

EFFECTS OF RADIATION AND CHEMICAL REACTION ON MHD CASSON FLUID FLOW THROUGH A POROUS MEDIUM

Chapala Sahoo¹, Bigyan Ranjan Rout², Jayaprakash Panda¹, and Kharabela Swain^{3,*}

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Abstract

The current study is to present the behavior of natural convective MHD casson fluid flow in a porous medium and it is subjected to thermal radiation and chemical reaction along with thermal and solutal buoyancy. The governing equations are transformed to non-dimensional form and solutions are obtained using perturbation method taking Eckert number as parameter taking small value. The variations of velocity, temperature and concentration with regard to different parameters are presented through graphs and table. The results and discussion section brings out the important effects of the characterising parameters involved in the present study. A few important findings are as follows. The buoyancy force quickens to attain the ambient state earlier than the magnetic field. The increase in skin friction indicates progressive thinning of boundary layer reversely, the decrease leads to thickening of boundary layer; not a desirable outcome. Nusselt number bears positive sign implies that heat flows from plate to fluid. That produces destabilizing effect. The care should be taken to control or regulate the values of the parameters for thermal stability of the flow.

Keywords: Casson Fluid; Chemical Reaction; MHD; Porous Medium; Thermal Radiation

¹ Department of Mathematics, VSSUT, Burla, Odisha, India. E-mail: humulu2013@gmail.com, ORCID: 0009-0003-6402-8563; jppanda_math@vssut.ac.in, ORCID: 0000-0001-6857-1094

² Department of Mathematics, SCS (A) College, Puri, Odisha, India. E-mail: bigyanomkar@gmail.com, ORCID: 0000-0001-9890-1744

³ Department of Mathematics, GIFT Autonomous, Bhubaneswar, Odisha, India. E-mail: kharabela1983@gmail.com, ORCID: 0000-0001-5079-2796

* Corresponding author

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Introduction

Natural convective flows of Casson fluid on a vertical surface are widely investigated for their potential applicability in engineering and environmental processes. When mass and heat transfer occur due to buoyancy caused by thermal diffusivity, concentration with chemical substances, it is common to see it in both natural and industrial conditions where mass and heat transfer occur. It has drawn increasing attention in current decades as its relevance in a variety of technical, astrophysical, and geophysical applications such as cosmic jets, magnetised plasma flow, high speed plasma wind, underground energy transport, nuclear reactors as coolant, packed catalytic reactors, polymer production etc. Radiation is used extensively in the manufacturing sector, gas turbines, nuclear power plants, and a variety of propulsion mechanisms for space vehicles, satellites, missiles, and aircraft. Attia and Ahmed (2010) proposed the Casson fluid's transient Couette flow analysis among parallel plates utilizing heat transfer analysis. The analytical solution for Casson fluid's magnetohydrodynamic boundary layer flow is given by Bhattacharyya *et al.* (2013). Mukhopadhyay (2013) investigated thermal radiation impacts on Casson fluid's heat as well as flow transfer analysis across an unstable stretched sheet with blowing and suction effects. Shehzad *et al.* (2013) examined mass transfer of Casson fluid on MHD flow with chemical reaction.

Motsumi and Makinde (2012) studied the viscous dissipation factor's (namely, Eckert number), thermal radiation along with diffusion on nanofluids' boundary layer flow such as Al_2O_3 -water along with Cu-water. Makinde (2012) observed a rise in surface temperature of moving plate along with thermal boundary layer's thickness in another theoretical research on the cumulative impact of Newtonian heating. Ec (Eckert number) and $\text{Pr} \times \text{Ec}$ (Brinkmann number) can be utilized for measuring viscous dissipation depending on acceptable variables. In addition, Abd El-Aziz (2014) investigated unstable mixed convection in air flow. For flow analysis a dual solution of Casson fluid owing for shrinking or stretching sheet has been developed by Kameshwaran *et al.* (2014). Nandeppanavar (2015, 2016) also examined the Casson fluid's heat transfer analysis owing for stretching sheet under convective heating conditions, obtaining both analytical as well as numerical findings for Runge-Kutta fourth order and Kummer's function approach using shot methodology. For boundary layer flow of Jeffrey fluid across an exponentially extending sheet, Sajid and Hayat (2005) presented an analytical solution.

Bidin and Nazar (2009) provided numerical solution to an identical issue a short time after that. Ishak (2011) investigated the radiation impact on the MHD boundary layer flow of viscous fluid across an exponentially extending sheet.

Sahoo *et al.* (2011) studied the MHD convective boundary layer flow along with heat transfer via stretched porous wall. Panda *et al.* (2012) investigated flow through porous media and in MHD flow mass as well as heat transfer in the existence of suction as well as flowing over an accelerating surface. Mixed convective MHD flow as well as heat transmission in porous media at stagnation point has been analyzed by Sahoo *et al.* (2013). A spontaneous convective MHD flow was inspected by Rout *et al.* (2014). Venkata Ramudu *et al.* (2019) examined the Impact of injection/suction on MHD Casson fluid flow.

