THE EFFECTS OF THERMAL RADIATION AND VISCOUS DISSIPATION ON HEAT AND MASS DIFFUSION FLOW PAST AN OSCILLATING INFINITE VERTICAL PLATE WITH VARIABLE TEMPERATURE EMBEDDED IN A POROUS MEDIUM

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Abstract : An analysis is performed to study the effect of thermal radiation and viscous dissipation on unsteady flow past an oscillating infinite vertical plate through porous medium with variable temperature, heat and mass transfer. The non- linear, coupled partial differential equations together with boundary condition are reduced to dimensionless form. The governing equations are solved using perturbation method. The results are obtained for Velocity, Temperature, and Concentration profiles for different physical parameters like Phase angle, Thermal Grashof number, Modified Grashof number, Permeability parameter, Eckert number, Prandtl number, Schmidt number and time. It is observed that heat and mass transfer, viscous dissipation and porous medium affect the flow pattern significantly.

IndexTerms : Heat Transfer, Mass Transfer, Oscillating plate, Thermal Radiation, viscous dissipation and Porous Medium.

INTRODUCTION

The heat and mass transfer combination with various chemical reactions have attained great importance in the process and have grabbed a considerable amount of attention in recent times. The heat and mass transfer happen simultaneously in evaporation in water body, drying, desert cooler and wet cooling towers. The fast growth of the electronic technology effect has warranted and the cooling of electric equipment ranges differently from individual transistors to the main frame of the computation telephone switch boards.

The Radiation heat transfer becomes very important when technological process takes place at a higher temperature and the effects cannot be neglected. The MHD flow heat and mass transfer effect of radiation becomes more important industrially. For the design of the pertinent equipment radiation heat transfer becomes prominent many processes in engineering areas occur at high temperature.

Soundalgekar (1972) presented viscous dissipation effects on unsteady free convective flow past an Infinite vertical porous plate with constant suction. Murthy. and Singh (1997) examined the effect of viscous dissipation on a non-Darcy natural convection regime. The viscous dissipation effects on unsteady free convection and mass transfer flow past an accelerated vertical porous plate with suction was studied by Bala Siddulu Malga and Naikoti Kishan (2011). Girish Kumar et al (2012) studied the mass transfer effects on MHD flows exponentially accelerated isothermal vertical plate in the presence of chemical reaction through porous media.

Rout et al (2013) repotted the MHD heat and mass transfer of chemical reaction fluid flow over a moving vertical plate in the presence of heat source with convective surface boundary condition. Radiation effects on unsteady MHD free convective heat and mass transfer flow past a vertical porous plate embedded in a porous medium with viscous dissipation was investigated by Mohammed Ibrahim, Sankar Reddy and Roj (2014). Siva Reddy Sheri Srinivasa Raju et al (2015) presented the Transient MHD free convection flow past a porous vertical plate in presence of viscous dissipation.

I. FORMULATION OF THE PROBLEM

Radiation, viscous dissipation effect on heat and mass transfer flow in an oscillating plate with variation in temperature is examined in this chapter. Here the plate is taken along the x-axis vertically and y-axis perpendicular to it. The plate is oscillating at $t' > 0$ with the velocity $u_0 \cos \omega' t'$ and the concentration, temperature, level increases linearly with a time t'. A chemical reaction of first order is recorded in concentration equation and viscous dissipation is considered in energy equation.

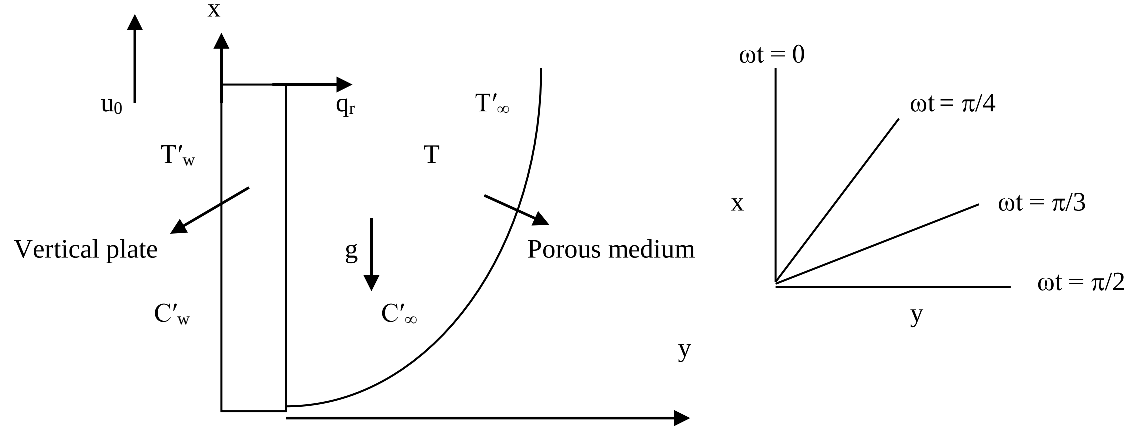

Figure 1: physical configuration and coordinate system

By usual Boussinesq's approximation, the equations are:

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

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

$$\frac{\partial C'}{\partial t'} = D\,\frac{\partial^2 C'}{\partial y^2} - K_\ell\,(C' - C'_\infty) \tag{3}$$

The initial and boundary conditions for the velocity, temperature and concentration fields are

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

where $A = \left(\frac{u_0^2}{\nu}\right)$

with u' is the velocity of the fluid along the plate in x-direction, t' is the time, g is the acceleration due to gravity, β_T is the coefficient of volume expansion β_C^* is the coefficient of thermal expansion with concentration, T'_w is the wall temperature, T'_∞ is the free stream temperature, C'_w is the species concentration at the plate surface, C'_∞ is the free stream concentration, ν is the kinematic viscosity, ρ is the density of the fluid, C_p is the specific heat at constant pressure, κ is the thermal conductivity of the fluid, μ is the viscosity of the fluid, q_r is the radiative heat flux, D is the molecular diffusivity, k' is the permeability of the porous medium and K_ℓ is the chemical reaction parameter.

