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Aligned Magnetic Field and Diffusion Thermo Effect on Unsteady MHD Free Convective Flow past an Inclined Surface

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Abstract
This paper is focused on the study of unsteady free convective flow of a viscous, incompressible and electrically conducting fluid past an inclined plate through a porous medium in the presence of aligned magnetic field, chemical reaction and diffusion thermo effects. The free stream velocity is supposed to follow the exponentially increasing small perturbation law. The non-dimensional governing equations are solved analytically by two-term harmonic and non-harmonic functions. The velocity, temperature and concentration distributions are discussed in detail through graphs for different values of parameters entering into the problem. Also skin friction coefficient, rate of heat transfer and rate of mass transfer are derived.
Keywords: *Aligned magnetic field, inclined plate, porous, chemical reaction, unsteady.*

1. Introduction

Simultaneous heat and mass transfer flow through porous medium has many engineeering and physical applications such as drying of porous solids, geothermal resorvoirs, enriched oil revovery, thermal insultaion, and cooling of nuclear reactors. In the presence or absence of a porous medium, the combined thermal convection past a semi-infinite vertical plate has been studied by many authors [1-4]. The problem of free convection and mass transfer flow of an electrically conducting fluid past an inclined heated surface under the influence of a magnetic field has attracted interest in view of its application to geophysics, astrophysics and many engineering problems, such as cooling of nuclear reactors, the boundary layer control in aerodynamics and cooling towers. In light of these applications, Natural convection over an inclined plate was first studied experimentally by Rich [5]. Chen et al. [6] have obtained a numerical solution for the problem of natural convection over an inclined plate with variable surface temperature. Free convection heat transfer from an isothermal plate with arbitrary inclination was investigated by W.S. Yu and H.T. Lin [7]. Chamkha [8] developed a mathematical model governing boundary layer flow past an inclined plate embedded in a porous medium with non-uniform transverse magnetic field. The effects of thermal radiation and hydromagnetic on unsteady free convective flow past an vertical isothermal infinite oscillating plate are presented by Muthucumarswamy [9]. Manjulatha et al. [10] focused on aligned magnetic field effect of free convective steady flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical porous plate with heat source and radiation absorption. Asogwa [11] analyzed the radiative and chemical reaction effects over exponentially accelerated vertical infinite plate in the occurrence of constant mass flux. Ramaprasad et al. [11] have studied the free convective heat and mass trasnfer flow past an inclined moving surface of an electrically conducting, viscous, incompressible fluid in the presence of magnetic field.
Mass transfer is one of the usually encountered occurrences in chemical industries as well as in physical and biological sciences. When fluid is at rest, mass transfer takes place; the mass is transferred purely by molecular diffusion resulting from concentration gradients. For small concentration of the mass in the fluid and small mass transfer rates, the convective heat and mass transfer process are similar in nature. A number of investigations have already been carried out with combined heat and mass transfer under the assumption of different physical situations. In many chemical engineering processes, there does occur, the chemical reaction between a foreign mass and the fluid in which the

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plate is at rest. These processes take place in numerous industrial applications, namely, polymer production, manufacturing of ceramics or glassware, and food procession. Mohammed Ibrahim [12] studied numerically a problem of two dimensional unsteady MHD flow past a vertical porous plate with porous medium and chemical reaction. Jagadish Prakash et al. [13] investigated heat and mass transfer characteristics of unsteady heat absorbing fluid flow in an vertical wavy plate under the influence of chemical reaction and thermal radiation. Mythreye et al. [14] investigated the heat absorption and chemical reaction effects on unsteady MHD free convective flow past a semi-infinite vertical moving plate embedded in a porous medium. Ramaprasad et al. [15] have studied the free convective heat and mass trasnfer flow past an inclined moving surface of an electrically conducting, viscous, incompressible fluid in the presence of magnetic field. Guriviredddy et al., [16] investigated chemical reaction and soret effect on unsteady free convective flow past a moving porous plate in the presence of thermal radiaiton and pressure gradient. Kumaresan and Vijaya Kumar [17] examined the unsteady magneto hydrodynamic chemically reacting visco elatic fluid flow past a vertical plate with thermal radiation and uniform temperature. Very recently, Rajkumar et al. [18] studied viscous dissipation effects on MHD laminar flow past a semi-infinite vertical porous plate with heat generation and chemical reaction. Balakrihsna et al., [19] analyzed the effects of chemical reaction, thermal radiation and heat absorption on casson fluid flow past an infinite inclined surface embedded in a porous medium.