Mahapatra *et al.* (2010) conferred the chemical reaction's impacts on free convection flow using porous material. Nadeem *et al.* (2012) examined the Casson fluid's MHD flow across an exponentially decreasing sheet in a Casson fluid. Mohamed *et al.* (2010) and Mohammed Ibrahim (2013) provided the outcomes of thermal radiation impacts on fluid's free convective MHD flow by porous medium in existence of chemical reaction and internal heat generation. Raju *et al.* (2017) investigated the numerical study of radiation absorption along with chemical impacts. Khan *et al.* (2022) observed the entropy generation associated with flow and heat transfer of Sisko nanofluid. For fluid flow, Heat transfer analysis across exponentially expanding porous sheet having heat flux on surface has been examined in a medium which is porous in nature by Nazeer *et al.* (2022). Omar *et al.* (2022) studied the Hall current and Soret effects on unsteady MHD rotating flow of second Grade fluid through porous media under the influences of thermal radiation and chemical reaction. Ahmed *et al.* (2022) numerically Computed the effects of Gyrotactic Microorganisms in MHD radiative Eyring-Powell nanomaterial flow by a static /moving wedge with Darcy-Forchheimer model. Ali *et al.* (2023) studied unsteady MHD flow of Casson fluid past a vertical surface using Laplace transformation technique. Farooq *et al.* (2015) studied MHD flow of a Jeffrey fluid with Newtonian heating. Recently, Senapati *et al.* (2022) investigated the slip flow analysis on magnetohydrodynamic flow of a Casson fluid over a nonlinearly permeable stretching sheet embedded in a porous medium. They found that Eckert number enhances the rate of heat transfer but reduces the mass transfer at the bounding surface. Biswal *et al.* (2023) studied the

boundary layer flow and heat transfer of thermally radiative Casson nanofluid over a stretching sheet with chemical reaction and internal heat source. Swain *et al.* (2022) examined the Brownian motion and thermophoresis effect the unsteady 2D flow of Casson nanofluid over a stretching sheet entrenched in a porous medium using Buongiorno model. Baitharu *et al.* (2024) studied the steady two-dimensional flow of chemically reacting and electrically conducting Casson fluid over a permeable flat stretching sheet in a saturated porous medium in the presence of transverse magnetic field.

The current work is related to the effect of thermal radiation and chemical reaction on a time independent incompressible free convective MHD casson fluid flow embedded in a semi-infinite region bounded by vertical surface in a porous medium. The energy equation is extended to include the contributions of internal heat generation, thermal radiation, and viscous dissipation, whereas the concentration equation is augmented by a chemical reaction term. The Eckert number (Ec) is a measure of the dissipation effect due to frictional heat in the flow. As $Ec = \frac{v_0^2}{c_p(T_w - T_\infty)}$, the present assumption is valid for $Ec \ll 1$. Hence, v_0 must be small. The present analysis is valid for slow motion of the fluid. We have considered upto first order of Ec and neglected the contribution of Ec^2 (second term) which is small. The findings are examined for their temperature, velocity, along with concentration patterns, among other characteristics.

Mathematical Formulation

In this paper, we examine an incompressible steady viscous natural convective MHD casson fluid flow embedded in a semi-infinite region bounded by vertical surface in a porous medium. In the vertical direction, the x-axis is taken parallel to the surface, while in the horizontal direction, the y-axis is taken perpendicular to the surface. A uniform magnetic field is applied perpendicular to the surface. The flow geometry of the present model is exhibited in Figure 1.

The governing equations for the steady flow of Casson fluid are as follows:

$$\frac{\partial v^*}{\partial y^*} = 0, \quad (1)$$

$$v \frac{\partial u^*}{\partial y^*} = v \left(1 + \frac{1}{\beta} \right) \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T_\infty) - \frac{v}{Kp} u^* + g\beta^*(C^* - C_\infty) - \frac{\sigma B_0^2}{\rho} u^*, \quad (2)$$

$$v \frac{\partial T^*}{\partial y^*} = \frac{\alpha}{\rho C_p} \frac{\partial^2 T^*}{\partial y^{*2}} + \frac{v}{C_p} \left(1 + \frac{1}{\beta} \right) \left(\frac{\partial u^*}{\partial y^*} \right)^2 - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y^*} - \frac{Q_0}{\rho C_p} (T^* - T_\infty), \quad (3)$$

$$v \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} - KrC^*. \quad (4)$$

Here v_0 is +ve as well as v^* is normal suction velocity which is independent of time. The boundary conditions are

$$u^* = 0, T^* = T_w, C^* = C_w \text{ at } y^* = 0$$

$$u^* \rightarrow 0, T^* \rightarrow T_\infty, C^* \rightarrow C_\infty \text{ as } y^* \rightarrow \infty. \quad (5)$$

From Equation (1)

$$v^* = \text{const} = -v_0 \quad (6)$$

Presenting some non-dimensional factors such as

$$u = \frac{u^*}{v_0}, y = \frac{v_0 y^*}{v}, \theta = \frac{T^* - T_\infty}{T_w - T_\infty}, C = \frac{C^* - C_\infty}{C_w - C_\infty}, Pr = \frac{\rho v c_p}{\alpha}, Sc = \frac{v}{D}, Gr = \frac{v g \beta (T_w - T_\infty)}{v_0^3}, Q = \frac{v Q_0}{v_0^2 \rho C_p}, Gc = \frac{v g \beta^* (C_w - C_\infty)}{v_0^3}, Ec = \frac{v_0^2}{c_p (T_w - T_\infty)}, K = \frac{v_0^2}{v^2} Kp, k_0 = \frac{v}{v_0^2} Kr, R = \frac{16 \sigma^* T_\infty^3}{3 k_s \alpha}. \quad (7)$$

By utilizing the Rossenland approximation q_r takings the value

$$q_r = -\frac{4\sigma^*}{3k_s} \frac{\partial T^4}{\partial y} \quad (8)$$

where Stefan-Boltzman constant is defined by σ^* , Rossenland mean absorption coefficient is given by k_s .