From the Rosseland approximation, assume the radiative heat flux as:

$$\frac{\partial q_r}{\partial y} = -4\,a^*\sigma\left(T_\infty'^4 - T'^4\right) \tag{5}$$

Here σ - denote the Stefan - Boltzmann constant, a^* -denotes mean absorption coefficient respectively. The temperature differences in the flow are sufficiently little. By Taylor series the T'^4 may be expanded about T'_∞ and omitting higher order terms

$$T'^4 = 4\,T_\infty'^3\,T' - 3\,T_\infty'^4 \tag{6}$$

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

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

The basics equations and boundary conditions should write in dimensionless form, so now introduced the following non-dimensional quantities

$$\begin{aligned}
&U = \left(\frac{u'}{u_0}\right), \quad t = \left(\frac{t'\,u_0^2}{\nu}\right), \quad Y = \left(\frac{y\,u_0}{\nu}\right), \quad \theta = \left(\frac{T' - T'_\infty}{T'_w - T'_\infty}\right)\\
&Gr = \left(\frac{g\,\beta_T\,\nu\,(T'_w - T'_\infty)}{u_0^3}\right), \quad Gc = \left(\frac{g\,\beta_c^*\,\nu\,(C'_w - C'_\infty)}{u_0^3}\right), \quad \phi = \left(\frac{C' - C'_\infty}{C'_w - C'_\infty}\right)\\
&Pr = \left(\frac{\mu\, C_p}{\kappa}\right), \quad k = \left(\frac{u_0^2\, k'}{\nu^2}\right), \quad Ec = \left(\frac{u_0^2}{k\,(T'_w - T'_\infty)}\right), \quad Sc = \left(\frac{\nu}{D}\right)\\
&Kr = \left(\frac{\nu\, K_\ell}{u_0^2}\right), \quad \omega = \left(\frac{\nu\,\omega'}{u_0^2}\right), \quad R = \left(\frac{16\, a^*\,\nu^2\,\sigma\, T_\infty^3}{k\, u_0^2}\right)
\end{aligned} \tag{8}$$

where Gr -Thermal Grashof Number, Pr- Prandt Number, Gc-Modified Grashof Number, Sc-Schmidt Number, Kr - Chemical reaction parameter and R- Radiation parameter.

With the help of equations (5) - (8), equations (1) - (3) reduced to the following form

$$\frac{\partial U}{\partial t} = Gr\,\theta + Gc\,\phi + \frac{\partial^2 U}{\partial Y^2} - \left(\frac{1}{k}\right) U \quad (9)$$

$$\frac{\partial\theta}{\partial t} = \left(\frac{1}{Pr}\right)\left(\frac{\partial^2\theta}{\partial Y^2}\right) + \left(\frac{Ec}{Pr}\right)\left(\frac{\partial U}{\partial Y}\right)^2 - \left(\frac{R}{Pr}\right)\theta \quad (10)$$

$$\frac{\partial\phi}{\partial t} = \left(\frac{1}{Sc}\right)\left(\frac{\partial^2\phi}{\partial Y^2}\right) - Kr\,\phi \quad (11)$$

The negative sign of Kr in equation (11) indicates that the chemical reaction happen from higher level of concentration to lower level of concentration. The dimensionless forms of the boundary conditions (4) are

$$\begin{array}{llllll} U = 0, & \theta = 0, & \phi = 0 & \text{for all} & Y \le 0, & t \le 0 \\ U = \cos\omega t, & \theta = t, & \phi = t & \text{at} & Y = 0, & t > 0 \\ U \to 0, & \theta \to 0, & \phi \to 0 & \text{as} & Y \to \infty & t > 0 \end{array} \quad (12)$$

II. METHOD OF SOLUTION

Equation (9) to (11) cannot be solved by using the initial and boundary conditions (12) as they are coupled non-linear partial differential equations. The set of reduced ordinary differential equations can be solved analytically. The velocity, temperature and concentration represented as follows:

$$\begin{aligned} U &= U_0(y) + \epsilon\, e^{i\omega t}\, U_1(y) + o(\epsilon^2) \\ \theta &= \theta_0(y) + \epsilon\, e^{i\omega t}\, \theta_1(y) + o(\epsilon^2) \\ \phi &= \phi_0(y) + \epsilon\, e^{i\omega t}\, \phi_1(y) + o(\epsilon^2) \end{aligned} \quad (13)$$

Where the amplitude of oscillations ($\varepsilon << 1$) is very small. Substituting (13) in equations (9), (10) and (11) and neglecting the higher order terms of $o(\epsilon^2)$,

$$U_0'' - \left(\frac{1}{k}\right) U_0 = -\, Gr\,\theta_0 - Gc\,\phi_0 \quad (14)$$

$$U_1'' - \left(\frac{1}{k} + i\omega\right) U_1 = -\, Gr\,\theta_1 - Gc\,\phi_1 \quad (15)$$

$$\theta_0'' - R\,\theta_0 = -\,Ec\,U_0'^2 \quad (16)$$

$$\theta_1'' - (R + i\omega\,Pr)\,\theta_1 = -2\,Ec\,U_0'\,U_1' \quad (17)$$

$$\phi_0'' - Sc\,Kr\,\phi_0 = 0 \quad (18)$$

$$\phi_1'' - (Kr + i\omega)\,Sc\,\phi_1 = 0 \quad (19)$$

The corresponding boundary conditions for U, θ and ϕ are

$$\begin{array}{llll} U_0 = \cos\omega t, & U_1 = 0, & \theta_0 = t & \\ \theta_1 = 0, & \phi_0 = t, & \phi_1 = 0 & \text{at } y = 0 \\ U_0 \to 0, & U_1 \to 0, & \theta_0 \to 0 & \\ \theta_1 \to 0, & \phi_0 \to 0, & \phi_1 \to 0 & \text{as } y \to \infty \end{array} \quad (20)$$