2. Formulation of the Problem

We consider unsteady two-dimensional flow of laminar, incompressible, viscous, electrically conducting and heat absorbing fluid past an inclined plate embedded in a porous medium in the presence of chemical reaction and dufour effects. The flow is assumed to be in the x-direction, which is taken along the semi-infinite inclined plate and y-axis normal to it. A magnetic field of uniform strength B_0 is introduced normal to the direction of the flow. The free stream velocity follows the exponentially increasing small perturbation law. In addition, it is assumed that the temperature and the concentration at the wall as well as the suction velocity are exponentially varying with time. The governing equations for this investigation are based on the balances of mass, linear momentum, energy and concentration species.

$$\frac{\partial \upsilon^*}{\partial y^*} = 0 \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + \upsilon^* \frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \nu \frac{\partial^2 u^*}{\partial y^2} + g\cos\xi\beta_T(T - T_\infty) + g\cos\xi\beta_c(c - c_\infty) - \nu\frac{u^*}{K^*} - \frac{\sigma}{\rho}B_0^2 \sin^2\alpha\, u^* \tag{2}$$

$$\frac{\partial T}{\partial t^*} + \upsilon^* \frac{\partial T}{\partial y^*} = \alpha\frac{\partial^2 T}{\partial y^{*2}} - \frac{Q_0}{\rho c_p}(T - T_\infty) + \frac{DK_T}{c_s c_p}\frac{\partial^2 c}{\partial y^{*2}} \tag{3}$$

$$\frac{\partial c}{\partial t^*} + \upsilon^* \frac{\partial c}{\partial y^*} = D\frac{\partial^2 c}{\partial y^{*2}} - D_1(c - c_\infty) \tag{4}$$

The magnetic and viscous dissipations are neglected in this study. The third and fourth terms on the RHS of the momentum Eq. (2) denote the thermal and concentration buoyancy effects, respectively. The second and last terms of the energy Eq.(3) reperesents the heat absorption and diffusion thermo effects. Also, the second term in the Eq.(4) represents chemical reaction effect. The apporpriate boundary conditions for the velocity, temperature and concentration fields are

$$u^* = 0,\quad T = T_w + \varepsilon(T_w - T_\infty)e^{n^* t^*},\quad c = c_w + \varepsilon(c_w - c_\infty)e^{n^* t^*} \quad at \quad y^* = 0 \tag{5}$$

$$u^* \to U_\infty^* = U_0(1 + \varepsilon e^{n^* t^*}), T \to T_\infty,\quad c \to c_\infty \ as \ y^* \to \infty \tag{6}$$

It is clear from Eq.(1) that the suction velocity at the plate surface is a function of time only. Assuming that it takes the following exponential form:

$$\upsilon^* = -V_0(1 + \varepsilon A e^{n^* t^*}) \tag{7}$$

where A is a real positive constant, ε and εA are small less than unity, and V_0 is a scale suction velocity which has non-zero positive constant. Outside the boundary layer, Eq (2) gives

$$-\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} = \frac{\partial U_\infty^*}{\partial t^*} + \frac{\upsilon}{K^*}U_\infty^* + \frac{\sigma}{\rho}B_0^2\sin^2\alpha\, U_\infty^* \tag{8}$$