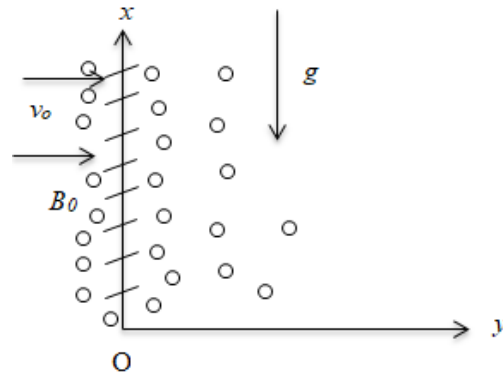


Figure 1. Flow Geometry

Temperature difference is expected to be significantly small, by T^4 Taylor series expansion as expressed by following

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4 \quad (9)$$

(By neglecting the higher order terms)

By using (8) and (9)

$$\frac{\partial q_r}{\partial y} = -\frac{16\sigma^* T_\infty^3}{3k_s} \frac{\partial^2 T}{\partial y^2} \quad (10)$$

Using the values of (7) along with (10) in the Equations system (1) - (4), is decreased to non-dimensional Equations and those are specified as

$$\left(1 + \frac{1}{\beta}\right) u'' + u' = -GcC - Gr\theta + \left(M + \frac{1}{K}\right) u = 0 \quad (11)$$

$$\theta'' + \frac{Pr}{1+R} \theta' - Q \frac{Pr}{1+R} \theta + \left(1 + \frac{1}{\beta}\right) \frac{Pr}{1+R} Ec(u')^2 = 0 \quad (12)$$

$$C'' + Sc C' = k_0 Sc C \quad (13)$$

The boundary conditions are

$$\begin{aligned} u=0, \theta=1, C=1 \quad \text{at } y=0; \\ u \rightarrow 0, \theta \rightarrow 0, C \rightarrow 0 \quad \text{as } y \rightarrow \infty \end{aligned} \quad (14)$$

For solving nonlinear system Equations. (11)-(13) having boundary conditions (14), θ , u and C are extended in Eckert number (Ec) powers. Taking very small Ec values this can be expressed as

$$\begin{aligned} u = u_0 + Ecu_1 + O(Ec^2), \theta = \theta_0 + Ec\theta_1 + O(Ec^2), \\ C = C_0 + EcC_1 + O(Ec^2) \end{aligned} \quad (15)$$

Substituting Equation (15) in Equations (11)-(13) as well as equating the terms' coefficient with equal Ec power and abandoning order terms Ec^2 along with higher orders, resulting equations are obtained;

Zeroth order equations are given by

$$u_0'' + Tu_0' = -TGr\theta_0 - TGcC_0 + T\left(\frac{1}{K} + M\right)u_0 = 0 \quad (16)$$

$$\theta_0'' + \frac{Pr}{1+R} \theta_0' - \frac{Pr}{1+R} Q\theta_0 = 0 \quad (17)$$

$$C_0'' + ScC_0' - k_0 ScC_0 = 0 \quad (18)$$

The corresponding boundary conditions are

$$u_0 = 0, \theta_0 = 0, C_0 = 1 \text{ at } y = 0;$$

$$u_0 \rightarrow 0, \theta_0 \rightarrow 0, C_0 \rightarrow 0 \text{ at } y \rightarrow \infty \quad (19)$$

First order equations are given by

$$u_1'' + Tu_1' = -TGr\theta_1 - TGcC_1 + T\left(\frac{1}{K} + M\right)u_1 \quad (20)$$

$$\theta_1'' + \frac{Pr}{1+R} \theta_1' + \frac{1}{T} \frac{Pr}{1+R} Ec(u_1')^2 = 0 \quad (21)$$

$$C_1'' + ScC_1' - k_0 ScC_1 = 0 \quad (22)$$

The equivalent boundary conditions are

$$u_1 = 0, \theta_1 = 0, C_1 = 0 \text{ at } y = 0;$$

$$u_1 \rightarrow 0, \theta_1 \rightarrow 0, C_1 \rightarrow 0 \text{ at } y \rightarrow \infty \quad (23)$$

Explaining the Equations (16)-(18) and (20)-(22) with boundary conditions (19) and (23), given solutions for u , θ , and C are given by:

$$\begin{aligned} u(y) = (A + B + Eck_{27}) \exp(m_6 y) \\ - A \exp(my) - B \exp(m_2 y) - \end{aligned} \quad (24)$$

$$EcGrT \left[\begin{aligned} &k_{20} \exp(my) + k_{21} \exp(2m_6 y) + \\ &k_{22} \exp(2my) + k_{23} \exp(2m_2 y) \\ &- k_{24} \exp(m_6 + m)y + \\ &k_{25} \exp(m_2 + m)y - k_{26} \exp(m_6 + m_2)y \end{aligned} \right]$$

$$\theta(y) = \exp(my) -$$

$$Ec \left[\begin{aligned} &k_{17} \exp(my) + k_{11} \exp(2m_6 y) + \\ &k_{12} \exp(2my) + k_{13} \exp(2m_2 y) - \\ &k_{14} \exp(m_6 + m)y + k_{15} \exp(m + m_2)y - \\ &k_{16} \exp(m_6 + m_2)y \end{aligned} \right] \quad (25)$$

$$C(y) = \exp(m_2 y) \quad (26)$$

where

$$T = \left(1 + \frac{1}{\beta}\right)^{-1}, m_2 = \frac{-Sc - \sqrt{Sc^2 + 4k_0 Sc}}{2},$$

$$m = \frac{-s - \sqrt{s^2 + 4sQ}}{2},$$

$$z = \frac{1}{K} + M, m_6 = \frac{-T - \sqrt{T^2 + 4Tz}}{2}, s = \frac{Pr}{1 + R}$$

$$A = \frac{TGr}{m^2 - Tm - Tz}, B = \frac{TGc}{m_2^2 - Tm_2 - Tz},$$

$$k_{11} = \frac{m_6^2 (A + B)^2}{4m_6^2 + 2sm_6 - sQ},$$

$$k_{12} = \frac{mA^2}{4m^2 + 2sm - sQ}, k_{13} = \frac{m_2 B^2}{4m_2^2 + 2sm_2 - sQ},$$

