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Viscous Dissipation and Radiation Effects on Unsteady Free Convective Flow past a Moving Vertical Plate Embedded in a Porous Medium: Finite Difference Method

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Abstract: The aim of the present work is to study the effects of viscous dissipation and thermal radiation on unsteady free convective flow past a moving infinite vertical plate in the presence of variable temperature. The equations of continuity, energy and diffusion, which govern the flow field, are solved numerically using Crank-Nicolson explicit finite difference method. The effect of different pertinent physical parameters on the velocity, temperature and concentration are discussed and presented graphically.
Keywords: Viscous dissipation, Radiation, Vertical Plate, Free Convection

I. INTRODUCTION

The heat transfer from different geometries embedded in a porous media has many engineering and geophysical applications such as geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed – bed catalytic reactors, cooling of nuclear reactors, and underground energy transport. A very significant area of research in radiative heat transfer, at the present time is the numerical simulation of combined radiation and convection/conduction transport processes. The effort has arisen largely due to the need to optimize industrial system such as furnaces, ovens and boilers and the interest in our environment and in non-conventional energy source such as the use of salt-gradient solar ponds for energy collection and storage. In particular, natural convection induced by the simultaneous action of buoyancy forces resulting from thermal diffusion is of considerable interest in nature and in many industrial applications such as geophysics, oceanography drying processes and solidification of binary alloy. Convective heat transfer in porous media has received considerable attention in recent years owing to its importance in various technological applications such as fiber and granular insulation, electronic system cooling, cool combustors, oil extraction, thermal energy storage and flow through filtering devices, porous material regenerative heat exchangers. Viscous dissipation effects on natural convection flow along moving vertical plate with radiation and variable temperature studied by Abd EI-Naby *et al.* [1] studied the effects of radiation on unsteady free convective flow past a semi-infinite vertical plate with variable surface temperature using Crank-Nicolson finite difference method. Ch Kesavaiah et.al [2] Radiation and mass transfer effects on moving vertical plate with variable temperature and viscous Dissipation. They observed that, both the velocity and temperature are found to decrease with an increase in the temperature exponent. Ch Kesavaiah et.al. [3] Effects of the chemical reaction and radiation absorption on an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium with heat source and suction. Dulal Pal *et al.* [4] studied Perturbation analysis of unsteady magneto hydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Ganesan and Loganadhan [5] studied the radiation and mass transfer effect on flow of incompressible viscous fluid past a moving vertical cylinder using Rossel and approximation by the Crank-Nicolson finite difference method. Kim and Fedorov [7] analyzed transient mixed radiative convective flow of a micropolar fluid past a moving semi-infinite vertical porous plate. Rama Chandra Prasad *et al.* [10] studied radiation and mass transfer effects on two-dimensional flow past an impulsively started infinite vertical plate. Effects of the chemical reaction and radiation absorption on free convection flow through porous medium with variable suction in the presence of uniform magnetic field were studied by Sudheer Babu and Satyanarayana [11]. Takhar *et al.* [12] considered the effect of radiation on MHD free convection flow of a radiating gas past a semi-infinite vertical plate.

The aim of the present work is to study the effects of thermal radiation and viscous dissipation on moving infinite vertical plate in the presence of variable temperature and viscous dissipation. The equations of continuity, energy and diffusion, which govern the flow field, are solved numerically using Crank-Nicolson explicit finite difference method. The effect of different pertinent physical parameters on the velocity, temperature and concentration are discussed and presented graphically.

A. *Formulation Of The Problem*

Here the unsteady flow of a viscous incompressible fluid past an impulsively started infinite vertical plate with variable temperature and uniform mass diffusion, in the presence of thermal radiation, viscous dissipation is considered. The x – axis is taken along the plate in the vertically upward direction and the y – axis is taken normal to plate. It is also assumed that the radiation heat flux in the x – direction is negligible as compared to that in the y – direction. Initially, the plate and fluid are at the same temperature and concentration in a stationary condition. At time $t' > 0$, the plate is given impulsive motion in the vertical direction against gravitational field with constant velocity u_0, the plate temperature is raised linearly with time and the concentration level near the plate is raised C'_w. The fluid considered here is gray, absorbing – emitting radiation but a non-scattering medium. Then by usual Boussinesq's approximation, the flow of a radiative fluid governed by the following equations:

$$\frac{\partial u}{\partial t'} = g\beta\left(T - T_\infty\right) + g\beta^*\left(C' - C'_\infty\right) + \nu\frac{\partial^2 u}{\partial y^2} \tag{1}$$

