Free Convective Heat And Mass Transfer Radiative Flow Past An Impulsively Started Vertical Moving Plate With Uniform Heat And Mass Flux

Janardhan.kodidala, Jagadeeswara Pillai.k, and Viswanatha Reddy. G

Abstract— **In this paper, we studied analytically the thermal radiation effect on free convective flow of a viscous incompressible fluid past an impulsively started vertical plate with flux. The fluid is assumed to be gray absorbing-emitting but not a scattering medium and Rosseland approximation is used to describe the Radiative heat flux. The method of Laplace transform is used to solve dimensionless governing partial differential equations. The resulting velocity, temperature and concentration profiles as well as the skin friction, rate of heat and mass transfer have been obtained. Some important applications of physical interest for different type motion of the plate are discussed numerically through graphs.**

Keywords—Heat flux, Impulsively started vertical moving plate, Mass flux, Radiation.

I. Introduction

Radiative heat transfer plays an important role in manufacturing industries for the design of reliable equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering applications. The first exact solution of the Navier Stokes equation was given by stokes [23] which concerned with the flow of a viscous incompressible fluid past an infinite horizontal plate oscillating in its own plane in an infinite mass of stationary fluid. Chandrakala [5] studied the free convection flow of a viscous in compressible fluid past an infinite vertical oscillating plate with uniform heat flux in the presence of thermal radiation. Chandrakala [6] considered free convection flow past an impulsively started infinite vertical plate with uniform heat flux in the presence of thermal radiation. Kalidas Das [8] studied unsteady MHD free convection flow and mass transfer of a viscous, electrically conducting and chemically reacting incompressible fluid in presence of thermal radiation and under the influence of uniform magnetic field applied normal to an infinite vertical plate, which moves with time dependent velocity. Das [7] et.al developed the effect of heat and mass transfer on free convection flow near an infinite vertical plate embedded in porous medium, which moves with time dependent velocity in a viscous, electrically conducting incompressible fluid, under the influence of uniform magnetic field, applied normal to the plate.

Md Abdus Samad et.al [1] investigated a study of unsteady MHD free convection flow through a porous vertical flat plate immersed in a porous medium in presence of magnetic field with radiation. Madhusudhana Rao et.al [10]Analyzed two dimensional unsteady laminar boundary-layer flow of a viscous, incompressible, electrically conducting and heat-absorbing fluid along a semi-infinite vertical permeable moving plate with a uniform transverse magnetic field in presence of radiation, chemical reaction, soret effect and thermal diffusion effects. Krishna Reddy et.al [9] studied the effects of radiation have been discussed on unsteady MHD free convection heat and mass transfer flow on a viscous, incompressible, electrically conducting fluid past a vertical permeable moving plate with radiation.

Vijaya et.al [24] extended the effects of chemical reaction and radiation on unsteady MHD flow past an exponentially accelerated vertical plate with variable temperature and variable mass diffusion in the presence of applied transverse magnetic field. Muralidharan et.al [13] analyzed an unsteady flow past a uniformly accelerated infinite vertical plate with variable temperature and mass diffusion, in the presence of thermal radiation. Muthucumaraswamy et.al [15] investigated the thermal radiation effects on unsteady free convective flow over a moving vertical plate in the presence of variable temperature and uniform mass flux. Vijayalakshmi et.al [25] studied thermal radiation effects on unsteady free convective flow over a moving vertical plate in a rotating fluid. Few other researchers contributed in this area of research [28-35]

Bala Anki Reddy et.al [4] studied the radiation effects on unsteady flow of a viscous incompressible fluid past an exponentially accelerated infinite isothermal vertical plate with uniform mass diffusion is considered in the presence of magnetic field and heat source. Muralidharan et.al [14] analyzed Radiative heat transfer effects on unsteady flow of viscous incompressible fluid past a uniformly accelerated infinite vertical plate with variable temperature and uniform mass flux. Anand Rao et.al [3] investigated the radiation effect on an unsteady megnetohydrodynamic free convective flow past a vertical porous plate in the presence of soret.