The following are dimensionless variables:

$$u = \frac{u^*}{U_0},\quad \upsilon = \frac{\upsilon^*}{V_0},\quad y = \frac{V_0 y^*}{\upsilon},\quad U_\infty = \frac{U_\infty^*}{U_0},$$

$$Sc = \frac{\upsilon}{D},\quad M = \frac{\sigma \upsilon B_0^2}{\rho V_0^2},\quad Gr = \frac{\upsilon\beta_T g(T_w - T_\infty)}{U_0 V_0^2}$$

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$$U_p=\frac{u_p^*}{U_0},\quad t=\frac{t^*V_0^2}{\upsilon},\quad Kr=\frac{D_1\upsilon}{V_0^2},$$
$$\theta=\frac{T-T_\infty}{T_w-T_\infty},\quad \phi=\frac{c-c_\infty}{c_w-c_\infty},\quad n=\frac{n^*\upsilon}{V_0^2},\quad (9)$$
$$K=\frac{K^*V_0^2}{\upsilon^2},\quad \Pr=\frac{\upsilon\rho c_p}{k}=\frac{\upsilon}{\alpha},\quad Q=\frac{\upsilon Q_0}{\rho c_p V_0^2},$$
$$Gm=\frac{\upsilon\beta_c g(c_w-c_\infty)}{U_0V_0^2},\quad Du=\frac{DK_T}{\upsilon c_s c_p}\frac{(c_w-c_\infty)}{(T_w-T_\infty)}$$

In view of Eqs. (7) - (9), Eqs.(2) - (4) reduce to the following dimensionless form:

$$\frac{\partial u}{\partial t}-(1+\varepsilon Ae^{nt})\frac{\partial u}{\partial y}=\frac{\partial U_\infty}{\partial t}+\frac{\partial^2 u}{\partial y^2}+Gr_1\theta+Gm_1\phi+N(U_\infty-u)\quad (10)$$

$$\frac{\partial\theta}{\partial t}-(1+\varepsilon Ae^{nt})\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2}-Q\theta+Du\frac{\partial^2\phi}{\partial y^2}\quad (11)$$

$$\frac{\partial\phi}{\partial t}-(1+\varepsilon Ae^{nt})\frac{\partial\phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}-Kr\,\phi\quad (12)$$

where $N=(M\sin^2\alpha+\frac{1}{K})$, $Gr_1=Gr\cos\xi$, $Gm_1=Gm\cos\xi$ and *Gr, Gm, Pr, Q, Du, Sc, Kr,* α and ξ are the thermal Grashof number, solutal Grashof number, Prandtl number, heat absorption coefficient, dufour number, Schmidt number, chemical reaction parameter, aligned magnetic field parameter and inclined angle parameter.

The dimensionless form of the boundary conditions (5) and (6) become

$$u=0,\ \theta=1+\varepsilon e^{nt},\ \phi=1+\varepsilon e^{nt}\ \ at\ y=0\quad (13)$$
$$u\to U_\infty,\ \theta\to 0,\ \phi\to 0\quad as\quad y\to\infty\quad (14)$$

3. Solution of the Problem

Eqs. (10) – (12) represent a set of partial differential equations that cannot be solved in closed form. However, it can be reduced to a set of ordinary differential equations in dimensionless form that can be solved analytically. This can be done by representing the velocity, temperature and concentration as

$$u=u_0(y)+\varepsilon e^{nt}u_1(y)+O(\varepsilon^2)+\Lambda$$
$$\theta=\theta_0(y)+\varepsilon e^{nt}\theta_1(y)+O(\varepsilon^2)+\Lambda\quad (15)$$
$$\phi=h_0(y)+\varepsilon e^{nt}h_1(y)+O(\varepsilon^2)+\Lambda$$

Substituting Eq. (15) in to Eqs. (10) – (12), equating the harmonic and non-harmonic terms, and neglecting the higher-order terms of O(ε^2), one obtains the following pairs of equations for (u_0,θ_0,h_0) and (u_1,θ_1,h_1).

