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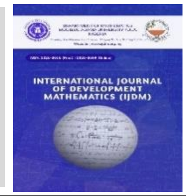

Effect of Ramped Temperature and Convection on Flow, Heat and Mass Transfer of a Chemically Reacting and Heat Absorbing Fluid Past a Vertical Plate

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ABSTRACT

This study investigates an unsteady magnetohydrodynamic (MHD) flow involving heat and mass transfer of an electrically conducting, viscous, incompressible, chemically reacting, and heat-absorbing fluid past a moving vertical plate. The plate features ramped temperature and concentration profiles, and the analysis incorporates thermal and mass diffusion effects. The governing equations for continuity, momentum, energy, and concentration which describe the problem are developed under the Boussinesq approximation. These nonlinear coupled partial differential equations (PDEs) are transformed from dimensional to nondimensional forms using a similarity variable. Additionally, expressions for skin friction, the Nusselt number, and the Sherwood number are derived. The PDEs are solved using the shooting method combined with a sixth-order Runge-Kutta numerical scheme, and the simulations are performed with the help of MAPLE. The effects of various flow parameters on fluid velocity, temperature, and species concentration are analyzed and presented graphically. The study also compares natural convection flow near a ramped temperature plate with ramped surface concentration to flow near an isothermal plate with uniform surface concentration. The results indicate that fluid velocity is higher in the case of an isothermal plate with uniform surface concentration compared to a ramped temperature plate with ramped surface concentration. Furthermore, the presence of a magnetic field is found to retard fluid flow in both scenarios.

1. Introduction

Theoretical/experimental investigations of convective boundary layer flow with heat and mass transfer induced due to a moving surface with a uniform or non-uniform velocity plays an important role in several manufacturing processes in industry which include the boundary layer flow along material handling conveyors, extrusion of plastic sheets, cooling of an infinite metallic plate in cooling bath, glass blowing, continuous casting and levitation, design of chemical processing equipment, formation and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of trees, damage of crops due to freezing, common industrial sight especially in power plants, etc. Osman et al. (2024) investigated analytical analysis of mixed convective MHD Casson Flow with Ramped Wall Temperature. Nagaraju et al. (2023) investigated chemical reaction and Soret effects on MHD convective flow of second grade fluid through an absorbent medium with ramped wall temperature as well as ramped surface concentration. Talha et al. (2020) analysed unsteady MHD free convection flow of some nanofluids with ramped wall velocity and ramped wall temperature accounting heat radiation and injection/consumption. Raptis and Kafousias (1986) examined steady MHD free convection flow through a porous medium bounded by an infinite plate with constant suction velocity. Raptis (1986) investigated unsteady two-dimensional natural convection flow of an

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electrically conducting, viscous and incompressible fluid along an infinite vertical plate embedded in a porous medium. Chamkha (1997) studied unsteady MHD free convection flow through a porous medium supported by a surface. Chamkha (1997) also studied MHD natural convection flow near an isothermal inclined surface adjacent to a thermally stratified porous medium. Aldoss et al. (1995) investigated combined free and forced convection flow from a vertical plate embedded in a porous medium in the presence of a magnetic field. Kim (2000) analyzed unsteady MHD free convection flow past a moving semi-infinite vertical porous plate embedded in a porous medium with variable suction. Jha (1991) considered hydromagnetic free convection and mass transfer flow past a uniformly accelerated moving vertical plate through a porous medium. Ibrahim et al. (2004) investigated unsteady hydromagnetic free convection flow of micro-polar fluid and heat transfer past a vertical porous plate through a porous medium in the presence of thermal and mass diffusions with a constant heat source. Makinde and Sibanda (2008) examined MHD mixed convective flow with heat and mass transfer past a vertical plate embedded in a porous medium with constant wall suction. Makinde (2009) analysed hydromagnetic mixed convection flow and mass transfer over a vertical porous plate with constant heat flux embedded in a porous medium. Makinde (2010) also investigated MHD boundary layer flow with heat and mass transfer over a moving vertical plate with a convective surface boundary condition.