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

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y^2} \tag{3}$$

Initial and boundary conditions are as follows:

$$\begin{aligned}
&t' \le 0: \quad u = 0, \quad T = T_\infty, C' = C'_\infty \qquad \textit{for all} \quad y\\
&t' > 0: \quad u = u_0, \quad T = T_\infty + \left(T_w - T_\infty\right)At', C' = C'_w \quad \textit{at} \quad y = 0\\
&\qquad\qquad u = 0, \quad T \to T_\infty, C' = C'_\infty \qquad \textit{as} \quad y \to \infty
\end{aligned} \tag{4}$$

where $A = \frac{u_0^2}{\nu}$ is constant, t' time, T temperature of the fluid near the plate, T'_w temperature of the plate, T'_∞ temperature of the fluid far away from the plate, C dimensionless concentration, C' species concentration in the fluid, C'_w concentration of the plate, C'_∞ concentration of the fluid far away from the plate, C_p specific heat constant pressure u_0 velocity of the plate, ν kinematic viscosity, μ coefficient of viscosity, q_r radiative heat flux in the y-direction, k thermal conductivity of the fluid, ρ density, D mass diffusion coefficient, g acceleration of gravity, β volumetric coefficient of thermal expansion, t dimensionless time, u velocity of the fluid in the x-direction, u_0 velocity of the plate, The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y} = -4a^*\sigma\left(T_\infty^4 - T^4\right) \tag{5}$$

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We assume that the temperature differences within the flow are sufficiently small such that T^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T^4 in a Taylor series about T_∞ and neglecting higher-order terms, thus

$$T^4 \cong 4T_\infty^{\ 3}T - 3T_\infty^4 \tag{6}$$

By using equations (5) and (6), equation (2) reduces to

$$\rho C_p \frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} + 16a^*\sigma T_\infty^3 \left(T_\infty - T\right) \tag{7}$$

On introducing the following non-dimensional quantities

$$U = \frac{u}{u_0},\quad Y = \frac{yu_0}{\nu},\quad t = \frac{t'u_0^{\ 2}}{\nu},\quad \theta = \frac{T - T_\infty}{T_w - T_\infty},\quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}$$

$$Sc = \frac{\nu}{D}, R = \frac{16a^*\nu^2\sigma T_\infty^3}{k u_0^{\ 2}}, Gr = \frac{g\beta\nu\left(T_w - T_\infty\right)}{u_0^{\ 3}},\quad \phi = \frac{\nu Q_0}{\rho C_p u_0^{\ 2}} \tag{8}$$

$$Ec = \frac{u_0^2}{C_p(T_w - T_\infty)},\quad \Pr = \frac{\rho\nu C_p}{k},\quad Gc = \frac{g\beta^*\nu\left(C'_w - C'_\infty\right)}{u_0^{\ 3}}$$

where a^* absorption coefficient, $\Pr$ Prandtl number, Gc mass Grashof number, Gr thermal Grashof number, U dimensionless velocity, Sc Schmidt number, ϕ heat absorption parameter, θ dimensionless temperature, Y dimensionless coordinate axis to normal to the plate, y coordinate axis normal to the plate R radiation parameter, σ electrical conductivity of the fluid, β^* concentration expansion coefficients.

In equations (1), (3) and (7), leads to

$$\frac{\partial U}{\partial t} = Gr\,\theta + Gc\,C + \frac{\partial^2 U}{\partial Y^2} \tag{9}$$

$$\Pr\frac{\partial\theta}{\partial t} = \frac{\partial^2\theta}{\partial Y^2} - R\theta + \Pr Ec\left(\frac{\partial U}{\partial Y}\right)^2 \tag{10}$$

$$Sc\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial Y^2} \tag{11}$$

Initial and boundary conditions in non-dimensional form are:

$$\begin{array}{llll} & U = 0, & \theta = 0, C = 0 & for\ \ all\quad y,t \le 0 \\ T > 0: & U = 1, & \theta = t,\ C = 1 & at\quad y = 0 \\ & U = 0, & \theta \to 0, C \to 0 & as\quad y \to \infty \end{array} \tag{12}$$