$$k_{14} = \frac{2(A + B)Am m_6}{m_6 - \alpha},$$

$$k_{15} = \frac{2ABmm_2}{(m + m_2)^2 + 2s(m + m_2) - sQ},$$

$$k_{16} = \frac{2m_2 m_6 (A + B)B}{(m_2 + m_6)^2 + 2s(m_2 + m_6) - sQ},$$

$$k_{17} = -k_{11} - k_{12} - k_{13} + k_{14} - k_{15} + k_{16}$$

$$k_{20} = \frac{k_{17}}{m^2 + Tm - Tz}, k_{21} = \frac{k_{11}}{4m_6^2 + 2Tm_6 - Tz},$$

$$k_{22} = \frac{k_{12}}{4m^2 + 2Tm - Tz}, k_{23} = \frac{k_{13}}{4m_2^2 + 2Tm_2 - Tz},$$

$$k_{24} = \frac{k_{14}}{(m_6 + m)^2 + T(m_6 + m) - Tz},$$

$$k_{25} = \frac{k_{15}}{(m_2 + m)^2 + T(m_2 + m) - Tz},$$

$$k_{26} = \frac{k_{16}}{(m_2 + m_6)^2 + T(m_2 + m_6) - Tz},$$

$$k_{27} = k_{20} + k_{21} + k_{22} + k_{23} - k_{24} + k_{25} - k_{26}$$

Skin friction, Sherwood Number along with Nusselt Number

$$\tau = \left[\frac{\partial u}{\partial y} \right]_{y=0} = (A + B)m_6 - Am - Bm_2 + Em_6 k_{27}$$

$$-EcGrT \left[\begin{array}{l} k_{20}m + 2k_{21}m_6 + 2k_{22}m + \\ 2k_{23}m_2 - k_{24}(m_6 + m) + \\ k_{25}(m_2 + m) - k_{26}(m_2 + m_6) \end{array} \right]$$

$$Nu = - \left[\frac{\partial \theta}{\partial y} \right]_{y=0}$$

$$= -m - Ec \left[\begin{array}{l} k_{17}m + 2k_{11}m_6 + 2k_{12}m + 2k_{13}m_2 - \\ k_{14}(m_6 + m) + k_{15}(m_2 + m) - \\ k_{16}(m_2 + m_6) \end{array} \right]$$

$$Sh = - \left(\frac{\partial C}{\partial y} \right)_{y=0} = -m_2$$

Results and Discussion

The results and discussion has been carried out to bring out the effects of pertinent parameters affecting the momentum, heat and mass transport of Casson fluid in an unbounded flow domain. Table 1 shows the comparative study of previous work reported in the literature with that of the present work. It is found that both the results are in good agreement.

Table 1. Comparison of $-\theta'(0)$ for different values of Pr when $K = R = Q = 0, \beta \rightarrow \infty$ (Newtonian fluid)

Pr	Biswal <i>et al.</i> (2023)	Present study
2	0.911382	0.911536
7	1.895431	1.895754
20	3.353937	3.354239
70	6.461928	6.462158

Figure 2 represents the velocity profile for various values of magnetic parameter keeping other parameter constant as mentioned in the figure. It is observed that velocity decreases with increase in

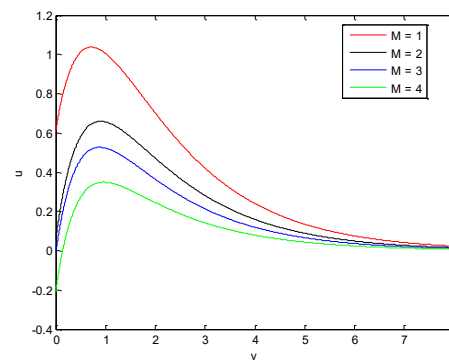


Figure 2. Velocity profiles versus M when $Pr = 0.71$, $E = 0.05$, $ko = 1$, $R = 0.1$, $Sc = 0.22$, $Q = Gc = Gr = 5$

magnetic parameter due to resistive Lorentz force. Further, it is seen that boundary layer thickness decreases resulting momentum transport confined within the few layers adjacent to the bounding surface.

Figure 3 shows the effect of Grashof number on velocity variation. For positive values of Grashof number ($Gr > 0$) which implies the heating of the fluid and cooling of the plate. This is otherwise known as buoyancy assisting force. The velocity increases for $Gr > 0$ whereas for $Gr < 0$ (buoyancy resisting), the velocity decreases. On careful observation it is seen that the fluid flow attains the ambient state or potential flow condition earlier than the magnetic field.

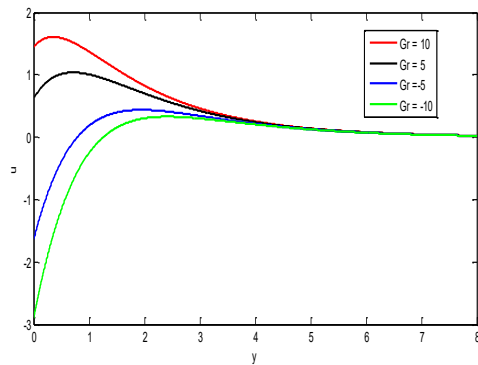


Figure 3. Velocity profiles versus Gr when $Pr = 0.71$, $E = 0.05$, $ko = 1$, $M = 1$, $Q = 5$, $R = 0.1$, $Sc = 0.22$, $Gc = 5$

Figure 4 shows the effect of Gc i.e. the counterpart of Gr (thermal buoyancy). The buoyancy effect of Gc on the fluid flow due to solutal concentration of the fluid mass, generates the buoyancy thrust. The striking difference is that

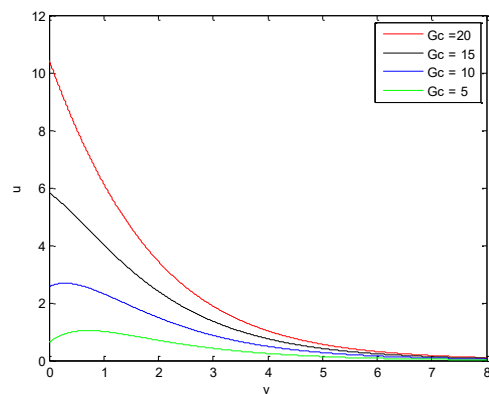


Figure 4. Velocity profiles versus Gc when $Pr = 0.71$, $Ec = 0.05$, $ko = 1$, $R = 0.0$, $Sc = 0.22$, $Gr = 5$

the velocity runs down in the neighborhood of the bounding surface for solutal Grashof number Gc whereas in case of Gr it increases in the neighborhood of the plate.