It is noticed that there may be an appreciable temperature difference between the surface of the solid body and ambient fluid in so many fluid flow problems of practical interests. This prompted many researchers to consider temperature-dependent heat sources and/or sinks, which may have strong influence on heat transfer characteristics, Vajravelu and Nayfeh (1992). The research studies related to heat generating and/or heat absorbing fluid flow are of considerable importance in several physical problems viz. fluids undergoing exothermic and/or endothermic chemical reaction, Vajravelu and Nayfeh (1992), its applications in the field of nuclear energy, Crepeau et al. (1992), convection in Earth's mantle McKenzie et al. (1974), post-accident heat removal. (Baker et al., 1976), fire and combustion modeling (Delichatsios, 1988), development of metal waste from spent nuclear fuel (Westphal, 1994), etc. Exact mathematical modeling of internal heat generation/absorption is very much complicated. It is found that some simple mathematical models yet idealized may present their average behavior for most of the physical situations. Taking into consideration of this fact, Sparrow and Cess (1961) discussed the effects of temperature-dependent heat absorption in their research study on steady stagnation point flow and heat transfer. Moalem (1976) investigated steady heat transfer in a porous medium with temperature-dependent heat source. Prabhakar et al. (2024) investigated Transient thermal convective and radiative diffusion–reaction of magneto-metallic Brinkman-type nanofluid flow with isothermal and ramped temperature impacts. Talha et al. (2020) carried out a comprehensive study on Influence of Ramped Wall Temperature and Ramped Wall Velocity on Unsteady Magnetohydrodynamic Convective Maxwell Fluid Flow. Chamkha and Khaled (2000) considered hydromagnetic combined heat and mass transfer by natural convection from a permeable vertical plate embedded in a fluid-saturated porous medium in the presence of heat generation or absorption. Faiza et al. (2022) examined time fractional model of Brinkman type nanofluid with ramped wall temperature and concentration. Kamel (2001) investigated unsteady hydromagnetic convection flow due to heat and mass transfer through a porous medium bounded by an infinite vertical porous plate with temperature-dependent heat sources and sinks. Chamkha (2004) studied unsteady hydromagnetic two dimensional convective laminar boundary layer flow with heat and mass transfer of a viscous, incompressible, electrically conducting and temperature- dependent heat absorbing fluid along a semi-infinite vertical permeable moving plate in the presence of a uniform transverse magnetic field. Lawal and Jibrin (2024) examined Magneto-Hydrodynamic Natural Convection Flow in a Concentric Annulus with Ramped Temperature and Ramped Motion of the Boundaries. Makinde (2012) investigated heat and mass transfer by MHD mixed convection stagnation point flow toward a vertical plate embedded in a highly porous medium with radiation and internal heat generation. In all these investigations, numerical/analytical solution is obtained by assuming conditions for the velocity and temperature at the plate as continuous and well defined. However, there are several problems of practical interests which may require non-uniform or arbitrary conditions at the plates. Keeping in view this fact, several researchers, namely, Hayday et al. (1967), Kelleher (1971), Kao (1997), Lee and Yovanovich (1991) and Chandran et al. (2005) studied natural convection flow from a vertical plate with step discontinuities in the surface temperature considering different aspects of the problem. Patra et al. (2012) investigated the effects of radiation on natural convection flow of a viscous and incompressible fluid near a vertical flat plate with ramped temperature. They compared the effects of radiative heat transfer on natural convection flow near a ramped temperature plate with the flow near an isothermal plate. Seth and Ansari (2010) investigated unsteady hydromagnetic natural convection flow of a viscous, incompressible, electrically conducting and temperature-dependent heat absorbing fluid past an impulsively moving vertical plate with ramped temperature in a porous medium taking into account the effects of thermal diffusion. Subsequently, Seth et al. (2011) extended the problem studied by Seth and Ansari (2010) to consider the effects of rotation on flow-field. In many chemical engineering processes, there does occur the chemical reaction between a foreign mass and the fluid. Chemical reactions can be classified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. These processes take place in numerous industrial applications viz. polymer production, manufacturing of ceramics or glassware, food processing, etc. Afify (2004) studied the effect of radiation on free convective flow and mass transfer past a vertical isothermal cone surface with chemical reaction in the presence of a transverse magnetic field. Muthucumaraswamy and Chandrakala (2006) investigated radiative heat and mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction. Bhaskar (2024) investigated Unsteady Flow Past an Exponentially Accelerated Vertical Plate With Ramped Plate Heat Flux. Ibrahim et al. (2008) analyzed the effect of chemical reaction and radiation absorption on the unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source. Bakr (2011) discussed the effects of chemical reaction on MHD free convection and mass transfer flow of a micro-polar fluid with oscillatory plate velocity and constant heat source in a rotating frame of reference. Venkata (2023) examined Unsteady MHD Free Convection Flow of a Second Grade Casson Fluid with Ramped Wall Temperature. Chamkha (2003) studied MHD flow of a uniformly stretched vertical permeable surface in the presence of heat generation/absorption and chemical reaction. Chamkha et al. (2011) discussed the effects of Joule heating, chemical reaction and thermal radiation on unsteady hydromagnetic natural convection boundary layer flow with heat and mass transfer of a micropolar fluid from a semi-infinite heated vertical porous plate in the presence of a uniform transverse magnetic field. Bhattacharya and Layek (2012) obtained similarity solution of MHD boundary layer flow with mass diffusion and chemical reaction over a porous flat plate with suction/blowing. Recently, Mohamed et al. (2013) investigated unsteady MHD free convection heat and mass transfer boundary layer flow of viscous, incompressible, optically thick and electrically conducting fluid through a porous medium along an impulsively moving hot vertical plate in the presence of homogeneous chemical reaction of first order and temperature-dependent heat sink. They obtained analytical solution of the governing equations in closed form by Laplace transform technique.

The objective of the present investigation is to study ramped temperature and ramped surface concentration of unsteady Magnetohydrodynamic flow with heat and mass transfer of a chemically reacting and heat absorbing fluid past a porous vertical plate in the presence of thermal radiation. The research works also extend the work of Seth et al. (2014) to include heat absorption, thermal radiation and chemical reaction.This study may find application in solar collection systems, fire dynamics in insulations, geothermal energy systems, catalytic reactors, nuclear waste repositories, recovery of petroleum products.

2. Problem Formulation

Consider unsteady hydromagnetic natural convection flow with heat and mass transfer of an electrically conducting, viscous, incompressible, chemically reacting and temperature-dependent heat absorbing fluid past an accelerated moving infinite vertical plate embedded in a porous medium in the presence of thermal and mass diffusions. Choose the co-ordinate system in such a way that x'-axis is along the plate in upward direction, y'-axis normal to the plane of the plate and z'-axis perpendicular to $x'y'$-plane. The fluid is permeated by uniform transverse magnetic field B_0 applied parallel to y'-axis. Initially, i.e. at time $t' \leq 0$, both fluid and plate are at rest and maintained at uniform temperatures T'_∞ and uniform surface concentration C'_∞. At time $t' > 0$, plates start moving in x'-direction against the gravitational field with time dependent velocity $U(t')$. Temperature of the plate is raised or lowered to $T'_\infty + (T'_w - T'_\infty)t'/t_0$ and the level of concentration at the surface of the plate is raised or lowered to $C'_\infty + (C'_w - C'_\infty)t'/t_0$ when $0 < t' \leq t_0$. Thereafter, i.e. at $t' > t_0$, plate is maintained at the uniform temperature T'_w and the level of concentration at the surface is preserved at uniform concentration C'_w. Here t_0 is characteristic time. It is assumed that there exists a homogeneous chemical reaction of first order with constant rate K'_2 between the diffusing species and the fluid. The schematic diagram of the physical problem is shown in Figure. 1. Since the plate is of infinite extent along x' and z'-directions and is electrically non-conducting, all physical quantities except pressure depend on y' and t' only. The induced magnetic field produced by fluid motion is neglected in comparison