B. Solution of The Problem

The unsteady, non-linear, coupled partial differential equations (9), (10) and (11) along with their boundary and initial conditions (12) have been solved numerically using an explicit finite difference scheme of Crank-Nicolson type which is discussed by many authors Ganesan and Loganathan [5], Ganesan and Rani [6], Muthucumaraswamy and Ganesan [8] , Bapuji *et al.* [9] and Ramachandra Prasad *et al.* [10] The equivalent finite difference scheme of equations for (9), (10) and (11) are as follows:

$$\left[\frac{u_{i,j+1}-u_{i,j}}{\Delta t}\right]=Gr\left[\theta_{i,j}\right]+Gc\left[\phi_{i,j}\right]+\left[\frac{u_{i+1,j}-2u_{i,j}+u_{i-1,j}}{(\Delta Y)^2}\right] \tag{13}$$

$$\left[\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t}\right]=\frac{1}{\Pr}\left[\frac{\theta_{i+1,j}-2\theta_{i,j}+\theta_{i-1,j}}{(\Delta Y)^2}\right]-\frac{R}{\Pr}\left[\theta_{i,j}\right]+Ec\left[\frac{u_{i+1,j}-u_{i,j}}{\Delta Y}\right] \tag{14}$$

$$\left[\frac{\phi_{i,j+1}-\phi_{i,j}}{\Delta t}\right]=\frac{1}{Sc}\left[\frac{\phi_{i+1,j}-2\phi_{i,j}+\phi_{i-1,j}}{(\Delta Y)^2}\right] \tag{15}$$

here, index *i* refers to *y* and *j* refers to time, the mesh system is divided by taking $\Delta y = 0.1$.
From the initial conditions in (12) we have the following equivalent

$$\left.\begin{array}{l} u(0,0)=0,\ \theta(0,0)=0,\ \phi(0,0)=0 \\ u(i,0)=0,\ \theta(i,0)=0,\qquad \phi(i,0)=0\ \ forall\ \ i,\ \ except\ \ i=0 \end{array}\right\} \tag{16}$$

The boundary conditions from (12) are expressed in finite-difference form as follows

$$\left.\begin{array}{l} u(0,j)=1,\ \theta(0,j)=t,\ \phi(0,j)=1,\ \ forall\ j \\ u(1,j)=0,\ \theta(1,j)=0\ \ \phi(1,j)=0\ \ \ forall\ j \end{array}\right\} \tag{17}$$

infinity is taken as *y* = 4.1. First the velocity at the end of the time step namely $(u_{i,j+1})$, *i* = 1 to 200 is computed from the equation (13) and temperature $(\theta_{i,j+1})$, *i* = 1 to 200 from equation (14) and concentration $(\phi_{i,j+1})$, *i* = 1 to 200 from equation (15). The procedure is repeated until *t* = 1 (i.e., j = 400). During computation Δt was chosen as 0.0025. These computations are carried out for Pr = 1, 7, 11.4; Sc = 0.3, 0.6, 2.01; R = 0.2, 2, 5, 10, 20; Gr = 2, 5; Gc = 2, 5; E = 0.01, 0.02, 0.03, 0.04; t = 0.2, 0.4, 0.6, 1.0.

