RADIATION EFFECTS ON OSCILLATING VERTICAL PLATE IN THE PRESENCE OF FIRST ORDER CHEMICAL REACTION WITH VARIABLE TEMPERATURE

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.***Abstract***: An exact investigation is performed to study the unsteady flow past an infinite vertical oscillating plate with variable temperature and mass diffusion, in the presence of thermal radiation and homogeneous chemical reaction of first order. The fluid considered here is a gray, absorbing-emitting radiation but a non-scattering medium. The solution of the dimensionless governing equations has been obtained by the Laplace transform method for velocity,temparature,concentration when the plate is oscillating harmonically in its own plane. The effects of temperature, concentration and velocity are discussed in graphical format for different physical parameters like phase angle, radiation parameter, chemical reaction parameter, Schmidt number, mass Grashof number,thermal Grashof number and time. It has been found that the velocity increases with decreasing phase angle ωt . It is also observed that the velocity increases with decreasing thermal radiation parameter or chemical reaction parameter.

IndexTerms: chemical reaction, gray, oscillating, radiation, vertical plate, heat and mass transfer.

NOMENCLATURE

A , n	constant
B_0	external magnetic field
C'	species concentration in the fluid
C'_w	concentration of the plate
C'_∞	concentration of the fluid far away from the plate
C	dimensionless concentration
C_p	specific heat at constant pressure
D	mass diffusion coefficient
Gc	mass Grashof number
Gr	thermal Grashof number
g	acceleration due to gravity
k	thermal conductivity
K_l	chemical reaction parameter
K	dimensionless chemical reaction parameter
q_r	radiative heat flux in the y-direction
R	radiation parameter
M	magnetic field parameter
Pr	Prandtl number
Sc	Schmidt number

T_∞ temperature of the fluid far away from the plate

T_w temperature of the plate

T temperature of the fluid near the plate

t' time

t dimensionless time

u velocity of the fluid in the x-direction

u_0 velocity of the plate or amplitude of oscillation

U dimensionless velocity

x spatial coordinate along the plate

y coordinate axis normal to the plate

Y dimensionless coordinate axis normal to the plate

Greek Symbols

α thermal diffusivity

β volumetric coefficient of thermal expansion

β^* volumetric coefficient of expansion with concentration

μ cofficient of viscosity

σ electric conductivity

ν kinematic viscosity

ρ density of the fluid

θ dimensionless temperature

η similarity parameter

$erfc$ complementary error function

ω' frequency of oscillation

ω dimensionless frequency of oscillation

ωt phase angle

∞ conditions in the free stream

INTRODUCTION

Thermal radiation is an important factor in the thermodynamic analysis of many high temperature systems like solar collectors, boilers and furnaces. The simultaneous effect of heat and mass transfer in the presence of thermal radiation has an important role in manufacturing industries for the design of fins, nuclear power plants, steel rolling , gas turbines,cooling of towers and various propulsion device for aircraft, materials processing, energy utilization, temperature measurements, remote sensing for astronomy and space exploration, food processing and cryogenic engineering, as well as numerous agricultural, health and military applications.

England and Emery(1969) have studied the thermal radiation effects of a optically thin gray gas bounded by a stationary vertical plate. Radiation effect on mixed convection along a isothermal vertical plate were studied by Hossain and Takhar(1996). Raptis and Perdikis(1999) discussed the effects of thermal radiation and free convection flow past a moving vertical plate. The governing equations were solved analytically. Das *et al*(1996) have analyzed radiation effects on flow past an impulsively started infinite isothermal vertical plate.

The Effect of a chemical reaction depend whether the reaction is homogeneous or heterogeneous. This depends on whether they occur at an interface or as a single phase volume reaction. In well-mixed systems, the reaction is heterogeneous, if it takes place at an interface and homogeneous, if it takes place in solution. Das *et al* (1999) have analyzed the effect of homogeneous first order chemical reaction on the flow past an impulsively started infinite vertical plate with uniform heat flux and mass transfer. Again, mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction studied by Das *et al* (1994). The dimensionless governing equations were solved by the usual Laplace-transform technique and the solutions are valid only at lower time level.

The flow of a viscous, incompressible fluid past an infinite isothermal vertical plate, oscillating in its own plane, was solved by Soundalgekar (1979). The effect on the flow past a vertical oscillating plate due to a combination of concentration and temperature differences was discussed extensively by Soundalgekar and Akolkar (1983). Radiation effects on the oscillatory flow past vertical in the presence of uniform temperature analyzed by Mansour(1990). The governing were solved by perturbation technique. The effect of mass transfer on the flow past an infinite vertical oscillating plate in the presence of constant heat flux has been studied by Soundalgekar et al. (1994).

Sundar Raj et al. (2011) have analyzed the flow past an accelerated infinite vertical plate with variable temperature and mass diffusion again Nagarajan et al. (2011) have studied chemical reaction and radiation effects on vertical oscillating plate with variable temperature and mass diffusion and Sundar Raj and Nagarajan (2018) were discussed heat Transfer on flow past a linearly vertical accelerated plate with constant temperature and variable mass diffusion.

Sundar Raj and Nagarajan (2019) have analyzed the heat Transfer Consequences on an Elevated Isothermal Vertical Plate with Constant Temperature and Mass Flux.Sundar Raj et al. (2011) discussed the hydromagmetic flow past an accelerated vertical plate with variable temperature and mass diffusion. and the mass transfer effects on linearly accelerated vertical plate with heat flux and variable mass diffusion were studied in (2017)..