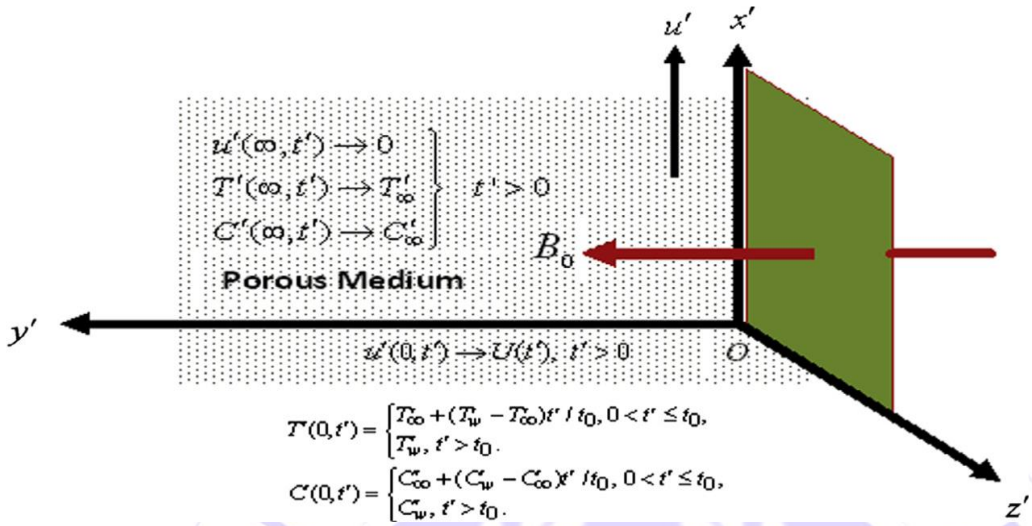

Figure 1 Schematic diagram of the physical problem.

with the applied one. This statement is justified because the magnetic Reynolds number is very small for liquid metals and partially ionized fluid which was discussed by Cramer and Pai (1973). They also considered that no external electric field is applied so the effect of polarization of fluid is negligible. This corresponds to the case where no energy is added or extracted from the fluid by electrical means. Taking into consideration the assumptions made above, the governing equations for natural convection flow with heat and mass transfer of an electrically conducting, incompressible, viscous, chemically reacting, and temperature-dependent heat absorbing fluid through a porous medium in the presence of thermal and mass diffusions, under Boussinesq approximation, are given by;

$$\frac{\partial u'}{\partial t'} = v\frac{\partial^2 u'}{\partial y'^2} + \frac{\partial^2 u'}{\partial x'^2} - \frac{\sigma B^2{}_0}{\rho}u' - \frac{v}{K'_1} + g\beta^*(T' - T'_\infty) + g\beta^*(C' - C'_\infty) \quad (1)$$

$$\frac{\partial T'}{\partial t'} = \alpha'\left(\frac{\partial^2 T'}{\partial x'^2} + \frac{\partial^2 T'}{\partial y'^2}\right) - \frac{Q_0}{\rho C_p}(T' - T'_\infty), + \frac{1}{\rho C_p}\frac{\partial q}{\partial y} \quad (2)$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial x'^2} + D\frac{\partial^2 C'}{\partial y'^2} - K'_2(C' - C'_\infty), \quad (3)$$

Appropriate initial and boundary conditions for fluid velocity, fluid temperature and species concentration are given by;

$$u' = 0, T' = T'_\infty, C' = C'_\infty \text{ for } y' \geq 0 \text{ and } t' \leq 0, \quad (4)$$

$$u' = U(t') \text{ at } y' = 0 \text{ for } t' > 0, \quad (5)$$

$$\left.\begin{aligned} T' &= T'_\infty + \frac{(T'_w - T'_\infty)t'}{t_0}, \\ C' &= C'_\infty + \frac{(C'_w - C'_\infty)t'}{t_0}, \end{aligned}\right\} \text{at } y' = 0 \text{ for } 0 < t' \leq t_0 \quad (6)$$

$$T' = T'_w, C' = C'_w, \text{ at } y' = 0 \text{ for } t' > t_0 \quad (7)$$

$$u' \to 0, T' \to T'_\infty, C' \to C'_\infty, \text{ as } y' \to \infty \text{ for } t' > 0 \quad (8)$$

In order to represent equations (1), (2) and (3) along with initial and boundary conditions equation in equations (4), (5), (6), (7) and (8) in dimensionless form, the following dimensionless quantities and parameters are introduced.

$$y=\frac{y'}{U_0t_0}\ ,\ \ u=\frac{u'}{U_0}\ ,\ \ t=\frac{t'}{t_0}\ ,\ \ T=\frac{T'-T'_\infty}{T'_w-T'_\infty}\ ,\ \ C=\frac{C'-C'_\infty}{C'_w-C'_\infty}\ ,$$

$$G_r=\frac{vg\beta'(T'_w-T'_\infty)}{U^3{}_0},\ \ G_c=\frac{vg\beta^*(C'_w-C'_\infty)}{U^3{}_0},\ \ M=\frac{\sigma B^2{}_0v}{\rho U^2{}_0},\ \ K_1=\frac{K'_1U^2{}_0}{v^2},\qquad (9)$$

$$P_r=\frac{v}{\alpha'}\ ,\ \ S_c=\frac{v}{D}\ ,\ \ K_2=\frac{vK'_2}{U^2{}_0}\ ,\ \ \phi=\frac{vQ_0}{\rho C_pU^2{}_0}\ \ .Ra=\frac{vq}{\rho C_pU^2{}_0}$$

Using dimensionless quantities and parameters defined in (9), equations (1), (2) and (3) in dimensionless form, become;

$$\frac{\partial u}{\partial t}=\frac{\partial^2u}{\partial y^2}+\frac{\partial^2u}{\partial x^2}-Mu-\frac{u}{K_1}+G_rT+G_cC,\qquad (10)$$

$$\frac{\partial T}{\partial t}=\frac{1}{P_r}\left(\frac{\partial^2T}{\partial x^2}+\frac{\partial^2T}{\partial y^2}\right)-\phi T+Ra+\text{Ra},\qquad (11)$$

$$\frac{\partial C}{\partial t}=\frac{1}{S_c}\left(\frac{\partial^2C}{\partial x^2}+\frac{\partial^2C}{\partial y^2}\right)-K_2C.\qquad (12)$$

According to the above non-dimensionalization process, characteristic time t_0 may be defined as

$$t_0=\frac{v}{U^2{}_0}\qquad (13)$$

Appropriate initial and boundary conditions (2.4), in dimensionless form, assume the following form;

$u=0,\ \ T=0,\ \ C=0$ for $y\geq 0$ and $t\leq 0,$ (14)

$u=F(t)$ at $y=0$ for $t>0,$ (15)

$T=t,\quad C=t$ at $y=0$ for $0<t<1,$ (16)

$T=1,\quad C=1$ at $y=0$ for $t>1,$ (17)

$u\to 0,\quad T\to 0,\quad C\to 0$ as $y\to\infty$ for $t>0,$ (18)

Where $F(t)=\frac{U(t')}{U_0}$.