II. RESULTS AND DISCUSSIONS

In order to get physical insight into the problem, the velocity, temperature, and concentration fields have been discussed by assigning numerical values of magnetic parameter M, thermal Grashof number Gr, the solutal Grash of number Gm, Prandtl number $\Pr$, Schmidt number *Sc*, the radiation parameter R and the Eckert number Ec. In figure (1) the effect of the velocity for different values of thermal Grashof number (Gr) and mass Grashof number (Gc) are shown graphically in the presence of thermal radiation. It is observed that the velocity increases with increasing thermal Grashof number or mass Grash of number. This is due to the fact that buoyancy force enhances fluid velocity and increase the boundary layer thickness with increase in the value of $Gr\ or\ Gc$. It is interesting to note that the velocity increases tremendously with increasing mass Grash of number as compared to the thermal Grashof number. Figures 3 represent the velocity profiles for different values of $\Pr$ with $Gr = 2, Gc = 5, Sc = 2.01, R = 2.0, t = 0.4$. It is seen that velocity decreases as Pr increases. This is an agreement with the physical fact that the thermal boundary layer thickness decreases with increasing $\Pr$. The velocity profiles for different values of the radiation parameter are shown in figure (2). We note from this figure that there is decrease in the horizontal velocity profiles with increase in the radiation parameter R. The increase of the radiation parameter R leads to decrease the boundary layer thickness and to enhance the heat transfer rate in the presence of thermal and solutal buoyancy force. Figure (3) illustrates the variation of dimensionless velocity function (u) versus y with various Schmidt number. Schmidt number Sc measures the relative effectiveness of momentum and mass transport by diffusion. Further, it is observed that the momentum boundary layer decreases with increase in the value of Sc. Figure (4) illustrates the variation of dimensionless velocity function (u) versus y with various Prandtl number. Prandtl number measures the relative effectiveness of momentum and mass transport by diffusion. Further, it is observed that the momentum boundary layer decreases with increase in the value of Prandtl number. The influence of the time t on velocity profiles is illustrated in Figure (5). It is seen that the velocity increases with the increase of t values. The effect of Eckert number E on temperature profiles is shown in figure (6). Here Ec expresses the relationship between the kinetic energy in the flow and the enthalpy. It embodies the conversion of kinetic energy into internal energy by work done against the viscous fluid stresses. Although this parameter is often used in high-speed compressible flow, for example in rocket aerodynamics at very high altitude, it has significance in high temperature incompressible flows, which are encountered in chemical engineering systems, radioactive waste repositories, nuclear engineering systems etc. Positive Eckert number implies cooling of the wall and therefore a transfer of heat to the fluid. We conclude that with the increase of Eckret number leads to increases the temperature. From figure (7) it is observed that as increase in the Prandtl number results an increase of the thermal boundary layer thickness and in general lower average temperature within the boundary layer. The reason is that smaller values of $\Pr$ are equivalent to increase in the thermal conductivity of the fluid and therefore heat is able to diffuse away from the heated surface more rapidly for higher values of $\Pr$. Hence in the case of smaller Prandtl numbers as thermal boundary layer is thicker and the heat transfer is reduced. The temperature profiles for different values of thermal radiation parameter $(R = 0.2, 2.0, 5.0, 10.0), t = 0.2$ and $\Pr = 0.71$ are shown in figure (8). The effect of thermal radiation parameter is important temperature profiles. Further, it is observed from this figure that increase in the radiation parameter decreases the temperature distribution in the thermal boundary layer due to decrease in the thickness of the thermal boundary layer with thermal radiation parameter R. This is because large values of radiation parameter corresponds to an increase in dominance of conduction over radiation, thereby decreasing the buoyancy force and the thickness of the thermal boundary layer. Figure (9) illustrates the influences of t on the temperature. It is obvious from the figure that the maximum velocity attains in the vicinity of the plate then decreases to zero as $y \to \infty$. It is noted that the temperature increases with increasing time t. This is due to the fact that heat energy is stored in the liquid as time increases. Figure (10) concerns with the effect of Sc on the concentration. As the Schmidt number increases, the concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. Reductions in the concentration distributions are accompanied by simultaneous reductions in the velocity and concentration boundary layers.

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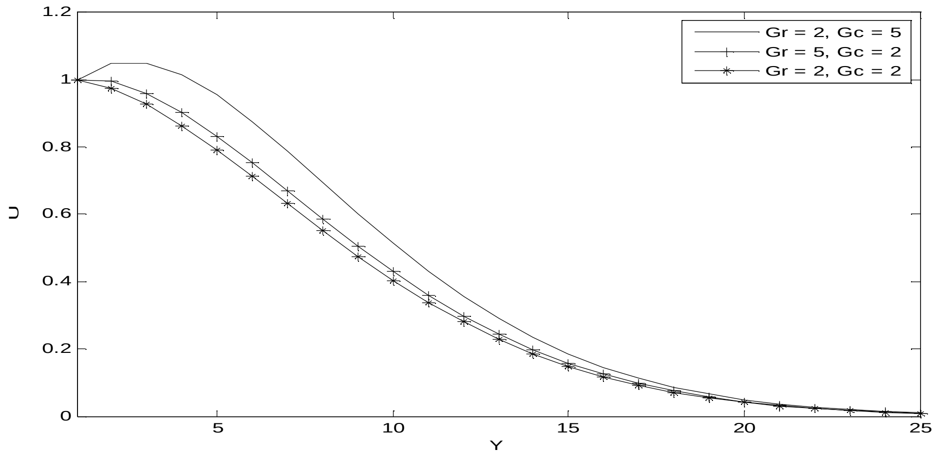