Rajeswara Rao et.al [16] studied a numerical solution of the

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unsteady radiative, free convection flow with heat and mass transfer of an incompressible viscoelastic fluid past an impulsively started vertical plate. Ahmed et.al [2] analyzed unsteady flow of a viscous incompressible fluid past an exponentially accelerated moving vertical plate. Seth et.al [21] studied the effects of radiation and rotation on unsteady hydromagnetic free convection flow of a viscous incompressible electrically conducting fluid past an impulsively moving infinite vertical plate with ramped temperature in a porous medium. Seth et.al [22] investigated the effects of radiation and rotation on unsteady hydromagnetic free convection flow of a viscous incompressible electrically conducting fluid past an impulsively moving infinite vertical plate with ramped temperature in a porous medium.

Rajput et.al [17] studied MHD flow past an impulsively started vertical plate with variable temperature and mass diffusion. Muralidharan [12] analyzed the closed form solution of flow past a parabolic starting motion of the infinite vertical plate with uniform heat flux and variable mass diffusion. Sanatan Das et.al [20] studied Radiation effect on the natural convection flow of an optically thin viscous incompressible fluid near a ver-tical plate with ramped wall temperature in a porous medium. Rajput et.al [18] analyzed Thermal radiation effect on a transient MHD flow with mass transfer past an impulsively fixed infinite vertical plate

Rajput et.al [19] studied Thermal radiation effect on a transient MHD flow with mass transfer past an impulsively fixed infinite vertical plate. Maitree et.al [11] extended the combined effects of rotation and radiation on the unsteady hydrodynamic flow past an impulsively accelerated vertical plate with ramped plate temperature. The aim of the present investigation is to analyze the effect of heat and mass transfer on the unsteady free convection flow of a viscous, electrically conducting incompressible fluid over impulsively started vertical plate.

II. FORMATION OF THE PROBLEM

We consider unsteady free convective heat and mass transfer flow of a viscous incompressible and electrically conducting radiating fluid past an impulsively started semi-infinite non- conducting vertical plate with uniform heat and mass flux. We consider Cartesian coordinate system to describe the physical configuration and the x-axis is taken along the plate in vertically upward direction and the y-axis is taken normal to the plate.

Initially, for time $t^1 \leq 0$, the plate and the fluid are maintained at the same constant temperature T'_∞ in a stationary condition with the same species concentration C'_∞ at all points. Subsequently $t^1 > 0$, the plate is assumed to be accelerating with a velocity $u_0\ f(t^1)$ in its own plane along the x-axis instantaneously the temperature of the plate and the concentration are raised to $\frac{-q}{\kappa}$ and $\frac{J''}{D}$ respectively, which are hereafter regarded as constant.

Under the above assumptions and boundary layer and Boussinesq approximations, the governing equations are as follows.

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

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_x}{\partial y'} \tag{2}$$

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

The associated boundary conditions are

$$\begin{aligned} &u' = 0, T' = T'_\infty, C' = C'_\infty\ \forall\ y' \geq 0, t \leq 0 \\ &u' = u_0 f(t), \frac{\partial T'}{\partial y'} = \frac{-q}{k}, \frac{\partial C'}{\partial y'} = \frac{-J''}{D}\ \ at\ \ y' = 0, t > 0 \\ &u' \to 0,\ T' \to T'_\infty,\ C' \to C'_\infty\ \ as\, y' \to \infty, t > 0 \end{aligned} \tag{4}$$

The local radiant for the case of an optically thin gray gas is expressed by

$$q_r = \frac{-4\sigma}{3\kappa^*}\frac{\partial T'^4}{\partial y'} \tag{5}$$

It is assumed that the temperature differences within the flow are sufficiently small such that may be expressed as a linear function of the temperature. This is accomplished by expanding in a Taylor series about T'_∞ and neglecting higher order terms, thus

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \tag{6}$$

By using equation (6) and (5) in (2) reduces to

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa\frac{\partial^2 T'}{\partial y'^2} + \frac{16\sigma T'^3}{3\kappa^*}\frac{\partial^2 T'}{\partial y'^2} \tag{7}$$

On introducing the following dimensionless quantities

$$\begin{aligned} &u = \frac{u'}{u_0}, t = \frac{t' u_0^2}{\nu},\ y = \frac{y' u_0}{\nu}, \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \\ &\phi = \frac{C' - C'_\infty}{C'_w - C'_\infty}, S_c = \frac{\nu}{D} G_r = \frac{g\beta\gamma(T'_w - T'_\infty)}{u_0^3} \\ &G_c == \frac{g\beta^*\nu(C'_w - C'_\infty)}{u_0^3}, P_r = \frac{\mu C_p}{\kappa}, N = \frac{\kappa^*\kappa}{\phi\sigma T'^3_\infty} \end{aligned} \tag{8}$$

