World Applied Sciences Journal 22 (7): 975-984, 2013
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2013.22.07.495

Effect of Inclined Magnetic Field on Unsteady Free Convective Flow of Dissipative Fluid past a Vertical Plate

[1]*N.Sandeep* and [2]*V. Sugunamma*

[1]Department of Mathematics, School of Engineering and Technology, Jain University, Bangalore, India
[2]Department of Mathematics, Sri Venkateswara University, Tirupati, India

Abstract: The object of this paper is to analyze the effects of inclined magnetic field and radiation on free convective flow of dissipative fluid past a vertical plate through porous medium in presence of heat source. Boundary layer equations are derived and the resulting approximate non linear ordinary differential equations are solved analytically by using Soundalgekar proposed perturbative technique. The velocity, temperature fields are illustrated graphically. And skin friction coefficient is discussed through table for different parameters.

Key words: Unsteady free convection % Vertical plate % Heat source % Inclined Magnetic field % Radiation

INTRODUCTION

The problem of fluid flow in an electromagnetic field has been studied for its importance in geophysics, metallurgy and aerodynamic extrusion of plastic sheets and other engineering processes such as in petroleum engineering, chemical engineering, composite or ceramic engineering and heat exchangers. Radiative convective flows are encountered in countless industrial and environment processes e.g. heating and cooling chambers, fossil fuel combustion energy processes, evaporation from large open water reservoirs, astrophysical flows, solar power technology and space vehicle reentry. In the last five years, many investigations dealing with heat flow and mass transfer over a vertical porous plate with variable suction, heat absorption/ generation or Hall current have been reported. Singh [1] studied MHD free convection and mass transfer flows with Hall current, viscous dissipation, Joule heating and thermal diffusion. Azzam [2] presented radiation effects on the MHD mixed free-fixed convective flow past a semi-infinite moving vertical plate for high temperature differences. Chamkha [3] presented thermal radiation and buoyancy effects on hydro-magnetic flow over an accelerating permeable surface with heat source or sink. Chen [4] studied heat and mass transfer with variable wall temperature and concentration. Cookey *et al*. [5] investigated the influence of viscous dissipation and radiation on unsteady MHD free-convection flow past an infinite heated vertical plate in a porous medium with time dependent suction. Hayat and Abbas[6] presented the radiation effects on MHD flow in a porous space. Ogulu *et al*.[7] studied unsteady MHD free convective flow of a compressible fluid past a moving vertical plate in the presence of radiative heat transfer. Ogulu and Mbeledogu [8] studied 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. Pilani and Ganesan [9] presented finite difference analysis of unsteady natural convection MHD flow past an inclined plate with variable surface heat and mass flux. Recently, Prakash *et al*. [10] have studied MHD free convection and mass transfer flow of a micro-polar thermally radiating and reacting fluid with time dependent suction. England and Emery [11] have studied the thermal radiation effects of an optically thin gray gas bounded by a stationary vertical plate. Soundalgekar and Takhar [12] have considered the additive free convective flow of an optically thin gray-gas past a semi-infinite vertical plate. Radiation effects on mixed convection along an isothermal vertical plate were studied by Hossain and Takhar [13].

In many of above studies, the stationary vertical plate is considered. Raptis [14] studied radiation effects on flow of a micro polar fluid past a continuously moving plate. Raptis and Perdikis [15] studied the effects of thermal radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically.

Corresponding Author: N. Sandeep, Department of Mathematics,
School of Engineering and Technology, Jain University, Bangalore, India.

Das, *et al*. [16] have analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate. The governing equations were solved by the Laplace transform technique. Radiation in free convection is also examined by several investigators due to their important applications in the areas of prime importance. This is due to the significant role of thermal radiation in surface heat transfer when convection heat is assumed to be relative small particularly in free convection problems involving and absorbing emitting fluids. In all these studies the problem is confined to unsteady flow in a nonporous medium. However, it is observed that unsteady flow in case of porous medium was received less attention. The species generation in a homogeneous reaction is analogous to internal source of heat generation. In contrast, a heterogeneous reaction takes place in a restricted region or within the boundary of a phase. Therefore it can be treated as a boundary condition similar to the constant heat flux condition in the heat transfer.