Numerical approach will be adopted to solve the fluid flow models described by the equations (10), (11) and (12) subject to initial and boundary conditions (13), (14), (15), (16), (18).

2.1 Numerical Solution

The system of highly partial differential equations (10), (11) and (12) with the boundary conditions (13) to (18) are solved by a numerical approach via shooting method with the sixth-order Runge-Kutta method for different moderate values of the flow, heat and mass transfer parameters. The effective Broyden technique is adopted in order to improve the initial guesses and to satisfy the boundary conditions at infinity. Maple software is used to code and simulate the above numerical procedure.

3. Results and Discussion

For the purpose of studying the effect of magnetic field, thermal buoyancy force, species buoyancy force, heat absorption, chemical reaction and time on flow-field in the boundary layer region, the numerical values of fluid velocity are displayed graphically in Figs. 2-7 for various values of magnetic parameter M, thermal Grashof number G_r, solutal Grashof number G_c, heat absorption

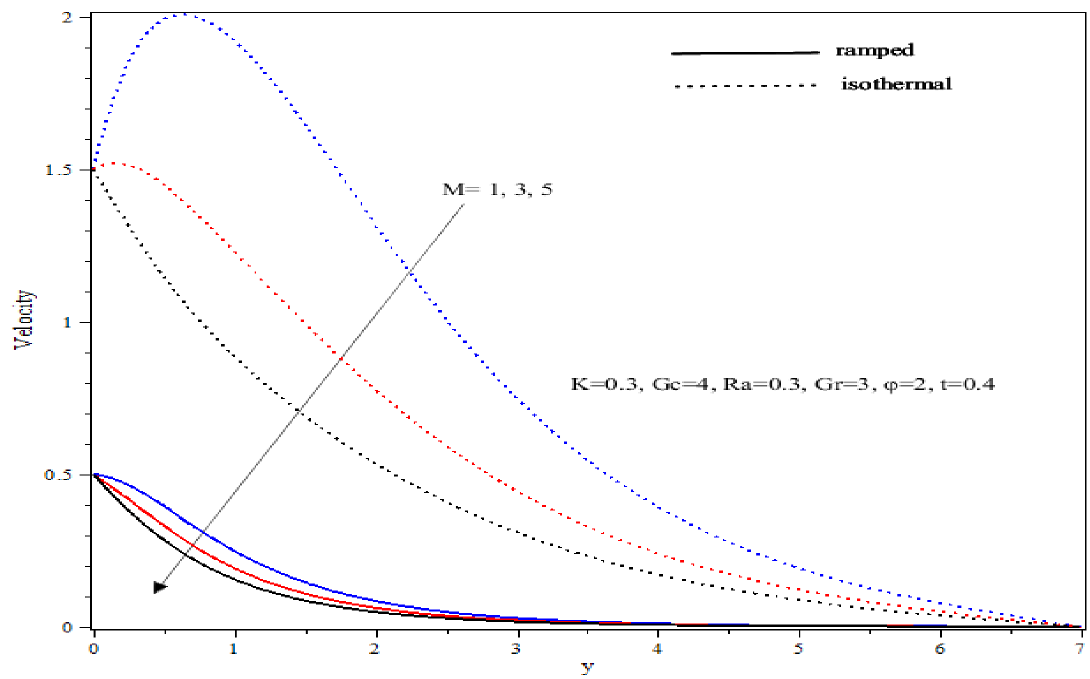

Figure 2 Influence of Magnetic Parameter M on velocity profiles

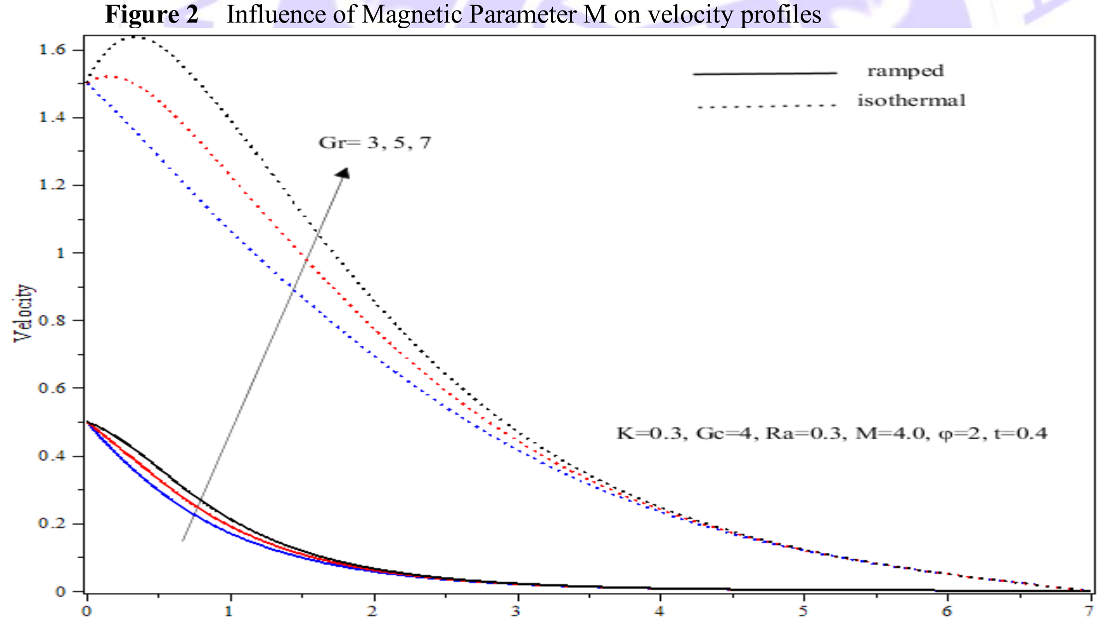

Figure 3: Influence of thermal Grashof number Gr on velocity profile