Figure 5 depicts the effect of Eckert number (Ec) which measures the thermal dissipation resulting an increase in velocity near the plate.

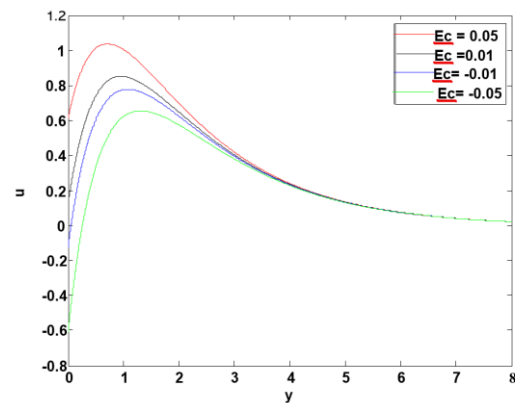


Figure 5. Velocity profiles versus Ec when $Pr = 0.71$, $ko = 1$, $M = 1$, $Q = 5$, $R = 0.1$, $Gr = Gc = 5$, $Sc = 0.22$

Figure 6 shows the effect of various values of Pr on velocity distribution. Higher the values of Pr lower down the velocity because higher values of Pr indicates the low thermal conductivity. Hence, the momentum transport decreases, so that the velocity distribution decreases.

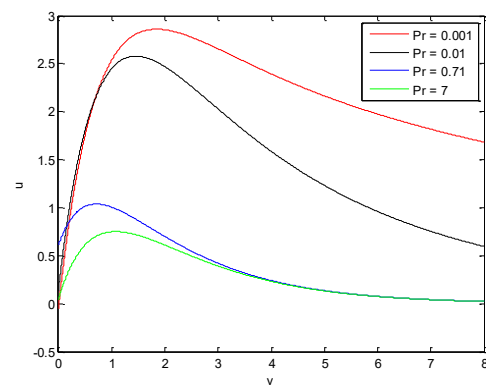


Figure 6. Velocity profiles versus Pr when $E = 0.05$, $Q = 5$, $M = 1$, $ko = 1$, $Sc = 0.22$, $R = 0.1$, $Gr = Gc = 5$

Figure 7 shows the effect of Schmidt number (Sc) on velocity profile. Higher values of Schmidt number decreases the velocity as the increase in Sc relates to heavier diffusing species. A peculiarity is

marked in the neighborhood layers of the bounding surface. It is to note that the velocity shoots up to high value near the neighborhood layer when $Sc = 0.22$.

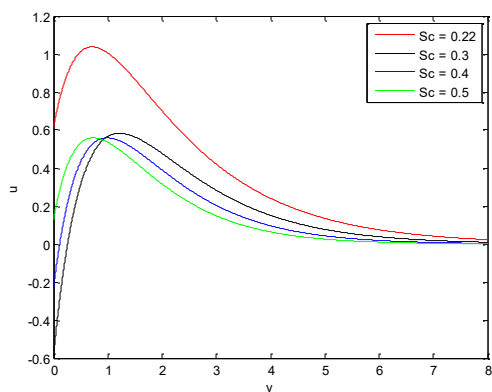


Figure 7. Velocity profiles versus Sc when $Pr = 0.71$, $M = 1$, $E = 0.05$, $ko = 1$, $R = 0.1$, $Gc = Gr = 5$

Figure 8 shows that as the porosity of the medium increases, the velocity increases. Particularly for $K = 1.2$ and $Sc = 0.22$, the velocity increases significantly near the plate.

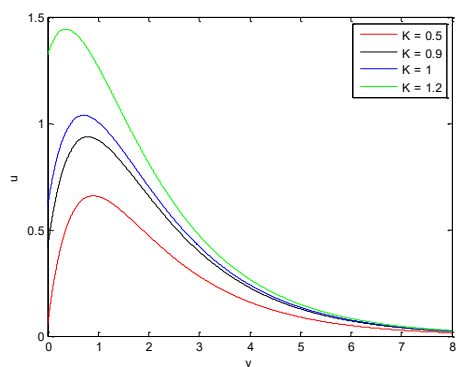


Figure 8. Velocity profiles versus K when $Pr = 0.71$, $Ec = 0.05$, $R = 0.1$, $ko = 1$, $M = 1$, $Gc = Gr = 5$, $Sc = 0.22$

Figure 9 depicts the effect of chemical reaction on velocity. It is seen that for generative reaction ($ko < 0$), the velocity increases and for destructive reaction ($ko > 0$), the velocity decreases.

Figure 10 shows that the increase in radiation parameter (R) leads to a fall in magnitude of the velocity in the present analysis.

Figure 11 shows the effect of Casson fluid parameter (β) contributing to a non-Newtonian fluidity i.e. increase in value of Casson parameter ($\beta \rightarrow \infty$, Newtonian fluid) increases the velocity in the

bounding layers because the nonlinear sheared flow gathers less momentum than the Newtonian counterpart.