The heat source/sink effects in thermal convection, are significant where there may exist a high temperature differences between the surface (e.g. space craft body) and the ambient fluid. Heat generation is also important in the context of exothermic or endothermic chemical reactions. Ramachandra Prasad *et al*. [17] analyzed the radiation effects on an unsteady two dimensional hydromagnetic free convective boundary layer flow of a viscous incompressible fluid past a semi-infinite vertical plate with mass transfer in the presence of heat source or sink. Gebhart and Mollendorf [18] and Gebhart [19] have shown that viscous dissipative heat is important when the free convective flow field is of extreme size or the flow is at extremely low temperature or in a high gravity field. Singh and Sacheti [20] followed the study by Soundalgekar and Hiremath [21], which looked at the flow past an impulsively started infinite isothermal vertical plate in a dissipative fluid. A few other works of interest in this area include Ogulu and Prakash [22], Kim[23] and Makinde [24], A.Ogulu and O.D. Makinde [25].

The object of this study is to analyze the effects of radiation and inclined magnetic field on free convective flow of dissipative fluid past a vertical plate through porous medium with heat source by applying a simple perturbation technique. Most of the studies mentioned above have applied one numerical technique or the other, whereas here we have used a much simpler time-saving technique.

Mathematical Formulation: We consider the two-dimensional unsteady flow of an incompressible, electrically conducting viscous Boussinesq fluid in a Cartesian (x^1,y^1) coordinate system with a transversely applied magnetic field, so that in the spirit of Gebhart (1962), Singh and Sacheti (1988) and Gebhart and Mollendorf (1969) the proposed governing equations are

$$\frac{\partial u'}{\partial t'} = v\frac{\partial^2 u'}{\partial y'^2} + g\,b\,(T - T_\infty) - \frac{n}{k}u' - BSin^2 y\,u' \tag{1}$$

$$\frac{\partial T}{\partial t'} = \frac{k}{r\,c_p}\frac{\partial^2 T}{\partial y'^2} + \frac{n}{c_p}\left(\frac{\partial u'}{\partial y'}\right)^2 - \frac{\partial q_r'}{\partial y'} + Q(T - T_\infty) \tag{2}$$

$$\frac{\partial^2 q_r'}{\partial y'^2} - 3a^2 q_r' - 16a\,s\,T_\infty^3\frac{\partial T}{\partial y'} = 0 \tag{3}$$

where u' is the velocity component, T is temperature, t' is time, L is the kinematics coefficient of viscosity, D is fluid density, c_p is the specific heat capacity at constant pressure, k is the thermal conductivity, 6 is porosity, Q is volumetric rate of heat generation/absorption q_r' is the radiative flux vector, F is the electrical conductivity, $B = \frac{s\,B_0^2}{r}$ is the applied magnetic field, R inclined angle, g is the acceleration due to gravity, $ is the coefficient of volume expansion due to temperature and subscript 4 denotes conditions in the free stream. For an optically thin fluid we have (Israel-Cookey *et al*., (2002))

$$\frac{\partial q_r'}{\partial y'} = 4a^2(T - T_\infty) \tag{4}$$

where

$$a^2 = \int_0^\infty dl\,\frac{\partial B}{\partial T} \tag{5}$$

and "^{2} is the absorption coefficient, 8 is frequency, B is Planck's function and * is the radiation absorption coefficient.

The initial and boundary conditions are (Singh and Sacheti, (1988)).

t'#0: u'=0,T=T_4 For all y'

$$t' > 0:\begin{cases} u' = U, \dfrac{\partial T}{\partial y'} = -\dfrac{q}{k}, at, y' = 0 \\ u' \to 0, T = T_\infty, as, y' \to \infty \end{cases} \tag{6}$$

where q is the constant heat flux at the plate surface.

We find it convenient to now introduce the following non-dimensional quantities and parameters

$$y=\frac{y'U}{v},\ t=\frac{t'U^2}{v},\ u=\frac{u'}{U},\ \Pr=\frac{r v c_p}{k},$$
$$G\mathrm{r}=\frac{g b v^2 q}{kU^4},\ M^2=\frac{s B_0{}^2 v}{rU^2},\ q=\frac{kU(T-T_\infty)}{qv}$$
$$k=\frac{kU^2}{n^2},\ Ec=\frac{kU^3}{C_P n q},\ Ra=\frac{4a^2 v}{U^2},\ S=\frac{Qv}{U^2} \quad (7)$$

where Pr is the Prandtl number, Gr is the Grashof number, M is the Hartmann number, Ra is the radiation parameter and S is the heat source parameter.

$$\frac{\partial u}{\partial t}=\left(\frac{\partial^2}{\partial y^2}-M^2 Sin^2 y\ -k\right)u+Grq \quad (8)$$

$$\Pr\frac{\partial q}{\partial t}=\left(\frac{\partial^2}{\partial y^2}-(Ra-S)\Pr\right)q+Ec\Pr\left(\frac{\partial u}{\partial y}\right)^2 \quad (9)$$

