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Mhd Free Convection Flow Of Dissipative Fluid Past An Exponentially Accelerated Vertical Plate

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ABSTRACT
Aim of the paper is to investigate the hydromagnetic effects on the unsteady free convection flow, heat and mass transfer characteristics in a viscous, incompressible and electrically conducting fluid past an exponentially accelerated vertical plate by taking into account the heat due to viscous dissipation. The problem is governed by coupled non-linear partial differential equations. The dimensionless equations of the problem have been solved numerically by the unconditionally stable finite difference method of Dufort – Frankel's type. The effects of governing parameters on the flow variables are discussed quantitatively with the aid of graphs for the flow field, temperature field, concentration field, skin-friction, Nusselt number and Sherwood number.

Key words: MHD, free convection, viscous dissipation, finite difference method, exponentially accelerated plate, variable temperature and concentration.

I. INTRODUCTION

Free convection flow involving coupled heat and mass transfer occurs frequently in nature and in industrial processes. A few representative fields of interest in which combined heat and mass transfer plays an important role are designing chemical processing equipment, formation and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of fruit trees, crop damage due to freezing, and environmental pollution. Hydromagnetic flows and heat transfer have become more important in recent years because of its varied applications in agricultural engineering and petroleum industries. Recently, considerable attention has also been focused on new applications of magneto-hydrodynamics (MHD) and heat transfer such as metallurgical processing. Melt refining involves magnetic field applications to control excessive heat transfer rate. Other applications of MHD heat transfer include MHD generators, plasma propulsion in astronautics, nuclear reactor thermal dynamics and ionized-geothermal energy systems.

Pop and Soundalgekar [1] have investigated the free convection flow past an accelerated infinite plate. Singh and Soundalgekar [2] have investigated the problem of transient free convection in cold water past an infinite vertical porous plate. An excellent summary of applications can be found in Hughes and Young [3]. Takar et al. [4] analyzed the radiation effects on MHD free convection flow past a semi-infinite vertical plate using Runge-Kutta-Merson quadrature. Samria et al. [5] studied the hydromagnetic free convection laminar flow of an elasto-viscous fluid past an infinite plate. Recently the natural convection flow of a conducting visco-elastic liquid between two heated vertical plates under the influence of transverse magnetic field has been studied by Sreehari Reddy et al. [6].

In all these investigations, the viscous dissipation is neglected. The viscous dissipation heat in the natural convective flow is important, when the flow field is of extreme size or at low temperature or in high gravitational field. Such effects are also important in geophysical flows and also in certain industrial operations and are usually characterized by the Eckert number. A number of authors have considered viscous heating effects on Newtonian flows. Israel-Cookey et al. [7] 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. Zueco Jordan [8] used network simulation method (NSM) to study the effects of viscous dissipation and radiation on unsteady MHD free convection flow past a vertical porous plate. Suneetha et al. [9] have analyzed the effects of viscous dissipation and thermal radiation on hydromagnetic free convection flow past an impulsively started vertical plate. Hitesh Kumar [10] has studied the boundary layer steady flow and radiative heat transfer of a viscous incompressible fluid due to a stretching plate with viscous dissipation effect in the presence of a transverse magnetic field. Recently The effects of radiation on unsteady MHD free convection flow of a viscous incompressible electrically conducting fluid past an exponentially accelerated vertical plate in the presence of a uniform transverse magnetic field on taking viscous and Joule dissipations into account have been studied by Maitree Jana et.al [11].

The study of heat and mass transfer is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. Possible applications of this type of flow can be found in many industries like power industry and chemical process industries.

Muthukumaraswamy et al. [12] investigated mass diffusion effects on flow past a vertical surface. Mass diffusion and natural convection flow past a flat plate studied by researchers like Chandrasekhara et al. [13] and Panda et al. [14]. Magnetic effects on such a flow is investigated by Hossain et al. [15] and Israel et al. [16]. Sahoo et al. [17] and Chamkha et al. [18] discussed MHD free convection flow past a vertical plate through porous medium in the presence of foreign mass. Chaudhary et.al. [19] have studied the MHD flow past an infinite vertical oscillating plate through porous medium, taking account of the presence of free convection and mass transfer. Very recently Siva Nageswara Rao et.al [20] have investigate the convective study of heat and mass transfer flow of a viscous electrically conducting fluid in a vertical wavy channel under the influence of an inclined magnetic fluid with heat generating sources.

The objective of the present work is to study the transient free convection flow of an incompressible viscous fluid past an exponentially accelerated vertical plate by taking into account viscous dissipative heat, under the influence of a uniform transverse magnetic field in the presence of variable surface temperature and concentration. We have extended the problem of Muthucumaraswamy et al. [21] in the absence of chemical reaction.

II. MATHEMATICAL ANALYSIS

The transient MHD free convection flow of an electrically conducting, viscous dissipative incompressible fluid past an exponentially accelerated vertical infinite plate with variable temperature and concentration has been presented. The present flow configuration is shown in Figure 1.

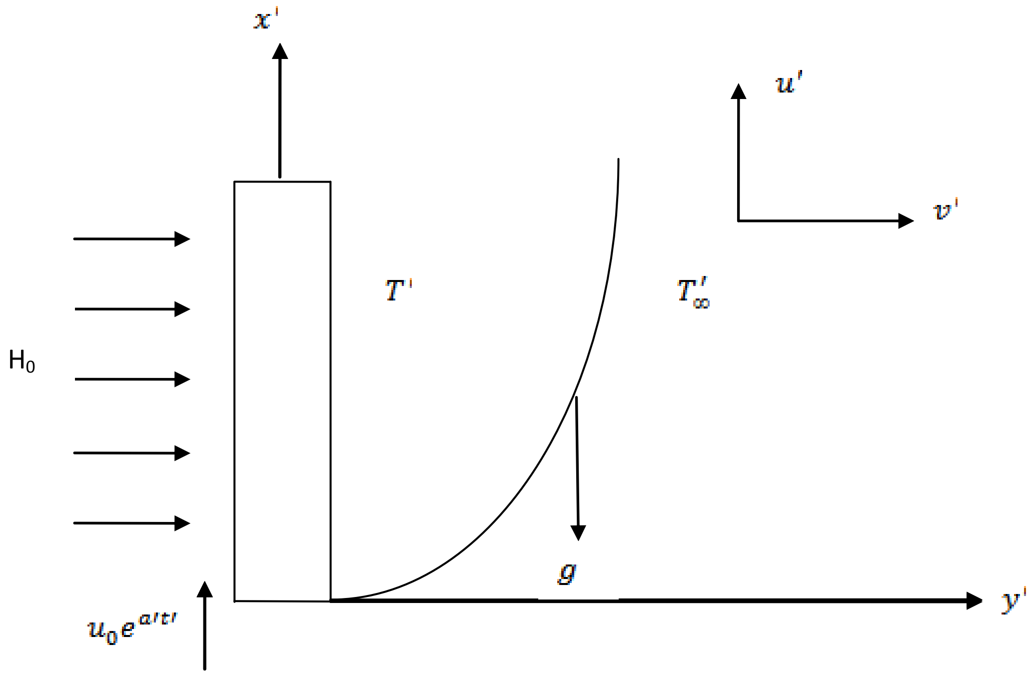

Figure (1): Flow configuration and coordinate system

The x'- axis is taken along the plate in the vertically upward direction and the y'– axis is taken normal to the plate. Since the plate is considered infinite in x'- direction, all flow quantities become self-similar away from the leading edge. Therefore, all the physical variables become functions of t' and y' only. At time $t' \le 0$, the plate and fluid are at the same temperature T'_∞ and concentration C'_∞ lower than the constant wall temperature T'_w and concentration C'_w respectively. At $t' > 0$, the plate is exponentially accelerated with a velocity