Nagarajan et al. (2010) have discussed the hydromagnetic effects on oscillating vertical plate with variable temperature and chemical reaction. and also the first order chemical reaction on MHD flow past an oscillating vertical plate in the presence of thermal radiation was analyzed in (2011).

It is proposed to study thermal radiation effects on unsteady flow of a viscous incompressible fluid past an infinite vertical oscillating plate with variable temperature and mass diffusion. The dimensionless governing equations are solved using the Laplace transform technique. The solutions are in terms of exponential and complementary error function.

. BASIC EQUATIONS AND ANALYSIS

Here the unsteady flow of a viscous incompressible fluid which is initially at rest and surrounds an infinite vertical plate with temperature T_∞ and concentration C'_∞. Here, the x -axis is taken along the plate in the vertically upward direction and the y -axis is taken normal to the plate. Initially, it is assumed that the plate and the fluid are of the same temperature and concentration. At time $t' > 0$, the plate starts oscillating in its own plane with frequency ω' and the temperature of the plate is raised linearly with respect to time and the concentration level near the plate is raised to C'_∞. The fluid considered here is a gray, absorbing-emitting radiation but a non-scattering medium. It is also assumed

that there exists a homogeneous first order chemical reaction between the fluid and species concentration. Then by usual Boussinesq's approximation, the unsteady flow is governed by the following equations:

Equation of momentum:

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

Energy equation with radiation:

$$\rho\,C_p\frac{\partial T}{\partial t'} = k\frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y} \qquad (2)$$

Mass diffusion equation with chemical reaction:

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y^2} - K_l\,C' \qquad (3)$$

In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. A reaction is said to be of the order n, if the reaction rate is proportional to the n^{th} power of the concentration. In particular, a reaction is said to be first order, if the rate of reaction is directly proportional to concentration itself.

With the following initial and boundary conditions:

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

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

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

It is assumed 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

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

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

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

The dimensionless quantities are defined as

$$U = \frac{u}{u_0}, \quad t = \frac{t' u_0^{\;2}}{\nu}, \quad Y = \frac{y u_0}{\nu}, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty},$$

$$Gr = \frac{g\,\beta\,\nu\,(T_w - T_\infty)}{u_0^{\;3}}, \quad C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Gc = \frac{\nu\, g\,\beta^*\,(C'_w - C'_\infty)}{u_0^{\;3}}, \tag{8}$$

$$\Pr = \frac{\mu C_p}{k}, \quad Sc = \frac{\nu}{D}, \quad R = \frac{16 a^* \nu^2 \sigma T_\infty^{\;3}}{k u_0^{\;2}}, \quad K = \frac{\nu K_l}{u_0^{\;2}}, \quad \omega = \frac{\omega' \nu}{u_0^{\;2}}$$

Equations (1) to (4) reduces to

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

$$\frac{\partial \theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial Y^2} - \frac{R}{\Pr}\,\theta \tag{10}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial Y^2} - K\,C \tag{11}$$

The initial and boundary conditions in non dimensional form are

$$\begin{aligned} & U = 0\,,\ \theta = 0\,,\ C = 0,\ \text{for all } Y, t \le 0 \\ t > 0:\quad & U = \cos \omega t\,,\ \theta = t,\ C = n,\ \text{at } Y = 0 \\ & U = 0\,,\ \theta \to 0, C \to 0\ \text{as}\ Y \to \infty \end{aligned} \tag{12}$$

All the physical variables are defined in the nomenclature. The solutions are obtained for hydrodynamic flow field in the presence of thermal radiation and chemical reaction.

I. SOLUTION PROCEDURE

The equations (9) to (11), subject to the boundary conditions (12), are solved by the usual Laplace transform technique and the solutions are derived as follows:

$$\begin{aligned} \theta = \frac{t}{2}&\left[\exp(Y\sqrt{R})\, erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}} + \sqrt{at}\right) + \exp(-Y\sqrt{R})\, erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}} - \sqrt{at}\right)\right] \\ &- \frac{Y\Pr}{4\sqrt{R}}\left[\exp(-Y\sqrt{R})\, erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}} - \sqrt{at}\right) - \exp(Y\sqrt{R})\, erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}} + \sqrt{at}\right)\right] \end{aligned} \tag{13}$$

$$C=\frac{n}{2}\left[\exp(Y\sqrt{K\,Sc})\,erfc\left(\frac{Y\sqrt{Sc}}{2\sqrt{t}}+\sqrt{Kt}\right)+\exp(-Y\sqrt{K\,Sc})\,erfc\left(\frac{Y\sqrt{Sc}}{2\sqrt{t}}-\sqrt{Kt}\right)\right] \quad (14)$$

$$U=\frac{\exp(i\omega t)}{4}\left[\exp(Y\sqrt{i\omega})\,erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{i\omega t}\right)+\exp(-Y\sqrt{i\omega})\,erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{i\omega t}\right)\right]$$

$$+\frac{\exp(-i\omega t)}{4}\left[\exp(Y\sqrt{-i\omega})\,erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{-i\omega t}\right)+\exp(-Y\sqrt{-i\omega})\,erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{-i\omega t}\right)\right]$$

$$+2(d+e)\,erfc\left(\frac{Y}{2\sqrt{t}}\right)+2\,t\,b\,d\left[\left(1+\left(\frac{Y^2}{2t}\right)\right)erfc\left(\frac{Y}{2\sqrt{t}}\right)-\frac{Y}{\sqrt{\pi t}}\exp\left(-\left(\frac{Y}{2\sqrt{t}}\right)^2\right)\right]$$