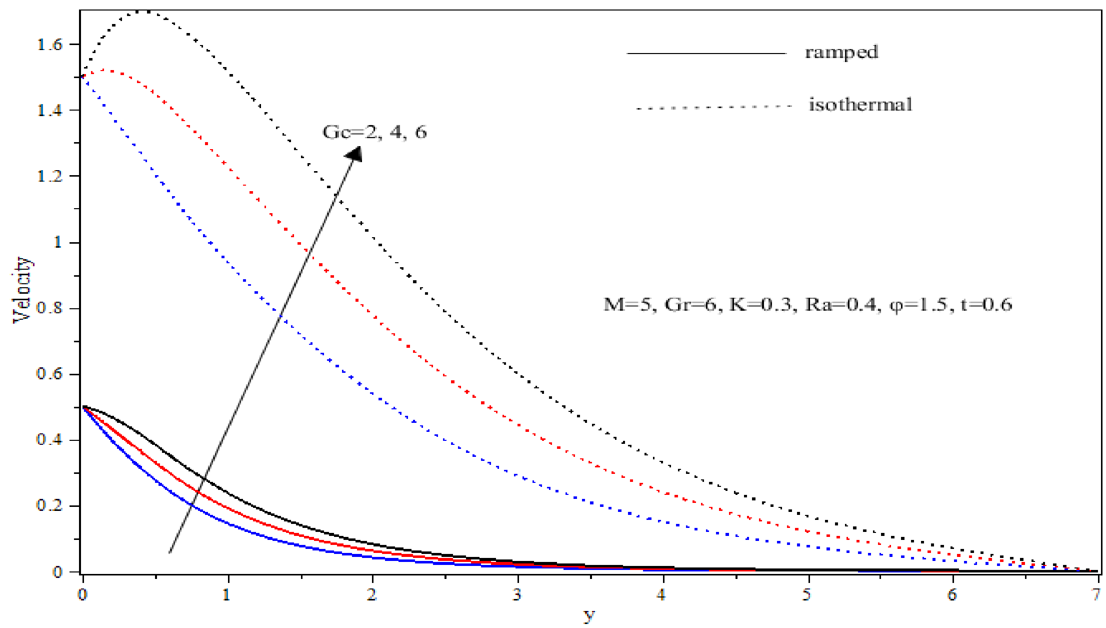

Figure 4: Influence of solutal Grashof number Gc on velocity profile

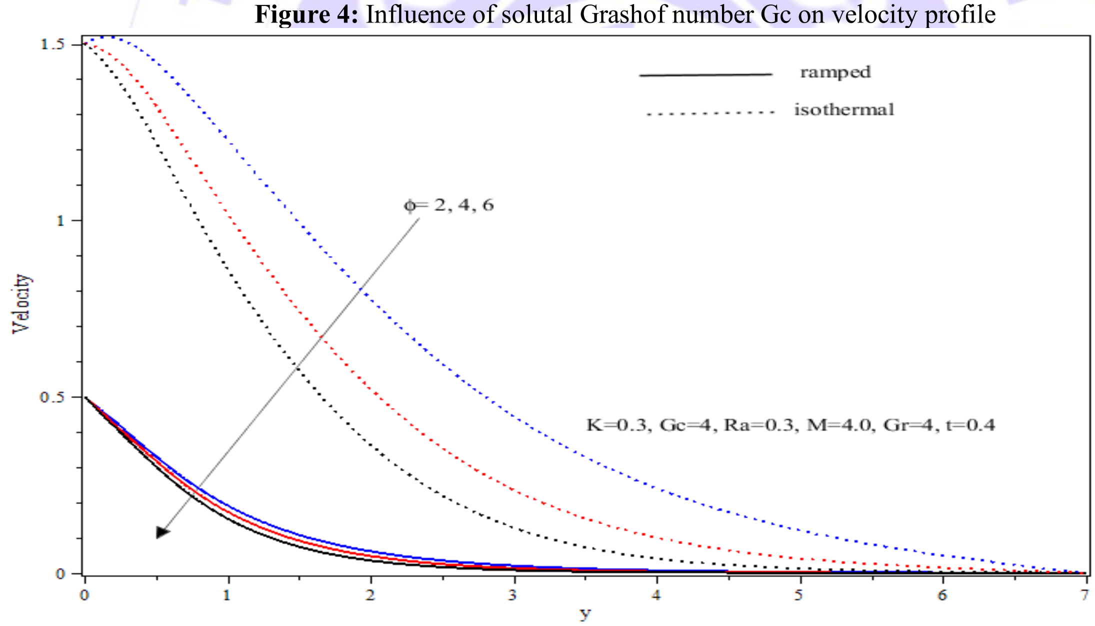

Figure 5: Influence of heat absorption coefficient on Velocity profiles

coefficient ϕ, chemical reaction parameter K, and time t. It is evident from Figs. 2-7 that, for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, fluid velocity u increases rapidly in the region near the surface of the plate, reaches a maximum distinctive value and then decreases gradually on increasing boundary layer coordinate y to approach free stream value. Fig. 2 shows the effect of magnetic field on the fluid velocity. For both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, fluid velocity decreases on increasing magnetic parameter M. This implies that the magnetic field has retarding effect on fluid flow for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration. This is due to the fact that the application of a magnetic field to an electrically conducting fluid gives rise to a resistive force called Lorentz force which has a tendency to slow down the motion of fluid in the boundary layer region. Figs. 3 and 4 describe the effect of thermal buoyancy force and species buoyancy force on fluid velocity. The thermal Grashof number G_r signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force. The