The equations (14) - (19) cannot be solved and exact solutions are not possible as they are coupled and non – linear. For incompressible fluid flows Eckert number is very small so expand $U_0, U_1, \theta_0, \theta_1, \phi_0, \phi_1$ in the following form,

$$\begin{aligned} f_0(y) &= f_{01}(y) + Ec\, f_{02}(y) \\ f_1(y) &= f_{11}(y) + Ec\, f_{12}(y) \end{aligned} \quad (21)$$

Substituting (21) in equation (14) to (19), the coefficient of Ec equating to zero and omitting the higher order terms of Ec^2.

$$U_{01}'' - \left(\frac{1}{k}\right) U_{01} = -\, Gr\,\theta_{01} - Gc\,\phi_{01} \quad (22)$$

$$U_{02}'' - \left(\frac{1}{k}\right) U_{02} = -\, Gr\,\theta_{02} - Gc\,\phi_{02} \quad (23)$$

$$U_{11}'' - \left(\frac{1}{k} + i\omega\right) U_{11} = -\, Gr\,\theta_{11} - Gc\,\phi_{11} \quad (24)$$

$$U_{12}'' - \left(\frac{1}{k} + i\omega\right) U_{12} = -\, Gr\,\theta_{12} - Gc\,\phi_{12} \quad (25)$$

$$\theta_{01}'' - R\,\theta_{01} = 0 \quad (26)$$

$$\theta_{02}'' - R\,\theta_{02} = -\,U_{01}'^2 \quad (27)$$

$$\theta_{11}'' - (R + i\omega\,Pr)\,\theta_{11} = 0 \quad (28)$$

$$\theta_{12}'' - (R + i\omega\,Pr)\,\theta_{12} = -2\,U_{01}'\,U_{11}' \quad (29)$$

$$\phi_{01}'' - Sc\,Kr\,\phi_{01} = 0 \quad (30)$$

$$\phi_{02}'' - Sc\,Kr\,\phi_{02} = 0 \quad (31)$$

$$\phi_{11}'' - (Kr + i\omega)\,Sc\,\phi_{11} = 0 \quad (32)$$

$$\phi_{12}'' - (Kr + i\omega)\, Sc\, \phi_{12} = 0 \tag{33}$$

The respective boundary conditions

$$\begin{array}{llll} U_{01} = \cos\omega t, & U_{02} = 0, & \theta_{01} = t & \\ \theta_{02} = 0, & \phi_{01} = t, & \phi_{02} = 0 & \\ U_{11} = 0, & U_{12} = 0, & \theta_{11} = 0 & \\ \theta_{12} = 0, & \phi_{11} = 0, & \phi_{12} = 0 & \text{at } y = 0 \\ U_{01} \to 0, & U_{02} \to 0, & \theta_{01} \to 0 & \\ \theta_{02} \to 0, & \phi_{01} \to 0, & \phi_{02} \to 0 & \\ U_{11} \to 0, & U_{12} \to 0, & \theta_{11} \to 0 & \\ \theta_{12} \to 0, & \phi_{11} \to 0, & \phi_{12} \to 0 & \text{as } y \to \infty \end{array} \tag{34}$$

Velocity, temperature and concentration distributions are obtained by solving the equations (22) - (33) with the boundary conditions (34).

$$U(y.t) = a_1 \exp(m_3 y) + a_2 \exp(m_1 y) + a_3 \exp(m_4 y) + Ec\{a_4 \exp(m_3 y) + \\ + a_5 \exp(2m_4 y) + a_6 \exp(2m_3 y) + a_7 \exp(2m_1 y) + a_8 \exp[(m_3 + m_4) y] \\ + a_9 \exp[(m_1 + m_3) y] + a_{10} \exp[(m_1 + m_4) y] + a_{11} \exp(m_4 y)\} \tag{35}$$

$$\theta(y.t) = t \exp(m_3 y) + Ec\{b_1 \exp(2m_4 y) + b_2 \exp(2m_3 y) + b_3 \exp(2m_1 y) + \\ + b_4 \exp[(m_3 + m_4) y] + b_5 \exp[(m_1 + m_3) y] + b_6 \exp[(m_1 + m_4) y] \\ + b_7 \exp(m_3 y)\} \tag{36}$$

$$C(y.t) = t \exp(m_1 y) \tag{37}$$

IV. SKIN FRICTION

The velocity field in non dimensional form of the skin friction as:

$$\tau = \left(\frac{\partial U}{\partial Y}\right)_{Y=0}$$

$$\tau = a_1 m_3 + a_2 m_1 + a_3 m_4 + Ec\{a_4 m_3 + +2 a_5 m_4 + 2 a_6 m_3 + 2 a_7 m_1 \\ + a_8 (m_3 + m_4) + a_9 (m_1 + m_3) + a_{10} (m_1 + m_4) + a_{11} m_4\} \tag{38}$$

V. NUSSELT NUMBER

The rate of heat transfer for Nusselt number (Nu) dimensionless form at the plate is