$u' = u_0 \exp(a't')$ in its own plane and the plate temperature and concentration are raised linearly with time t'. A uniform magnetic field of intensity H_0 is applied in the y' – direction. Therefore the velocity and the magnetic field are given by $\bar{q} = (u, v)$ and $\bar{H} = (0, H_0)$. The fluid being electrically conducting the magnetic Reynolds number is much less than unity and hence the induced magnetic field can be neglected in comparison with the applied magnetic field in the absence of any input electric field. The heat due to viscous dissipation is taken into an account. Under the above assumptions as well as Boussinesq's approximation, the equations of conservation of mass, momentum, energy and species governing the free convection boundary layer flow past an exponentially accelerated vertical plate can be expressed as:

$$\frac{\partial v'}{\partial y'} = 0 \tag{1}$$

$$\frac{\partial u'}{\partial t'} = g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) + \upsilon \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma \mu_e^2 H_0^2}{\rho} u' \tag{2}$$

$$\rho C_p \frac{\partial T'}{\partial t'} = k \frac{\partial^2 T'}{\partial y'^2} + \mu \left(\frac{\partial u'}{\partial y'}\right)^2 \tag{3}$$

$$\frac{\partial C'}{\partial t'} = D \frac{\partial^2 C'}{\partial y'^2} \tag{4}$$

with the following initial and boundary conditions:

$$u' = 0, \quad T' = T'_\infty \quad C' = C'_\infty; \quad \text{for all } y', t' \le 0$$

$$t' > 0: \quad u' = u_0 \exp(a't'),$$
$$T' = T'_\infty + (T'_w - T'_\infty) A t',$$
$$C' = C'_\infty + (C'_w - C'_\infty) A t', \quad \text{at } y' = 0$$
$$u' \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty, \quad \text{as } y' \to \infty \tag{5}$$

Where $A = \frac{u_0^2}{\upsilon}$, T'_w and C'_w are constants not wall values.

On introducing the following non-dimensional quantities:

$$u = \frac{u'}{u_0}, \quad t = \frac{t' u_0^2}{\upsilon}, \quad y = \frac{y' u_0}{\upsilon}, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \quad M = \frac{\sigma \mu_e^2 H_0^2 \upsilon}{\rho u_0^2},$$

$$Gr = \frac{g\beta\upsilon(T'_w - T'_\infty)}{u_0^3}, \quad \Pr = \frac{\mu C_p}{k}, \quad E = \frac{u_0^2}{C_p(T'_w - T'_\infty)}, \quad a = \frac{a'\upsilon}{u_0^2} \tag{6}$$

$$Gc = \frac{g\beta^*\upsilon(C'_w - C'_\infty)}{u_0^3}, \quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Sc = \frac{\upsilon}{D}$$

in equations (1) to (5), lead to

$$\frac{\partial u}{\partial t} = Gr\theta + GcC + \frac{\partial^2 u}{\partial y^2} - Mu \tag{7}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr} \frac{\partial^2 \theta}{\partial y^2} + E\left(\frac{\partial u}{\partial y}\right)^2 \tag{8}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc} \frac{\partial^2 C}{\partial y^2} \tag{9}$$

The initial and boundary conditions in non-dimensional quantities are

$$u = 0, \quad \theta = 0, \quad C = 0 \quad \text{for all} \quad y, t \le 0$$
$$t > 0: u = \exp(at), \quad \theta = t, \quad C = t \quad \text{at} \quad y = 0 \tag{10}$$
$$u \to 0, \quad \theta \to 0, \quad C \to 0 \quad \text{as} \quad y \to \infty$$

The skin-friction, Nusselt number and Sherwood number are the important physical parameters for this type of boundary layer flow, which in non-dimensional form respectively are given by:

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0} \tag{11}$$

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} \tag{12}$$

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} \tag{13}$$

III. NUMERICAL TECHNIQUE

Equations (7) – (9) are coupled non-linear partial differential equations and are to be solved under the initial and boundary conditions of equation (10). However exact solution is not possible for this set of equations and hence we solve these equations by the unconditionally stable explicit finite difference method of DuFort – Frankel's type as explained by Jain et. al. [22]. The finite difference equations corresponding to equations (7) – (9) are as follows:

$$\left(\frac{u_{i,j+1}-u_{i,j-1}}{2\Delta t}\right)=\left(\frac{u_{i-1,j}-u_{i,j+1}-u_{i,j-1}+u_{i+1,j}}{(\Delta y)^2}\right)+\frac{Gr}{2}\left(\theta_{i,j+1}+\theta_{i,j-1}\right)$$

$$+\frac{Gc}{2}\left(C_{i,j+1}+C_{i,j-1}\right)-\frac{M}{2}\left(u_{i,j+1}+u_{i,j-1}\right) \qquad (14)$$

$$\frac{\theta_{i,j+1}-\theta_{i,j-1}}{2\Delta t}=\frac{1}{\Pr}\left(\frac{\theta_{i-1,j}-\theta_{i,j+1}-\theta_{i,j-1}+\theta_{i+1,j}}{(\Delta y)^2}\right)+E\left(\frac{u_{i+1,j}-u_{i,j}}{\Delta y}\right)^2 \qquad (15)$$

$$\frac{C_{i,j+1}-C_{i,j-1}}{2\Delta t}=\frac{1}{Sc}\left(\frac{C_{i-1,j}-C_{i,j+1}-C_{i,j-1}+C_{i+1,j}}{(\Delta y)^2}\right) \qquad (16)$$

Initial and boundary conditions take the following forms

$$u_{i,0}=0,\quad \theta_{i,0}=0,\quad C_{i,0}=0 \quad \text{for all} \quad i\neq 0$$
$$u_{0,j}=\exp\left(a.j.\Delta t\right),\quad \theta_{0,j}=j.\Delta t,\quad C_{0,j}=j.\Delta t$$
$$u_{L,j}=0,\quad \theta_{L,j}=0,\quad C_{L,j}=0 \qquad (17)$$

Where L corresponds to ∞.

Here the suffix 'i' corresponds to 'y' and 'j' corresponds to 't'. Also $\Delta t=t_{j+1}-t_j$ and $\Delta y=y_{i+1}-y_i$.

Here we consider a rectangular grid with grid lines parallel to the coordinate axes with spacing Δy and Δt in space and time directions respectively. The grid points are given by $y_i = i.\Delta y$, i = 1,2,3,---,L-1 and $t_j = j.\Delta t$, j = 1,2,3,---, P. The spatial nodes on the jth time grid constitute the jth layer or level. The maximum value of y was chosen as 12 after some preliminary investigations, so that the two of the boundary conditions of equation (17) are satisfied. Here the maximum value of y corresponds to y = ∞. After experimenting with few sets of mesh sizes, they have been fixed at the level Δy = 0.05 and the time step Δ*t* = 0.000625, in this case, spacial mesh size is reduced by 50% and the results are compared. It is observed that when mesh size is reduced by 50% in y – direction, the result differ only in the fifth decimal place.

