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Effect of thermophoresis, thermal radiation and heat generation on the Casson fluid flow over an exponentially stretching surface

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ABSTRACT

Thermophoresis and radiative heat transfer on the unsteady boundary layer flow of a Casson fluid past an exponentially porous stretching sheet under the influence of a magnetic field in the presence of heat source/sink and chemical reaction is analysed. The governing partial differential equations of the flow are transformed into non-linear ordinary differential equations using similarity variables which are then solved numerically employing shooting technique along with Runge-Kutta iterative scheme. The graphical results reveal that the suction and magnetic field decelerate the velocity while the Casson parameter shows an opposite trend. The thermal boundary layer thickness is increased by the Casson parameter and heat source parameter. The rate of heat transfer is enhanced by thermal radiation parameter. The thermophoresis parameter along with Schmidt number is found to reduce the concentration predominantly.

Introduction

Recently the boundary layer flows of non-Newtonian fluids induced by stretching surfaces attracted the attention of researchers due to their wide range of applications in engineering and industry. For example, in the process of extrusion, application of paints, wire drawing, metal spinning, hot rolling etc. Following the initial study of Sakiadis [1] several researchers studied various aspects of the heat and mass transfer and flow involving stretching surface. Investigations on aerosol deposition gained significance owing to their applications in engineering and aerosol technology. For example, the deposition of the contaminant particle deposition on the gadgets in the electronic industry assumes a vital role to maintain its quality. Also thermophoresis is important in the transport of micro particles owing to a temperature gradient in the surrounding fluid which exerts a net force on the particle as a result of the imbalance in the forces that occur due to molecular collisions from hotter and colder regions and the direction of the force is towards the colder region. This process is mostly found with aero colloidal particles than with colloidal particles.

Thermophoresis is found to be one of the important mechanisms of mass transfer in the process of modified chemical vapor deposition. Also the thermophoretic deposition of the radioactive particles is observed to be one of the reasons for the accidents to occur in nuclear reactors. The principle of thermophoresis is employed in the manufacturing of graded index silicon dioxide and germanium dioxide optical fiber. Goldsmith and May [2] appear to be the first researchers to investigate on thermophoretic transport in a one-dimensional flow to measure the thermophoretic velocity. Following this initial study several researchers studied the effect of thermophoresis in different directions [3–8].

However, studies of thermophoresis on non-Newtonian fluid flows in literature are limited. The studies considering the non-Newtonian fluids involving thermophoresis have abundant applications in industry as majority of industrial fluids are non-Newtonian. Hayat and Qasim [9] analysed the heat and mass characteristics of the Maxwell fluid induced by a stretching surface under the influence of a magnetic field in the presence of thermophoresis and thermal radiation. Their graphical solutions reveal that the effect of thermophoretic parameter on temperature and mass transfer is to enhance. Stanford Shateyi et al. [10] made a study of the MHD flow of a Maxwell fluid past a vertical stretching sheet in the presence of thermophoresis and chemical reaction with first order chemical reaction and thermal radiation. Shehzad et al. [11] analysed the impact of thermophoresis on the radiative flow of a Jeffrey fluid over a linearly stretching surface considering joule heating. The works dealing with thermophoresis in Casson fluid are very limited. Animasaun [12] made an analysis of a Casson fluid flow past porous vertical plate subject to a magnetic field in the presence of viscous dissipation, nth order chemical reaction and thermophoresis treating the thermal conductivity and viscosity of the Casson fluid as a linear function of temperature.

To the best of the knowledge of the authors no study is available in literature to understand the effect of thermophoresis on the Casson fluid flow past an exponentially stretching surface. Hence, in this paper we made an attempt to analyse influence of thermophoresis, temperature dependent heat source on the unsteady boundary layer flow heat and mass transfer of a Casson fluid over an exponentially stretching sheet with first order chemical reaction.

Mathematical Formulation

Consider the flow of an incompressible viscous fluid past a flat sheet which coincides with the plane y = 0. The fluid flow is confined to $y > 0$. Application of two equal and opposite forces along the x-axis leads to the stretching of wall, keeping the

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origin fixed. The constitutive equation of a Casson fluid is as follows:

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + P_y/\sqrt{2\pi}\right)e_{ij}, \pi > \pi_c \\ 2\left(\mu_B + P_y/\sqrt{2\pi_c}\right)e_{ij}, \pi < \pi_c \end{cases}$$

Here, $\pi = e_{ij}e_{ij}$ and e_{ij} are the (i, j)th component of the deformation rate, π is the product of the component of deformation rate with itself, π_c is a critical value of this product based on the non-Newtonian model, μ_B is plastic dynamic viscosity of the non-Newtonian fluid and P_y is the yield stress of the fluid. The stretching surface is assumed to have the