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

$$Nu = -t\, m_3 - Ec\{2 b_1 m_4 + 2 b_2 m_3 + 2 b_3 m_1 + b_4 (m_3 + m_4) \\ + b_5 (m_1 + m_3) + b_6 (m_1 + m_4) + b_7 m_3\} \tag{39}$$

VI. SHERWOOD NUMBER

The mass transfer rate is given in terms of Sherwood number as

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

$$Sh = -t\, m_1 \tag{40}$$

where

$$m_1 = -\sqrt{S_C\, Kr},\ m_2 = -\sqrt{Sc\,(Kr + i\omega)},\ m_3 = -\sqrt{R},\ m_4 = -\sqrt{\left(\frac{1}{k}\right)},\ m_5 = -\sqrt{(R + i\omega\, Pr)}$$

$$m_6 = -\sqrt{\left(\frac{1}{k} + i\omega\right)},\ a_1 = \left(\frac{-Gr\, t}{m_3^2 - m_4^2}\right),\ a_2 = \left(\frac{-Gc\, t}{m_1^2 - m_4^2}\right),\ a_3 = (\cos\omega t - a_1 - a_2),\ a_4 = \left(\frac{-Gr\, b_7}{m_3^2 - m_4^2}\right)$$

$$a_5 = \left(\frac{-Gr\, b_1}{4 m_4^2 - m_4^2}\right),\ a_6 = \left(\frac{-Gr\, b_2}{4 m_3^2 - m_4^2}\right),\ a_7 = \left(\frac{-Gr\, b_3}{4 m_1^2 - m_4^2}\right),\ a_8 = \left(\frac{-Gr\, b_4}{(m_3 + m_4)^2 - m_4^2}\right),\ a_9 = \left(\frac{-Gr\, b_5}{(m_1 + m_3)^2 - m_4^2}\right)$$

$$a_{10} = \left(\frac{-Gr\, b_6}{(m_1 + m_4)^2 - m_4^2}\right),\ a_{11} = -(a_4 + a_5 + a_6 + a_7 + a_8 + a_9 + a_{10}),\ b_1 = \left(\frac{-m_4^2\, a_3^2}{4 m_4^2 - m_3^2}\right),\ b_2 = \left(\frac{-m_3^2\, a_1^2}{4 m_3^2 - m_3^2}\right)$$

$$b_3 = \left(\frac{-m_1^2\, a_2^2}{4 m_1^2 - m_3^2}\right),\ b_4 = \left(\frac{-2 m_4 m_3\, a_1 a_3}{(m_3 + m_4)^2 - m_3^2}\right),\ b_5 = \left(\frac{-2 m_1 m_3\, a_1 a_2}{(m_1 + m_3)^2 - m_3^2}\right),\ b_6 = \left(\frac{-2 m_1 m_4\, a_3 a_2}{(m_1 + m_4)^2 - m_3^2}\right)$$

$$b_7 = -(b_1 + b_2 + b_3 + b_4 + b_5 + b_6)$$

VII. RESULTS AND DISCUSSIONS

In figures (2) - (39) are shows the effects of various physical parameters. The Schmidt number Sc and Prandtl number Pr is chosen 0.6, 0.71 corresponds to water. The different physical parameters numerical values taken for Gr, Gc, Kr, R, Sc, Pr and time of the velocity, temperature and concentration are computed and studied graphically.

In figure (2) the velocity profiles for phase angle ($\omega t = 0, \pi/4, \pi/3, \pi/2$) are considered. When phase angle ωt raises the velocity reduced. In figure (3) and (4) velocity profiles for thermal and mass Grashof number Gr, Gc are shown. When the thermal and mass Grashof number Gr, Gc raises the velocity also raised. The permeability of the porous medium enlarges the velocity amplifies is presented in figure (5). The substance capacity to allow liquid or gas all the way through its pores or voids is called Permeability of porous medium. The proportionality invariable for Permeability is defined in Darcy's law. The stress pitch applied to the porous medium is related to the flow rate and fluid properties defined by Darcy's law.

The Velocity profile for diverse values Eckert number is plotted in figure (6). The relation among kinetic energy and the enthalpy is expressed by the Eckert number. The viscous dissipative heat raises is evident that the velocity of the fluid raised. Hence the velocity amplified when the increasing values of Eckert number. The study of time (t = 0.2, 0.4, 0.6, 0.8) displaced in figure (7). It is experiential that the velocity enhances when time t raised (Das et al). The effect of the velocity for the chemical reaction (Kr = 0.2, 2, 6, 10) is illustrated in figure (8). When reduce the chemical reaction the trend shows that the velocity enhanced. This trend shows that there is a fall in velocity due to the increasing values of the chemical reaction parameter. (Das, Deka, and Soundalgekar).

The effect of velocity for different values of the Radiation parameter (R = 0,2, 0.4, 0.6, 0.8),Gc = 5, Gr = 5, Kr = 0.5, t = 0.2, k = 1, Ec = 0.1, Pr = 0.71, Sc = 0.6 and $\omega t = \pi/2$ is exposed in figure (9).when the radiation parameter reduced the velocity raised. In the occurrence of high thermal radiation it is experimental that the velocity reduced. In figure (10) the velocity profile is plotted for the influence of Schmidt Number Sc. when the Schmidt number Sc boosted, it is evidently understand that the velocity decreased. Figure (11) displays that the temperature profiles increases as time t is increased. In figure (12) temperature profiles for different values of Eckert number are presented. The measure of the kinetic energy and the specific enthalpy different between of the fluid the Eckert number plays an important role. For the raising values of Eckert number the thermal boundary layer raises.

