^* \frac{\partial u^*}{\partial y^*} = \mu \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\mu}{K^*} u^* - \frac{\sigma B_0^2}{\left(1 + m^2\right)} u^* + \rho g \beta_T \left(T^* - T_\infty\right) \cos \alpha + \rho g \beta_C \left(C^* - C_\infty\right) \cos \alpha \tag{2}$$

$$\rho c_p v^* \frac{\partial T^*}{\partial y^*} = \alpha_1 \frac{\partial^2 T^*}{\partial y^{*2}} + \mu \left(\frac{\partial u^*}{\partial y^*}\right)^2 - \frac{\partial q_r^*}{\partial y^*} + \sigma B_0^2 u^{*2} - Q_0 \frac{\partial}{\partial y^*} \left(T^* - T_\infty\right)$$
(3)

$$v^* \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} - R^* \left(C^* - C_{\infty} \right) + D_1 \frac{\partial^2 T^*}{\partial y^{*2}}$$
(4)

$$\frac{\partial q_r^*}{\partial y^*} = 4 \left(T^* - T_{\infty} \right) I' \tag{5}$$

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 wall and $e_{b\lambda}$ is Planck's function.

The boundary conditions for velocity, temperature and concentration fields are

$$u^* = 0, T^* = T_W, C^* = C_W \quad at \ y = 0$$

$$u^* \to 0, T^* \to T_{\infty}, C^* \to C_{\infty} \quad as \ y \to \infty$$

$$(6)$$

Introduce the following dimensionless variables and quantities

$$y = \frac{v_0 y^*}{v}, u = \frac{u^*}{v_0}, \theta = \frac{T^* - T_{\infty}}{T_W - T_{\infty}}, C = \frac{C^* - C_{\infty}}{C_W - C_{\infty}}, M^2 = \frac{B_0^2 v^2 \sigma}{v_0^2 \mu}, M_1 = \frac{M^2}{1 + m^2}, K = \frac{K^* v_0^2}{v^2},$$

$$Gr = \frac{\rho g \beta_T v^2 (T_W - T_{\infty})}{v_0^3 \mu}, \quad Gm = \frac{\rho g \beta_C v^2 (C_W - C_{\infty})}{v_0^3 \mu}, \quad \Pr = \frac{\mu c_p}{\alpha_1}, \quad R = \frac{R^* v}{v_0^2}, \quad Ec = \frac{v_0^2}{c_p (T_W - T_{\infty})},$$

$$F = \frac{4vI^*}{\rho c_p v_0^2}, \quad H = \frac{Q_0}{\rho c_p v_0}, \quad Sc = \frac{v}{D}, \quad So = \frac{D_1 (T_W - T_{\infty})}{v(C_W - C_{\infty})}$$
(7)

The respective non-dimensional governing equations of (2) to (4) after using (7) becomes

$$\frac{\partial^2 u}{\partial y^2} + \frac{\partial u}{\partial y} - \left(\frac{1}{K} + M_1\right) u = -Gr\,\theta\cos\alpha - GmC\cos\alpha \tag{8}$$

$$\frac{\partial^2 \theta}{\partial y^2} + \Pr\left(1 - H\right) \frac{\partial \theta}{\partial y} + \Pr Ec \left(\frac{\partial u}{\partial y}\right)^2 - \Pr F \theta + \Pr Ec M^2 u^2 = 0$$
(9)

$$\frac{\partial^2 C}{\partial y^2} + Sc \frac{\partial C}{\partial y} - Sc R C + Sc So \frac{\partial^2 \theta}{\partial y^2} = 0$$
(10)

Where α is the angle of inclination, g is acceleration due to gravity, B_0 is magnetic field component along y^* -axis, C_p is specific heat at constant pressure, D_1 is molecular diffusivity, T_W is temperature at the wall, T_{∞} is temperature far away from the plate, C_w is concentration at the wall, C_{∞} is concentration far away from the plate, m is hall parameter, M is magnetic parameter, K is permeability parameter, Gr is Grashof number, Gm is Modified Grashof number, R is chemical reaction parameter, Pr is Prandtl number, Ec is Eckert number, F is radiation parameter, H is heat source parameter, Sc is Schmidt number, So is Soret number.