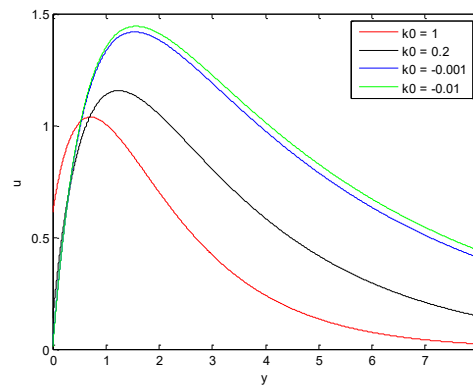


Figure 9. Velocity profiles versus ko when $Pr = 0.71$, $E = 0.05$, $Q = 5$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gr = Gc = 5$

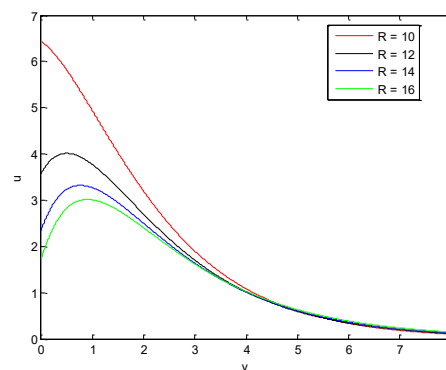


Figure 10. Velocity profiles versus R when $Pr = 0.71$, $E = 0.05$, $ko = 1$, $M = 1$, $Sc = 0.22$, $Q = Gr = Gc = 5$

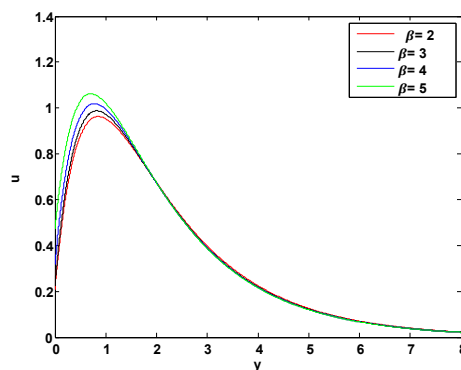


Figure 11. Velocity profiles versus β when $Pr = 0.71$, $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

From Figure 12 it is seen that the increase in the value of heat source ($Q > 0$) decreases the velocity of the fluid because in the equation (3), the last term is having a negative sign.

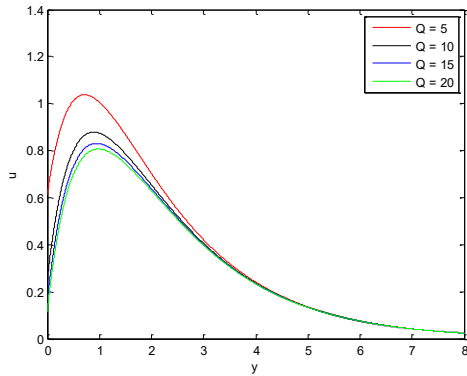


Figure 12. Velocity profiles versus Q when $Pr = 0.71$, $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

From Figure 13 it is observed that an increase in Grashof number ($Gr > 0$) increases the temperature. This indicates heating of the plate (buoyancy assisting) whereas when $Gr < 0$ implies the reverse process i.e. buoyancy opposing. Hence, as $|Gr|$ increases, the temperature increases.

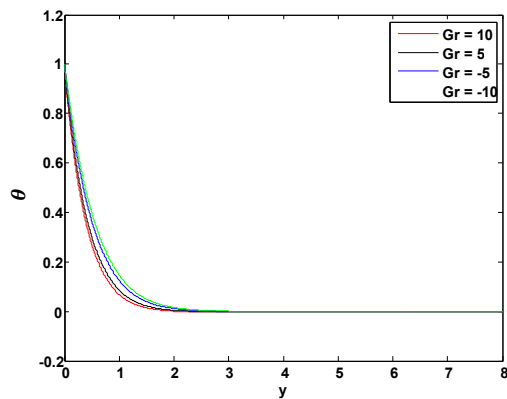


Figure 13. Temperature profiles versus Gr when $Pr = 0.71$, $Q = 5$, $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gc = 5$

Figure 14 is devoted to solutal Grashof number (Gc). It is interesting to note that the effect of Gc on temperature distribution is opposite to that of Gr i.e. for $Gc > 0$; as Gc increases, the temperature decreases and for $Gc < 0$, as $|Gc|$ increases temperature also decreases. The following reason may attributed for this reverse affect. From the high values of Gc it is evident that the heavier diffusing

species are the diffusing medium is liquid. So that Gc takes such high values resulting absorbing the thermal energy leading to lower down the temperature in the flow domain. For air medium: $0.2 < Sc < 2.0$.

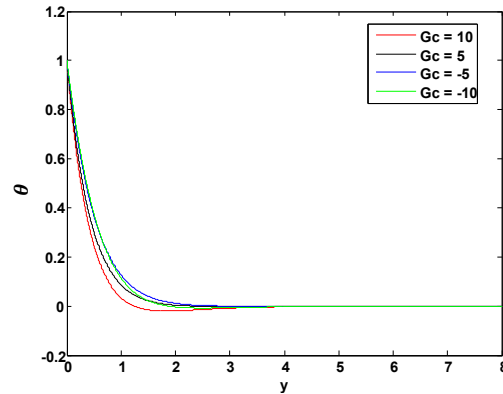


Figure 14. Temperature profiles versus Gc when $Pr = 0.71$, $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gr = 5$

From Figure 15 it is seen that as Pr increases, the temperature decreases as higher Pr indicates lower thermal conductivity.