The influence of Gc, k are shown in figure (17) and (18) and through these figures it is clear that temperature profile increases with increase of Modified Grashof number and Permeability parameter. Temperature profiles for different values of Kr, ωt, Gr and Sc are represented in figure (13), (15), (16) . Here temperature profile decreases as Kr, ωt, Gr and Sc increases. For the temperature profiles the effect of thermal radiation parameter is very significant. For the raising values of radiation parameter it is observed that the temperature reduced is illustrated in figure (14).

The unlike values of time (t) for the Concentration profiles are potted in figure (19). It is understandable that the dimensionless concentration profiles enhance as time (t) is better. The Schmidt Number (Sc) variations are presented in concentration profiles figure (20). The analytical results show that the effect of increasing Schmidt Number results in a decreasing concentration distribution across the boundary layer. When the Schmidt number rises it is experiential that wall concentration reduced. In figure (21) the chemical reaction parameters (Kr = 0.2, 2, 6, 10) variation are presented for the concentration profile. In concentration field of the fluid is dominated by the effect of the chemical reaction parameter. For the declining values of the chemical reaction it is experiential that the wall concentration raised.

VIII. CONCLUSION

In the occurrence of homogeneous chemical reaction of first order the problem of flow past an oscillating endless perpendicular plate is examined. The effect of velocity, Temperature and Concentration for different parameters like ωt, Gr, Gc, k, Ec, Kr, R, Sc an time t are studied. The conclusion shows that

- The velocity amplifies with increase in the Thermal Grashof Number, Modified Grashof Number, Permeability parameter, Eckert Number and time whereas the velocity decreases with increase in Phase angle, Chemical reaction parameter, Schmidt Number Sc and Radiation parameter R.
- When the Modified Grashof Number, Eckert Number, Permeability and time raises the temperature also raised where as the Chemical reaction parameter, Radiation parameter, Phase angle, Thermal Grashof Number and Schmidt Number reduces the temperature.
- The concentration drops off with increase in Schmidt Number and Chemical reaction parameter and increases with increase in time.
- Raising values of the Radiation and Chemical reaction parameter lead to diminish in the values of the Skin-Friction but rising of Thermal Grashof Number, Modified Grashof Number, Permeability parameter, Phase angle and Eckert Number raises the skin friction.
- Nusselt Number raises when raise in the Radiation parameter, Chemical reaction parameter and Schmidt Number parameters, but the Eckert Number, Phase angle, Thermal Grashof Number, Modified Grashof Number and Permeability parameter reduce the Nusselt Number.

- Sherwood Number enhances with the increase in Schmidt Number and Chemical reaction parameter.

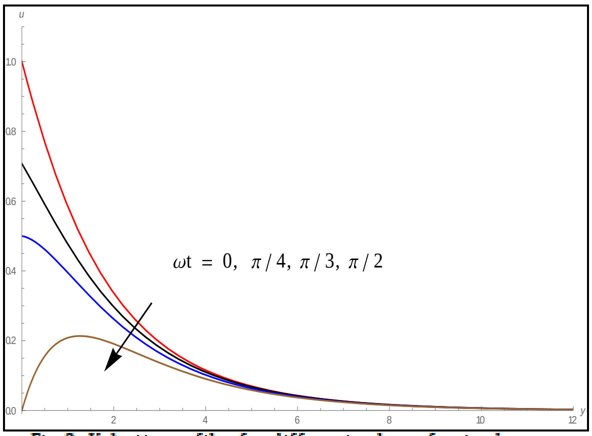

Fig.2: Velocity profiles for different values of ωt *when*
$Gr = 2, Gc = 2, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6$

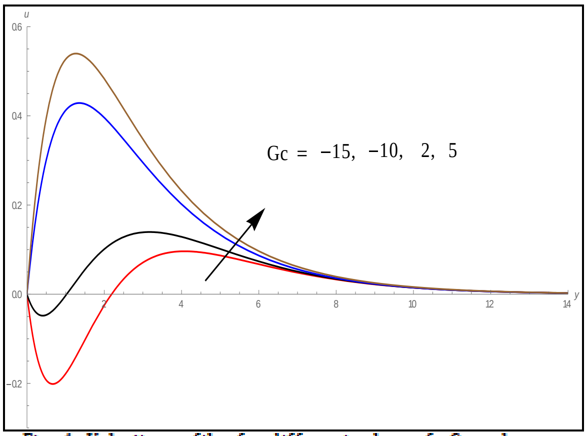

Fig. 4: Velocity profiles for different values of Gc when
$Gr = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

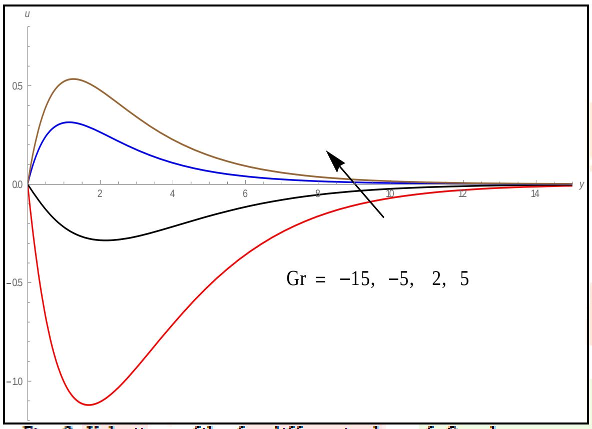

Fig. 3: Velocity profiles for different values of Gr when
$Gc = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