The equations (1), (3) and (7), reduces to

$$\frac{\partial u}{\partial t} = G_r\theta + G_c\phi + \frac{\partial^2 u}{\partial y^2} \tag{9}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{a}\frac{\partial^2 \theta}{\partial y^2} \tag{10}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{S_c}\frac{\partial^2 \phi}{\partial y^2} \quad (11)$$

The corresponding boundary conditions are

$$u = 0,\ \theta = 0,\ C = 0\ \forall\ y' \geq 0,\ t \leq 0$$
$$u = f(t), \frac{\partial \theta}{\partial y} = -1, \frac{\partial \phi}{\partial y} = -1\ at\ y = 0, t > 0 \quad (12)$$
$$u \to 0, \theta \to 0, \phi \to 0\ \ as\ y \to \infty, t > 0$$

III. ANALYTICAL SOLUTION

In order to obtain the solution of the present problem, we employed the Laplace transform technique. By using the Laplace transform technique to the system of equations (9) to (11), with boundary conditions (12), we obtained the solutions as follows.

$$\theta = \frac{2\sqrt{t}}{\sqrt{a}}\left[\frac{\exp(-\eta^2 a)}{\sqrt{\pi}} - \eta\sqrt{a}\, erfc(\eta\sqrt{a})\right] \quad (13)$$

$$\phi = \frac{2\sqrt{t}}{\sqrt{S_c}}\left[\frac{\exp(-\eta^2 S_c)}{\sqrt{\pi}} - \eta\sqrt{S_c}\ erfc(\eta\sqrt{S_c})\right] \quad (14)$$

$$u = \Phi(y,t) + A(y,t) + B(y,t) \quad (15)$$

Where

$$\Phi(y,t) = L^{-1}\left\{\overline{f}(s)\exp(-y\sqrt{s})\right\}, \overline{f}(s) = L\{f(t)\} \quad (16)$$

$$A(y,t) = -\frac{G_r}{3\sqrt{a}(-a+1)}t^{\frac{3}{2}}\left\{\frac{4}{\sqrt{\pi}}(1+\eta^2)\exp(-\eta^2) - \eta(6+4\eta^2)erfc(\eta)\right\} + \frac{G_r}{3\sqrt{a}(-a+1)}t^{\frac{3}{2}} \left\{\frac{4}{\sqrt{\pi}}(1+a\eta^2)\exp(-a\eta^2) - \eta\sqrt{a}(6+4a\eta^2)erfc(\eta\sqrt{a})\right\} \quad (17)$$

$$B(y,t) = -\frac{G_c}{3\sqrt{S_c}(-S_c+1)}t^{\frac{3}{2}}\left\{\frac{4}{\sqrt{\pi}}(1+\eta^2)\exp(-\eta^2) - \eta(6+4\eta^2)erfc(\eta)\right\} + \frac{G_c}{3\sqrt{S_c}(-S_c+1)}t^{\frac{3}{2}} \left\{\frac{4}{\sqrt{\pi}}(1+S_c\eta^2)\exp(-S_c\eta^2) - \eta\sqrt{S_c}(6+4S_c\eta^2)erfc(\eta\sqrt{S_c})\right\} \quad (18)$$

Where $a = \frac{3NP_r}{3N+4P_r}$ and $\eta = \frac{y}{2\sqrt{t}}$

Since non-dimensional temperature θ(y,t) and non-dimensional species concentration ϕ(y,t) is clearly described in equation (13) and equation (14), so we shall confine ourselves to non-dimensional velocity u(y,t) for various types of f(t).Here the expressions (15)-(18) are the general solutions of the present problem which include the effects of heating (cf.term A), diffusion(cf.term B).

IV. APPLICATIONS OF THE GENERAL SOLUTIONS

In this section we now consider some important cases of flow as given below.