The values of C, θ and u are known at all grid points at t = 0 from the initial conditions. The values of C, θ and u at time level 'j+1' using the known values at previous time level 'j' are calculated as follows. The values of 'C' are calculated explicitly using the equation (16) at every nodal point at (j+1)th time level. Thus, the values of 'C' are known at every nodal point at (j+1)th time level. Similarly the values of 'θ' are calculated from equation (15). Using the values of 'C' and 'θ' at (j+1)th time level in equation (14), the values of 'u' at (j+1)th time level are found in similar manner. This process is continued to obtain the solution till desired time't'. Thus the values of C, θ and u are known, at all grid points in the rectangular region at the desired time level.

The local truncation error is O(Δt+Δy+(Δt/Δy)^2) and it tends to zero when (Δt/Δy) tends to zero as Δy tends to zero. Hence the scheme is compatible. The finite difference scheme is unconditionally stable. Compatibility and stability ensures the convergence of the scheme.

The derivatives involved in equatiosn (11) - (13) are evaluated using five point approximation formula.

The accuracy of the present model has been verified by comparing with the theoretical solution of Muthucumaraswamy et al. [21] through Figure 2 and the agreement between the results is excellent. This has established confidence in the numerical results reported in this paper.

IV. RESULTS AND DISCUSSION

It is very difficult to study the influence of all governing parameters involved in the present problem "the effects of viscous dissipation, heat and mass transfer on the transient MHD free convection flow in the presence of chemical reaction of first order". Therefore, this study is focused on the effects of governing parameters on the transient velocity, temperature as well as on the concentration profiles. To have a physical feel of the problem we, exhibit results to show how the material parameters of the problem affect the velocity, temperature and concentration profiles. Here we restricted our discussion to the aiding of favourable case only, for fluids with Prandtl number Pr = 0.71 which represent air at 20^0 C at 1 atmosphere. The value of thermal Grashof number *Gr* is taken to be positive, which corresponds to the cooling of the plate. The diffusing chemical species of most common interest in air has Schmidt number (*Sc*) and is taken for Hydrogen (*Sc* = 0.22), Oxygen (Sc = 0.66), and Carbon dioxide (*Sc* = 0.94).

Extensive computations were performed. Default values of the thermo physical parameters are specified as follows:

Magnetic parameter *M* = 2, thermal Grashof number *Gr* = 5, mass Grashof number *Gc* = 5, acceleration parameter *a* = 0.5, Prandtl number *Pr* = 0.71(air), Eckert number *E* = 0.05, Schmidt number *Sc* = 0.22 (hydrogen) and time *t* = 0.2 and 0.6. All graphs therefore correspond to these values unless otherwise indicated.

The effects of governing parameters like magnetic field, thermal Grashof number as well as mass Grashof number, acceleration parameter, viscous dissipation, Prandtl number, and time on the transient velocity have been presented in the respective Figures 3 to 9 for t = 0.2 and t = 0.6 in presence of foreign species *'Sc = 0.22'*.

Figure (3) illustrate the influences of *'M'*. It is found that the velocity decreases with increasing magnetic parameter for air (*Pr = 0.71*) in presence of Hydrogen. The presence of transverse magnetic field produces a resistive force on the fluid flow. This force is called the Lorentz force, which leads to slow down the motion of electrically conducting fluid.

Figs. (4) and (5) reveal the velocity variations with *Gr* and *Gc* for t = 0.2 and t = 0.6 respectively. It is observed that greater cooling of surface (an increase in *Gr*) and increase in *Gc* results in an increase in the velocity for air. It is due to the fact increase in the values of thermal Grashof number and mass Grashof number has the tendency to increase the thermal and mass buoyancy effect. This gives rise to an increase in the induced flow.

The effect of acceleration parameter (*a*) on the transient velocity (*u*) is plotted in Figure (6). It is noticed that an increase in acceleration parameter leads to increase in *u*.

Fig.(7) display the effects *'E'* on the velocity field for the cases Gr > 0, Gc > 0 respectively. Eckert number is the ratio of the kinetic energy of the flow to the boundary layer enthalpy difference. The effect of viscous dissipation on flow field is to increase the energy, yielding a greater fluid temperature and as a consequence greater buoyancy force. The increase in the buoyancy force due to an increase in the dissipation parameter enhances the velocity in cooling of the plate.

The effect of Prandtl number *'Pr'* on the velocity variations is depicted in Fig (8) for cooling of the plate. The velocity for Pr=0.71 is higher than that of Pr=7. Physically, it is possible because fluids with high Prandtl number have high viscosity and hence move slowly.

The effect of time*'t'* on the velocity in cooling of the plate is shown in Fig. (9). It is obvious from the figure that the velocity increases with the increase of time *'t'*.

Figure (10) reveals the transient temperature profiles against y (distance from the plate). The magnitude of temperature is maximum at the plate and then decays to zero asymptotically. The magnitude of temperature for air (*Pr*=0.71) is greater than that of water (*Pr*=7). This is due to the fact that thermal conductivity of fluid decreases with increasing '*Pr'*, resulting a decrease in thermal boundary layer thickness. Also the temperature increases with an increase in the time*'t'* for both air and water.

It is marked from Fig. (11) that the increasing value of the viscous dissipation parameter enhancing the flow temperature for t = 0.2 and t = 0.6.

Figure 12 illustrate the dimensionless concentration profiles (*C*) for Schmidt number. A decrease in concentration with increasing *'Sc'* is observed from this figure. Also, it is noted that the concentration boundary layer becomes thin as the Schmidt number increases.

The effects of magnetic field, thermal Grashof number, mass Grashof number acceleration parameter, Prandtl number, Eckert number, Schmidt number on the skin-friction against time *t* are presented in the figure 13. It is noticed that the skin friction increases with an increase in magnetic field, Prandtl number, Schmidt number and acceleration parmeter while it decreases with an increase in thermal Grashof number, mass Grashof number and Eckert number for air.

Figure 14 depicts the Nusselt number against time't' for various values of parameters *'M, Gr, Gc, Pr, E, Sc* and a*'*. Nusselt number for *Pr*=7 is higher than that of *Pr*=0.71. The reason is that smaller values of *Pr* are equivalent to increasing thermal conductivities and therefore heat is able to diffuse away from the plate more rapidly than higher values of Prandtl number. Hence, the rate of heat transfer is enhanced. It is found that the rate of heat transfer falls with increasing Gr, Gc, *E*. Also Nusselt number increases as magnetic parameter '*M,* Schmidt number *Sc* and acceleration paramenter *a'* increases.

It is marked from Fig. (15) that the rate of concentration transfer increases with increasing values of magentic parameter *'M',* Schmidt number *'Sc',* Pradtl number and acceleration paramenter *a'* while it decreases with an increase in Gr, Gc, E.

V. CONCLUSIONS

In this paper effects of viscous dissipation and MHD on free convection flow past an exponentially accelerated vertical plate with variable surface temperature and concentration have been studied numerically. Explicit finite difference method is employed to solve the equations governing the flow. From the present numerical investigation, following conclusions have been drawn:

- It is found that the velocity decreases with increasing magnetic parameter (M) and it increases as Gr, Gc and acceleration parameter 'a' increases.
- An increase in the dissipation parameter enhances the velocity in cooling of the plate.
- The velocity for Pr=0.71 is higher than that of Pr=7.
- The increasing value of the viscous dissipation parameter enhancing the flow temperature as well as temperature increases with an increase in the time*'t'* for both air and water. However, significantly, it is observed that the temperature decreases with increasing Pr.
- A decrease in concentration with increasing Schmidt number is observed.
- Skin friction increases with an increase in magnetic field, acceleration parameter, Schmidt number while it decrease with an increase in thermal Grashof number, mass Grashof number,

Eckert number for air. The magnitude of the Skin-friction for water is greater than air.