Here, $\pi = e_{ij}e_{ij}$ and e_{ij} are the (i, j)th component of the deformation rate, π is the product of the component of deformation rate with itself, π_c is a critical value of this product based on the non-Newtonian model, μ_B is plastic dynamic viscosity of the non-Newtonian fluid and P_y is the yield stress of the fluid. The stretching surface is assumed to have the velocity $U_w(x,t) = \frac{U_0}{(1-\alpha t)} e^{x/L}$, the temperature distribution $T_w(x,t) = T_\infty + \frac{T_0}{(1-\alpha t)^2} e^{x/2L}$ and the concentration distribution $C_w(x,t) = C_\infty + \frac{C_0}{(1-\alpha t)^2} e^{x/2L}$ where U_0 is the reference velocity, α is a positive constant with dimension reciprocal time, L is the reference length, t is the time, T_∞ is the fluid temperature far away from the stretching surface , T_0 is the fluid temperature adjacent to the stretching surface, C_∞ is the fluid concentration far away from the stretching surface and C_0 is the fluid concentration adjacent to the stretching surface. A uniform magnetic field of strength B is applied normal to the stretching surface which induces the magnetic effect in the direction of x-axis. The effect of the induced magnetic field is negligible by considering magnetic Reynolds number as small. The continuity, momentum, energy and concentration equations governing such type of flow invoking the Boussinesq's approximation can be written as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\left(1+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} + g\beta_T(T - T_\infty) + g\beta_C(C - C_\infty) - \frac{\sigma B^2}{\rho}u \quad (2)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{K}{\rho c_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} + \frac{Q_0}{\rho c_p}(T - T_\infty) \quad (3)$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - k(C - C_\infty) - \frac{\partial}{\partial y}(V_T C) \quad (4)$$

The boundary conditions are

u = U_w(x, t), v = $-V_w$(x, t), w = 0, T = T_w(x, t), C = C_w(x, t)

at y = 0,

u $\rightarrow$ 0, w $\rightarrow$ 0, T $\rightarrow$ T_∞, C $\rightarrow$ C_∞ as y $\rightarrow \infty$ (5)

The radiation heat flux by using Rosseland approximation can be written as

$$q_r = -\frac{4\sigma^*}{3K^*}\frac{\partial T^4}{\partial y} \quad (6)$$

Where σ^* is the Stefen-Boltzman constant and K^* is the absorption coefficient

If assuming that the temperature differences within the flow are sufficiently small so that T^4 could be approached as the linear function of temperature and hence we obtain

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \quad (7)$$

Substituting equation (6) into equation (3) results in

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{\rho c_p}\left[\left(K + \frac{16\sigma^* T_\infty^3}{3k^*}\right)\frac{\partial^2 T}{\partial y^2} + Q_0(T - T_\infty)\right] \quad (8)$$

where u, v are the fluid velocity components along x and y axes respectively, ν is the kinematic viscosity, g is the gravity field , β_T is the volumetric coefficient of thermal expansion, β_C is the coefficient of expansion with concentration, ρ is the density of the fluid, $\beta = \mu_B\sqrt{2\pi_c}/P_y$ is parameter of the Casson fluid, T is the fluid temperature, C is the fluid concentration, σ is the electrical conductivity, c_p is the specific heat at constant pressure, K is the thermal conductivity of the medium, q_r is the radiation heat flux, Q_0 is the uniform volumetric heat generation and absorption, D is the mass diffusivity, k is the chemical reaction, $V_w(x,t) = fw(U_0\nu/2L(1-\alpha t))^{1/2}e^{x/2L}$ is the velocity of suction $(V_w > 0)$, $fw \geq 0$ is the suction parameter and V_T is the thermophoresis velocity, following Talbot et al. [3] given by

$$V_T = \frac{k\nu}{T_{ref}}\frac{\partial T}{\partial y}$$

where T_{ref} is some reference temperature, the value of $k\nu$ represents the thermophoretic diffusivity.

We introduce the stream function $\psi(x,y)$ such that $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$.

The governing partial differential equations (2), (4) and (8) can be reduced to a set of ordinary differential equations on introducing the following similarity variables:

$$\eta = \sqrt{U_0/2\nu L(1-\alpha t)}\, e^{x/2L}\ w = U_0(1-\alpha t)^{-1} e^{x/L} h(\eta), \quad (9)$$

$$\psi(x,y) = \sqrt{2U_0\nu L/(1-\alpha t)}\, e^{x/2L} f(\eta), \quad (10)$$

$$T = T_\infty + T_0(1-\alpha t)^{-2} e^{x/2L}\,\theta(\eta), \tag{11}$$
$$C = C_\infty + C_0(1-\alpha t)^{-2} e^{x/2L}\,\phi(\eta), \tag{12}$$
$$B^2 = B_0^2(1-\alpha t)^{-1} \tag{13}$$
where B_0 is the magnetic field flux density.