A. Motion of the plate with zero velocity

Let f(t) =H(t) Heaviside unit functions, Then in this case we observe that the result (13),(14) are not affected and the expression (15) for u(y,t) becomes

$$u = A(y,t) + B(y,t)$$

B. Motion of the plate with unit velocity

Let f(t) =H(t) Heaviside unit functions, then in this case we observe that the result (13), (14) are unchanged and the expression (15) for u(y,t) becomes

$$u = erfc(\eta) + A(y,t) + B(y,t)$$

C. Motion of the plate with single acceleration

Let f (t) =H (t) t Heaviside unit functions, then in this case we observe that the result (13), (14) are unchanged and the expression (15) for u(y, t) becomes

$$u(y,t) = t\left\{(1+2\eta^2)erfc\{\eta\} - \frac{2\eta}{\sqrt{\pi}}\exp(-\eta^2)\right\} + A(y,t) + B(y,t)$$

D. Motion of the plate with periodic acceleration

Let $f(t) = H(t)\cos(\omega t)$ Heaviside unit functions, then the expression (13),(14) remains again in the same form but instead of (15),we get the following analytical expression.

$$u(y,t) = \frac{e^{-i\omega t}}{4}\left\{e^{-2\eta\sqrt{-i\omega t}} erfc(\eta - \sqrt{-i\omega t}) + e^{2\eta\sqrt{-i\omega t}} erfc(\eta + \sqrt{-i\omega t})\right\} + A(y,t) + \frac{e^{i\omega t}}{4}\left\{e^{-2\eta\sqrt{-i\omega t}} erfc(\eta - \sqrt{i\omega t}) + e^{2\eta\sqrt{-i\omega t}} erfc(\eta + \sqrt{i\omega t})\right\} + B(y,t)$$

V.SKIN FRICTION

Knowing the velocity field, we now study the effect of t,Pr,Sc ect. on the skin friction. In non-dimensional form, it is given by

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0} = -\frac{1}{2\sqrt{t}}\left(\frac{\partial u}{\partial \eta}\right)_{\eta=0}$$
$$= -\frac{1}{2\sqrt{t}}\left\{\left(\frac{\partial \Phi}{\partial \eta}\right)_{\eta=0} + \frac{2G_r t^{3/2}}{\sqrt{a}(\sqrt{a}+1)} + \frac{2G_c t^{3/2}}{\sqrt{S_c}(\sqrt{S_c}+1)}\right\}$$

A. when the plate is moving with uniform velocity then

$$\left(\frac{\partial \Phi}{\partial \eta}\right)_{\eta=0} = -\frac{2}{\sqrt{\pi}}$$

B. when the plate is moving with single acceleration then

$$\left(\frac{\partial \Phi}{\partial \eta}\right)_{\eta=0} = -\frac{4}{\sqrt{\pi}}t$$

C. when the plate is moving with periodic acceleration then

$$\left(\frac{\partial \Phi}{\partial \eta}\right)_{\eta=0} = -\frac{2}{\sqrt{\pi}} - e^{-i\omega t}\sqrt{-i\omega t}\, erfc\left(\sqrt{-i\omega t}\right) - e^{i\omega t}\sqrt{i\omega t}\, erfc\left(\sqrt{i\omega t}\right)$$

VI. NUSSELT NUMBER

An important phenomenon in this study is to understand the effect on the Nusselt number. In non-dimensional form, the rate of heat transfer is given by

$$N_u = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -\frac{1}{2\sqrt{t}}\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0} = 1$$

VII. SHERWOOD NUMBER

Another important physical quantities of interest is the Sherwood number whose non-dimensional form

$$S_h = -\left(\frac{\partial \phi}{\partial y}\right)_{y=0} = -\frac{1}{2\sqrt{t}}\left(\frac{\partial \phi}{\partial \eta}\right)_{\eta=0} = 1$$

VIII. DISCUSSION

In order to get physical insight into the problem velocity field, temperature and concentration field, skin-friction coefficient, rate of heat transfer and rate of mass transfer have been discussed by assigning numerical values to various parameters appeared in the equations obtained in mathematical formulation in the problem. To be realistic the values of prandtl number (Pr) are chosen for Mercury (Pr=0.025), air (Pr=0.71), water (Pr=7.0). the values of Schmidt number (Sc) are taken for hydrogen (Sc=0.22), Helium (Sc=0.30), Water-vapor (Sc=0.60). Two cases of general interest for Grashof number Gr>0 corresponding to cooling of the plate and Grasof number Gr<0 corresponding to heating of the plate are considered. For the figures of velocity profiles the numerical values of time (t=0.2,0.4,0.6), Radiation parameter (N=2,5,30), Prandtl number (Pr=0.025,0.71,7.0), Schmidt number (Sc=0.22,0.30,0.60),