The appropriate boundary conditions now become

t#0: u = 0, 2 = 0 for all y

$$t>0:\begin{cases}u=1,\dfrac{\partial q}{\partial y}=-1, at, y=0\\ u\to 0, q=0, as, y\to\infty\end{cases} \quad (10)$$

We seek the solution of Equations (5) and (6) subject to the conditions in Equation (7) as a power series in g, where g << 1. For all dependent variables we write

$$u(y,t)=u_0(y)+e e^{\mathrm{int}}u_1(y)$$
$$q(y,t)=q_0(y)+e e^{\mathrm{int}}q_1(y) \quad (11)$$

Substituting Equation (8) into Equations (5)–(6), we obtain the following
Sequence of approximations:

$$\frac{d^2u_0}{dy^2}-(M^2 Sin^2 y\ +k)u_0=-Grq_0 \quad (12)$$

$$\frac{d^2q_0}{dy^2}-(Ra-S)\Pr q_0=-Ec\Pr\left(\frac{du_0}{dy}\right)^2 \quad (13)$$

$$u_0=1,\frac{dq_0}{dy}=-1\ \text{ On } y=0\ \ u_0\to 0, q_0\to 0\ \text{ as }\ y\to\infty \quad (14)$$

For O (1) equations

$$\frac{d^2u_1}{dy^2}-\left(in+M^2 Sin^2 y\ +k\right)u_1=-Grq_1 \quad (15)$$

$$\frac{d^2q_1}{dy^2}-\Pr(in+Ra-S)q_1=-2Ec\Pr\left(\frac{du_0}{dy}\frac{du_1}{dy}\right) \quad (16)$$

u_1 = 0, 2$_1$ = 0 On y=0

u_1 6 0, 2$_1$ 6 0 As y 6 4 (17)

For O(g) equations.

As observed in Soundalgekar, the Eckert number Ec (viscous dissipation parameter) for incompressible flows is a small so we can further expand our flow variables as

$$u_0(y)=u_{01}(y)+Ecu_{02}(y)$$
$$u_1(y)=u_{11}(y)+Ecu_{12}(y)$$
$$q_0(y)=q_{01}(y)+Ecq_{02}(y)$$
$$q_1(y)=q_{11}(y)+Ecq_{12}(y) \quad (18)$$

Substituting Equation (18) into (12) to (17), we get

$$\frac{d^2u_{01}}{dy^2}-(M^2 Sin^2 y\ +k)u_{01}=-Grq_{01} \quad (19)$$

$$\frac{d^2q_{01}}{dy^2}-(Ra-S)\Pr q_{01}=-Ec\Pr\left(\frac{du_{01}}{dy}\right)^2 \quad (20)$$

$$\frac{d^2u_{11}}{dy^2}-\left(in+M^2 Sin^2 y\ +k\right)u_{11}=-Grq_{11} \quad (21)$$

$$\frac{d^2q_{11}}{dy^2}-\Pr(in+Ra-S)q_{11}=-2Ec\Pr\left(\frac{du_{01}}{dy}\frac{du_{11}}{dy}\right) \quad (22)$$

With boundary conditions

$$u_{01}=1,\frac{dq_{01}}{dy}=1\ \text{on}\ y=0\ u_{01}\to 0, q_{01}\to 0\ \text{ as }\ y\to\infty$$

$$u_{11}=0, q_{11}=0\ \ \text{on}\ y=0\ u_{11}\to 0, q_{11}\to 0\ \text{ as }\ y\to\infty \quad (23)$$

From equations (12) to (23) we get the final solutions as

$$\begin{aligned} u(y,t) &= A_2 \exp(-a_2 y) - A_1 \exp(-a_1 y) \\ &+ Ec \left\{ \begin{array}{l} B\exp(-a_2 y) + A_6 \exp(-a_1 y) - A_7 \exp(-2a_2 y) \\ -A_8 \exp(-2a_1 y) + A_9 \exp(-a\, y) \end{array} \right\} \\ &+ e e^{\text{int}} \left\{ \begin{array}{l} \left((1+A_{10})\exp(-a_4 y) - A_{10}\exp(-a_3 y)\right) \\ +Ec \left(\begin{array}{l} D\exp(-a_4 y) - A_{20}\exp(-a_3 y) \\ +A_{21}\exp(-b\, y) + A_{22}\exp(-\Omega y) \\ +A_{23}\exp(-h\, y) + A_{24}\exp(-x\, y) \end{array} \right) \end{array} \right\} \end{aligned} \tag{24}$$

$$\begin{aligned} q(y,t) &= \frac{1}{a_1}\exp(-a_1 y) + Ec \left\{ \begin{array}{l} A\exp(-a_1 y) - A_3 \exp(-2a_2 y) \\ -A_4 \exp(-2a_1 y) + A_5 \exp(-a\, y) \end{array} \right\} \\ &+ e e^{\text{int}} \left\{ \frac{1}{a_3}\exp(-a_3 y) + Ec \left(\begin{array}{l} C\exp(-a_3 y) - A_{16}\exp(-b\, y) \\ -A_{17}\exp(-\Omega y) - A_{18}\exp(-h\, y) \\ -A_{19}\exp(-x\, y) \end{array} \right) \right\} \end{aligned} \tag{25}$$

Where quantities involved in (24) and (25) are involved in appendix.