Using (9) to (13) in equations (2), (4) and (8) we obtain the following set of ordinary differential equations:

$$\left(1+\frac{1}{\beta}\right) f''' + ff'' - 2f'^2 - e^{-X}\left(A(2f' + \eta f'') + 2Mf' - 2e^{-X/2}(G_r\theta + G_c\phi)\right) = 0 \tag{14}$$
$$\theta''\left(1+\frac{4}{3}Nr\right) + Pr\left(f\theta' - f'\theta - e^{-X}\left(A(4\theta + \eta\theta')\right) + \delta\theta\right) = 0 \tag{15}$$
$$\phi'' + Sc\left(f\phi' - f'\phi - \tau(\theta'\phi' + \theta''\phi) - e^{-X}\left(A(4\phi + \eta\theta')\right) - \gamma\phi\right) = 0 \tag{16}$$
The corresponding boundary conditions are
$$\eta = 0:\ f = fw,\ f' = 1,\ \theta = 1,\ \phi = 1, \tag{17}$$
$$\eta \to \infty:\ f' \to 0,\ \theta \to 0,\ \phi \to 0, \tag{18}$$
Where the primes denote the differentiation with respect to η, $X = x/L$ is the dimensionless coordinate, $A = \alpha L/U_0$ is the unsteadiness parameter, $M = \sigma B_0^2 L/U_0\rho$ is magnetic parameter, $Gr = g\beta_T T_0 L/U_0^2$ is the Grashof number, $Gc = g\beta_c C_0 L/U_0^2$ is the solutal Grashof number, $Pr = \rho c_p \nu/k$ is the Prandtl number, $Nr = 4\sigma^* T_\infty^3/Kk^*$ is the thermal radiation parameter, $Sc = \nu/D$ is the Schmidt number, $\tau = -k\nu(T_w - T_\infty)/T_{ref}$ is the thermophoretic parameter, $\gamma = 2kL/U_w$ is the chemical reaction parameter, $\delta = 2Q_0 L/U_w \rho c_p$ is the heat source/sink parameter.

The physical quantities having engineering applications in this problem are the skin friction coefficient C_f and the local Nusselt number Nu_x and local Sherwood number Sh_x indicating physically the wall shear stress, the rate of heat transfer and the local surface mass flux respectively. From the following definitions

$$\tau_w = \left(\mu_B + \frac{P_y}{\sqrt{2\pi}}\right)\left(\frac{\partial u}{\partial y}\right)_{y=0}$$
$$q_w = -k\left(\frac{\partial T}{\partial y}\right)_{y=0}$$
$$M_w = -D_m\left(\frac{\partial C}{\partial y}\right)_{y=0} \tag{19}$$
The dimensionless local wall shear stress, local surface heat flux and the local surface mass flux for an impulsively started plate are respectively obtained as
$$C_f = \tau_w/\rho\, U_w{}^2,\ Nu_x = q_w x/k(T_w - T_\infty),$$
$$Sh_x = M_w x/D_m(C_w - C_\infty) \tag{20}$$
$$C_f\sqrt{Re_x} = \left(1+\frac{1}{\beta}\right) f''(0)\text{'}\ Nu_x/\sqrt{Re_x} = -\theta'(0)\text{'}\ Sh_x/\sqrt{Re_x} = -\phi'(0) \tag{21}$$
where

$\mu = k/\rho c_p$ is the dynamic viscosity of the fluid and

$Re_x = x\,U_w/\nu$ is Reynolds number.

Results and Discussion

The present analysis is focussed to understand the effects of thermophoresis and chemical reaction on the unsteady flow of a Casson incompressible fluid past an exponentially stretching sheet in the presence of temperature dependent heat source and thermal radiation. The governing equations of the flow are solved by employing the Runge-Kutta fourth order method along with the shooting technique. The accuracy of the numerical scheme is ensured by comparing the present results with those of Magyari and Keller [13], Bidin and Nazar [14], El-Aziz [15], Ishak [16] and Pramanik [17] in the absence of thermophoresis, magnetic field, thermal and solutal buoyancy, heat generation/absorption and suction for a steady flow i.e. τ = X = A = Gr = Gc = δ = M = Nr = fw = φ = 0. The compared values of –θ'(0) are presented in Table which is found to be in good agreement with them.

Table 1. Values of $[-\theta'(0)]$ for several values of Prandtl number for Newtonian fluid.

Pr	Magyari and Keller [13]	Bidin and Nazar [14]	El-Aziz [15]	Ishak [16]	Pramanik [17]	Present Results with Nr=0, fw=0
1	0.9548	0.9547	0.9548	0.9548	0.9547	0.9549
2		1.4714		1.4715	1.4714	1.4714
3	1.8691	1.8691	1.8691	1.8691	1.8691	1.8691
5	2.5001		2.5001	2.5001	2.5001	2.5001
10	3.6604		3.6604	3.6604	3.6603	3.6603

In order to analyze the effects of thermophoresis, thermal buoyancy force, solutal buoyancy force, chemical reaction, heat source/absorption, thermal radiation and unsteadiness on the flow-field, the computational values of the velocity of the fluid in the boundary layer region, temperature distribution and mass concentration are presented graphically for various values of Casson parameter β, magnetic parameter M, thermophoretic parameter γ suction parameter fw, thermal Grashof number Gr, solutal Grashof number Gc, Prandtl number Pr, heat source parameter δ, unsteady parameter A, thermal radiation parameter Nr, chemical reaction parameter γ and Schmidt number Sc.