The corresponding non-dimensional boundary conditions are

$$\begin{array}{ccc} u=0, \ \theta=1, \ C=1 & at \ y=0 \\ u\to0, \ \theta\to0, \ C\to0 & as \ y\to\infty \end{array} \right\}$$
(11)

METHOD OF SOLUTION

To solve the system of partial differential equations (8) - (10), we follow the perturbation method by using *Ec* as the perturbation parameter. Therefore the expressions for velocity, temperature and concentration are assumed in the following form:

$$u(y) = u_0(y) + Ec u_1(y) + o(Ec^2) \theta(y) = \theta_0(y) + Ec \theta_1(y) + o(Ec^2) C(y) = C_0(y) + Ec C_1(y) + o(Ec^2)$$
(12)

Substituting the above expressions (12) in the equations (8) - (10) and equating the coefficients of like powers of Ec^0 and Ec^1 (neglecting the coefficient of Ec^2), we get the following set of ordinary differential equations.

Zeroth order equations

$$u_0'' + u_0' - (M_1 + \frac{1}{K})u_0 = -Gr\cos\alpha\theta_0 - Gm\cos\alpha C_0$$
(13)

$$\boldsymbol{\theta}_{0}^{"} + \Pr(1 - H)\boldsymbol{\theta}_{0}^{'} - \Pr F \boldsymbol{\theta}_{0} = 0$$
⁽¹⁴⁾

$$C_0'' + Sc C_0' - Sc R C_0 = -Sc So \theta_0''$$
(15)

First order equations

$$u_{1}'' + u_{1}' - (M_{1} + \frac{1}{K})u_{1} = -Gr\cos\alpha\theta_{1} - Gm\cos\alpha C_{1}$$
(16)

$$\theta_{1}^{''} + \Pr(1 - H)\theta_{1}^{'} - \Pr F\theta_{1} = -\Pr u_{0}^{'2} - \Pr M^{2} u_{0}^{2}$$
(17)

$$C_{1}^{''} + ScC_{1}^{'} - ScRC_{1} = -ScSo\theta_{1}^{''}$$
(18)

The corresponding boundary conditions become

$$u_0 = 0, \quad u_1 = 0, \quad \theta_0 = 1, \quad \theta_1 = 0, \quad C_0 = 1, \quad C_1 = 0 \quad at \quad y = 0 \\ u_0 \to 0, \quad u_1 \to 0, \quad \theta_0 \to 0, \quad \theta_1 \to 0, \quad C_0 \to 0, \quad C_1 \to 0 \quad as \quad y \to \infty$$

$$(19)$$

Solving the equations (13) to (18) under the boundary conditions (19) we get

$$u(y) = \left[A_{6}e^{m_{5}y} + (A_{3} + A_{5})e^{m_{1}y} + A_{4}e^{m_{3}y}\right] + Ec\left[A_{30}e^{m_{5}y} + A_{22}e^{m_{3}y} + A_{23}e^{m_{1}y} + A_{24}e^{2m_{5}y} + A_{25}e^{2m_{1}y} + A_{26}e^{2m_{3}y} + A_{27}e^{(m_{1}+m_{5})y} + A_{28}e^{(m_{1}+m_{3})y} + A_{29}e^{(m_{3}+m_{5})y}\right]$$
(20)

$$\theta(y) = e^{m_1 y} + Ec \Big[A_{13} e^{m_1 y} + A_7 e^{2m_5 y} + A_8 e^{2m_1 y} + A_9 e^{2m_3 y} + A_{10} e^{(m_1 + m_5) y} + A_{11} e^{(m_1 + m_3) y} + A_{12} e^{(m_3 + m_5) y} \Big]$$
(21)

$$C(y) = [A_{2}e^{m_{3}y} + A_{1}e^{m_{1}y}] + Ec \Big[A_{21}e^{m_{3}y} + A_{14}e^{m_{1}y} + A_{15}e^{2m_{5}y} + A_{16}e^{2m_{1}y} + A_{17}e^{2m_{3}y} + A_{18}e^{(m_{1}+m_{5})y} + A_{19}e^{(m_{1}+m_{3})y} + A_{20}e^{(m_{3}+m_{5})y}\Big]$$
(22)