$$u_0''+u_0'-Nu_0=-Gr_1\theta_0-Gm_1h_0-N\quad (16)$$
$$u_1''+u_1'-(N+n)u_1=-Au_0'-n-N-Gr_1\theta_1-Gm_1h_1\quad (17)$$
$$\theta_0''+\Pr\theta_0'-Q\Pr\theta_0=-\Pr Duh_0''\quad (18)$$
$$\theta_1''+\Pr\theta_1'-(n+Q)\Pr\theta_1=-\Pr A\theta_0'-\Pr Duh_1''\quad (19)$$
$$h_0''+Sch_0'-KrSch_0=0\quad (20)$$
$$h_1''+Sch_1'-Sc(n+Kr)h_1=-ScAh_0'\quad (21)$$

Where a prime denotes ordinary differentiation with respect to y.

The corresponding boundary conditions can be written as

$$\begin{aligned}&u_0=0,\ u_1=0,\ \theta_0=1,\ \theta_1=1,\\ &h_0=1,\ h_1=1\quad at\quad y=0\\ &u_0=1,\ u_1=1,\ \theta_0\to 0,\ \theta_1\to 0,\\ &h_0\to 0,\ h_1\to 0\quad as\quad y\to\infty\end{aligned}\quad (22)$$

Solutions of equations (16) – (21) subject to equation (22) can be shown to be

$$u_0=1+C_9e^{-m_1y}+C_{10}e^{-m_3y}+C_{11}e^{-m_5y}\quad (23)$$
$$u_1=C_{12}e^{-m_1y}+C_{13}e^{-m_2y}+C_{14}e^{-m_3y}+C_{15}e^{-m_4y}+C_{16}e^{-m_5y}+C_{17}e^{-m_6y}+1\quad (24)$$
$$\theta_0=C_3e^{-m_1y}+C_4e^{-m_3y}\quad (25)$$
$$\theta_1=C_5e^{-m_1y}+C_6e^{-m_2y}+C_7e^{-m_3y}+C_8e^{-m_4y}\quad (26)$$
$$h_0=e^{-m_1y}\quad (27)$$
$$h_1=C_1e^{-m_1y}+C_2e^{-m_2y}\quad (28)$$

The skin friction coefficient, the rate of heat transfer in terms of Nusselt number and the rate of mass transfer in terms of Sherwood number are essential physical parameters for boundary layer flow.

Skin Friction Coefficient:

$$\tau=\left.\frac{\partial u}{\partial y}\right|_{y=0}$$
$$=(-m_1C_9-m_3C_{10}-m_5C_{11})+\varepsilon e^{nt}(-m_1C_{12}-m_2C_{13}-m_3C_{14}-m_4C_{15}-m_5C_{16}-m_6C_{17})\quad (29)$$

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Nusselt Number:

$$Nu = \left.\frac{\partial \theta}{\partial y}\right|_{y=0}$$
$$= (-m_1 C_3 - m_3 C_4) + \varepsilon e^{nt}(-m_1 C_5 - m_2 C_6 - m_3 C_7 - m_4 C_8) \quad (30)$$

Sherwood Number:

$$Sh = \left.\frac{\partial \phi}{\partial y}\right|_{y=0}$$
$$= (-m_1) + \varepsilon e^{nt}(-m_1 C_1 - m_2 C_2) \quad (31)$$

4. Results and Discussion

Numerical evaluation of the analytical results reported in the previous section was performed and a representative set of results is reported graphically in Figures 1-4. These results are obtained to illustrate the influence of the heat absorption coefficient *Q*, Dufour number *Du*, Magnetic field parameter M, Prandtl number Pr, the thermal Grashof number Gr, solutal Grashof number Gm, aligned magnetic field parameter α and inclined angle parameter ξ.