Skin-Friction Coefficient: Skin-friction Coefficient at the plate (ô) is given by

$$\begin{aligned} t &= \left(-\frac{\partial u}{\partial y} \right)_{y=0} \\ &= a_2 A_2 - a_1 A_1 - Ec\{ -a_2 B - a_1 A_6 + 2a_2 A_7 + 2a_1 A_8 - a\, A_9 \} \\ &- e e^{\text{int}} \left\{ \left(-a_4(1+A_{10}) + a_3 A_{10}\right) + Ec \left(\begin{array}{l} -a_4 D + a_3 A_{20} - b\, A_{21} - \Omega A_{22} \\ -h\, A_{23} - x\, A_{24} \end{array} \right) \right\} \end{aligned} \tag{26}$$

RESULTS AND DISCUSSION

In order to study the behavior of velocity (u) and temperature (*2*) fields, a comprehensive numerical computation is carried out for various values of the parameters that describe the flow characteristics and the results are reported in terms of graphs as shown in Figures and Table I. Here Eckert number (which is very small in parameter values for free convective flow) may be interpreted as a constant measure of the heat due to viscous dissipation and takes the values 0.01 and 0.05, as this will be more appropriate from the practical point of view. Here we analysed the results at two inclined angles $y = \frac{p}{2}$ (Black) and $y = \frac{p}{6}$ (Red)

In Table I we depict the effect of material parameters on the skin friction *J*. We observe that increase in the radiation parameter results in an increase in the skin friction for both heating and cooling of the plate by free convection current and increase of Eckert number causes decrease of skin friction. On the other hand, increase in the heat source parameter leads to a increase in the skin friction when the plate is cooled by free convection current (Gr > 0) but an decrease in the skin friction when the plate is heated by free convection current (Gr < 0).

Table I : Effect of material parameters on the skin friction:

Gr	*Er*	pr	*Ra*	*S*	*J*
2	0.01	0.71	3	0.5	1.37221
2	0.05	0.71	3	0.5	1.34752
5	0.01	0.71	3	0.5	0.35830
5	0.05	0.71	3	0.5	0.100930
5	0.05	0.71	2	0.5	-0.607131
-5	0.01	0.71	3	0.5	3.699112
5	0.01	0.71	2	0.5	-0.340284
-5	0.01	0.71	2	0.5	4.373066
-2	0.01	7.0	2	0.5	2.196923
-2	0.01	7.0	2	1.0	2.257558
2	0.01	7.0	2	1.0	1.807792
5	0.05	7.0	3	1.0	1.436303

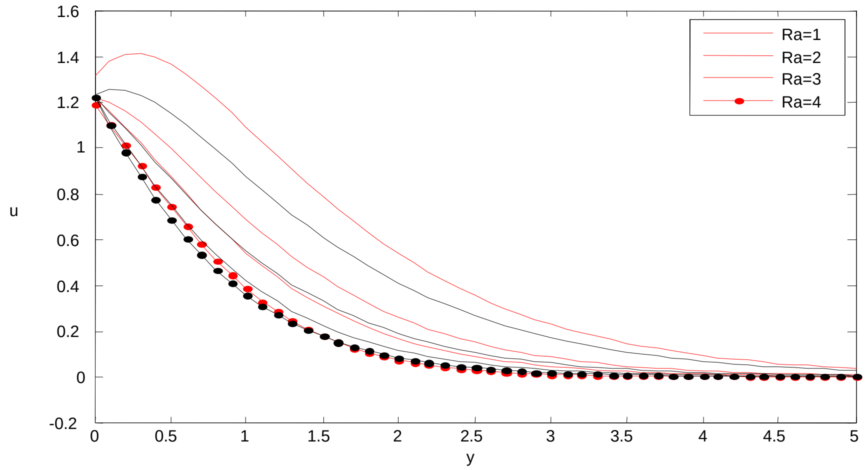

Fig. 1: Effect of Radiation parameter (Ra) on velocity field u
When M=1,Ec=0.01,n=1=t,k=2;S=0.5;B=0.4,*g*=0.04;Pr=0.71,Gr=5.