$$-d\exp(bt)\left[\exp(Y\sqrt{b})\,erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{bt}\right)+\exp(-Y\sqrt{b})\,erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{bt}\right)\right]$$

$$-e\exp(ct)\left[\exp(Y\sqrt{c})\,erfc\left(\frac{Y}{2\sqrt{t}}+\sqrt{ct}\right)+\exp(-Y\sqrt{c})\,erfc\left(\frac{Y}{2\sqrt{t}}-\sqrt{ct}\right)\right]$$

$$-d(1+bt)\left[\exp(Y\sqrt{R})\,erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{at}\right)+\exp(-Y\sqrt{R})\,erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{at}\right)\right]$$

$$+bd\frac{Y\Pr}{\sqrt{R}}\left[\exp(-Y\sqrt{R})\,erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{at}\right)-\exp(Y\sqrt{R})\,erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{at}\right)\right]$$

$$+d\exp(bt)\left[\exp(Y\sqrt{\Pr(a+b)})\,erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{(a+b)t}\right)+\exp(-Y\sqrt{\Pr(a+b)})\,erfc\left(\frac{Y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{(a+b)t}\right)\right]$$

$$-e\left[\exp(Y\sqrt{K\,Sc})\,erfc\left(\frac{Y\sqrt{Sc}}{2\sqrt{t}}+\sqrt{Kt}\right)+\exp(-Y\sqrt{K\,Sc})\,erfc\left(\frac{Y\sqrt{Sc}}{2\sqrt{t}}-\sqrt{Kt}\right)\right]$$

$$+e\exp(ct)\left[\exp(Y\sqrt{Sc(K+c)})\,erfc\left(\frac{Y\sqrt{Sc}}{2\sqrt{t}}+\sqrt{(K+c)t}\right)+\exp(-Y\sqrt{Sc(K+c)})\,erfc\left(\frac{Y\sqrt{Sc}}{2\sqrt{t}}-\sqrt{(K+c)t}\right)\right] \quad (15)$$

Where, $a=\frac{R}{\Pr}$, $b=\frac{R}{1-\Pr}$, $c=\frac{KSc}{1-Sc}$, $d=\frac{Gr}{2b^2(1-\Pr)}$, $e=\frac{n\,Gc}{2c(1-Sc)}$, $\eta=\frac{Y}{2\sqrt{t}}$

erfc is called as complementary error function.

In order to get the physical insight into the problem, the numerical values of U have been computed from equation (15). While evaluating this expression, it is observed that the argument of the error function is complex and hence, we have separated it into real and imaginary parts by using the following formula:

$$erf(a+ib)=erf(a)+\frac{\exp(-a^2)}{2a\pi}[1-\cos(2ab)+i\sin(2ab)]$$

$$+\frac{\exp(-a^2)}{2a\pi}\sum_{n=1}^{\infty}\frac{\exp(-n^2/4)}{n^2+4}\left[f_n(a,b)+i\ g_n(a,b)\right]+\in(a,b)$$

Where, $f_n(a,b)=2a-2a\cosh(nb)\cos(2ab)+n\sinh(nb)\sin(2ab)$

$$g_n(a,b)=2a\cosh(nb)\sin(2ab)+n\sinh(nb)\cos(2ab)$$

$$\left|\in(a,b)\right|\approx 10^{-6}\ \left|erf(a+ib)\right|$$

V. RESULTS AND DISCUSSION

To get an actual perspective on the issue the mathematical estimations of the speed, temperature and fixation are determined for various estimations of the stage point, radiation boundary, attractive field boundary, Schmidt number and time. The purpose of the calculations given here is to assess the effect of different $\omega t,\ K,\ R,\ Sc$ and t upon the nature of the flow and transport in the presence of air $(\Pr=0.71)$ and water vapor $(Sc=0.6)$.

The Laplace transform solutions are in terms of exponential and complementary error function.

The temperature profiles are calculated for different values of time $(t=0.2,\ 0.4,\ 0.6,\ 1)$ are shown in figure 1 at $R=0.2$. It is observed that the temperature increases with increasing time t . The temperature profiles are obtained for different values of thermal radiation parameter $(R=0.2,\ 2,\ 5,\ 10)$ from equation (13) and these are shown in figure 2 for air at time $t=1$. The effect of thermal radiation parameter is important in temperature profiles. It is observed that the temperature increases with decreasing radiation parameter.

Figure 3 represents the effect of concentration profiles at time $t=1$ for different Schmidt numbers (Sc = 2.01,0.6,0.3,0.16)and $K=0.2$. The effect of concentration is important in concentration field. The profiles have the common feature that the concentration decreases in a monotone fashion from the surface to a zero value far away in the free stream. It is observed that the wall concentration increases with decreasing values of the Schmidt number. Figure 4 demonstrates the effect of the concentration profiles for different values of the chemical reaction parameter (K = 10, 5, 2, 0.2), $Sc=0.6$ and time $t=1$. It is observed that the concentration increases with decreasing chemical reaction parameter. The effect of concentration profiles for different values of time ($t=0.2, 0.4, 0.6, 1$), $K=2$ and $Sc=0.6$ are presented in figure 5. The trend shows that the wall concentration increases with increasing time t.