Skin friction: The non-dimensional shearing stress on the surface of a body, due to the fluid motion, is known as skin friction and is defined by the Newton's law of viscosity. The expression for the skin friction τ at the plate is given by

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = \left(\frac{\partial u_0}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial u_1}{\partial y}\right)_{y=0}$$

$$\tau = \left[A_6m_5 + (A_3 + A_5)m_1 + A_4m_3\right] + Ec\left[A_{30}m_5 + A_{22}m_3 + A_{23}m_1 + 2A_{24}m_5 + 2A_{25}m_1 + 2A_{26}m_3 + A_{27}(m_1 + m_5) + A_{28}(m_1 + m_3) + A_{29}(m_3 + m_5)\right]$$
(23)

Nusselt number: The expression for the Nusselt number is obtained from the gradient of the temperature. The non-dimensional form of the Nusselt number Nu at the plate is given by

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -\left\{ \left(\frac{\partial \theta_0}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial \theta_1}{\partial y}\right)_{y=0} \right\}$$

J. Chem. Bio. Phy. Sci. Sec. C, August 2017 – October, 2017, Vol. 7, No. 4; 906-920. [DDl: 10.24214/jcbps.C.7.4.90620.]

$$Nu = -\left\{m_1 + Ec\left[A_{13}m_1 + 2A_7m_5 + 2A_8m_1 + 2A_9m_3 + A_{10}(m_1 + m_5) + A_{11}(m_1 + m_3) + A_{12}(m_3 + m_5)\right]\right\} (24)$$

Sherwood number: The expression for the Sherwood number Sh is obtained from the gradient of the mass transfer is given by

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = -\left\{ \left(\frac{\partial C_0}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial C_1}{\partial y}\right)_{y=0} \right\}$$

$$Sh = -\left\{ [A_{2}m_{3} + A_{1}m_{1}] + Ec \left[A_{21}m_{3} + A_{14}m_{1} + 2A_{15}m_{5} + 2A_{16}m_{1} + 2A_{17}m_{3} + A_{18}(m_{1} + m_{5}) + A_{19}(m_{1} + m_{3}) + A_{20}(m_{3} + m_{5}) \right] \right\}$$
(25)

RESULTS AND DISCUSSION

The flow parameters play an important role in determining the magnitude of velocity of the flow field. The flow parameters affecting the velocity flow field are Magnetic parameter, Porosity parameter, Hall parameter, Soret number, Grashof number, Modified Grashof number and Heat source parameter. Figures 1-7 show the effects of these parameters on the velocity of the flow field.

Figure 1 displays the effect of Magnetic parameter on the velocity field. It is noticed that as the Magnetic parameter increases the velocity decreases. Figure 2 presents the effect of Porosity parameter on the velocity field. It is observed that as the Porosity parameter increases the velocity increases. Figure 3 depicts the effect of Hall parameter on the velocity field. It is seen that as the Hall parameter increases the velocity increases the velocity increases the velocity field. It is noticed that as the Soret number increases the velocity increases. Figure 5 shows the effect of Grashof number on the velocity field. It is observed that as the Grashof number increases the velocity increases. Figure 6 discusses the effect of Modified Grashof number on the velocity field. It is observed that as the Modified Grashof number on the velocity field. It is observed that as the Modified Grashof number on the velocity field. It is observed that as the Modified Grashof number on the velocity field. It is seen that as the Heat absorption parameter 7 represents the effect of Heat source parameter on the velocity field. It is seen that as the Heat absorption parameter decreases the velocity increases.