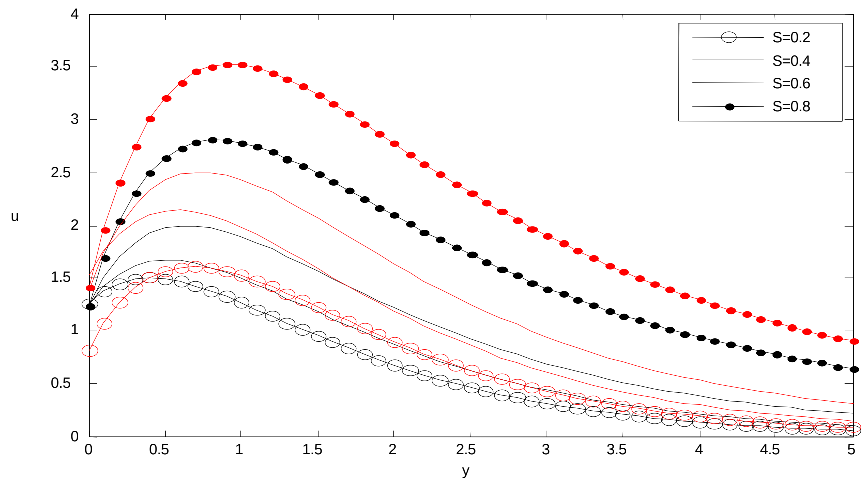

Fig. 2: Effect of Heat Source parameter (S) on velocity field u
When Gr=5,M=1,Ec=0.01,n=1=t,k=2;Ra=1;B=0.4,*g*=0.04;Pr=0.71.

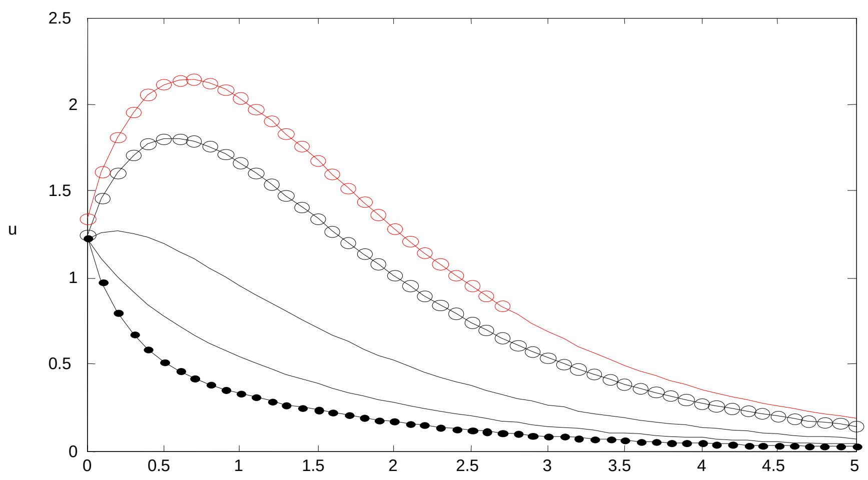

Fig. 3: Effect of Magnetic field (M) on velocity field u
When Gr=5,S=0.5,Ec=0.01,n=1=t,k=2;Ra=1;B=0.4,*g*=0.04;Pr=0.71.

Fig (1) depicts the velocity rises rapidly from unity at the plate, attains a maximum near the plate and decreases to the free stream value away from the plate and also we observe that velocity profiles decreases by increase of Radiation parameter (Ra). It is interesting to note that by decreasing inclined angle we observe that the gradual increase in fluid flow.

Fig (2) shows that the rapid increase of velocity from unity at the plate, attains a maximum near the plate and decreases to the free stream value away from the plate and also we observe that velocity profiles increases by increase of Heat source parameter (S). But at $y = \frac{p}{6}$ velocity increases rapidly and reached the peak value 3.5 near the plate and at lower level of heat source fluid flow starts at lower level.

From Figure (3) it is clear that the velocity profiles increases with decrease of magnetic field M, at lower magnetic field velocity profiles attains its maximum value near the plate. And at higher magnetic field velocity decreases rapidly .But at lower angle of inclination we can't identify any gradual decrease in fluid flow.

Figure (4) shows the effect of inclination angle on velocity profiles. It is evident that increasing of inclination angle causes the decrease of fluid velocity.

Fig (5) depicts the increase of velocity from unity at the plate and decreases away from the plate and also we observe that velocity profiles decreases by increase of Prandtl number (Pr). But at Pr = 1.0 and $y = \frac{p}{6}$ velocity starts at 3.5.