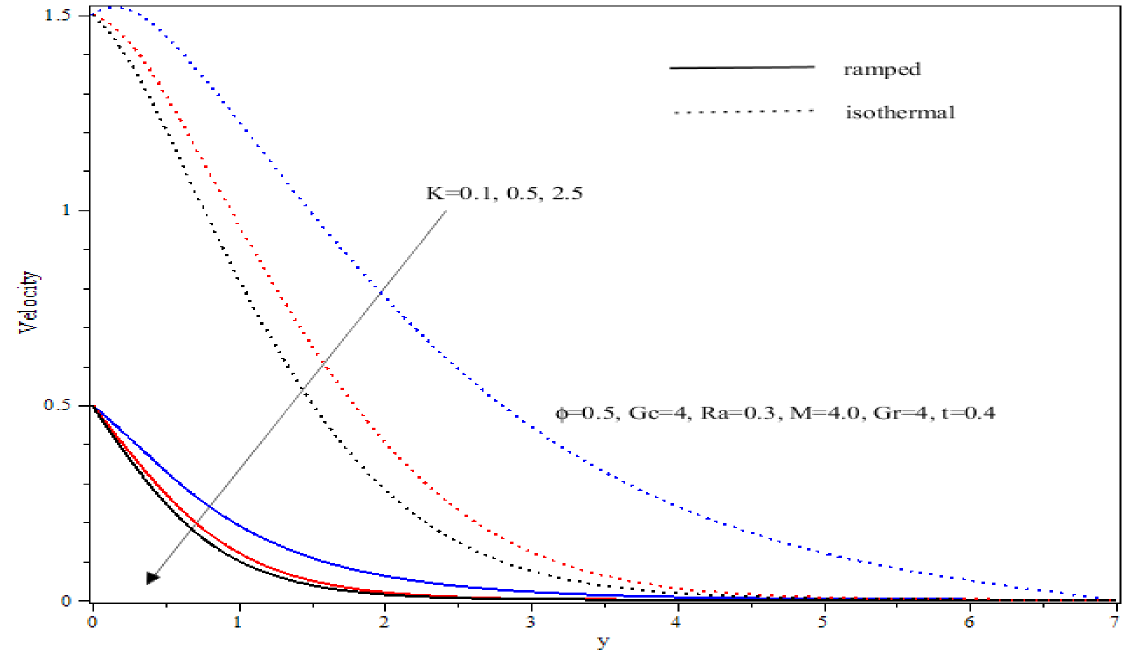

Figure 6: Influence of chemical reaction parameter on velocity profiles

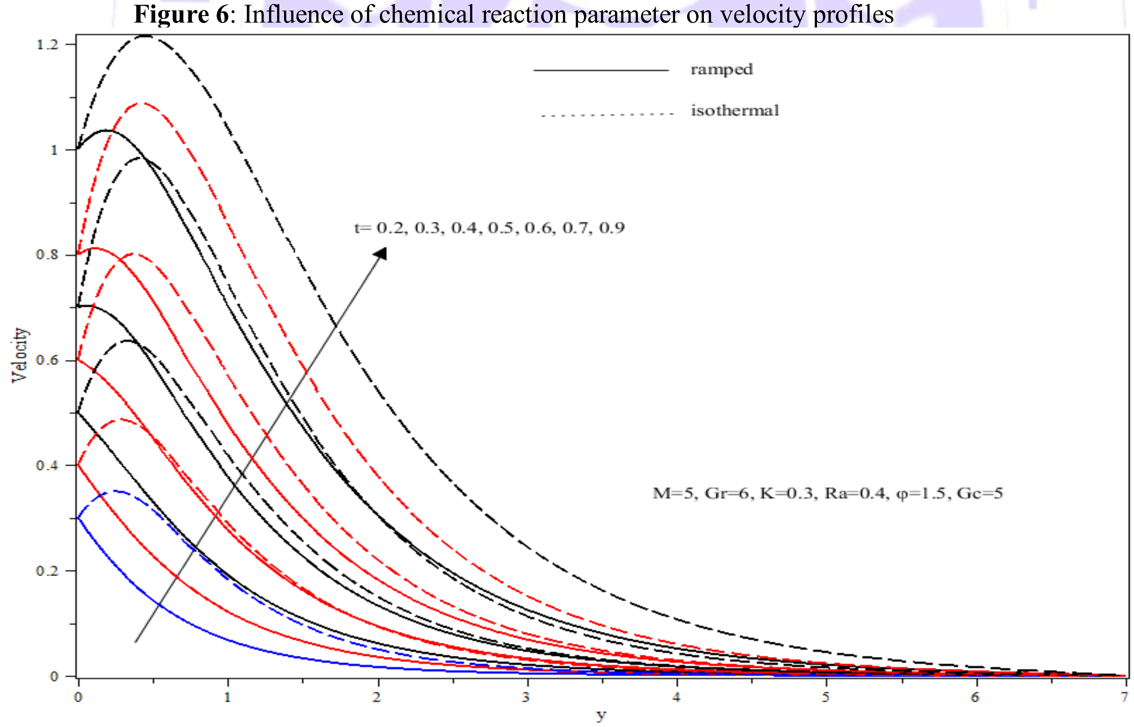

Figure 7: Influence of time on velocity profiles

solutal Grashof number G_c characterizes the ratio of the species buoyancy force and viscous hydrodynamic force. As expected, it is observed that, for both ramped temperatures. Plate with ramped surface concentration and isothermal plate with uniform surface concentration, fluid velocity increases on either G_r or G_c .This implies that fluid velocity is getting accelerated due to enrichment in either thermal buoyancy force or species buoyancy force. Fig. 5 demonstrates the effects of heat absorption on fluid velocity. It is observed that, for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, fluid