Figures 8-11 elucidate the temperature profiles of the flow field with the variation of the flow parameters such as Prandtl number, Heat source parameter, Radiation parameter and Soret number. Figure 8 displays the effect of Prandtl number on the temperature field. It is noticed that as the Prandtl number increases the temperature decreases. Figure 9 presents the effect of Heat source parameter on the temperature field. It is observed that as the Radiation parameter increases the temperature decreases. It is due to the fact that increase in radiation parameter results in the temperature within the boundary layer, as well as decreased thickness of the temperature boundary layers. Figure 11 illustrates the effect of Soret number on the temperature field. It is noticed that as the Soret number increases.

⁹¹² J. Chem. Bio. Phy. Sci. Sec. C, August 2017 – October, 2017, Vol. 7, No. 4; 906-920. [DDl: 10.24214/jcbps.C.7.4.90620.]

Figures 12-14 elucidate the concentration profiles of the flow field with the variation of the flow parameters such as Schmidt number, Chemical reaction parameter and Soret number. Figure 12 shows the effect of Schmidt number on the concentration field. It is seen that as the Schmidt number increases the concentration decreases. Figure 13 discusses the effect of Chemical reaction parameter on the concentration field. It is noticed that as the Chemical reaction parameter increases the concentration decreases. Figure 14represents the effect of Soret number on the concentration field. It is observed that as the Soret number increases the concentration field. It is observed that as the Soret number increases the concentration increases. Also Figure 15 displays the effect of Magnetic parameter on the skin friction. It is noticed that as the Magnetic parameter increases the skin friction decreases.



Figure 1: Effects of Magnetic parameter on the velocity profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1, F=1,Sc=0.60,R=0.1,So=2



Figure 3: Effects of Hall parameter on the velocity profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=1, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1, F=1,Sc=0.60,R=0.1,So=2



Figure 2: Effects of Porosity parameter on the velocity profiles

Ec=0.01,Gr=4,Gm=2,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1, F=1,Sc=0.60,R=0.1,So=2



Figure 4: Effects of Soret number on the velocity profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1,F=1,Sc=0.60,R=0.1

913 J. Chem. Bio. Phy. Sci. Sec. C, August 2017 – October, 2017, Vol. 7, No. 4; 906-920. [DDl: 10.24214/jcbps.C.7.4.90620.]



Figure 5: Effects of Grashof number on the velocity profiles

Ec=0.01,Gm=2,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1, F=1,Sc=0.60,R=0.1,So=2



Figure 7: Effects of Heat source parameter on the velocity profiles

Ec=0.01,Gr=5,Gm=5,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71, F=1,Sc=0.60,R=0.1,So=2



Figure 9: Effects of Heat source parameter on the temperature profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=2,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71, F=1,Sc=0.60,R=0.1,So=2



Figure 6: Effects of Modified Grashof number on the velocity profiles

Ec=0.01,Gr=4,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1,F=1,Sc=0.60,R=0.1,So=2



Figure 8: Effects of Prandtl number on the temperature profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=2,m=3, $\alpha = \frac{\pi}{6}$, H=1,F=1,Sc=0.60,R=0.1,So=2



Figure 10: Effects of Radiation parameter on the temperature profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=2,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71, H=1,Sc=0.60,R=0.1,So=2

914 J. Chem. Bio. Phy. Sci. Sec. C, August 2017 – October, 2017, Vol. 7, No. 4; 906-920. [DDl: I0.24214/jcbps.C.7.4.90620.]