Fig. 1 reveals that the velocity decreases throughout the boundary layer region with increasing values of the Casson parameter. The boundary layers become thinner with increasing values of β. Similar behaviour is observed by Animasaun [12] also. In the presence of suction the reduction is more as expected. Figs. 2 and 3 indicate that the temperature and concentration increase with increasing values of Casson parameter. The thickness of the thermal and solutal boundary layers increase with Casson parameter**.** In the presence of suction the enhancement in temperature and concentration is more pronounced.

From Fig. 4 it is evident that the velocity decreases throughout the boundary layer region with increasing values of magnetic field. The deceleration in the velocity is owing to the retarding action of the Lorentz force which arises due to the application of magnetic field and hence the thickness of the momentum boundary layer also decreases. Figs. 5 and 6 indicate that the temperature and concentration rise with increasing values of magnetic parameter and as a result the thermal and solutal boundary layers enlarge.

Figs. 7 – 9 illustrate the variation of velocity, temperature and concentration with unsteady parameter A in the presence of suction. It is seen that the velocity reduces throughout the boundary layer with increase in the unsteady parameter and the thickness of the associated hydrodynamic boundary layer decreases. Fig. 8 reveals that the temperature at a point falls significantly with increasing values of A and hence the thermal boundary layers shrink as time elapses. The rate of heat transfer is decreased with A. The species concentration at a point is seen to decrease with the unsteady parameter and the thickness of the solutal boundary layers decreases with increase in the unsteady parameter. It may be observed that the rate of mass transfer is decreased with A.

Figs. 10 and 11 depict the effect of thermal and solutal buoyancy forces on the velocity in the presence of suction. It is observed that the velocity is an increasing function of Gr and Gc. As Gr (Gc) amounts to the relative strength of thermal (solutal) buoyancy force to viscous force, both thermal and concentration buoyancy forces tend to accelerate the velocity throughout the boundary layer region.

Fig. 12 indicates that increasing values of Prandtl number decrease the temperature. The reduction in the thickness of the thermal boundary layer is justified for the reason that increasing values of Pr correspond to reduction in the thermal conductivity resulting in the fall of temperature. The influence of thermal radiation on temperature is depicted in Fig. 13. The temperature is enhanced for increasing values of Nr and thus resulting in thicker thermal boundary layers. From energy equation (15) we may infer that increasing values of thermal radiation facilitates increased thermal conduction treating

$$\mathbf{Pr}/(\mathbf{1}+\tfrac{4}{3}\mathbf{Nr})$$

as the effective Prandtl number.

From Fig. 14 the temperature is found to enhance in the presence of heat source. The heat source releases energy in the thermal boundary layer resulting in the rise of temperature. On increasing $\delta(>\mathbf{0}\ \ \textbf{heat source})$ the temperature further rises. In the case of heat absorption $\delta(<\mathbf{0}\ \textbf{heat sink})$ the temperature falls for decreasing values of $\delta(<\mathbf{0})$ owing to the absorption of energy in the thermal boundary layer.

Figs. 15 and 16 are the plots of velocity, temperature distributions showing the influence of suction/injection $\mathbf{f_w}$. It is observed that the velocity decreases with increasing suction parameter and the injection (blowing) accelerates the flow. The wall suction $(\mathbf{fw}>\mathbf{0})$ results in thinner boundary layers with a fall in the velocity. For blowing $(\mathbf{fw}<\mathbf{0})$ an opposite trend is noticed. $\mathbf{fw}=\mathbf{0}$ corresponds to the impermeable stretching surface. From Fig. 16 it is revealed that the temperature enhances with blowing and drops with increasing suction parameter. It is evident from Fig. 17 that mass concentration decreases with suction and enhances with blowing.

Fig. 18 shows the influence of thermophoresis parameter on mass concentration. It is evident that the concentration decreases as the thermophoresis parameter $\boldsymbol{\tau}$ increases owing to the smaller temperature differences between the wall temperature and the free stream. From Fig. 19 the species concentration is observed to reduce with increasing values of the Schmidt number throughout the region which is associated with thinner solutal boundary layers. Physically, the increase of Sc implies decrease of molecular diffusion D. Thus the mass diffusion leads to an enhancement in the species concentration.

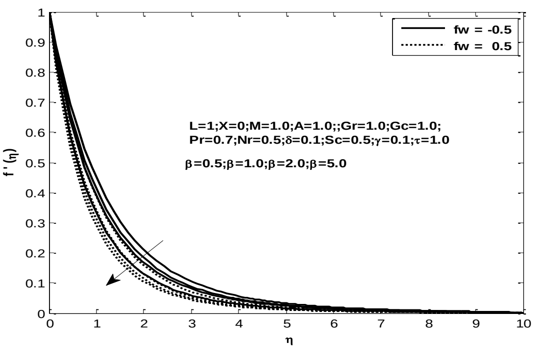

Figure 1. Velocity profiles for different Values of $\boldsymbol{\beta}$.