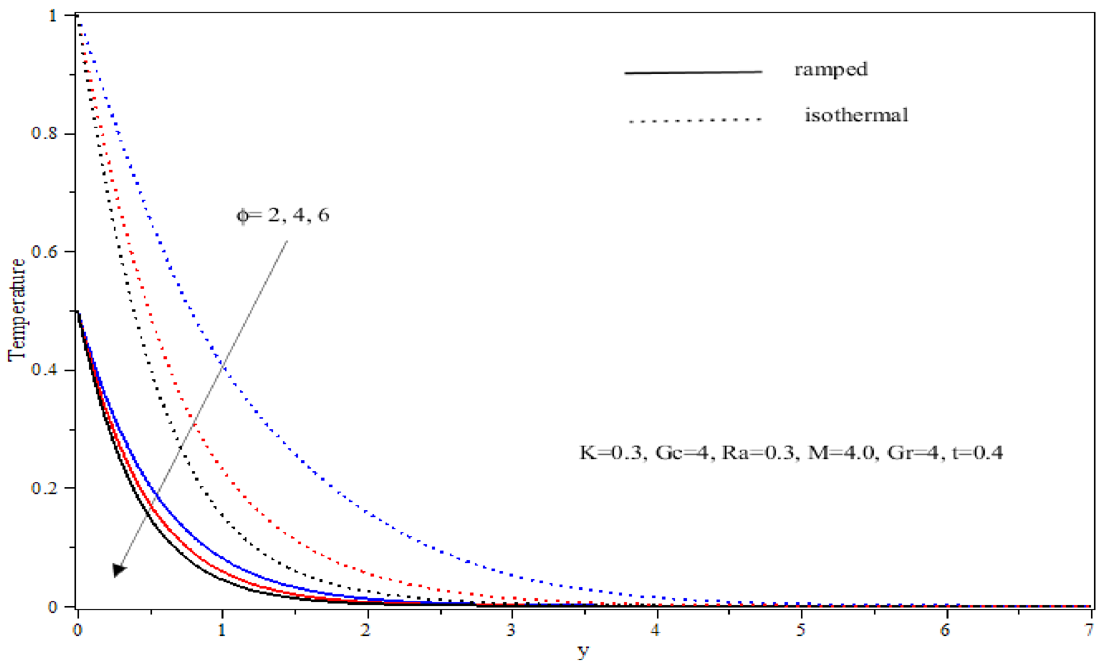

Figure 8: Influence of heat absorption coefficient on temperature profiles

velocity decreases on increasing ϕ. This implies that, both for ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, heat absorption tends to retard fluid velocity throughout the boundary layer region. Since the tendency of heat absorption (thermal sink) is to reduce the fluid temperature which causes the strength of thermal buoyancy force to decrease, resulting in a net reduction in the fluid velocity. Fig. 6 displays the effect of chemical reaction on fluid velocity. It is noticed that fluid velocity decreases on increasing K_2 for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration. This shows that chemical reaction has a retarding influence on fluid flow for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration. Fig. 7 represents the effects of time on fluid velocity. It is observed that fluid velocity increases on increasing time t. This implies that there is an improvement in fluid velocity for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration with the progress of time. It is noted that from Figs. 2-7 that fluid velocity is faster in the case of isothermal plate with uniform surface concentration than that in the case of ramped temperature plate with ramped surface concentration. The numerical solutions for fluid temperature and species concentration, computed from the numerical solutions are displayed graphically in Figs. 8-11 for different values of heat absorption coefficient ϕ, chemical reaction parameter K and time t. It is observed from Figs. 8-11 that fluid temperature and species concentration are maximum at the surface of the plate