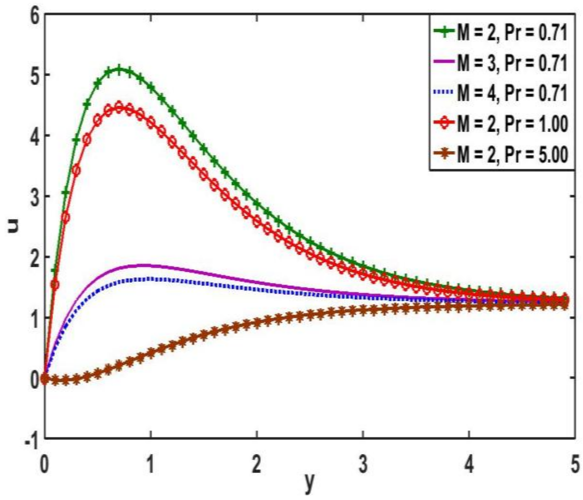

Fig.1: Effects of Pr and M on velocity profiles when A = 0.5, k = 0.5, n = 0.1, t = 1.0, ε = 0.2, Du= 1.0, *Q* = 0.1, Kr = 1.0, $\xi = \pi/6$, $\alpha = \pi/6$

The value of Schmidt number Sc is taken for water-vapour (Sc = 0.60) and Prandtl number for air (Pr = 0.71). Throughout the calculations physical variables Gr =2 and Gm = 2 are taken which correspond to a cooling problem.

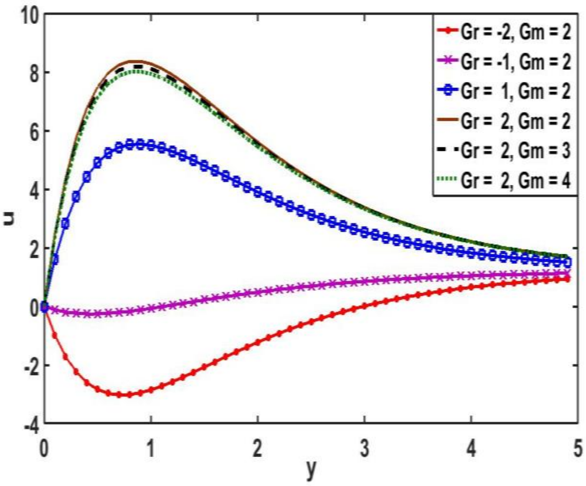

Fig.2: Effects of Gr and Gm on velocity profiles when A = 0.5, k = 0.5, n = 0.1, t = 1.0, ε = 0.2, Du = 1.0, M = 2, Kr = 1.0, $\xi = \pi/6$, $\alpha = \pi/6$

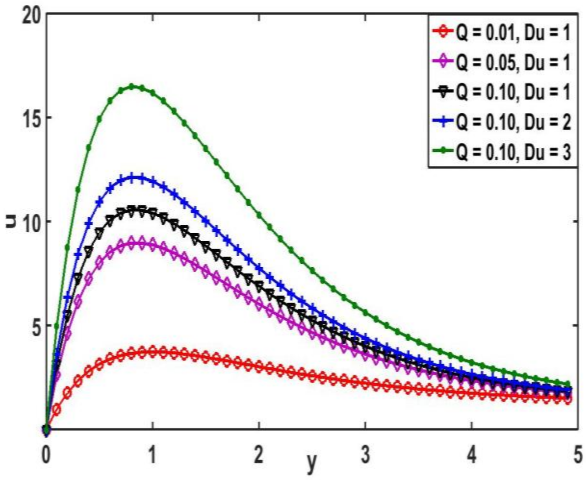

Fig.3: Effects of Q and Du on velocity profiles when A = 0.5, k = 0.5, n = 0.1, t = 1.0, ε = 0.2, *Q* = 0.1, M = 2, $\xi = \pi/6$, $\alpha = \pi/6$

In Figure 1, the effect of Prandtl number and increasing the magnetic field strength on the momentum boundary-layer thickness are illustrated. It is noticed that velocity of the fluid decreases with an increase of *Pr* and M. It is a well-established fact that the magnetic field presents a damping effect on the velocity field by creating a drag force that opposes the fluid motion, causing the velocity to decrease. The thermal Grashof number Gr signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. The solutal Grashof number Gm defines the ratio of the species buoyancy force to the viscous hydrodynamic force. From figure 2 as expected, it is observed that there is a rise in the velocity due to the enhancement of thermo buoyancy force and reduction in velocity due to species buoyancy force.