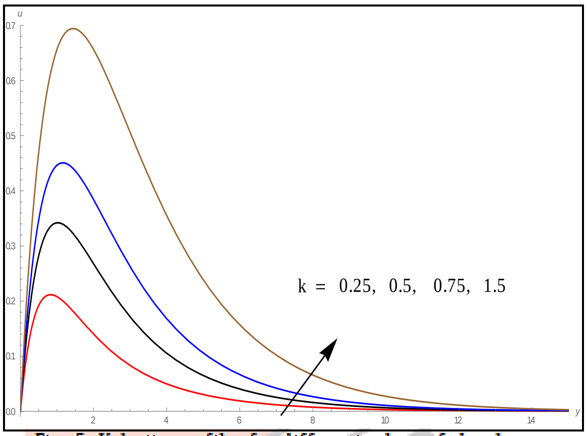

Fig. 5: Velocity profiles for different values of k when
$Gr = 5, Gc = 5, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

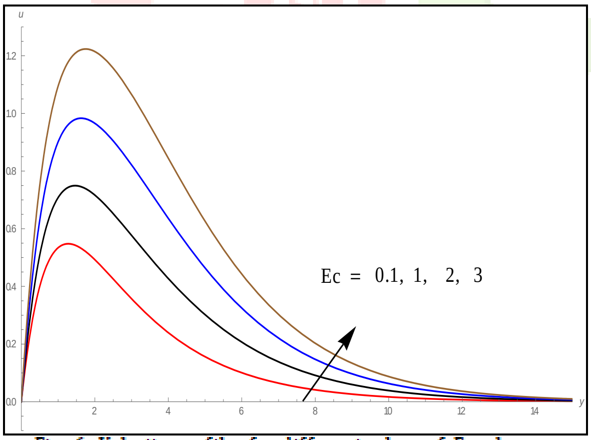

Fig. 6: Velocity profiles for different values of Ec when
$Gr = 5, Gc = 5, k = 1, Kr = 0.5, t = 0.2, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

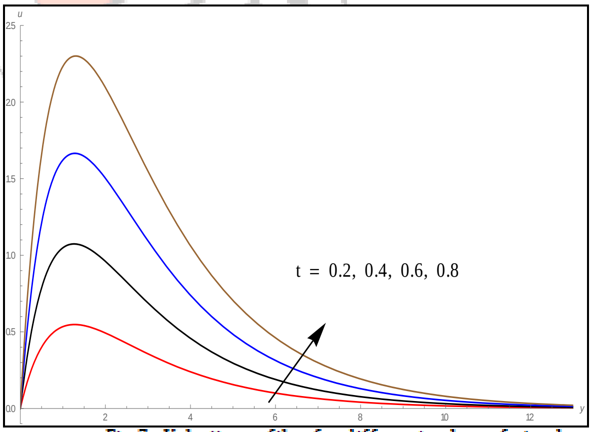

Fig.7: Velocity profiles for different values of t when
$Gr = 5, Gc = 5, k = 1, Kr = 0.5, R = 0.2, Ec = 0.1, Sc = 0.6, \omega t = 90^\circ$

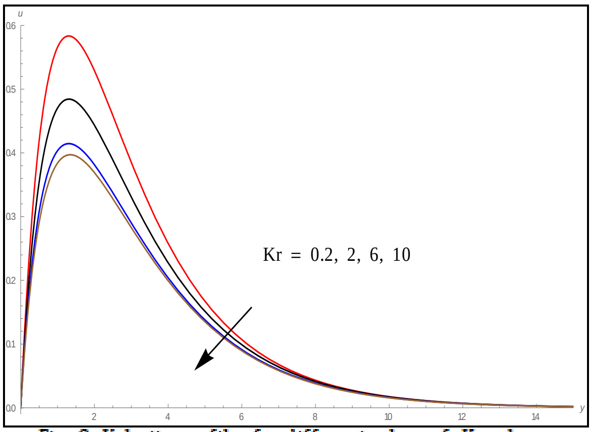

Fig. 8: Velocity profiles for different values of Kr when $Gr = 5, Gc = 5, k = 1, t = 0.2, R = 0.2, Ec = 0.1, Sc = 0.6, \omega t = 90^{\circ}$

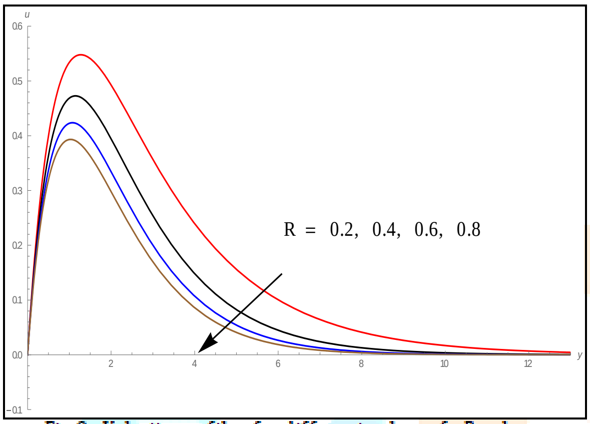

Fig. 9: Velocity profiles for different values of R when $Gr = 5, Gc = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, Sc = 0.6, \omega t = 90^{\circ}$

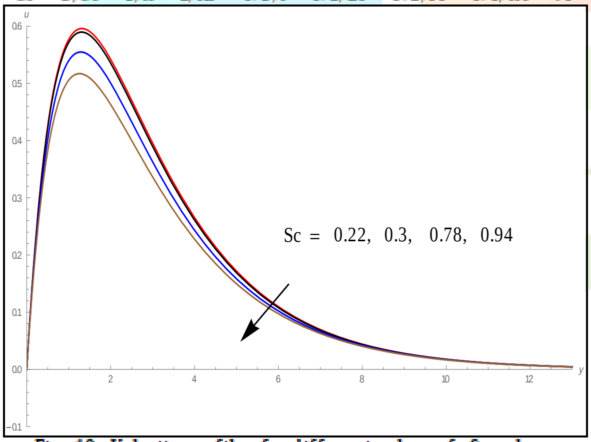

Fig. 10: Velocity profiles for different values of Sc when $Gr = 5, Gc = 5, k = 1, Kr = 0.5, t = 0.2, R = 0.2, Ec = 0.1, \omega t = 90^{\circ}$