Figure 11: Effects of Soret number on the temperature profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=2,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,



Figure 13: Effects of Chemical reaction parameter on the concentration profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71, H=1,F=1,Sc=0.60,So=2



Figure 12: Effects of Schmidt number on the concentration profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71, H=1,F=1,R=0.1,So=2



Figure 14: Effects of Soret number on the concentration profiles

Ec=0.01,Gr=4,Gm=2,K=0.5,M=1,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71, H=1,F=1,Sc=0.60,R=0.1



Figure 15: Effects of Magnetic parameter on skin-friction(function of Soret effect)

Ec=0.01,Gr=2,Gm=2,K=0.5,m=3, $\alpha = \frac{\pi}{6}$, Pr=0.71,H=1,F=1,Sc=0.60,R=0.1

CONCLUSION

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

- Growing of Magnetic parameter retards the velocity of the flow field.
- The Porosity parameter, Hall parameter, Soret number, Grashof number and Modified Grashof number accelerate the velocity of the flow field.
- Shrinking of Heat source parameter increases the velocity.
- Growing of Prandtl number and radiation parameter retard the temperature of the flow field.
- Shrinking of Heat source parameter decreases the temperature but growing of Soret number accelerates the temperature.
- Growing of Schmidt number and Chemical reaction parameter decrease the concentration distribution of the flow field.
- The Soret number increases the concentration of the flow field
- The Magnetic parameter decelerates the skin friction.

APPENDIX

$$m_{1} = -\frac{\left[\Pr(1-H) + \sqrt{\Pr^{2}(1-H)^{2} + 4\Pr F}\right]}{2}, m_{3} = -\frac{\left[Sc + \sqrt{Sc^{2} + 4Sc R}\right]}{2},$$

$$m_{5} = -\frac{\left[1 + \sqrt{1 + 4\left(M_{1} + \frac{1}{K}\right)}\right]}{2}, A_{1} = -\frac{Sc So m_{1}^{2}}{m_{1}^{2} + Scm_{1} - Sc R}, A_{2} = 1 - A_{1},$$

$$A_{3} = -\frac{Gr\cos\alpha}{m_{1}^{2} + m_{1} - \left(M_{1} + \frac{1}{K}\right)}, A_{4} = -\frac{Gm\cos\alpha A_{2}}{m_{3}^{2} + m_{3} - \left(M_{1} + \frac{1}{K}\right)}, A_{5} = -\frac{Gm\cos\alpha A_{1}}{m_{1}^{2} + m_{1} - \left(M_{1} + \frac{1}{K}\right)},$$

,

$$A_{6} = -(A_{3} + A_{4} + A_{5}), A_{7} = -\frac{\Pr A_{6}^{2} (m_{5}^{2} + M^{2})}{4m_{5}^{2} + 2\Pr (1 - H)m_{5} - \Pr F},$$

$$A_{8} = -\frac{\Pr (A_{3} + A_{5})^{2} (m_{1}^{2} + M^{2})}{4m_{1}^{2} + 2\Pr (1 - H)m_{1} - \Pr F}, A_{9} = -\frac{\Pr A_{4}^{2} (m_{3}^{2} + M^{2})}{4m_{3}^{2} + 2\Pr (1 - H)m_{3} - \Pr F},$$

$$A_{10} = -\frac{2 \operatorname{Pr} A_6 (A_3 + A_5) (m_1 m_5 + M^2)}{(m_1 + m_5)^2 + \operatorname{Pr} (1 - H) (m_1 + m_5) - \operatorname{Pr} F}$$

916 J. Chem. Bio. Phy. Sci. Sec. C, August 2017 – October, 2017, Vol. 7, No. 4; 906-920. [Dll: 10.24214/jcbps.C.7.4.90620.]