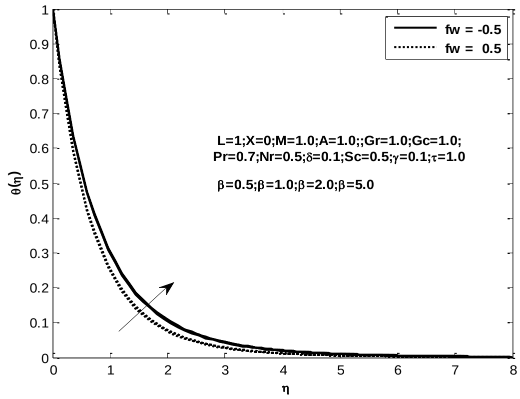

Figure 2. Temperature profiles for different values of β.

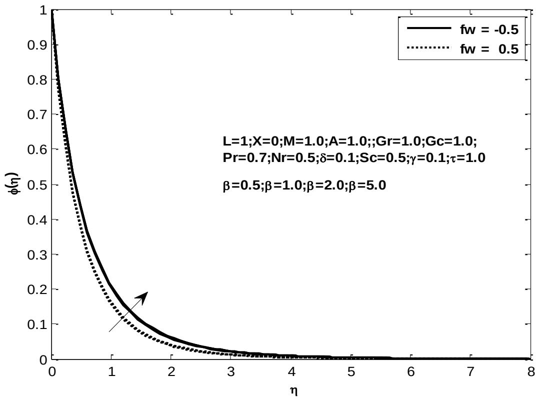

Figure 3. Concentration profiles for different values of β.

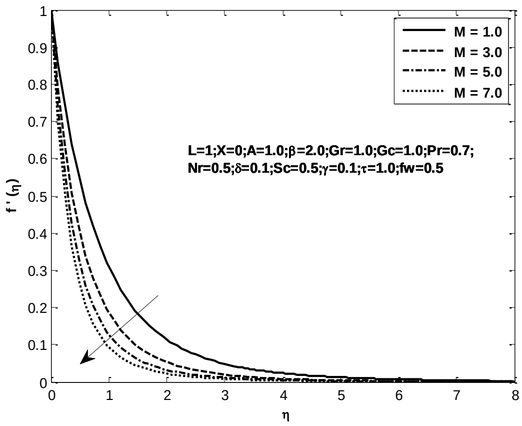

Figure 4. Velocity profiles for different Values of M.

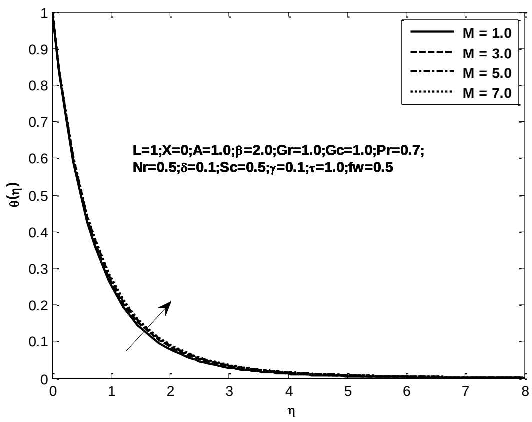

Figure 5. Temperature profiles for different values of M.

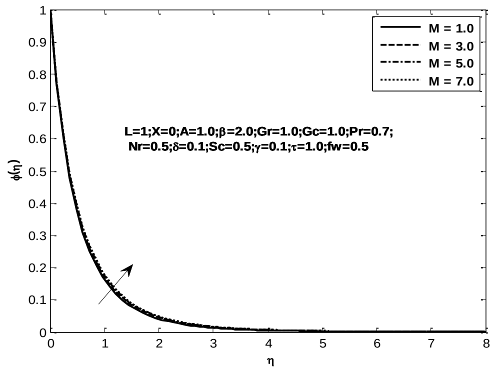

Figure 6. Concentration profiles for different values of M.

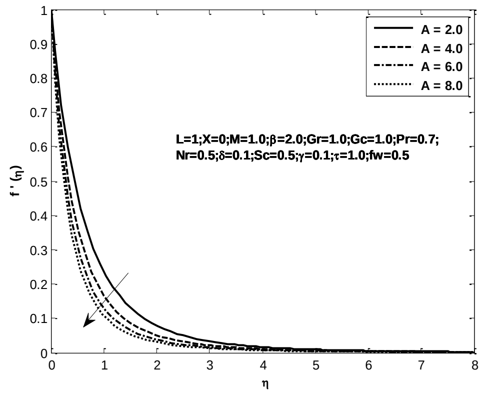

Figure 7. Velocity profiles for different values of A.

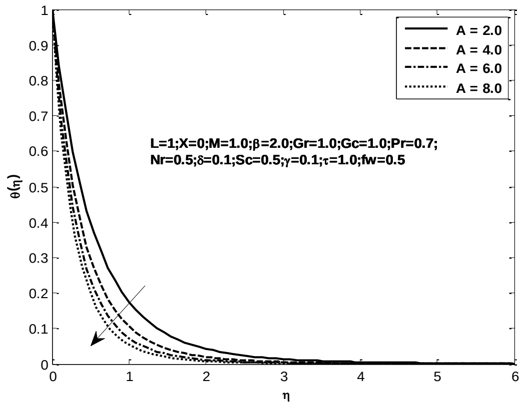

Figure 8. Temperature profiles for different values of A.