The velocity profiles for different phase angles ($\omega t=\pi/2, \pi/4, \pi/6, 0$), $Gr=Gc=2, R=5,\ K=2$ and $t=0.2$ are shown in figure 6. It is interesting to note that at $\omega t=0$, the plate is considered to be vertical and the velocity profile developed from $U=1$. At $\omega t=\pi/2$, the plate is considered to be horizontal and the velocity profiles developed from the origin. It is observed that the velocity increases with decreasing phase angle ωt.

Figure 7 illustrates the effect of the velocity for different values of the reaction parameter $(K=0.2,\ 5,\ 15)$, $\omega t=\pi/6$, $R=5,\ Gr=Gc=2$ and $t=0.4$. The trend shows that the velocity increases with decreasing chemical reaction parameter.

The effect of velocity for different values of the radiation parameter $(R=2,\ 5,\ 10)$, $\omega t=\pi/6$, $K=2$, $Gr=2$, $Gc=2$ and $t=0.6$ are shown in figure 8. It is observed that the velocity decreases in the presence of high thermal radiation. The trend shows that the velocity increases with decreasing radiation parameter.

The velocity profiles for different thermal Grashof number(Gr = 10, 2), massGrashof number $(Gc=2,\ 5)$, $\omega t=\pi/6$, $K=0.2$, $R=5$ and time $t=0.3$ are shown in figure 9. It is clear that the velocity increases with increasing thermal Grashof number or mass Grashof number. The effect of velocity profiles for different time $(t=0.2,\ 0.3,\ 0.4)$, $\Pr=0.71$, $Sc=0.6$, $\omega t=\pi/6$, $R=5$, $K=0.2$, $Gr=Gc=2$, are shown in figure 10. In this case, the velocity increases gradually with respect to time t.

. CONCLUSIONS

Thermal radiation effects on unsteady flow past an infinite vertical oscillating plate in the presence of variable temperature and uniform wall concentration is studied. The dimensionless equations are solved using Laplace transform technique. The effect of velocity, temperature and concentration for different parameters like ωt, R, K, Gr, Gc, Sc and t are studied. The study concludes that the velocity increases with decreasing phase angle ωt and radiation parameter R. The trend is just reversed with respect to time t. It is observed that the concentration increases with decreasing Schmidt number. The temperature decreases due to high thermal radiation. It is also observed that the leading edge effect is not affected by the oscillation of the plate.