$$\begin{split} A_{11} &= -\frac{2 \operatorname{Pr} A_{4} \left(A_{3} + A_{5}\right) \left(m_{1}m_{3} + M^{2}\right)}{\left(m_{1} + m_{3}\right)^{2} + \operatorname{Pr} \left(1 - H\right) \left(m_{1} + m_{3}\right) - \operatorname{Pr} F}, \\ A_{12} &= -\frac{2 \operatorname{Pr} A_{4} A_{6} \left(m_{3}m_{5} + M^{2}\right)}{\left(m_{3} + m_{5}\right)^{2} + \operatorname{Pr} \left(1 - H\right) \left(m_{5} + m_{5}\right) - \operatorname{Pr} F}, \\ A_{13} &= -\left(A_{7} + A_{8} + A_{9} + A_{10} + A_{11} + A_{12}\right), \\ A_{14} &= -\frac{Sc \, So \, m_{1}^{2} \, A_{13}}{m_{1}^{2} + Sc \, m_{1} - Sc \, R}, \\ A_{15} &= -\frac{4 Sc \, So \, m_{5}^{2} \, A_{5}}{4m_{5}^{2} + 2Sc \, m_{5} - Sc \, R}, \\ A_{17} &= -\frac{4 Sc \, So \, m_{3}^{2} \, A_{5}}{4m_{5}^{2} + 2Sc \, m_{5} - Sc \, R}, \\ A_{17} &= -\frac{4 Sc \, So \, m_{3}^{2} \, A_{5}}{4m_{5}^{2} + 2Sc \, m_{5} - Sc \, R}, \\ A_{17} &= -\frac{4 Sc \, So \, m_{3}^{2} \, A_{5}}{4m_{5}^{2} + 2Sc \, m_{5} - Sc \, R}, \\ A_{17} &= -\frac{4 Sc \, So \, m_{3}^{2} \, A_{5}}{4m_{5}^{2} + 2Sc \, m_{5} - Sc \, R}, \\ A_{19} &= -\frac{Sc \, So \left(m_{1} + m_{3}\right)^{2} \, A_{11}}{(m_{1} + m_{3})^{2} + Sc \left(m_{1} + m_{3}\right) - Sc \, R}, \\ A_{19} &= -\frac{Sc \, So \left(m_{1} + m_{3}\right)^{2} \, A_{11}}{(m_{1} + m_{3})^{2} + Sc \left(m_{1} + m_{3}\right) - Sc \, R}, \\ A_{21} &= -\left(A_{14} + A_{15} + A_{16} + A_{17} + A_{18} + A_{19} + A_{20}\right), \\ A_{22} &= -\frac{Gm \cos \alpha \, A_{21}}{m_{1}^{2} + m_{1} - \left(M_{1} + \frac{1}{K}\right)}, \\ A_{23} &= -\frac{\left(Gr \, A_{3} + Gm \, A_{14}\right) \cos \alpha}{m_{1}^{2} + m_{1} - \left(M_{1} + \frac{1}{K}\right)}, \\ A_{25} &= -\frac{\left(Gr \, A_{3} + Gm \, A_{16}\right) \cos \alpha}{\left(m_{1} + m_{5}\right)^{2} + \left(m_{1} + m_{5}\right) - \left(M_{1} + \frac{1}{K}\right)}, \\ A_{27} &= -\frac{\left(Gr \, A_{16} + Gm \, A_{16}\right) \cos \alpha}{\left(m_{1} + m_{5}\right)^{2} + \left(m_{1} + m_{5}\right) - \left(M_{1} + \frac{1}{K}\right)}, \\ A_{29} &= -\frac{\left(Gr \, A_{12} + Gm \, A_{20}\right) \cos \alpha}{\left(m_{1} + m_{5}\right)^{2} + \left(m_{1} + m_{5}\right) - \left(M_{1} + \frac{1}{K}\right)}, \\ A_{29} &= -\frac{\left(Gr \, A_{12} + Gm \, A_{20}\right) \cos \alpha}{\left(m_{1} + m_{5}\right)^{2} + \left(m_{1} + m_{5}\right) - \left(M_{1} + \frac{1}{K}\right)}, \\ A_{29} &= -\left(A_{22} + A_{22} + A_{24} + A_{25} + A_{26} + A_{27} + A_{28} + A_{29}\right). \end{split}$$

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Corresponding author: V. Amuthavalli,

Research Scholar, Dept. of Mathematics, Govt. Arts College, Tiruvannamalai, Tamilnadu, India. E-mail: vamuvalli@gmail.com On line publication Date: 14.9.2017