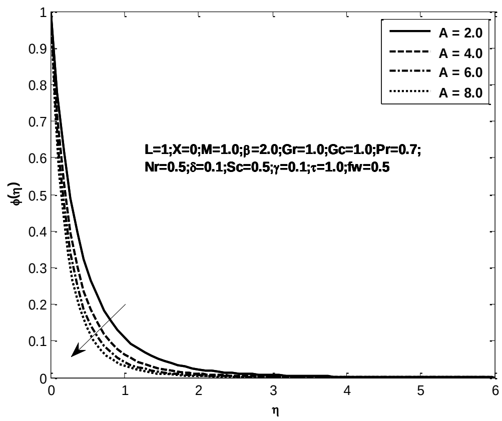

Figure 9. Concentration profiles for different values of A.

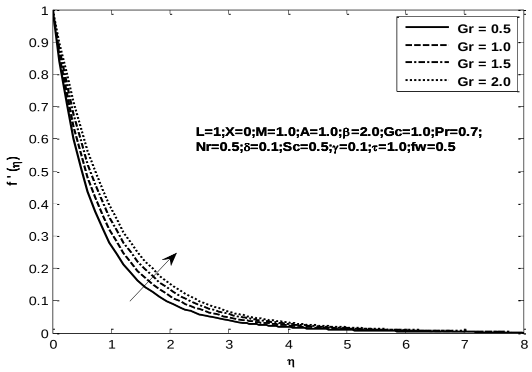

Figure 10. Velocity profiles for different values of Gr.

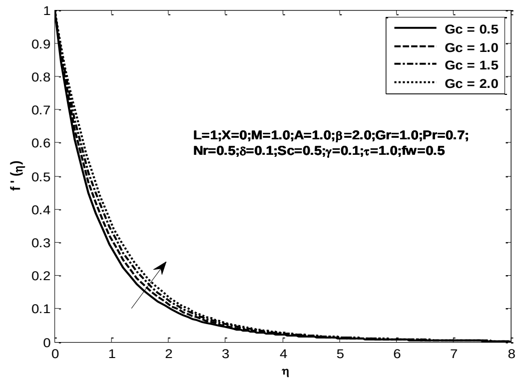

Figure 11. Velocity profiles for different values of Gc.

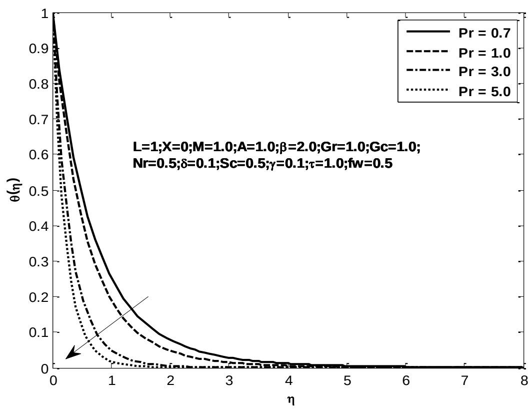

Figure 12. Temperature profiles for different values of Pr.

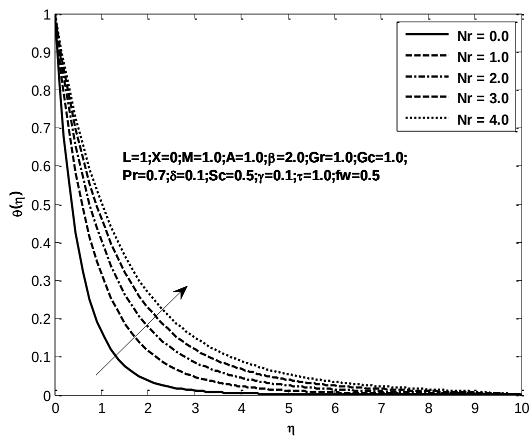

Figure 13. Temperature profiles for different values of Nr.

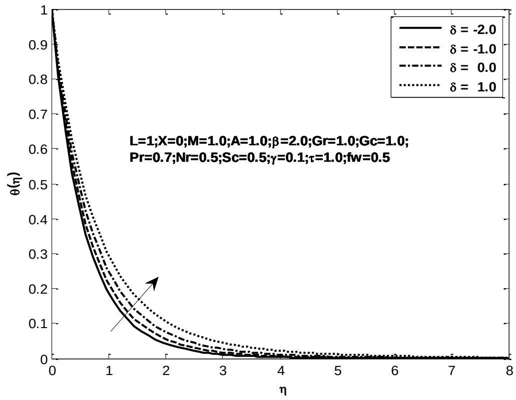

Figure 14. Temperature profiles for different values of δ.

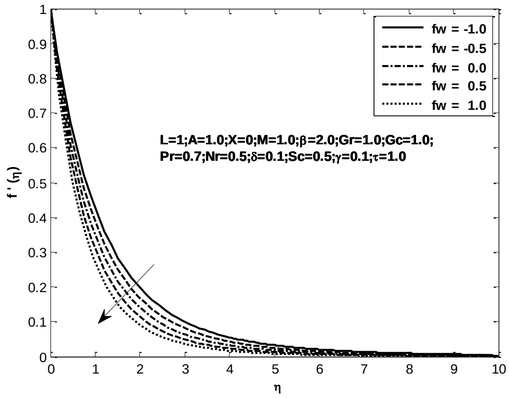

Figure 15. Velocity profiles for different values of fw.