Figure (1): Velocity profiles for different vlues of Gr, Gc

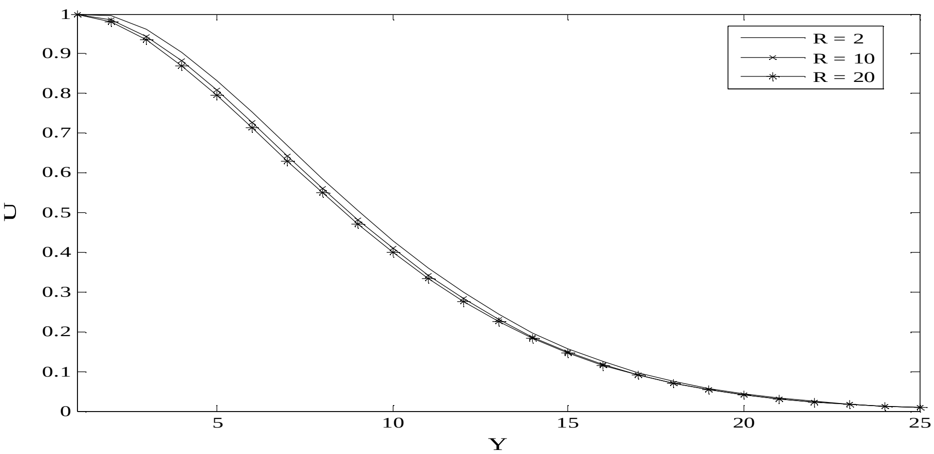

Figure (2): Velocity profiles for different vlues of R

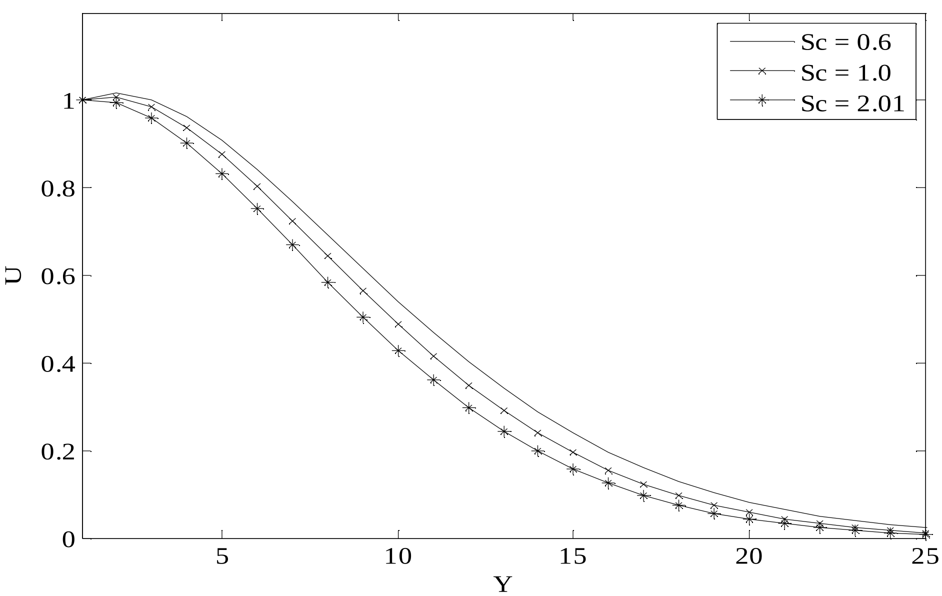

Figure (3): Velocity profiles for different vlues of Sc