From Figure (6) velocity profiles attains maximum near the plate at low porosity value but while decreasing the inclination angle and at lower porosity level the velocity of fluid is reversed.

Figure (7) shows an exponential increase in the fluid velocity from the plate surface to the free stream value away from the plate. However, it is interesting to note that as the increase of dissipation parameter Ec causes the increase of velocity near the palate in both cases of $y = \frac{p}{6}$ and $y = \frac{p}{2}$ and the gradual decrease of velocity afterwards.

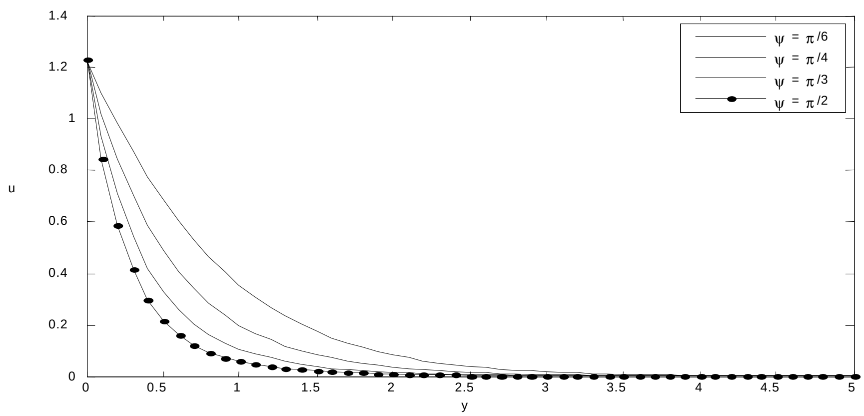

Fig. 4: Effect of Inclined angle (*R*) on velocity field u
When M=2, Gr=5,S=0.5,Ec=0.01,n=1=t,k=2;Ra=1;B=0.4,*g*=0.04;Pr=0.71.

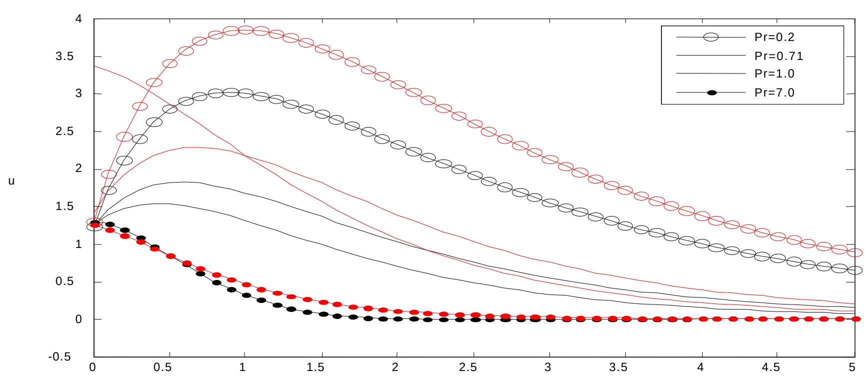

Fig. 5: Effect of Prandtl number (Pr) on velocity field u
When Gr=5,S=0.5,Ec=0.01,n=1=t,k=2;Ra=1;B=0.4,*g*=0.04;M=1.

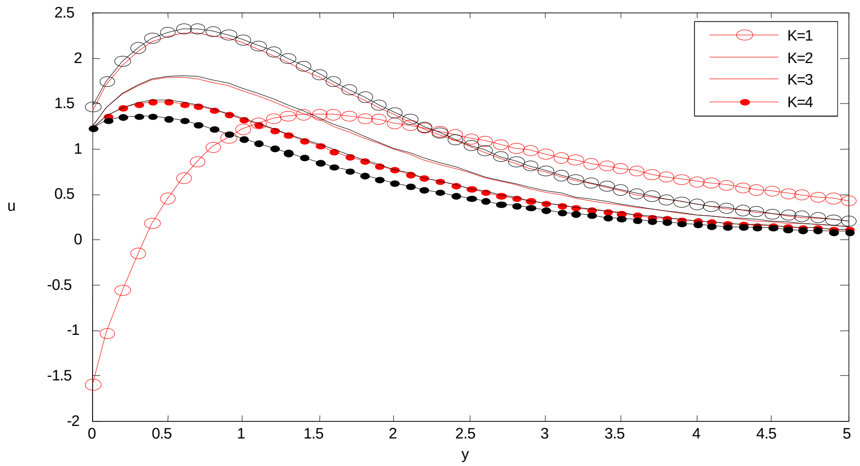

Fig. 6: Effect of Porosity parameter (k) on velocity field u
When Gr=5,S=0.5,Ec=0.01,n=1=t,Pr=0.71,Ra=1;B=0.4,g=0.04;M=1.