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Figure 3 displays the effects of heat absorption coefficient Q and Dufour number Du. It is observed that the velocity increases as the heat absorption coefficient Q or Dufour number Du increases. Figure 4 shows the effects of aligned magnetic field parameter α and inclined angle ξ on the velocity profile u. It is observed that the velocity decreases as the aligned magnetic field parameter α or inclined angle ξ increases.

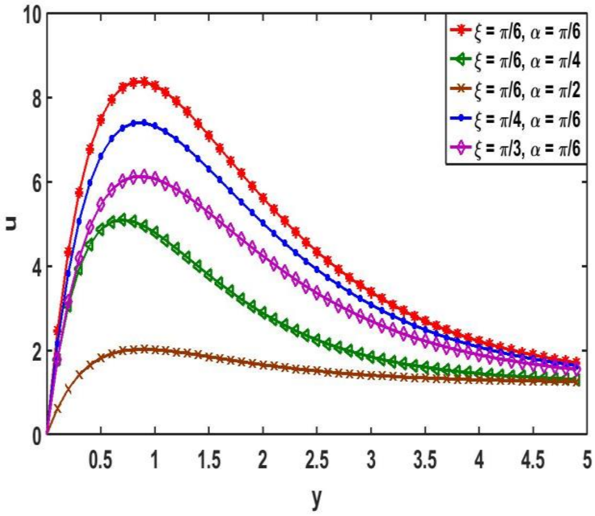

Fig.4: Effects of α and ξ on velocity profiles when A = 0.5, k = 0.5, n = 0.1, t = 1.0, ε = 0.2, Q = 1.0, M = 2, Du = 1.0, Q = 0.1

Table: The effects of Skin-friction coefficient

M	*K*	ξ	*Gr*	*Gm*	*Du*	α	τ
2	**1**	π/6	**2**	**2**	**1**	**π/6**	**27.8994**
3	1	π/6	2	2	1	π/6	7.1896
2	**0.1**	π/6	2	2	1	π/6	5.7547
2	**0.5**	π/6	2	2	1	π/6	20.8211
2	1	**π/4**	2	2	1	π/6	24.5892
2	1	**π/3**	2	2	1	π/6	20.2752
2	1	π/6	**3**	2	1	π/6	37.6630
2	1	π/6	2	**3**	1	π/6	27.1553
2	1	π/6	2	2	**2**	π/6	28.4112
2	1	π/6	2	2	1	**π/3**	20.8211
2	1	π/6	2	2	1	**π/2**	7.1734

From table it is noticed that there is a rise in skin friction coefficient with increase of permeability parameter *K* or thermal Grashof number *Gr* or Dufour number *Du* while it falls in the case of magnetic parameter *M* or inclined angle parameter ξ or solutal Grashof number *Gm* or aligned magnetic field parameter α.

5. Conclusions

The governing equations for unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical plate embedded in a porous medium with heat absorption and chemical reaction effect was formulated. The flow was subjected to a transverse magnetic field. A perturbation technique is employed to solve the resulting coupled partial equations. From the results the folloiwng conclusions are drawn.

- An increase in Prandtl number or magnetic parameter or species buoyancy force or inclined angle parameter or aligned magnetic field parameter leads to reduction in the velocity of the fluid.
- Velocity of the fluid increases due to thermal buoyancy force Gr or heat absorption coefficient Q or Dufour number Du.
- Skin friction coefficient accelerated due to rise in the permeability parameter *K* or thermal Grashof number *Gr* or Dufour number *Du* while it decreases due to magnetic field parameter *M* or inclined angle parameter ξ or solutal Grashof number *Gm* or aligned magnetic field parameter α.

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