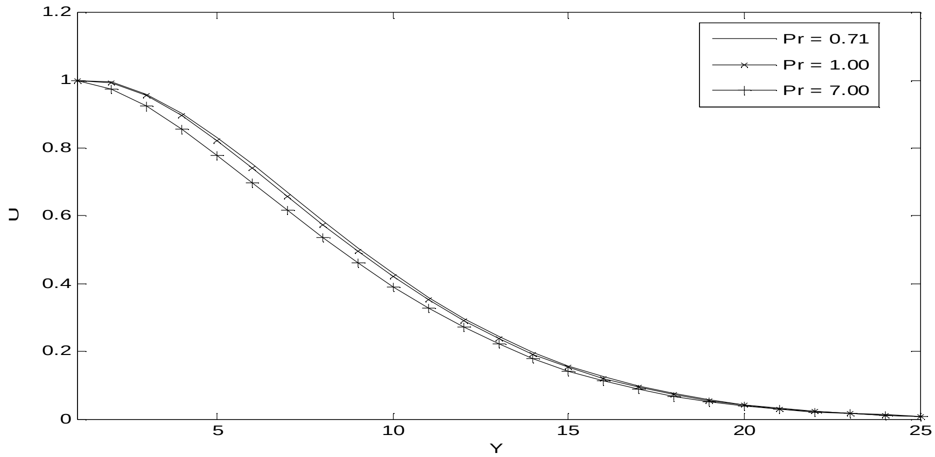

Figure (4): Velocity profiles for different vlues of Pr

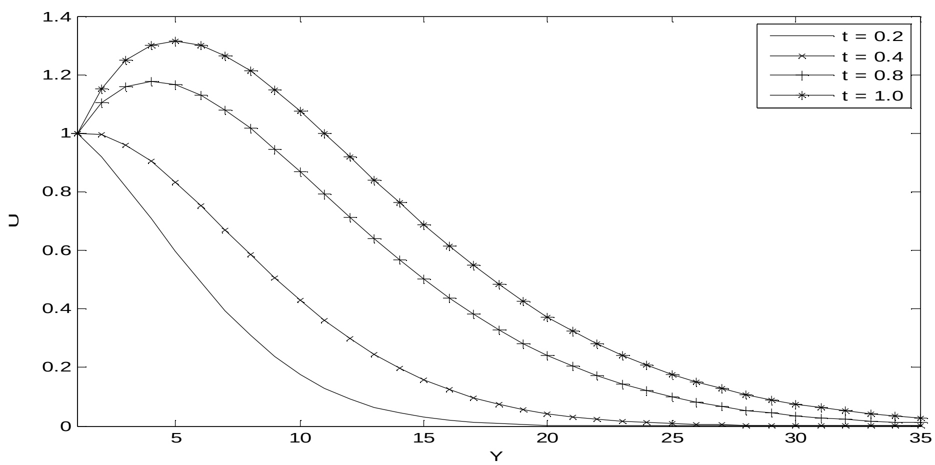

Figure (5): Velocity profiles for different vlues of t

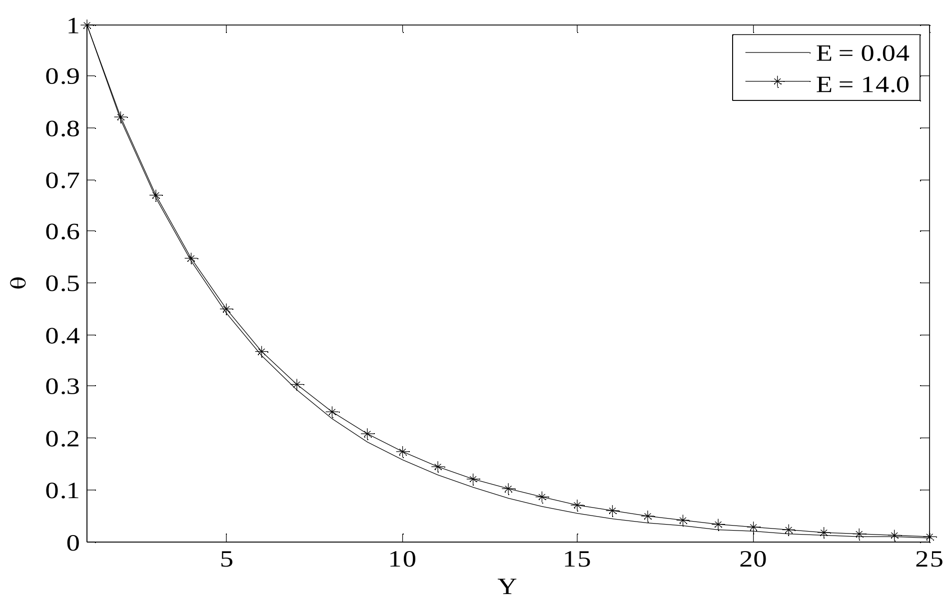

Figure (6): Temperature profiles for different vlues of E