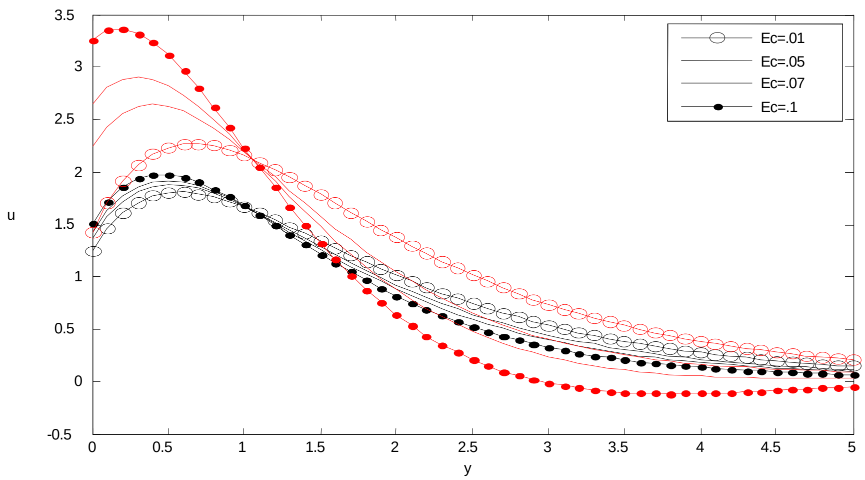

Fig. 7: Effect of Eckert number (Ec) on velocity field u
When,S=0.5,n=1=t,Ra=1,Pr=0.71,B=0.4,g=0.04,M=1.

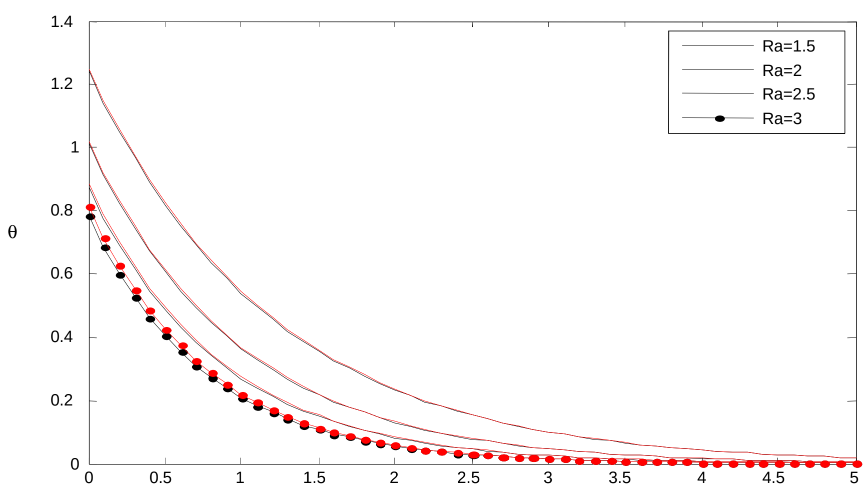

Fig. 8: Effect of Radiation parameter (Ra) on temperature field 2.
When Gr=5,S=0.5,n=1=t,k=2,Ec=0.01,Pr=0.71,B=0.4,g=0.04,M=1.

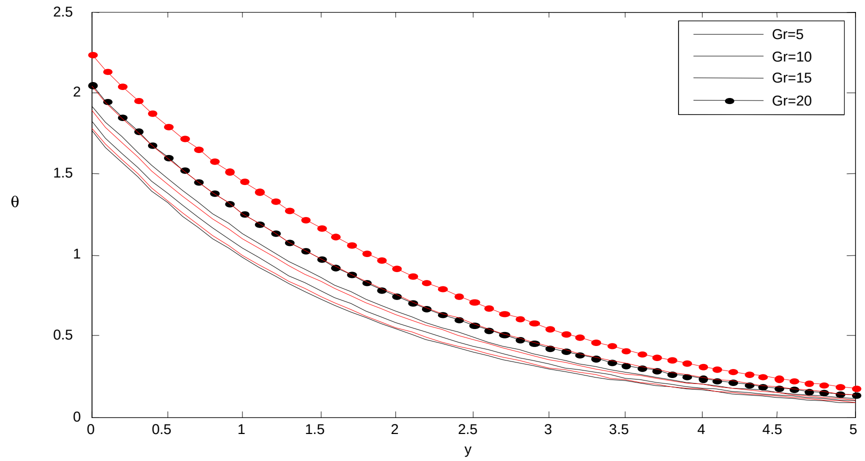

Fig. 9: Effect of Grashoff number (Gr) on temperature field 2.
When Ra=1,S=0.5,n=1=t,k=2,Ec=0.01,Pr=0.71,B=0.4,*g*=0.04,M=1.