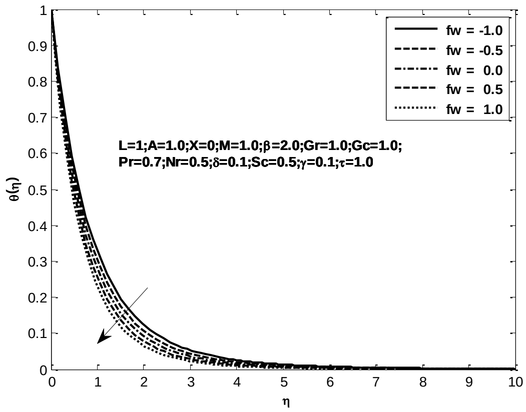

Figure 16. Temperature profiles for different values of fw.

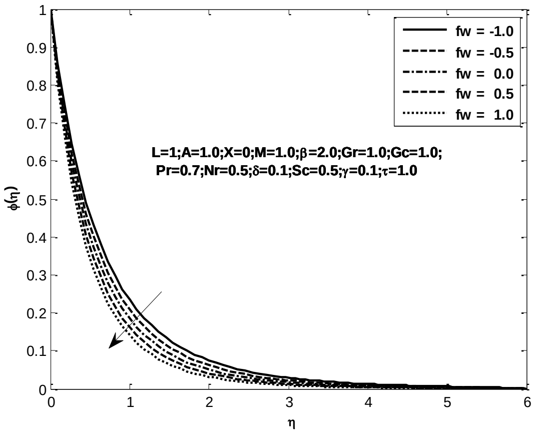

Figure 17. Concentration profiles for different values of fw.

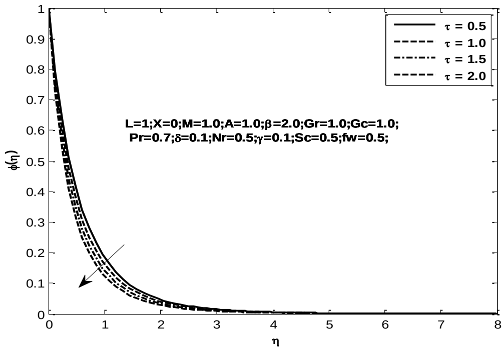

Figure 18. Concentration profiles for different values of τ.

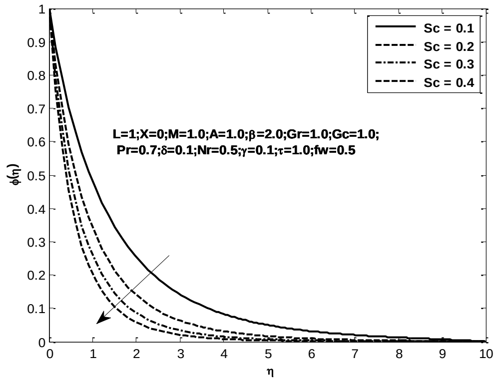

Figure 19. Concentration profiles for different values of Sc.

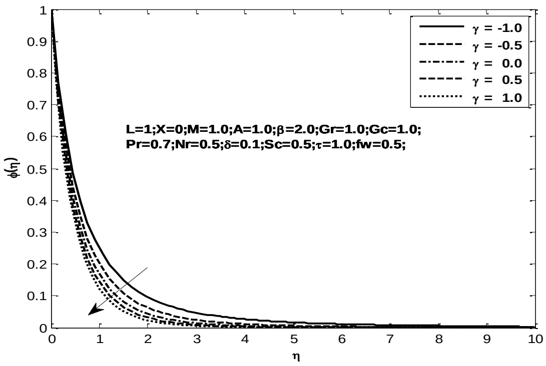

Figure 20. Concentration profiles for different values of γ.

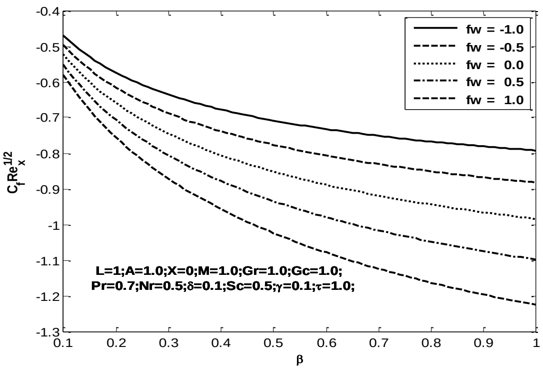

Figure 21. Variation of skin friction coefficient with β for different values of fw.