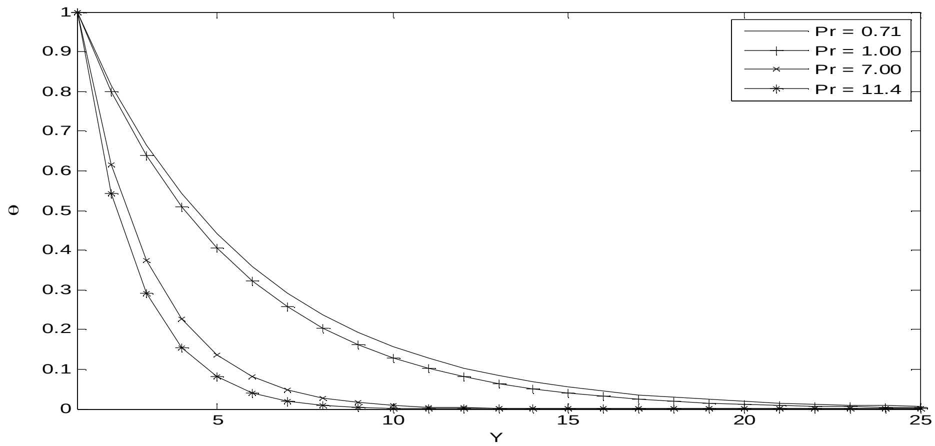

Figure (7): Temperature profiles for different vlues ofPr

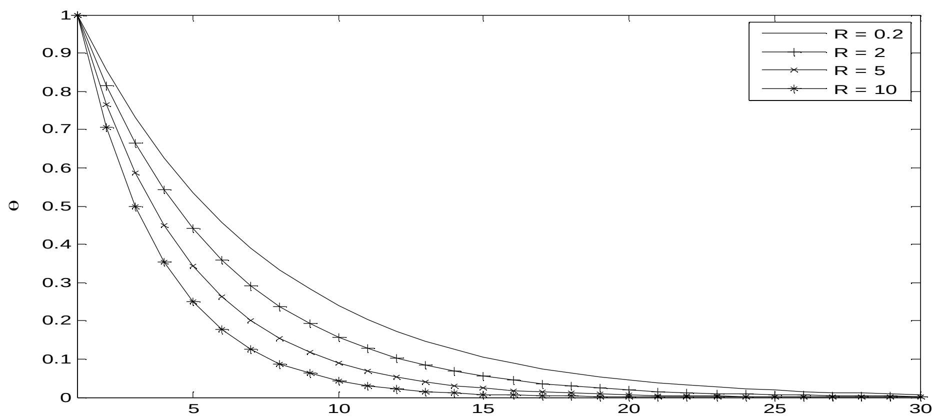

Figure (8): Temperature profiles for different vlues of R

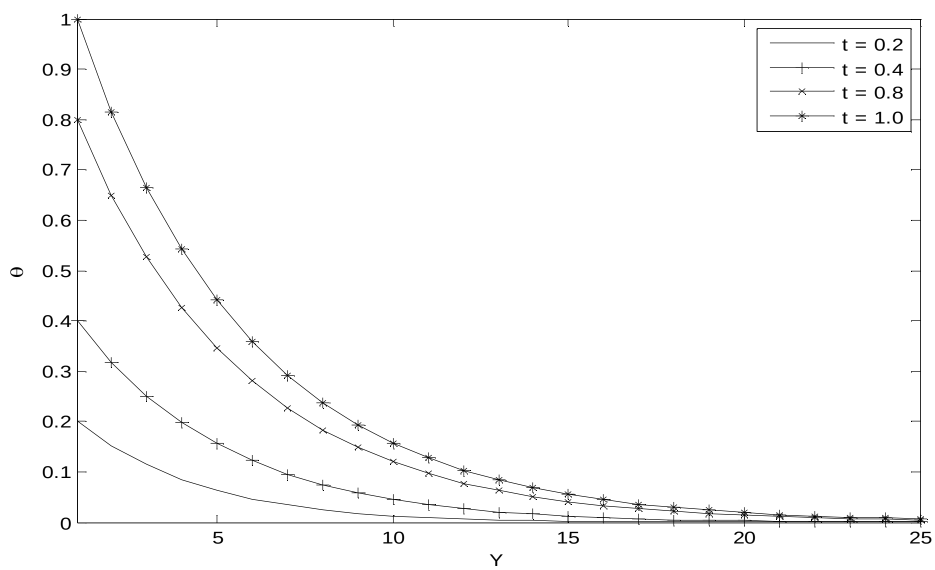

Figure (9): Temperature profiles for different vlues of t