- It is found that the rate of heat transfer falls with increasing magnetic field, acceleration parameter and Eckert number while it increases with an increase in thermal Grashof number.

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NOMENCLATURE

A, a', a	Constants
C_p	Specific heat at constant pressure $J.kg^{-1}K^{-1}$
C'	Species concentration $kg.m^{-3}$
C	Dimensionless concentration
D	Mass Diffusion coefficient $m^2.s^{-1}$
E	Eckert number
Gr	Thermal Grashof number
Gc	Mass Grashof number
g	Acceleration due to gravity $m.s^{-2}$
H_0	Magnetic field intensity $A.m^{-1}$
k	Thermal conductivity $W.m^{-1}.K^{-1}$
k_e	mean absorption coefficient
M	Magnetic parameter
Nu	Nusselt Number
$\Pr$	Prandtl number
q_r	the radiation heat flux.
Sc	Schmidt number
T'	Temperature of the fluid near the plate K
T	Dimensionless temperature of the fluid near the plate
t'	Time s
t	Dimensionless time
u'	Velocity of the fluid in the x' - direction $m.s^{-1}$
u_0	Velocity of the plate $m.s^{-1}$
u	Dimensionless velocity
y'	Coordinate axis normal to the plate m
y	Dimensionless coordinate axis normal to the plate

Greek symbols

β	Volumetric coefficient of thermal expansion K^{-1}
$\beta*$	Volumetric coefficient of thermal expansion with concentration K^{-1}
θ	Dimensionless temperature
μ	Coefficient of viscosity $Pa.s$
μ_e	Magnetic permeability $H.m^{-1}$
υ	Kinematic viscosity $m^2 s^{-1}$
ρ	Density of the fluid $Kg.m^{-3}$
σ	Electrical conductivity of the fluid $VA^{-1}m^{-1}$
σ_s	Stefan – Boltzmann Constant
τ	Dimensionless shear stress

Subscripts

w	Conditions at the wall
∞	Conditions in the free stream

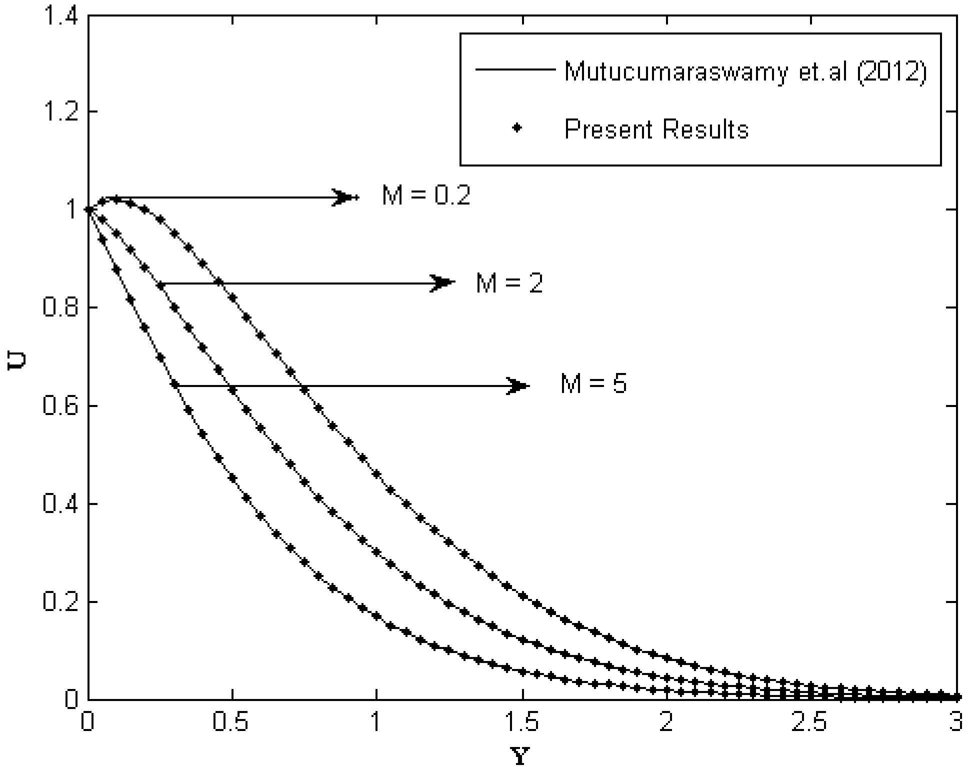

Figure (2): Velocity profile for different values of 'M' when Pr = 7, E = 0, a = 0.1 and K=0,