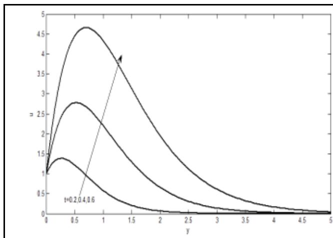

Fig1: Motion of the plate with unit velocity profiles for different values of t: N=2,Pr=0.71,Sc=0.22, Gr=10, Gc=10

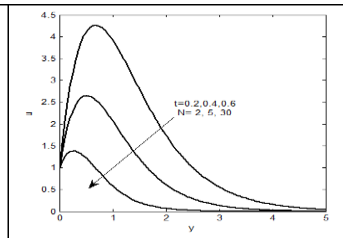

Fig2: Motion of the plate with unit velocity profiles for different values of t anN:Pr=0.71,Sc=0.22, Gr=10, Gc=10

Grashof number for heat transfer are chosen to be(Gr=5,10,15,20) and the values of modified Grashof number for mass transfer are taken as (Gc=5,10,15,20) corresponding to cooling of the plate phase angle (ωt=0,π/6, π/4, π/3, π/2) are considered to be fixed.

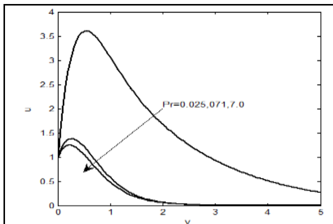

Fig3: Motion of the plate with unit velocity profiles for different values of Pr: t=0.2,N=2,Sc=0.22,Gr=10, Gc=10

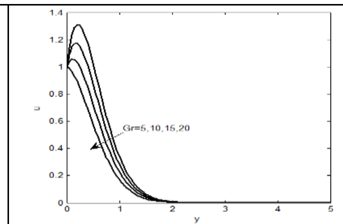

Fig4: Motion of the plate with unit velocity profiles for different values of Gr: t=0.2,N=2,Pr=0.71,Sc=0.22, Gc=10

The Motion of the plate with unit velocity profiles from figure (1) to figure (5), The Motion of the plate with single acceleration velocity profiles from figure (6) to figure (9) and The Motion of the plate with periodic acceleration velocity profiles from figure (10) and figure (11).

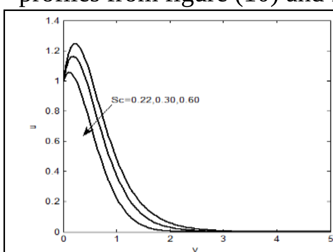

Fig5: Motion of the plate with unit velocity profiles for different values of Sc: t=0.2, N=2,Pr=0.71,Gr=10, Gc=10

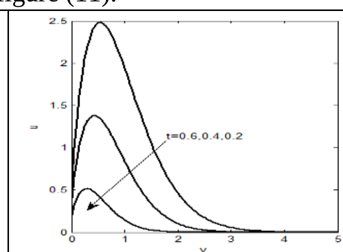

Fig6: Motion of the plate with single acceleration velocity profiles for different values of t: N=2, Pr=7.0, Sc=0.60,Gr=20, Gc=10

The velocity profiles for different values of time‘t’ are shown in fig (1). This shows that the velocity increases with increasing values of time‘t’. Figure (2) displays the effect of radiation parameter and time on the velocity, the velocity decreasing for increasing radiation parameter and time. The velocity profiles for different values of Pr are shown the unit velocity fig (3) and single acceleration velocity fig (7) it are observed the velocity ‘u’ decreases as increasing of prandtl number.

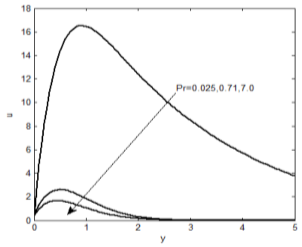

Fig7: Motion of the plate with single acceleration velocity profiles for different values of Pr:t=0.4,N=5, Sc=0.60, Gr=20,Gc=10

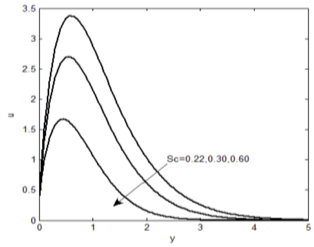

Fig8: Motion of the plate with single acceleration velocity profiles for different values of Sc: t=0.4, N=5,Pr=7.0, Gr=20,Gc=10

The unit velocity, sigle acceleration velocity profiles for different values of Schmidt number (Sc) are shown in fig (5) and fig (8). It can be seen that the velocity decreases as increasing the Schmidt number.