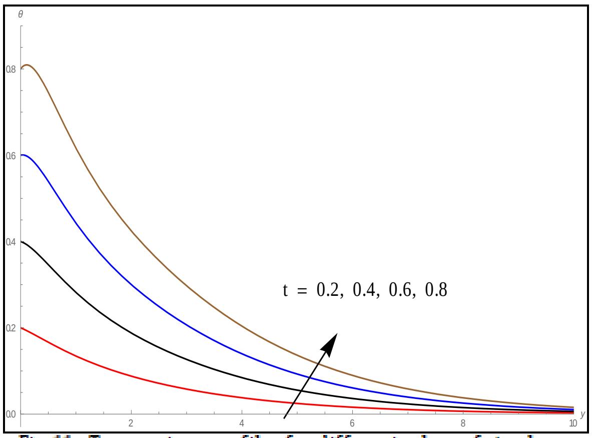

Fig. 11: Temperature profiles for different values of t when $Gr = 5, Gc = 5, k = 1, Kr = 0.5, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^{\circ}$

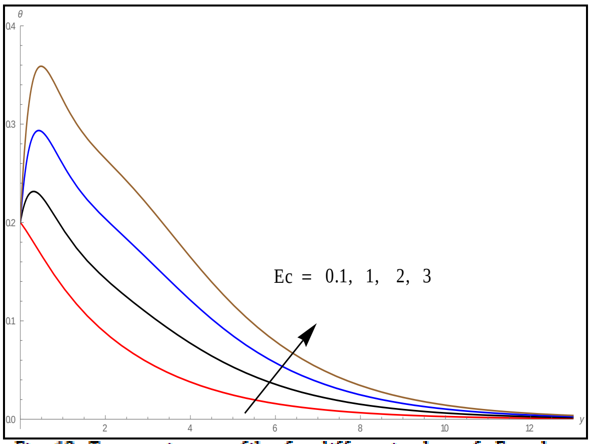

Fig. 12: Temperature profiles for different values of Ec when $Gr = 5, Gc = 5, k = 1, Kr = 0.5, t = 0.2, R = 0.2, Sc = 0.6, \omega t = 90^{\circ}$

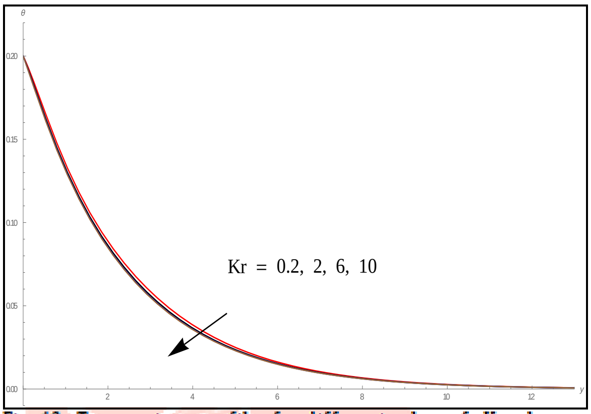

Fig. 13: Temperature profiles for different values of Kr when $Gr = 5, Gc = 5, k = 1, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^{\circ}$

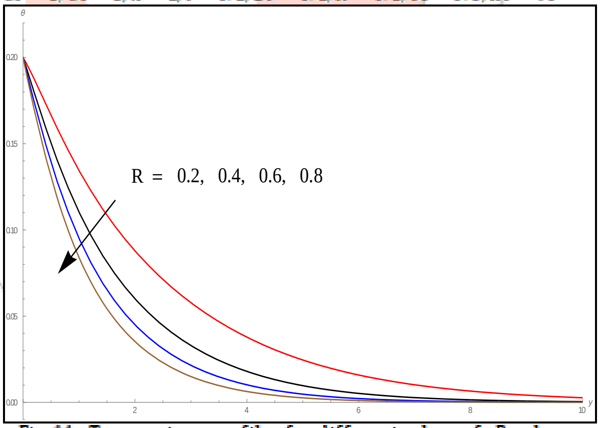

Fig. 14: Temperature profiles for different values of R when $Gr = 5, Gc = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, Sc = 0.6, \omega t = 90^{\circ}$

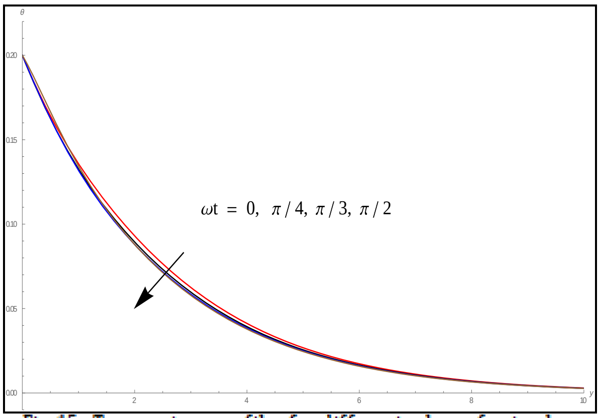

Fig. 15: Temperature profiles for different values of ωt when $Gr = 5, Gc = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6$