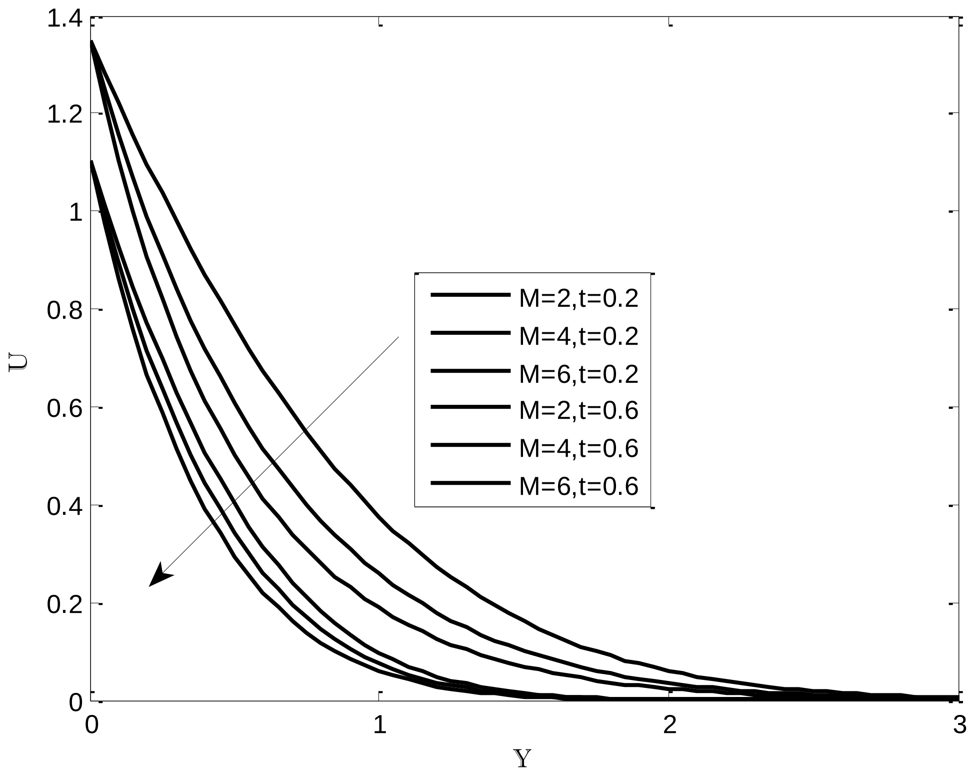

FIG. (3): VELOCITY PROFILE FOR DIFFERENT VALUES OF **'M'**

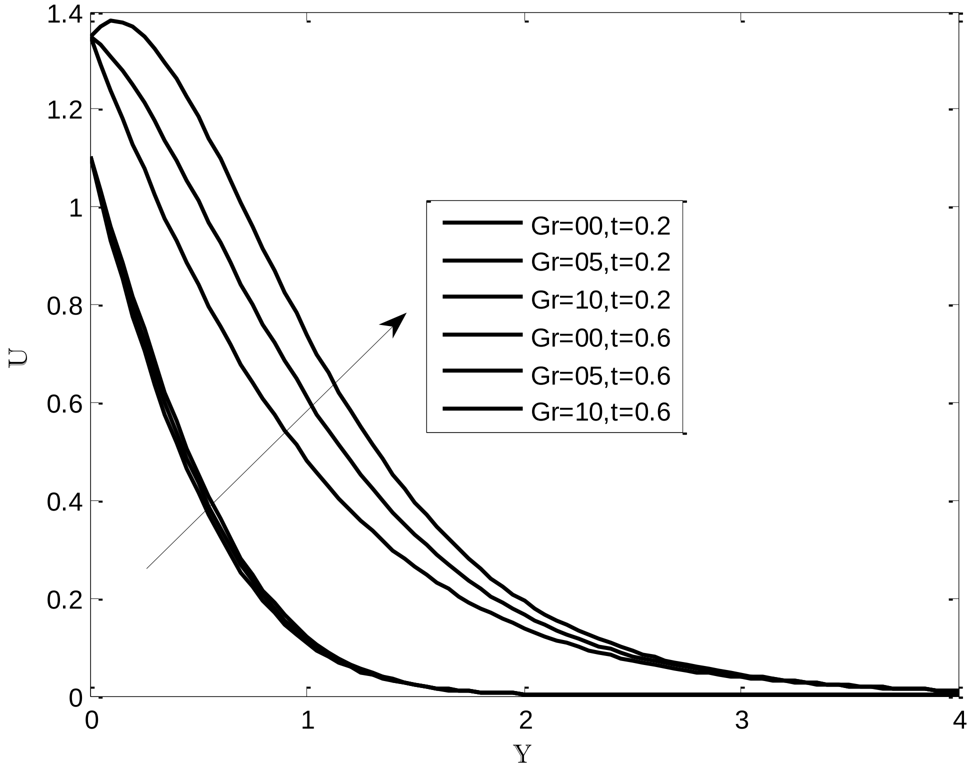

FIG. (4): VELOCITY PROFILE FOR DIFFERENT VALUES OF **'Gr'**

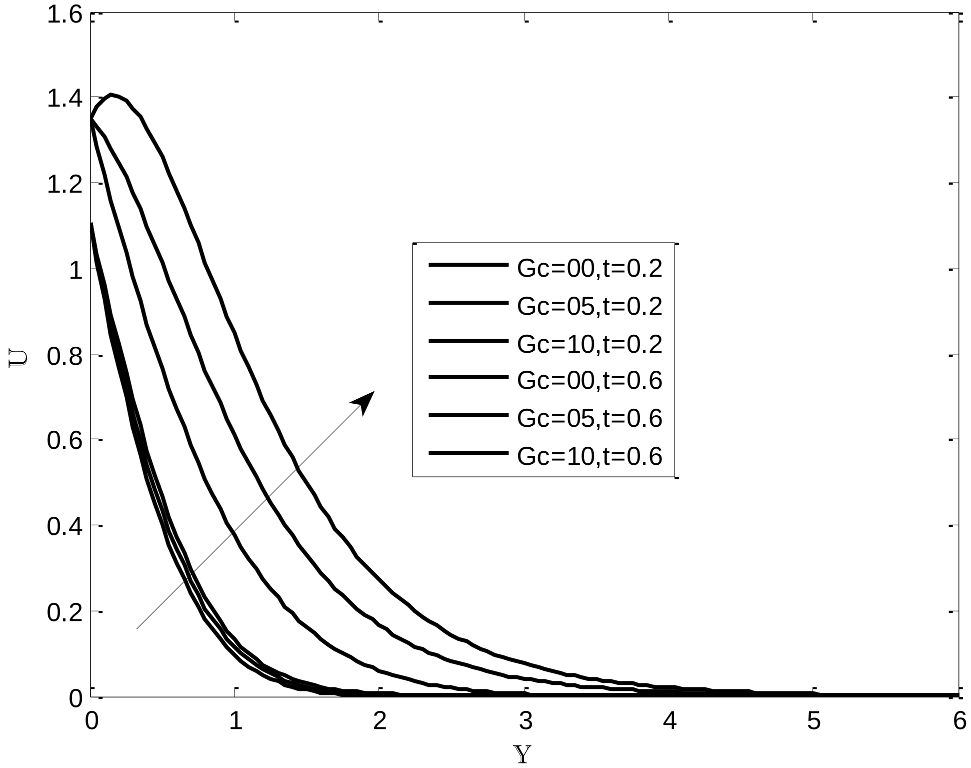

FIG. (5): VELOCITY PROFILE FOR DIFFERENT VALUES OF **'Gc'**

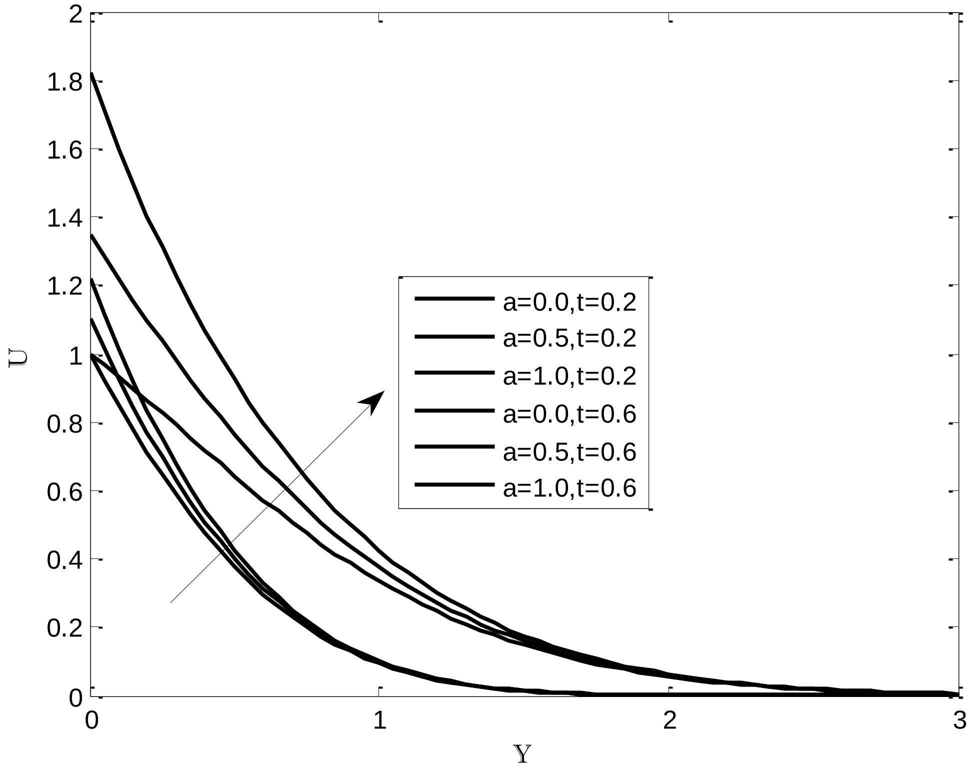