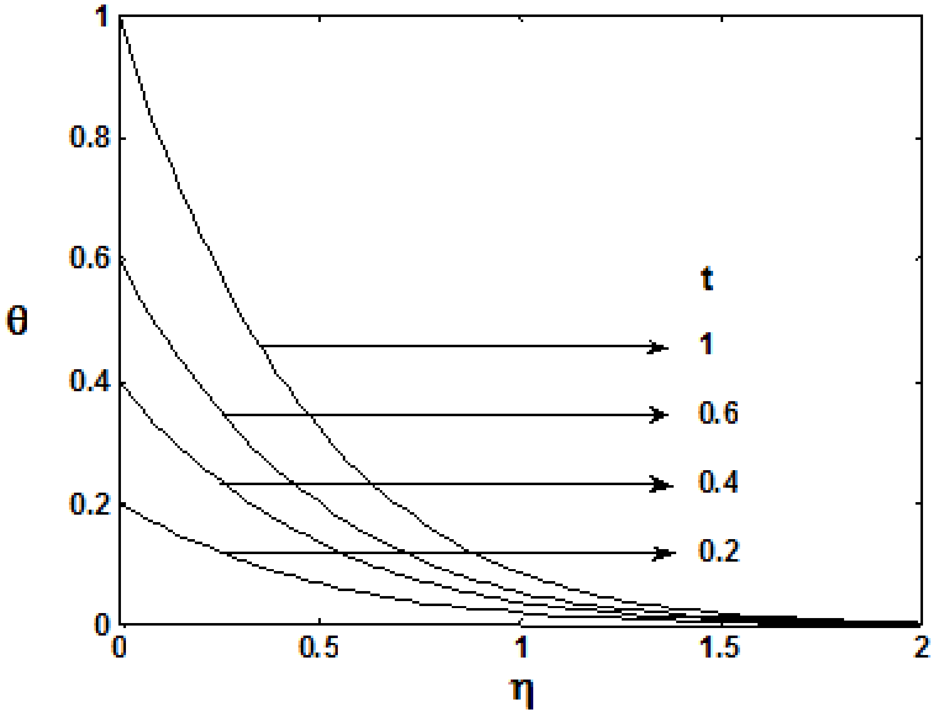

Fig. 1: Temperature profiles for different values of t

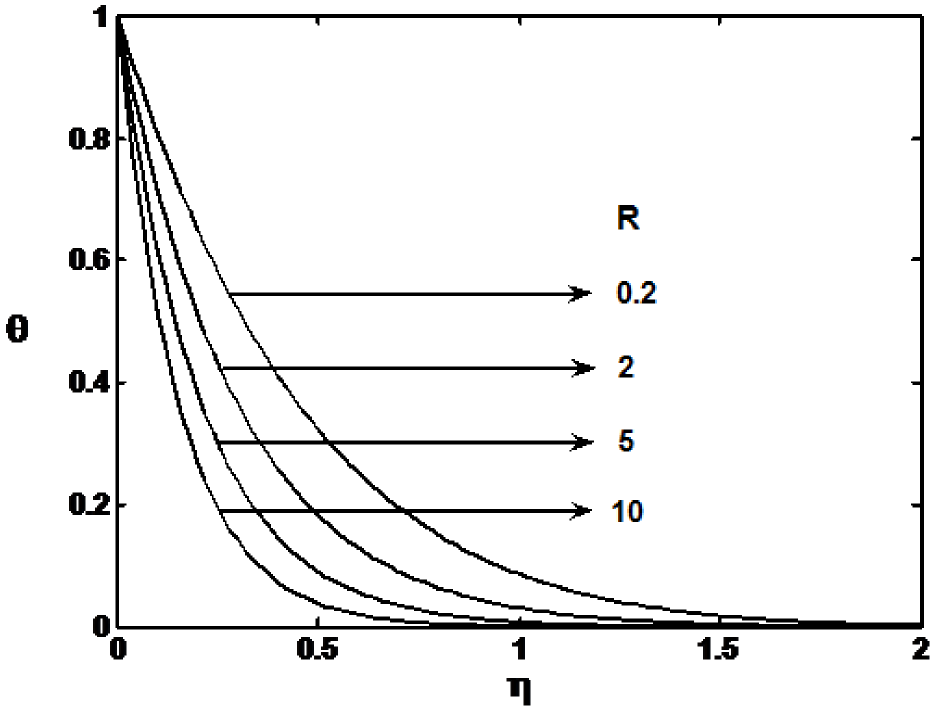

Fig. 2: Temperature profiles for different values of R

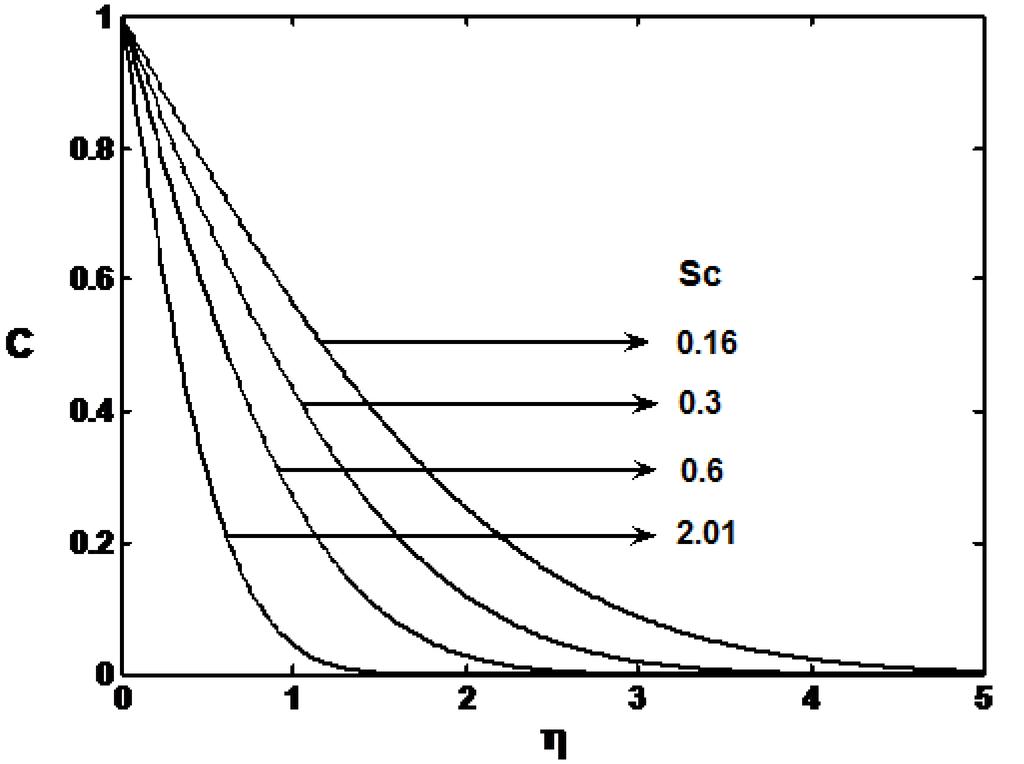