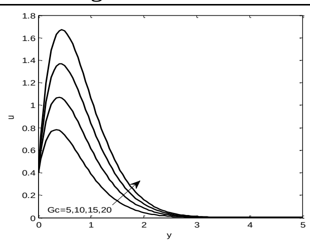

Fig9: Motion of the plate with single acceleration velocity profiles for different values of Sc: t=0.4,N=5, Pr=7.0,Gr=20

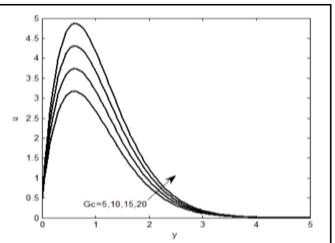

Fig10: Motion of the plate with periodic acceleration velocity profiles for different values of Gc:t=0.6, N=5, Pr=0.71, wt=π/3, Sc=0.60, Gr=20.

The velocity increase as increasing of mass Grashof number fig (9) and fig (10) with single acceleration velocity and periodic acceleration velocity. In fig (4) with unit velocity profiles are drawn for different values of thermal Grashof number (Gr).

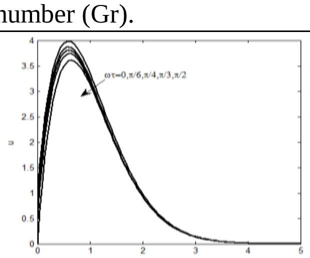

Fig11: Motion of the plate with periodic acceleration velocity profiles for different values of wt: t=0.6,N=5, Pr=0.71, Sc=0.60, Gr=20, Gc=20

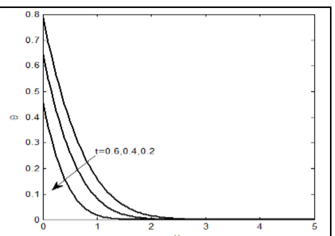

Fig12: Temperature profiles for different values of t: Pr=7.0,N=2

It can be observed that the velocity u decreases with the increasing of thermal Grashof number. The motion of the plate with single acceleration velocity profiles are shown in fig (6). It is noted that the velocity 'u' decreases as time't' decreasing. Fig (11) depicts the influence of the phase angle (ωt) with periodic acceleration velocity profile, it is observed that the velocity decreases as increasing of phase angle.

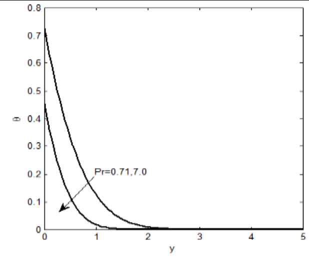

Fig13: Temperature profiles for different values of Pr: t=0.2,N=2

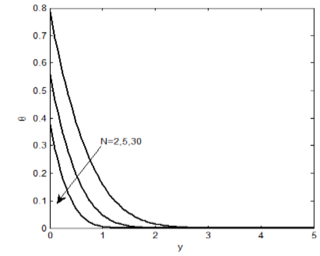

Fig14: Temperature profiles for different values of N: t=0.6,Pr=7.0

The temperature profiles are calculated for different values of time't' prandtl number 'Pr' and thermal radiation parameter 'N' are shown in fig (13) and fig (14), it is observed that temperature decreases with increasing of prandtl number, radiation parameter and time decreasing.

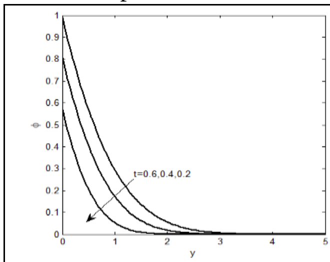

Fig15:Concentration profiles for different values of t: Sc=0.78

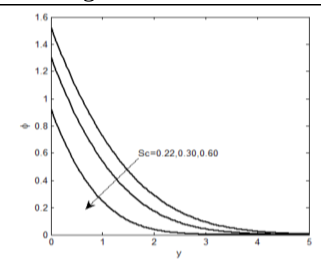

Fig16: Concentration profiles for different values of Sc: t=0.4

The concentration profiles for different values of time t and Schmidt number Sc are show in fig (15) and fig (16),it can be seen that as the time decreases, the velocity decreases. And Schmidt number increases the velocity decreases.

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