FIG. (6): VELOCITY PROFILE FOR DIFFERENT VALUES OF **'a'**

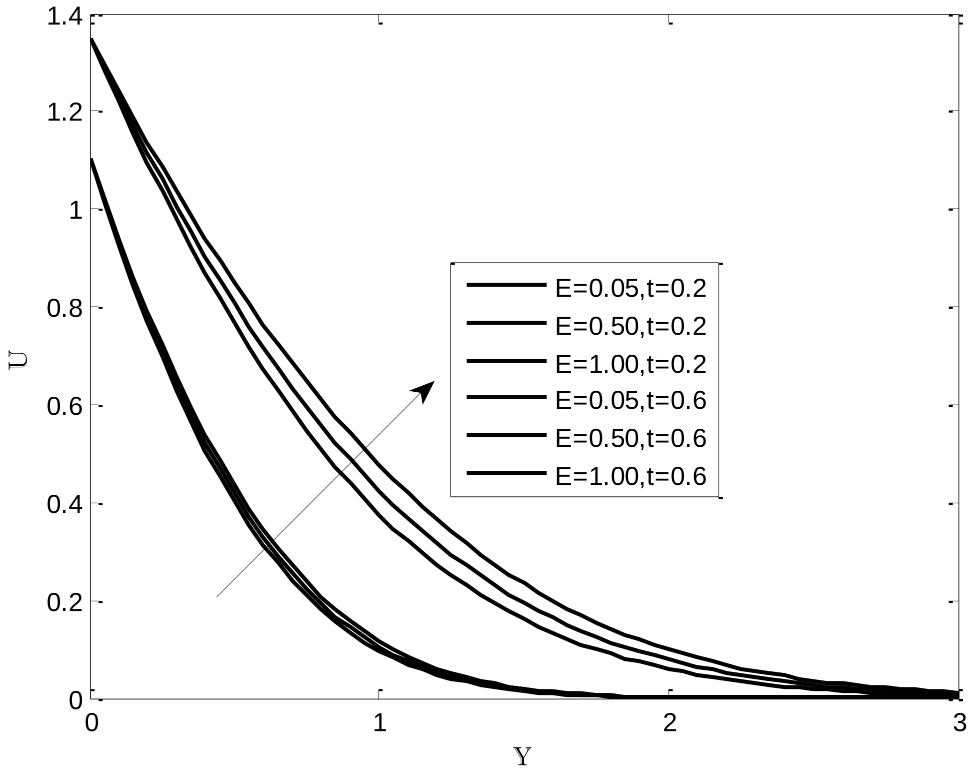

FIG. (7): VELOCITY PROFILE FOR DIFFERENT VALUES OF **'E'**

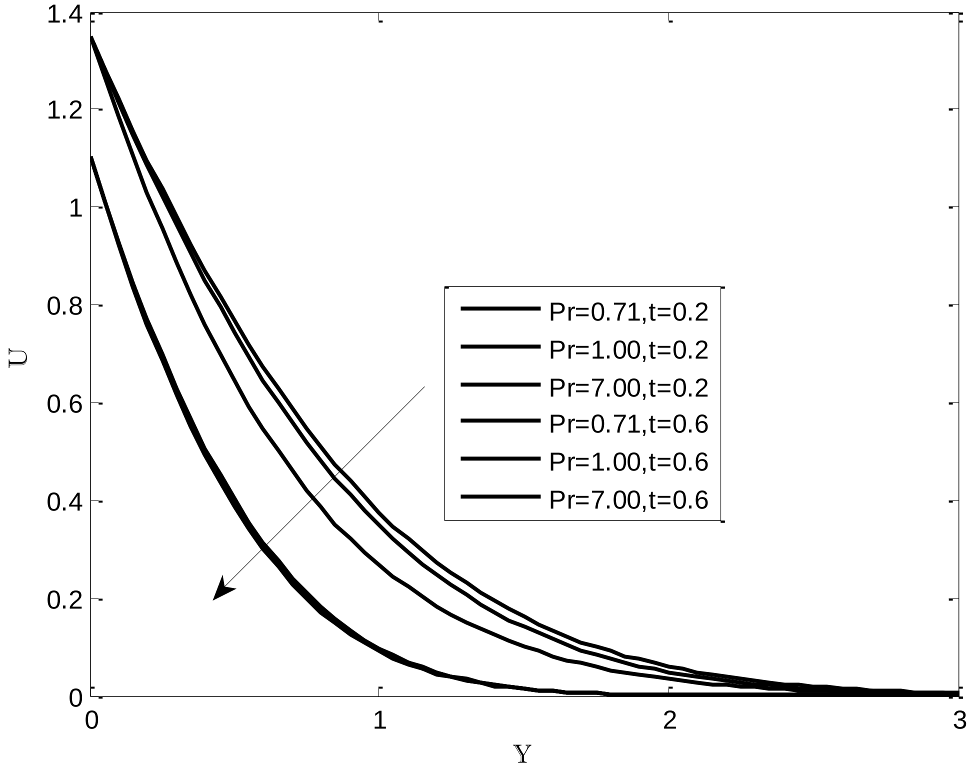

FIG. (8): VELOCITY PROFILE FOR DIFFERENT VALUES OF **'Pr'**

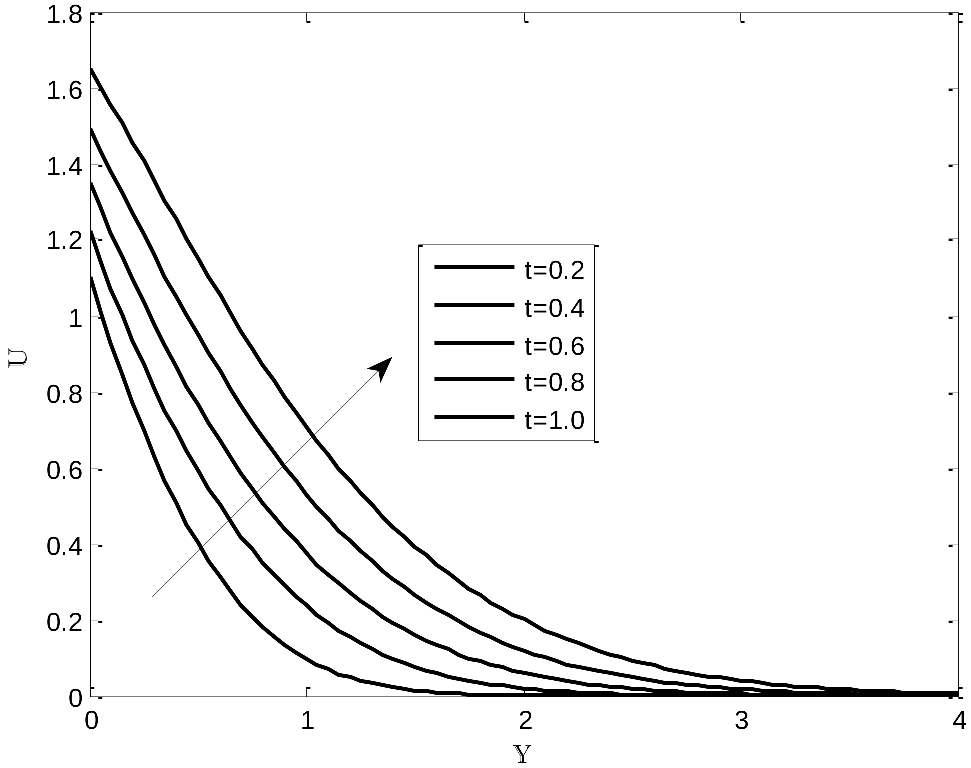

FIG. (9): VELOCITY PROFILE FOR DIFFERENT VALUES OF 't'