Fig. 3: Concentration profiles for different values of Sc

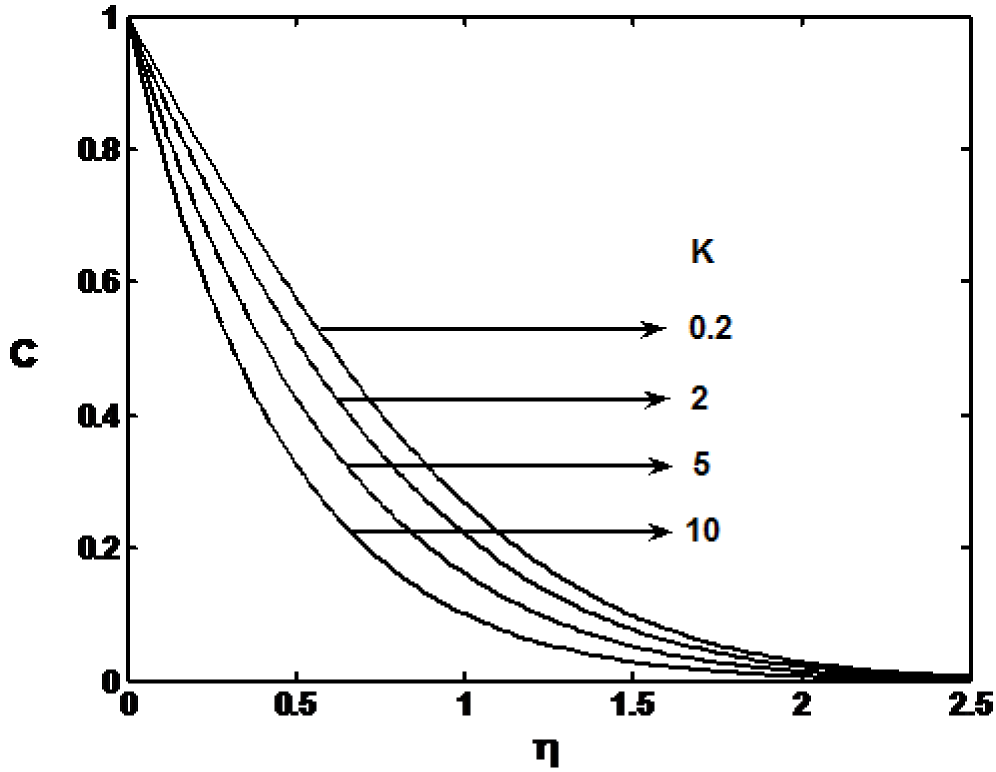

Fig. 4: Concentration profiles for different values of K

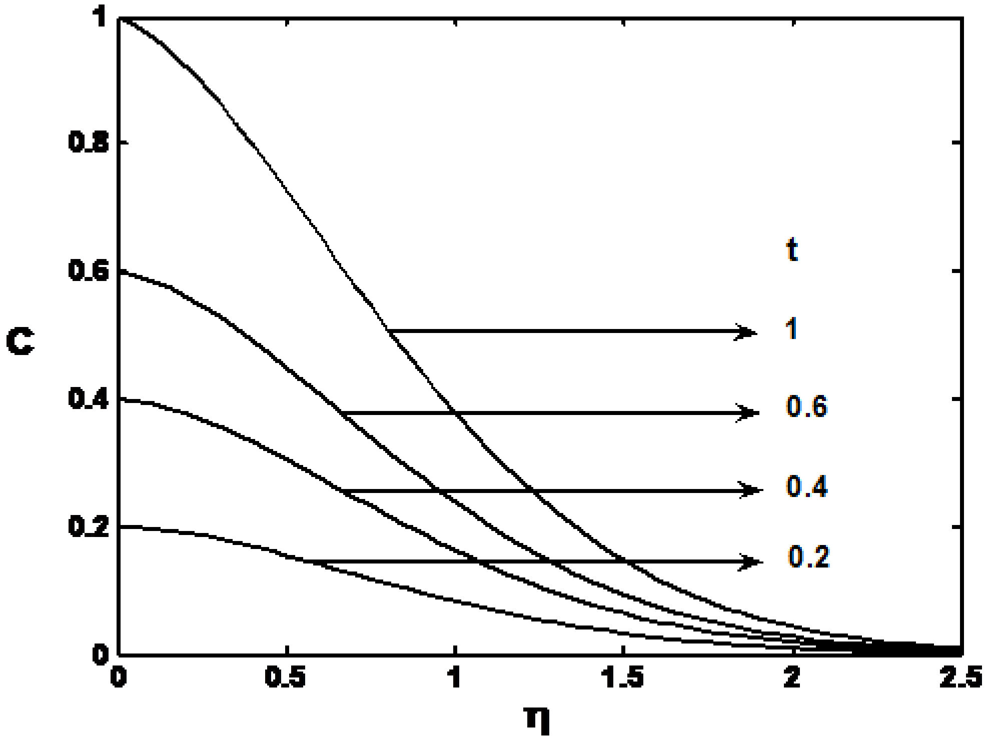

Fig. 5: Concentration profiles for different values of t