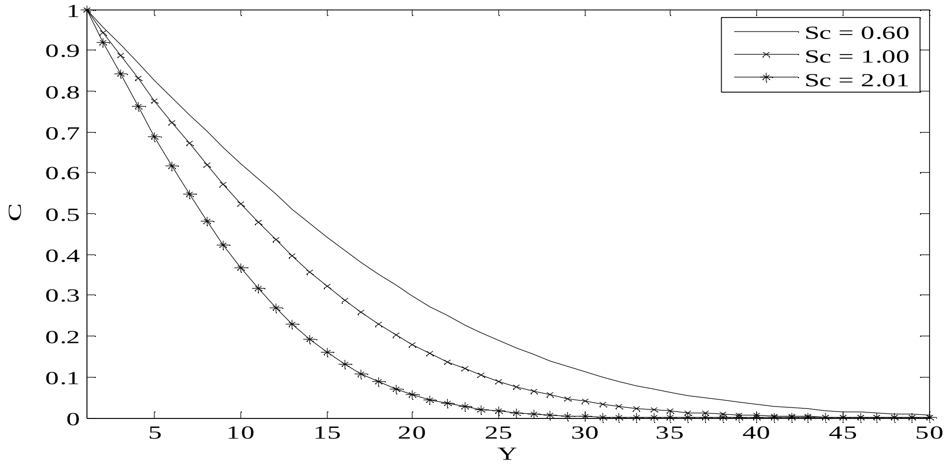

Figure (10): Concentration profiles for different vlues of Sc

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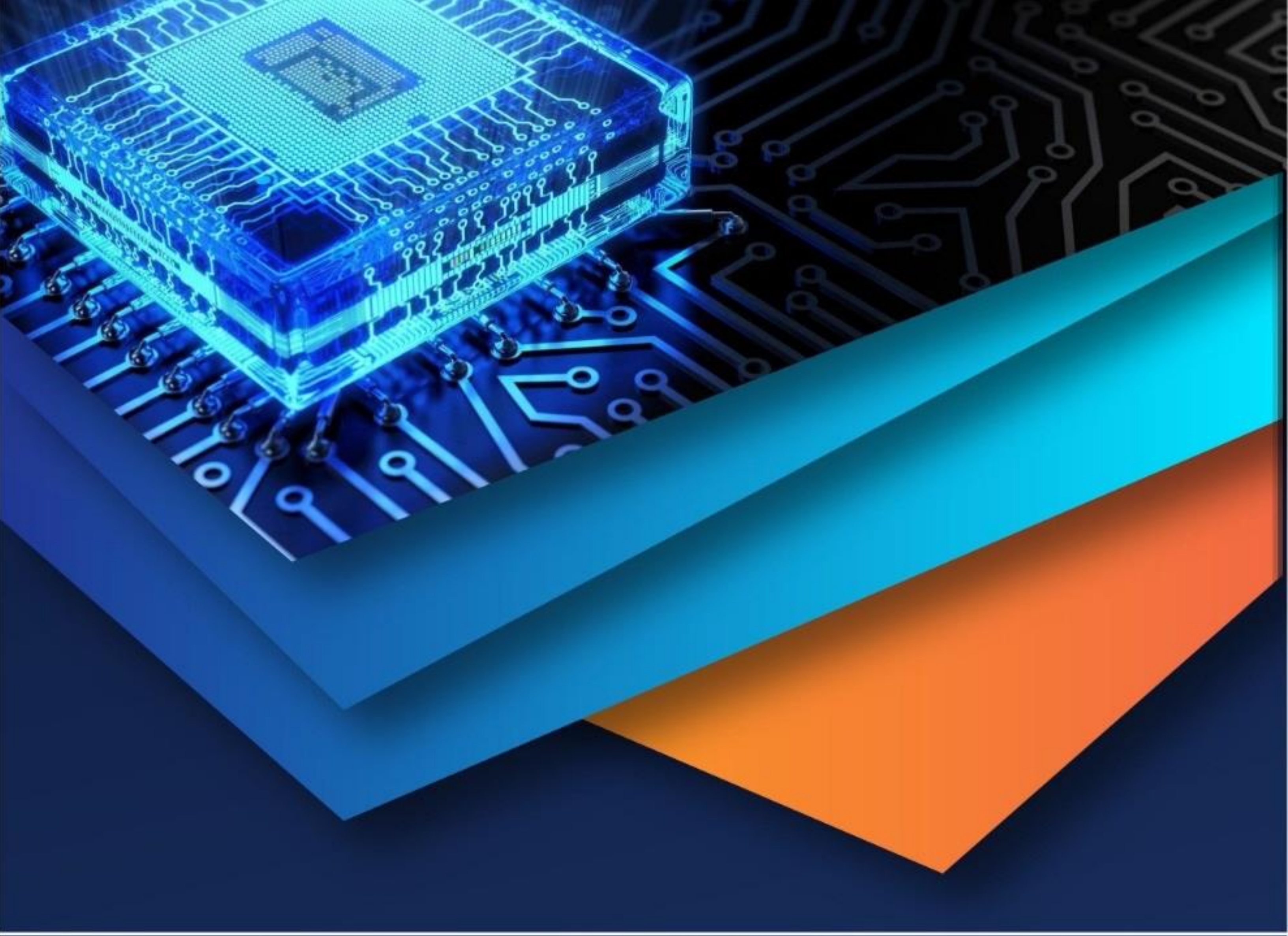

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