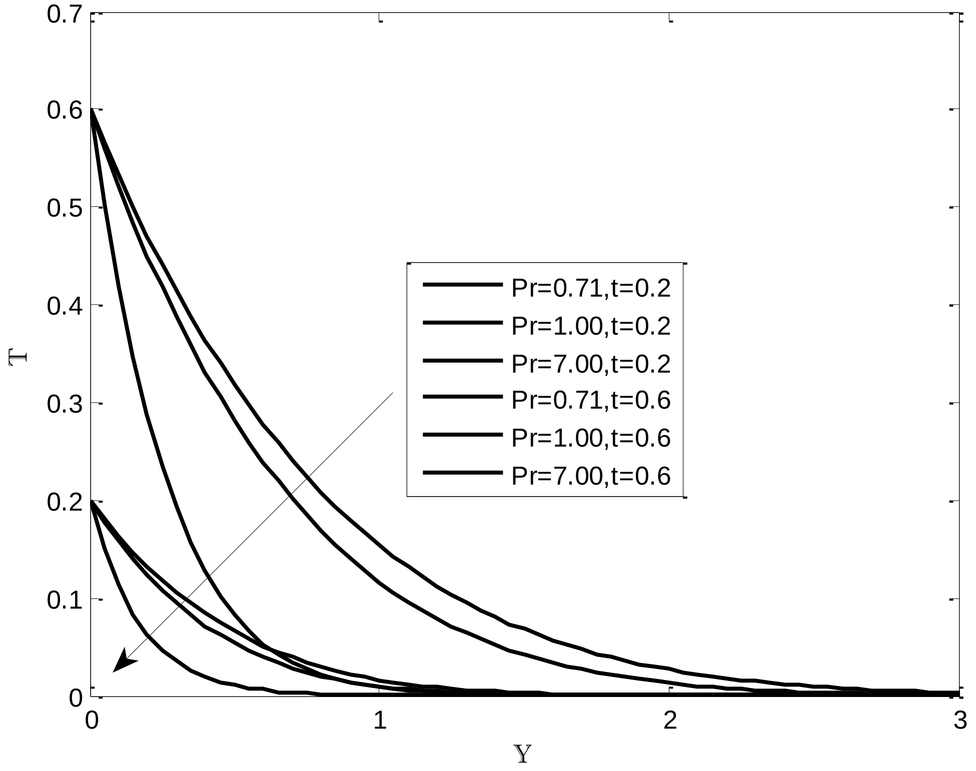

FIG.(10) : TEMPERATURE PROFILE FOR DIFFERENT VALUES OF **'Pr'**

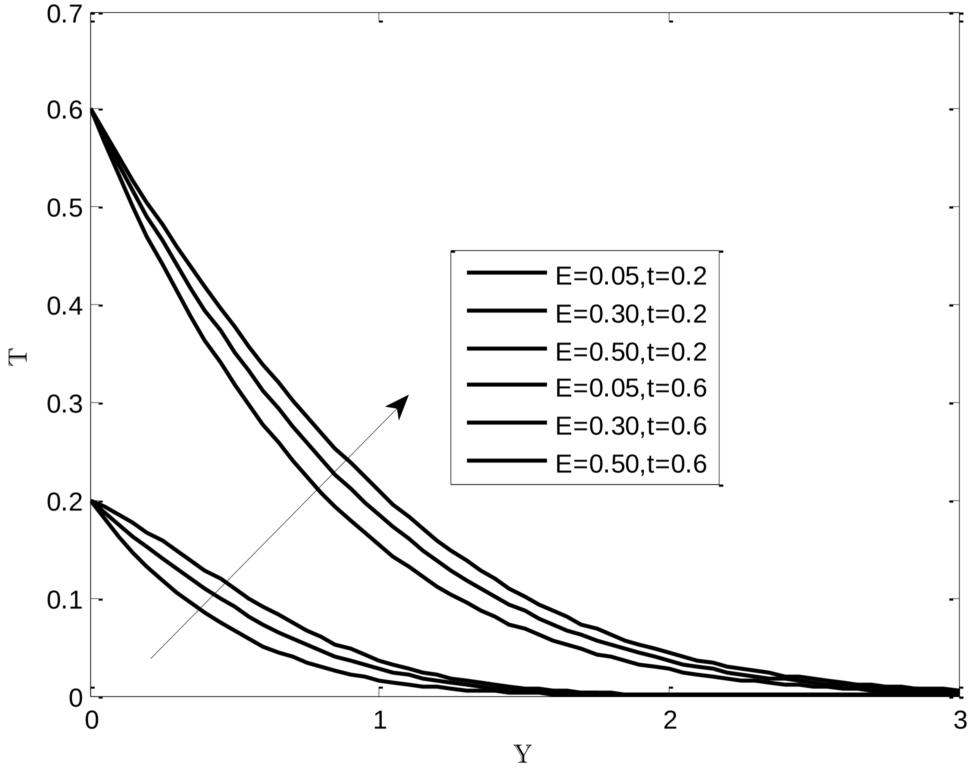

FIG.(11) : TEMPERATURE PROFILE FOR DIFFERENT VALUES OF **'E'**

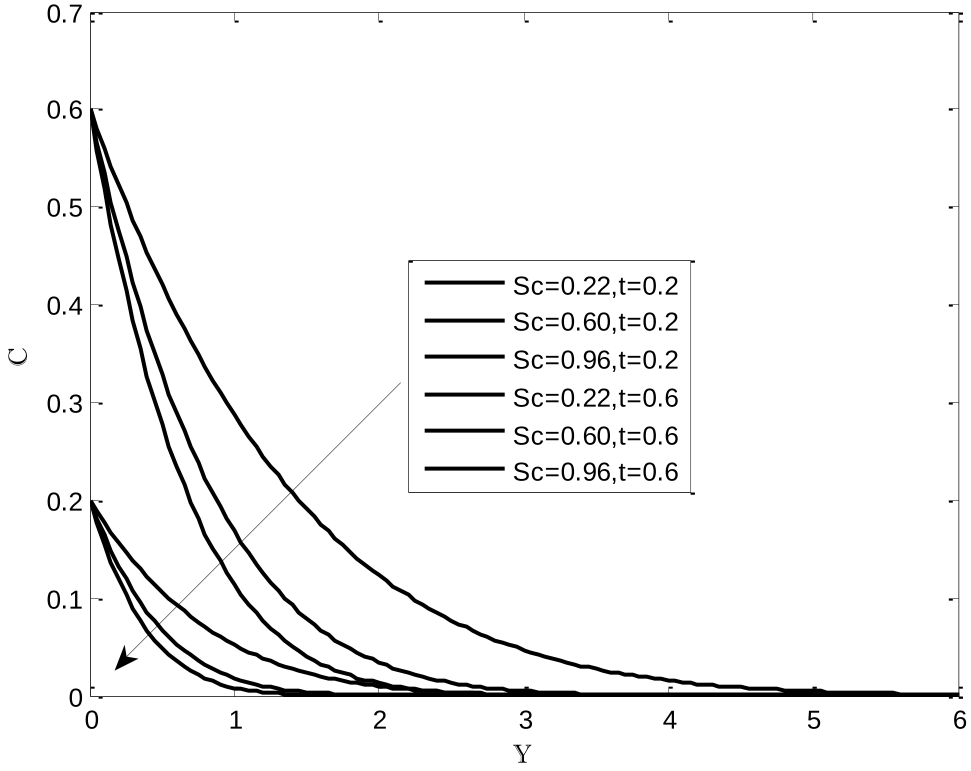