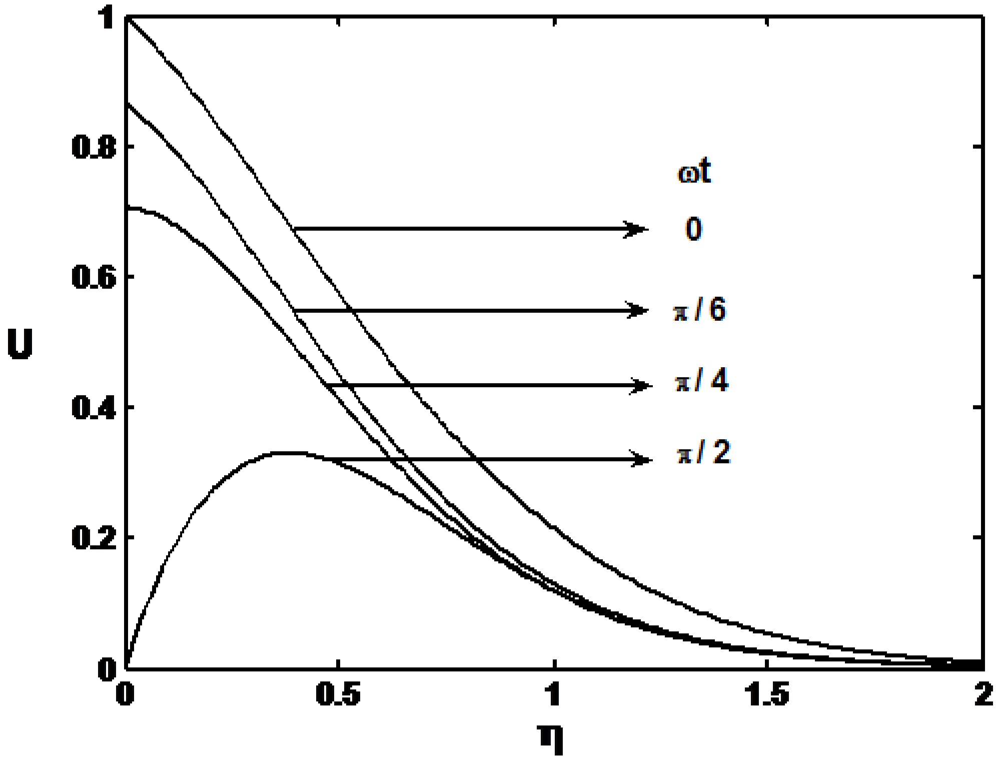

Fig. 6: Velocity profiles for different values of ωt

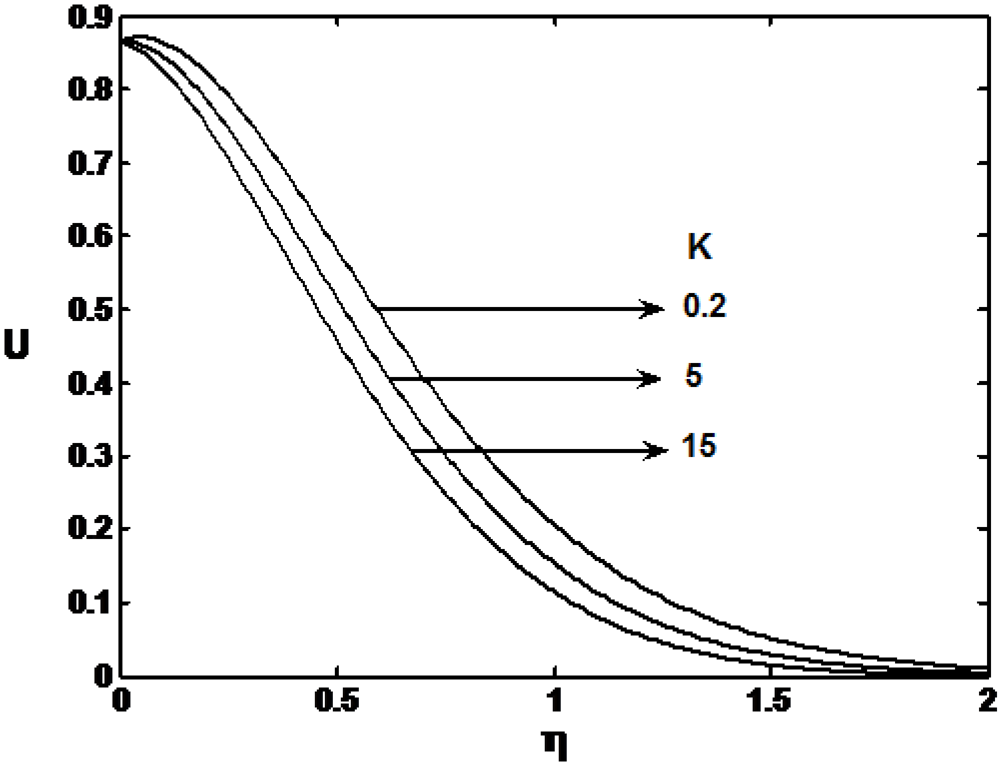

Fig. 7: Velocity profiles for different values of K

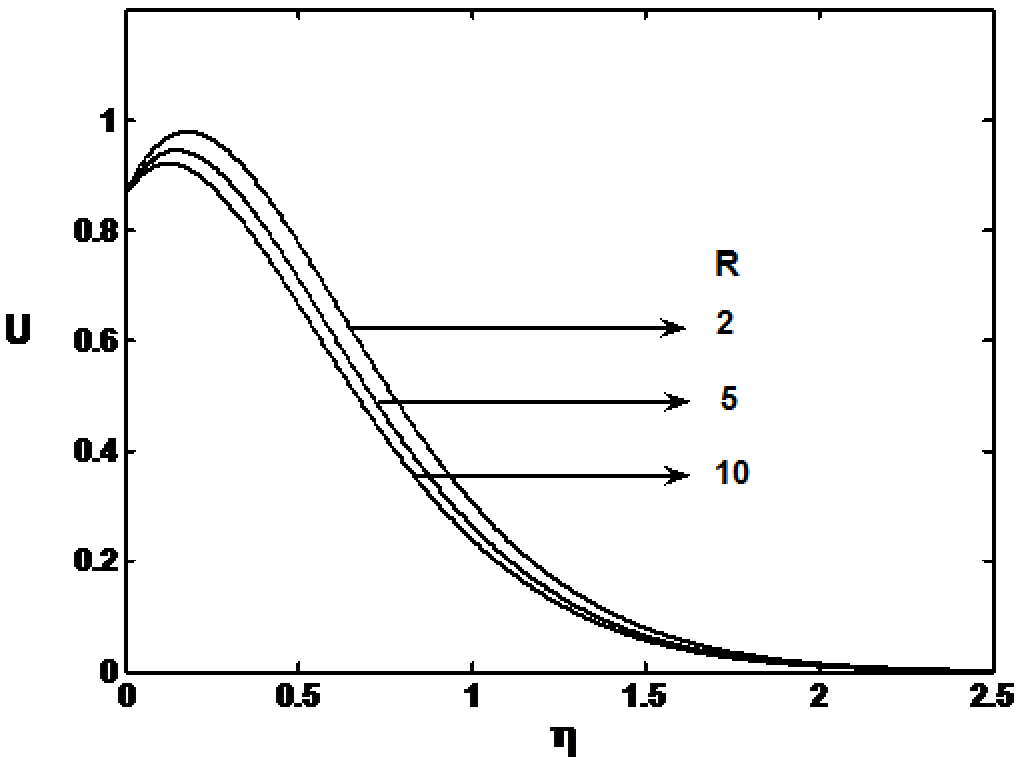

Fig. 8: Velocity profiles for different values of R