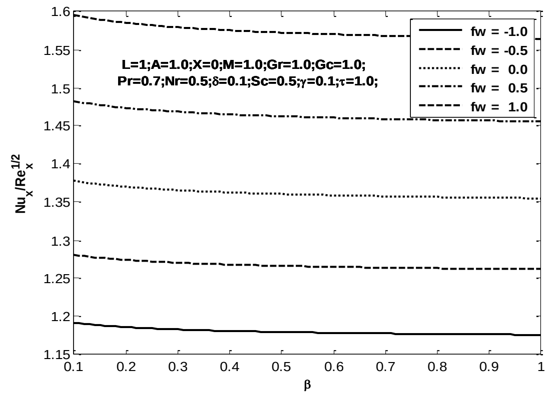

Figure 22. Variation of Nusselt number with β for different values of fw.

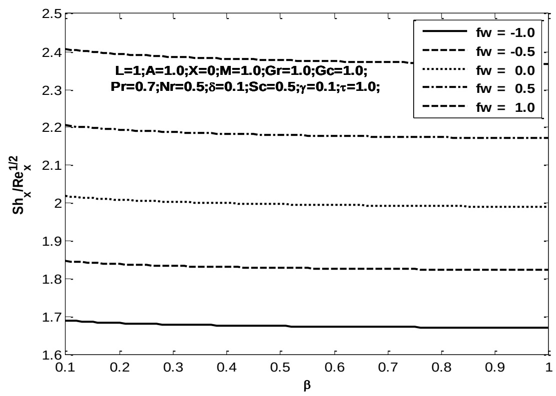

Figure 23. Variation of Sherwood number with β for different values of fw.

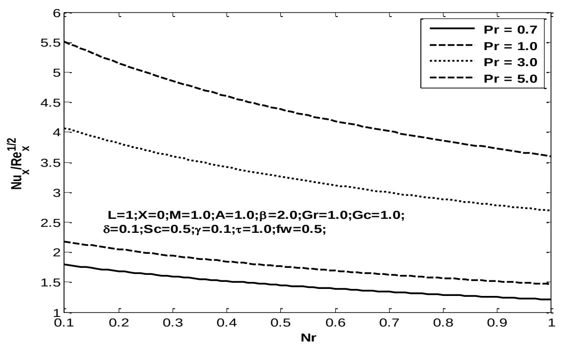

Figure 24. Variation of Nusselt number with Nr for different values of Pr

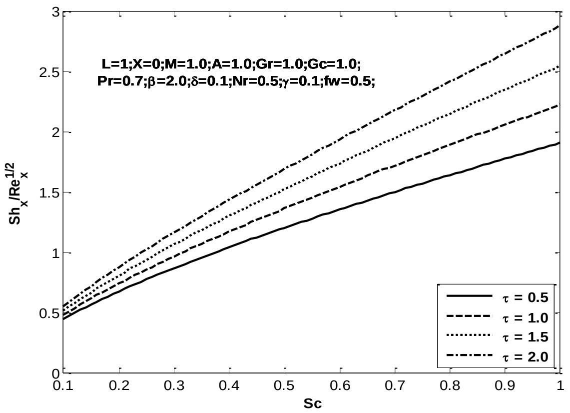

Figure 25. Variation of Sherwood number with Sc for different values of τ

The influence of chemical reaction rate parameter γ on the species concentration for generative chemical reaction is depicted in Fig. 20. It is found that species concentration with its highest value at the plate decreases slowly till it reaches the minimum value i.e., zero at far downstream. Further, increasing values of the chemical reaction parameter decrease concentration of species in the boundary layer due to the fact that destructive chemical reduces the thickness of the solutal boundary layer and increases the mass transfer.

From Fig. 21, it is noticed that the local skin friction coefficient decreases with increasing Casson parameter β in the presence of suction/injection. The values of skin friction coefficient in the presence of suction are less than those in the presence of injection. The Nusselt number decreases with Casson parameter and its values in the presence of injection are less than those when suction is present (Fig. 22). Local Sherwood number also decreases with Casson parameter. The rate of mass transfer is increased with Casson parameter. The values of local Sherwood number in the case of blowing are higher than in the case of suction and thus increased with the Casson parameter (Fig. 23).

Fig. 24 reveals that the rate of heat transfer is enhanced with thermal radiation parameter and reduces with Prandtl number. From Fig. 25 The local Sherwood number increases with Schmidt number and thermophoresis parameter. We may conclude that the combined effect of thermophoresis and Schmidt number is to reduce the mass transfer considerably.

Conclusions

The unsteady boundary layer flow of an incompressible, Casson electrically conducting fluid over an exponentially stretching sheet in the presence of thermophoresis, thermal radiation, temperature dependent heat source with chemical reaction and is analysed. It is observed that the velocity decreases with suction, magnetic field parameter, while an opposite trend is noted with blowing, Casson parameter. The temperature and concentration distributions increase with increasing magnetic field parameter, Casson parameter. The thickness of the thermal boundary layer increases with increasing values of radiation parameter, blowing and heat generation parameters while a reduction is noticed with suction parameter and heat absorption parameter. The skin friction coefficient is reduced with increasing Casson parameter. Heat transfer increases with thermal radiation parameter while it decreases with Prandtl number. The mass transfer rate decreases significantly due to the combined action of thermophoresis parameter and Schmidt number.

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