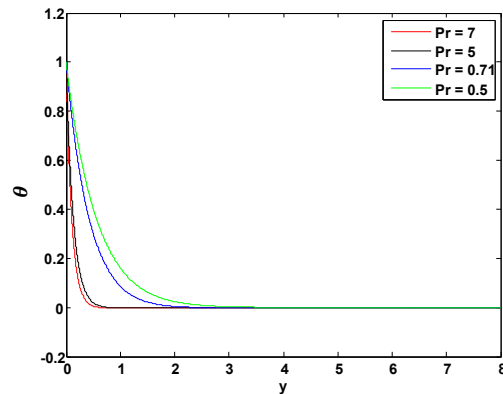


Figure 15. Temperature profiles versus Pr when $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

From Figure 16 it is concluded that for higher rate of destructive reaction ($ko > 0$) the temperature increases. On careful observation it is seen that when $ko = 0$ the temperature increases significantly. Thus, rate of chemical reaction to be regulated to avoid higher temperature of the fluid.

From Figure 17 it is seen that as the thermal radiation increases, temperature of the medium decreases. It is trivially true.

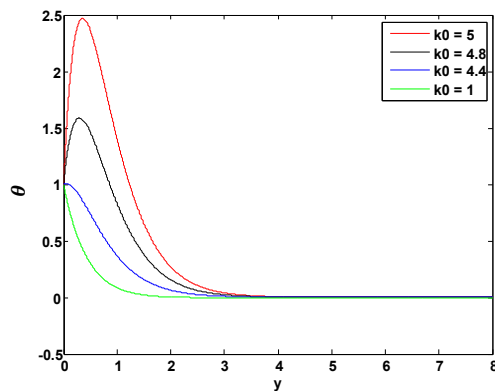


Figure 16. Temperature profiles versus k_0 when $Pr = 0.71$, $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Q = Gc = Gr = 5$

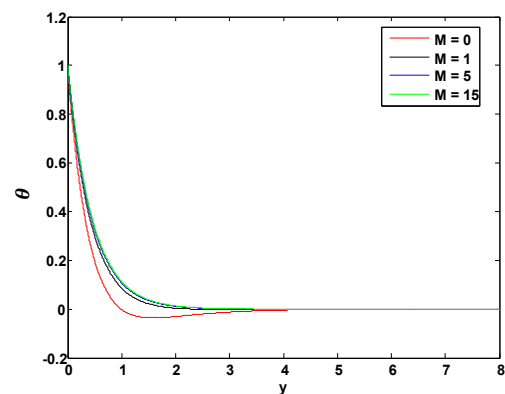


Figure 18. Temperature profiles versus M when $Pr = 0.71$, $Q = 5$, $Ec = 0.05$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

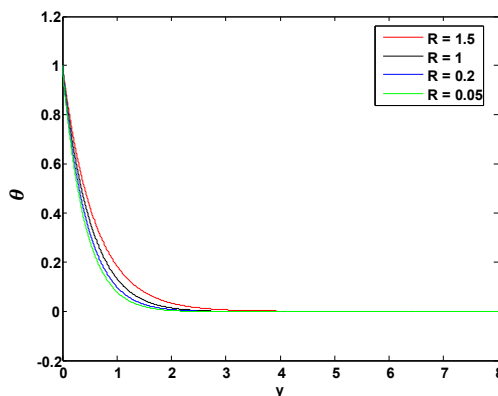


Figure 17. Temperature profiles versus R when $Pr = 0.71$, $Q = 5$, $Ec = 0.05$, $M = 1$, $Sc = 0.22$, $Gc = Gr = 5$

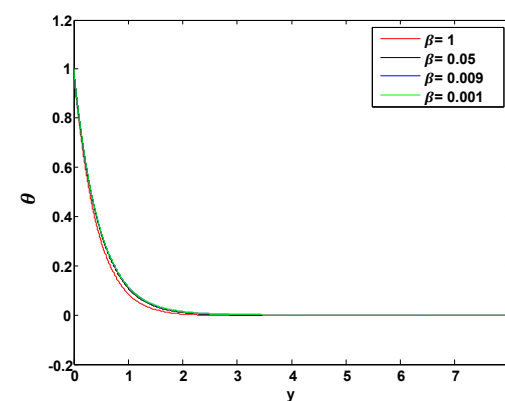


Figure 19. Temperature profiles versus β when $Pr = 0.71$, $Ec = 0.05$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

From Figure 18 it is seen that as magnetic field intensity increases (generating higher resistive Lorentz force), the temperature also increases as the resistive force increases opposing the momentum transport resulting higher temperature.

Figure 19 shows that as important parameter of the Casson fluid model (β) increases, temperature of the fluid flow decreases slightly. The interesting outcome of the present problem is that as $\beta \rightarrow \infty$ the model represents Newtonian viscous fluid, a thinner liquid than Casson fluid, hence the thermal energy propagates slowly resulting a decrease in temperature.

Figure 20 shows a fall in temperature for higher heat source (heat source measures the thermal power per unit volume) strength. This is due to a negative sign in the source term Equation (3). Otherwise increase in volumetric heat source contributes to higher temperature.

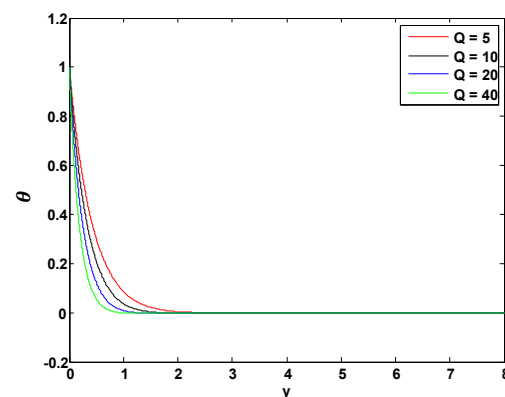


Figure 20. Temperature profiles versus Q when $Pr = 0.71$, $Ec = 0.05$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

Eckert number (Ec) drops down the solutal concentration (Figure 21). The Eckert number is a measure of dissipation effects in the flow. Hence, higher the thermal dissipation, lowers the concentration in the fluid flow.