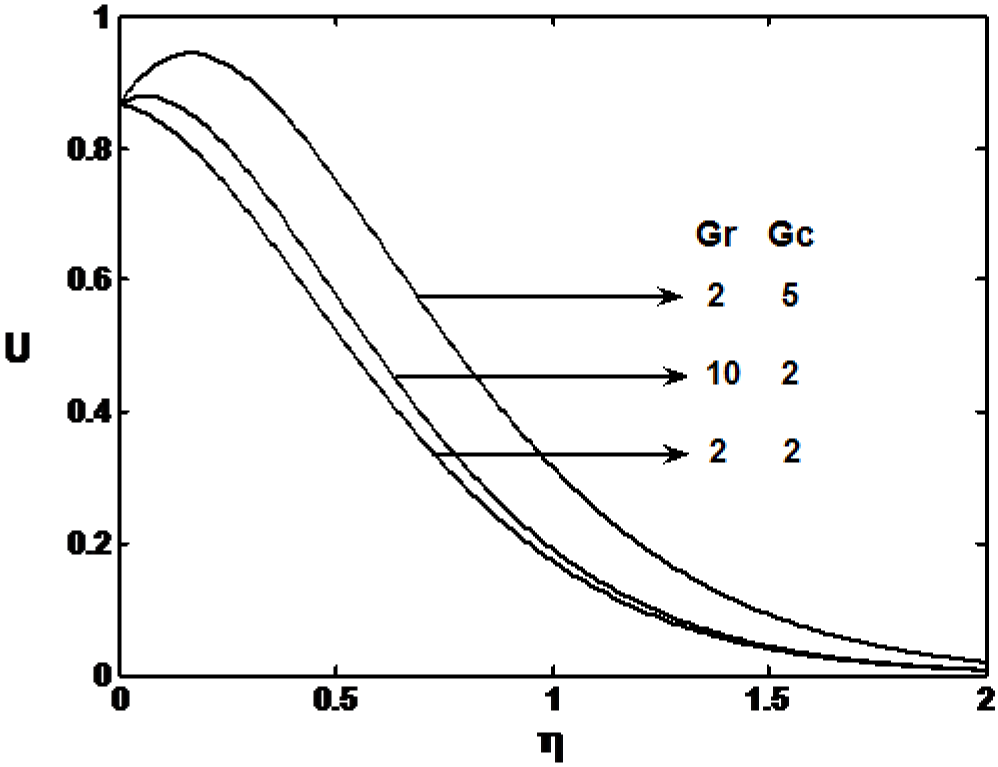

Fig. 9: Velocity profiles for different values of Gr, Gc

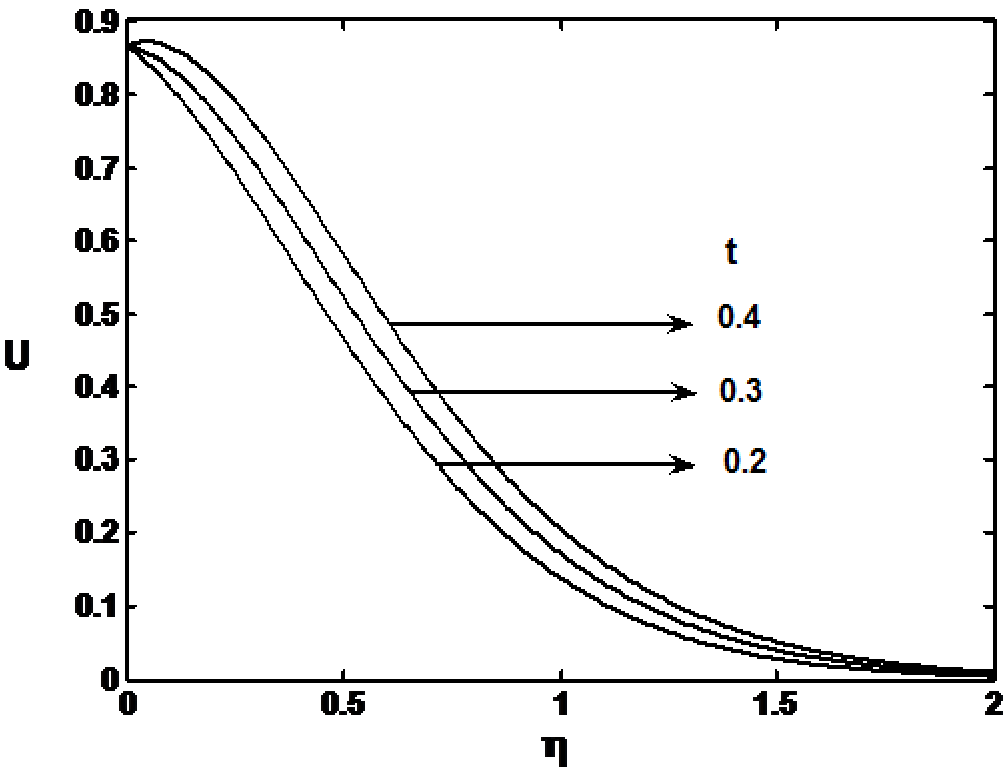

Fig. 10: Velocity profiles for different values of t

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