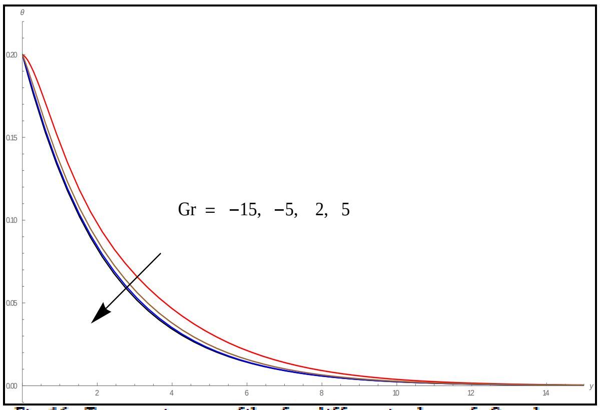

Fig. 16: Temperature profiles for different values of Gr when $Gc = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

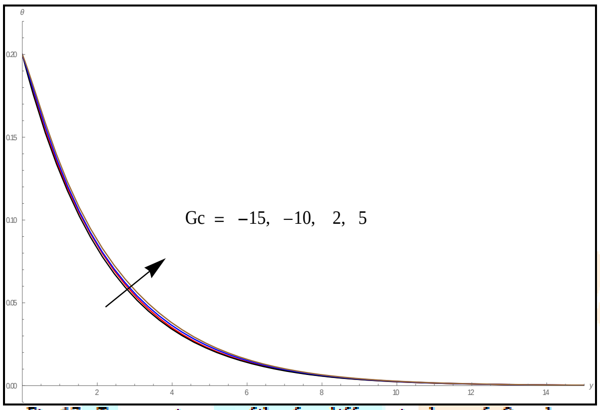

Fig. 17: Temperature profiles for different values of Gc when $Gr = 5, k = 1, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

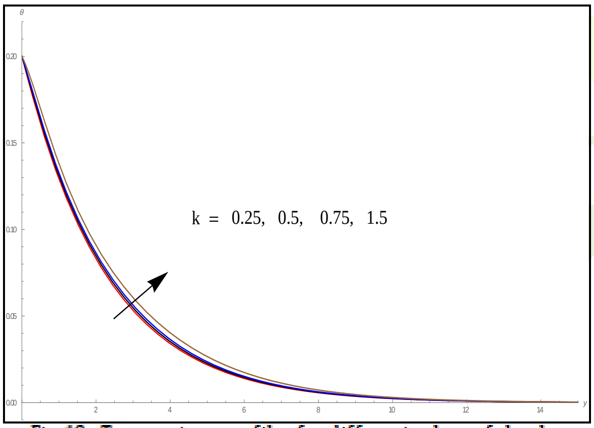

Fig. 18: Temperature profiles for different values of k when $Gr = 5, Gc = 5, Kr = 0.5, t = 0.2, Ec = 0.1, R = 0.2, Sc = 0.6, \omega t = 90^\circ$

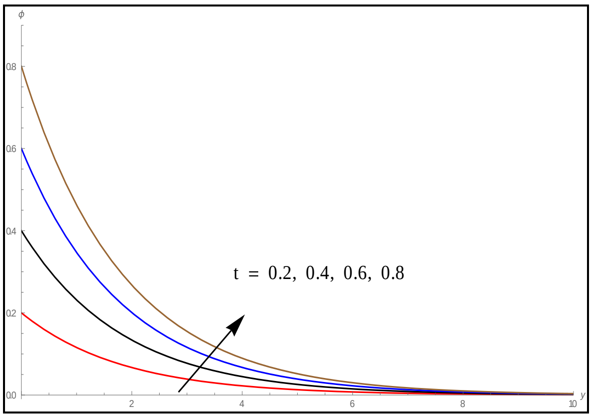

Fig. 19: Concentration profiles for different values of t when $Sc = 0.6, Kr = 0.5$

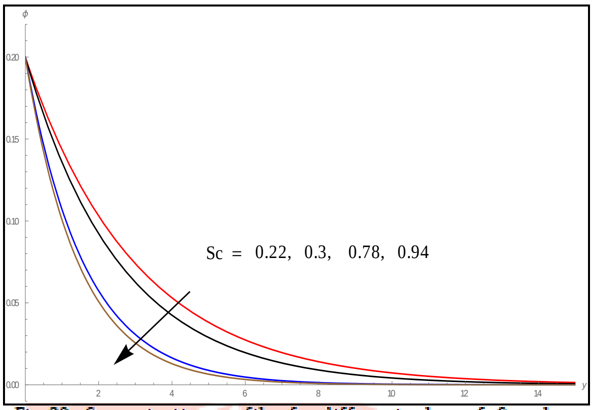

Fig. 20: Concentration profiles for different values of Sc when $t = 0.2, Kr = 0.5$

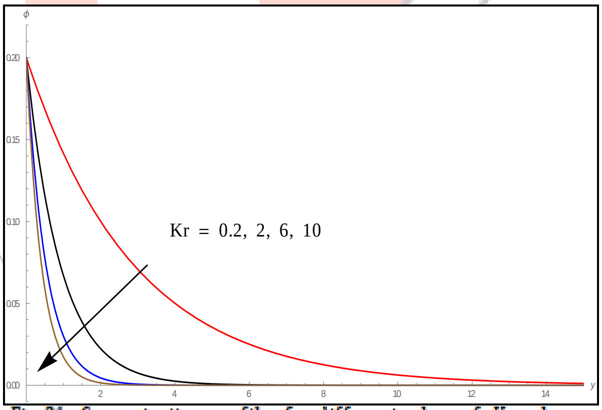

Fig. 21: Concentration profiles for different values of Kr when $t = 0.2, Sc = 0.6$

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