From Figure 22 it is inferred that for higher values of chemical reaction parameter quickens attainment of ambient state. In other words, the solutal concentration decreases with higher chemical reaction parameter.

The bounding surface conditions play a very important role for momentum transport and thermal/solutal energy transfer in the fluid flow. Hence, inference can be drawn whether the model acts as heat and mass exchange (act as coolant/heating device) of the fluid or the plate.

Table 2 shows that an increase in Gr , M , Ec , and β decreases the skin friction whereas Gc , Sc , K and R increases the skin friction (in case of Gc and Sc relates to $|Sf|$ as negative values appear). Further, the table shows that Nusselt number decreases for an increase in Gr , M , Gc , Ec , K and R and increases for Sc and β . Increase in magnetic parameter (M) from 1 to 3 gives rise to decrease in heat flux 4.3% at the bounding surface. The physical interpretation runs as: The increase in skin friction indicates progressive thinning of boundary layer reversely, the decrease leads to thickening of boundary layer; not a desirable outcome. The values of the parameters may be assigned as per the design requirement. Nusselt number bears positive sign throughout for variation of all the parameters. This means heat flows from plate to fluid. That produces destabilizing effect. The care should be taken to control or regulate the values of the parameters for thermal stability of the flow.

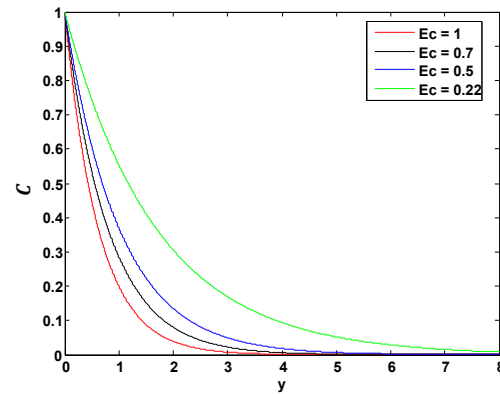


Figure 21. Concentration profiles versus Ec when $Pr = 0.71$, $R = 0.1$, $Sc = 0.22$, $Gc = Gr = 5$

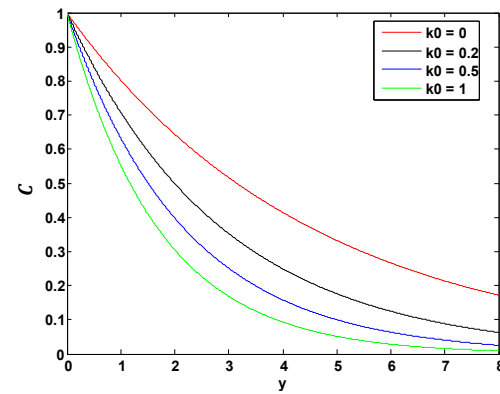


Figure 22. Concentration profiles versus k_0 when $Pr = 0.71$, $Ec = 0.05$, $M = 1$, $R = 0.1$, $Sc = 0.22$, $Gc = 5$

Table 2. Variation of skin friction and Nusselt number when $Pr = 0.71$

M	Gr	Gc	Ec	Sc	K	k_0	R	β	Sf	Nu
5	5	5	0.05	0.22	1	1	1	1	-4.8448	2.0468
3	5	5	0.05	0.22	1	1	1	1	-1.7193	2.0823
1	-5	5	0.05	0.22	1	1	1	1	5.3442	2.1760
1	5	5	0.05	0.22	1	1	1	1	-0.2441	2.0460
1	5	15	0.05	0.22	1	1	1	1	-4.8784	1.8827
1	5	10	0.05	0.22	1	1	1	1	-1.4948	1.9685
1	5	5	-0.05	0.22	1	1	1	1	1.4542	2.2499
1	5	5	0.05	0.22	1	1	1	1	-0.2441	2.0460
1	5	5	0.05	0.22	1	1	1	1	8.9426	0.2839
1	5	5	0.05	0.22	1	1	1	1	-0.2441	2.0460
1	5	5	0.05	0.6	1	1	1	1	-20.8142	7.5085
1	5	5	0.05	0.5	1	1	1	1	-2.3526	2.5573
1	5	5	0.05	0.22	1	1	1	1	-0.2441	2.0460
1	5	5	0.05	0.22	1.5	1	1	1	-7.9616	2.0096
1	5	5	0.05	0.22	1	0.5	1	1	0.8675	1.9038
1	5	5	0.05	0.22	1	0.2	1	1	0.7607	2.3505
1	5	5	0.05	0.22	1	1	10	1	11.7921	0.1480
1	5	5	0.05	0.22	1	1	12	1	11.7884	0.1480
1	5	5	0.05	0.22	1	1	1	0.5	0.8020	1.9985
1	5	5	0.05	0.22	1	1	1	1	-0.2441	2.0460

Conclusions

- The buoyancy force quickens to attain the ambient state earlier than the magnetic field.
- Low values of Schmidt number velocity shoots up to high value near the neighborhood layer when $Sc = 0.22$.
- For generative reaction ($ko < 0$), the velocity increases and for destructive reaction ($ko > 0$), the velocity decreases.
- Increase in value of Casson parameter ($\beta \rightarrow \infty$, Newtonian fluid) increases the velocity in the bounding layers because the nonlinear sheared flow gathers less momentum than the Newtonian counterpart.
- The increase in skin friction indicates progressive thinning of boundary layer reversely, the decrease leads to thickening of boundary layer; not a desirable outcome.
- Nusselt number bears positive sign implies that heat flows from plate to fluid. That produces destabilizing effect. The care should be taken to control or regulate the values of the parameters for thermal stability of the flow.

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