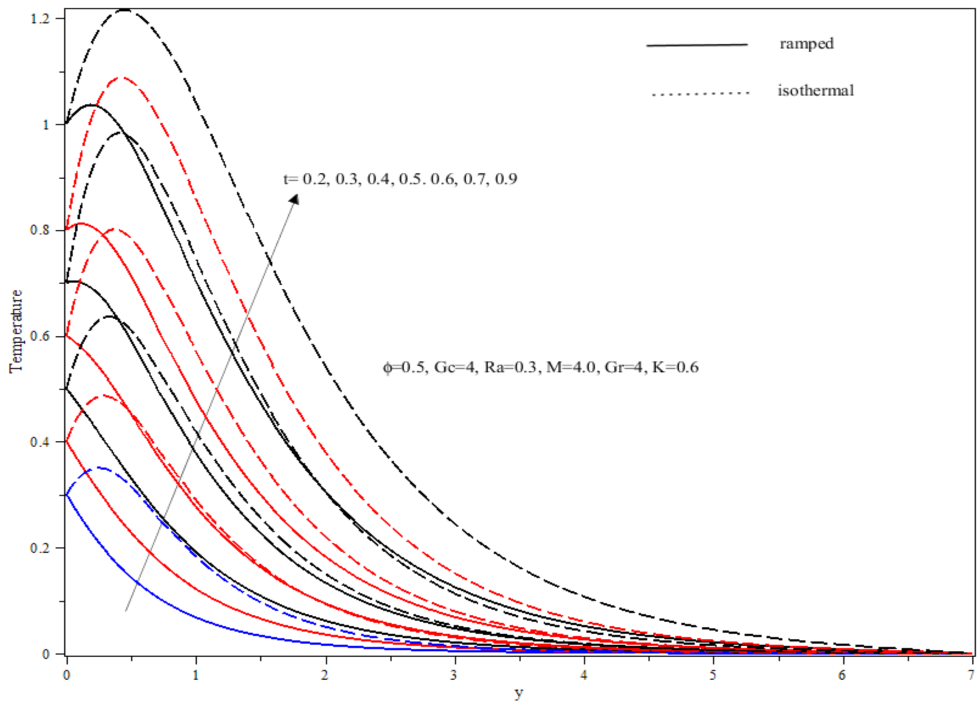

Figure 9: Influence of time on temperature profile

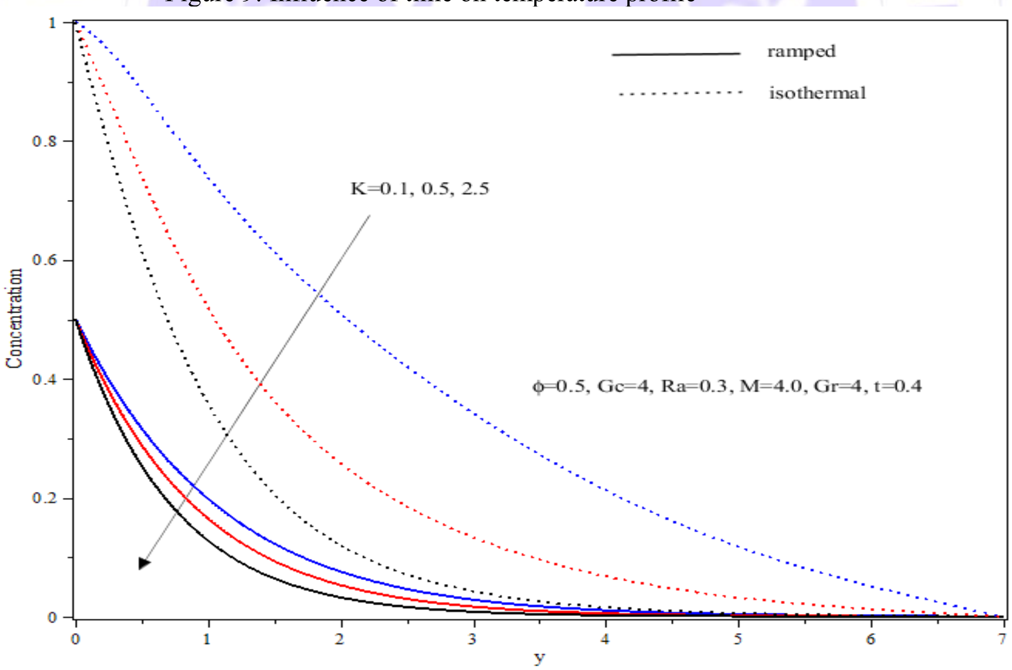

Figure 10: Influence of chemical reaction on concentration profiles

and decreases properly on increasing boundary layer coordinate y to approach free stream value. Figs 8 and 9 illustrate the effects of heat absorption coefficient ϕ and time t on fluid temperature. It is evident that, for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, fluid temperature decreases on increasing ϕ whereas it increases on increasing time t. This implies that, for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, heat absorption has a tendency to reduce the fluid temperature and there is a rise in fluid temperature

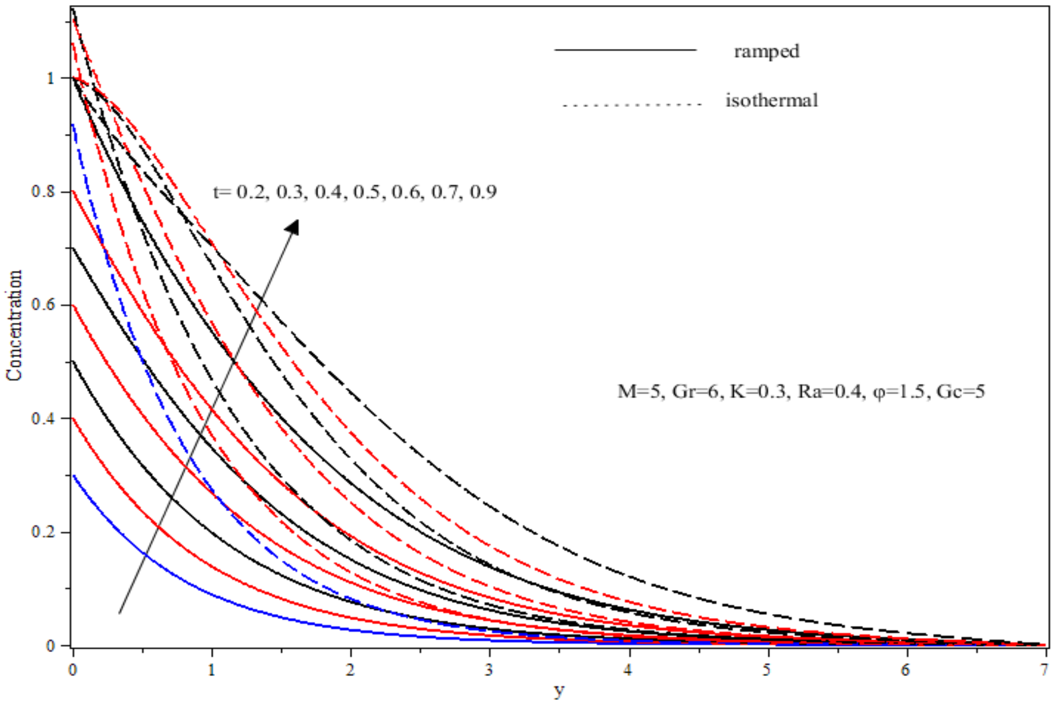

Figure 11: Influence of time on fluid on centration profiles

with the progress of time in the boundary layer region. Figs. 10 and 11 demonstrate the effects of chemical reaction parameter K and time *t* on species concentration. It is noticed that, for both ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration, chemical reaction tends to reduce species concentration and there is enrichment in species concentration with the progress of time. It may be noted from Figs. 8-11 that the fluid temperature and species concentration are lower in the case of ramped temperature plate with ramped surface concentration that in the case of isothermal plate with uniform surface concentration.

4. Conclusion

For both the ramped temperature plate with ramped surface concentration and the isothermal plate with uniform surface concentration, the magnetic field, heat absorption, and chemical reaction exert a retarding influence on fluid flow. However, fluid velocity increases over time. Heat absorption has the effect of reducing fluid temperature, although the overall fluid temperature rises as time progresses. Similarly, the chemical reaction tends to decrease species concentration, but there is an improvement in species concentration over time. In both cases—ramped temperature plate with ramped surface concentration and isothermal plate with uniform surface concentration—heat absorption increases the rate of heat transfer at the plate. For the ramped temperature plate with ramped surface concentration, the rate of heat transfers at the plate increases over time. In contrast, for the isothermal plate with uniform surface concentration, the rate of heat transfers at the plate decreases as time progresses. Additionally, for both configurations, the chemical reaction enhances the rate of mass transfer at the plate. Specifically, for the ramped temperature plate with ramped surface concentration, the rate of mass transfer at the plate increases over time. However, for the isothermal plate with uniform surface concentration, the rate of mass transfer at the plate decreases as time progresses.

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