FIG.(12) : CONCENTRATION PROFILE FOR DIFFERENT VALUES OF **'Sc'**

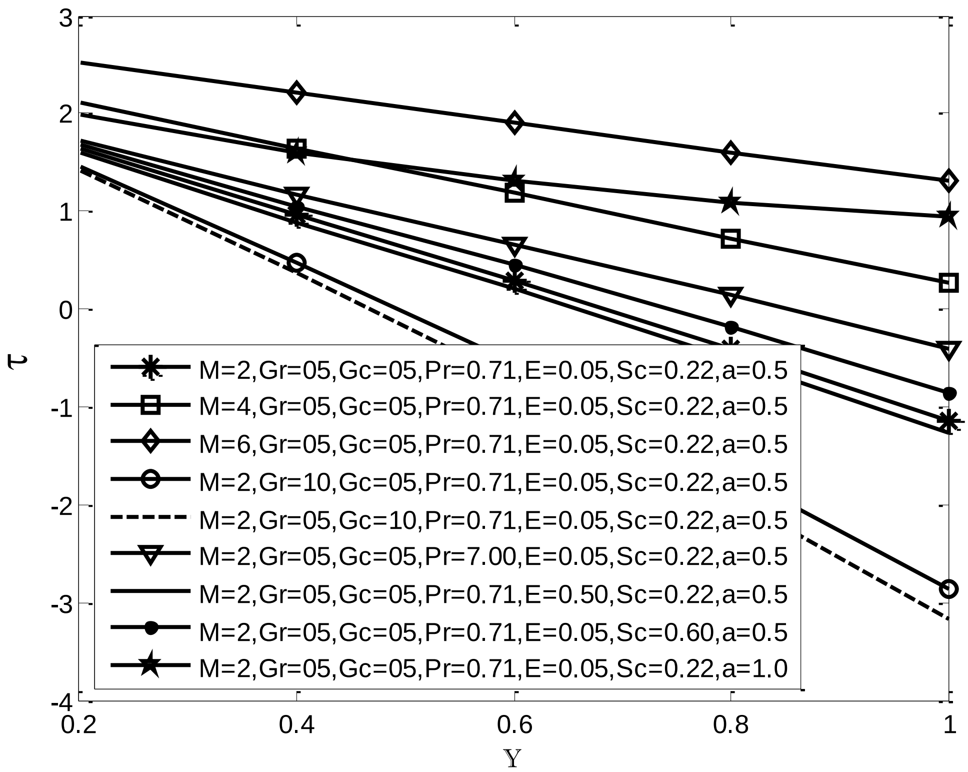

FIG.(13) : SKIN FRICTION PROFILE

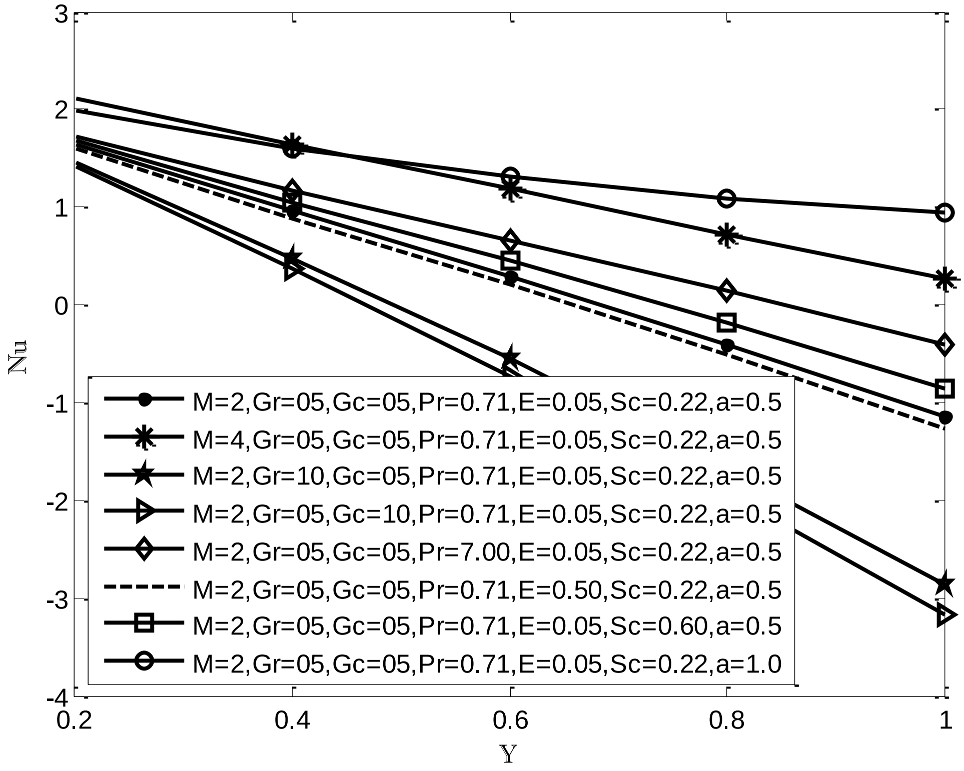

FIG.(14) : NUSSELT NUMBER PROFILE

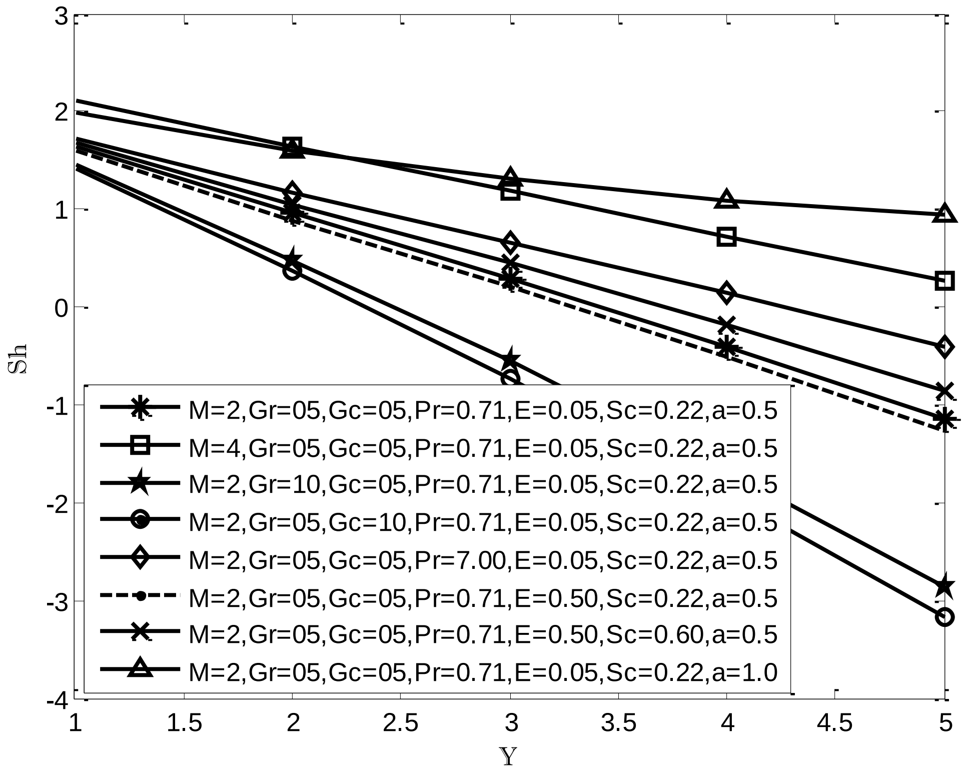

FIG.(15) : SHERWOOD NUMBER PROFILE