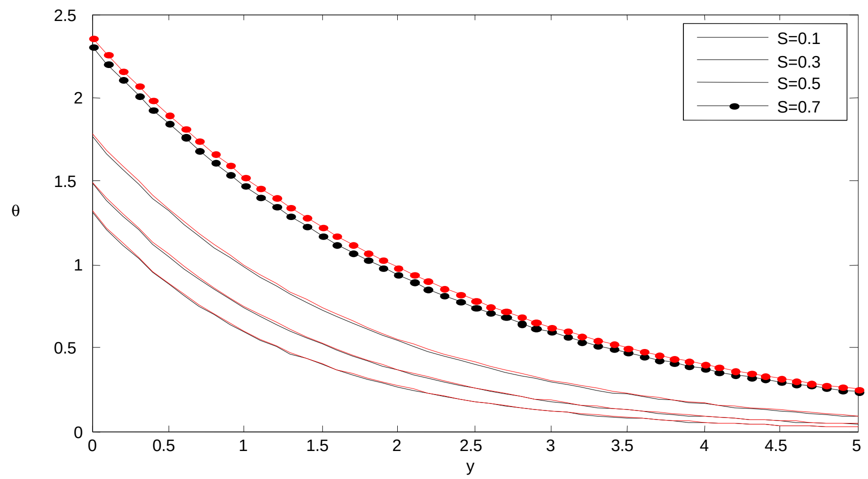

Fig. 10: Effect of Heat Source parameter (S) on temperature field 2.
When Ra=1,Gr=5,n=1=t,k=2,Ec=0.01,Pr=0.71,B=0.4,*g*=0.04,M=1.

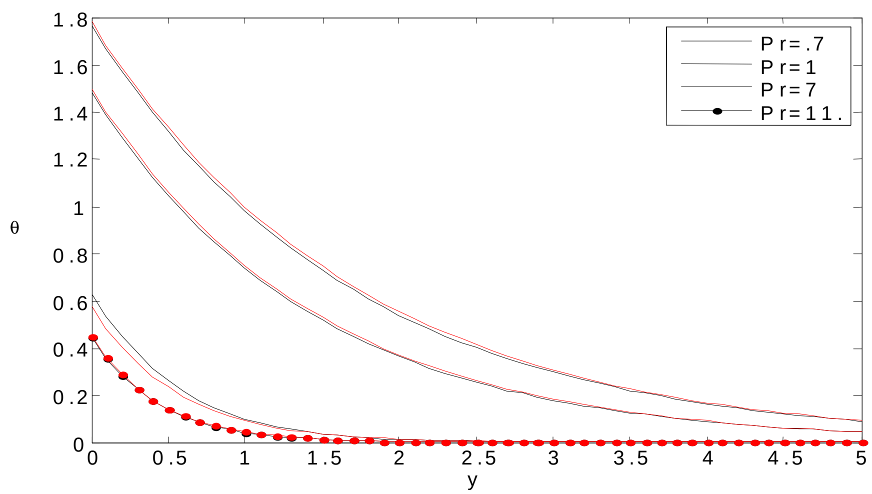

Fig. 11: Effect of Prandtl number (Pr) on temperature field 2.
When Ra=1,Gr=5,S=0.5,n=1=t,k=2,Ec=0.01,B=0.4,*g*=0.04,M=1.

Figure (8) shows an increase in the fluid temperature from the plate surface to the free stream value away from the plate by decreasing the radiation parameter. From figure (9) we observe that increase of Gr affects the increase in temperature.

From figure (10) we observe that the increase of heat source parameter causes the gradual increase in temperature profiles. But it is reversed in case of prandtl number from figure (11) it is clear that increase of prandtl number causes the decrease of temperature profiles.

But from Figures (8) to (11) we observe that decrease in inclination angle shows slight increase in temperature profiles.

CONCLUSIONS

- We conclude that decrease in inclination angle reduces the magnetic field effect. Because of this reason at $y = \frac{p}{6}$ fluid velocity and temperature increases slightly.
- We conclude that Increase in the viscous dissipation Ec results in a decrease in the skin friction Gr >0.
- Increase in Gr and Ra results increase in skin friction for Gr >0.
- But increase in Ra and decrease in Gr doesn't show much effect on increase or decrease in skin friction.
- Increase of heat source parameter causes the increase in velocity of fluid flow while Gr >0.

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