Effects of thermal radiation on Casson fluid flow and heat transfer over an unsteady stretching surface subjected to suction/blowing*

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The unsteady flow of a Casson fluid and heat transfer over a stretching surface in presence of suction/blowing are investigated. The transformed equations are solved numerically by using the shooting method. The exact solution corresponding to the momentum equation for the steady case is obtained. Fluid velocity initially decreases with the increase of unsteadiness parameter. Due to an increasing Casson parameter the velocity field is suppressed. Thermal radiation enhances the effective thermal diffusivity and the temperature rises.

Keywords: unsteady flow, Casson fluid, stretching surface, suction/blowing

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1. Introduction

Despite the overwhelming importance and frequent occurrence of non-Newtonian behavior of fluid in industry and technology, not so much attention has been paid to the investigation of the unsteady characteristics of such a type of fluid. Because of their complexity, there is no single constitutive equation which exhibits all properties of such non-Newtonian fluids. Therefore, a number of non-Newtonian fluid models have been proposed.[1–7] The simple fluid models, such as the power law and grade two or three models, have shortcomings in the sense that they yield results that have no accordance with fluid flows in reality. The power-law model is used to model fluids with shear-dependent viscosity but it cannot predict the effects of elasticity. The fluids of grade two or three can calculate the effects of elasticity but the viscosity in these models is not shear dependent. In addition, they cannot predict the effects of stress relaxation. A subclass of rate type fluids, namely the Maxwell model, can predict the stress relaxation. This rheological model excludes the complicating effects of shear-dependent viscosity from any boundary layer analysis.[8,9] Jelly, tomato sauce, honey, soup, concentrated fruit juices, etc. belong to a non-Newtonian fluid model called Casson fluid. Human blood can also be treated as a Casson fluid. Casson fluid can be defined as a shear thinning liquid which is assumed to have an infinite viscosity at zero rate of shear, a yield stress below which no flow occurs and a zero viscosity at an infinite rate of shear.[10]

The radiation heat transfer effects on different flows are very important in space technology and high temperature processes.[11,12] However, very little is known about the effects of radiation on the boundary layer.[13] Thermal radiation effects may play an important role in controlling heat transfer in the polymer processing industry where the quality of the final product depends, to some extent, on the heat controlling factors.[14–17] The radiative effects have important applications in physics and engineering. High temperature plasmas, cooling of nuclear reactors, liquid metal fluids, magnetohydrodynamics (MHD) accelerators, and power generation systems are some important applications of radiative heat transfer from a vertical wall to conductive gray fluids.[18] Moreover, the effect of thermal radiation on flow and heat transfer processes is of major importance in the design of many advanced energy conversion systems operating at high temperature.[19] Thermal radiation effects become important when the difference between the surface and the ambient temperature is large.[20]

In all the above mentioned studies, the flow and temperature fields are considered to be in a steady state. However, in some cases, the flow field, heat, and mass transfer can be unsteady due to a sudden stretching of the flat sheet or by a step change of the temperature of the sheet. A few papers have been published considering the case where the stretching force and surface temperature vary with time. Andersson *et al.*,[21] Dandapat *et al.*,[22,24] and Ali and Magyari[23] studied the problem of an unsteady isothermal stretching surface by using a similarity method to transform governing time-dependent boundary layer equations into a set of ordinary differential equations. Elbashbeshy and Bazid[25] presented similarity solutions of the boundary layer equations that describe the unsteady flow and heat transfer over an unsteady stretching sheet. Sharidan *et al.*[26] studied the unsteady flow and heat transfer over a stretching sheet in a viscous and incompressible fluid. Recently, Tsai *et al.*,[27] Ishak *et al.*,[28] Mukhopadhyay,[29–31] and Chamkha *et al.*[32] obtained similarity solutions for unsteady flow and heat transfer

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over a stretching sheet under different conditions. Hayat and Awais[33] analyzed the time dependent flow over a stretching surface. Bhattacharyya *et al.*[34] analyzed the effects of slip on unsteady boundary layer stagnation point flow passing through a stretching sheet. Hayat *et al.*[35] discussed the three-dimensional flow of Jeffery fluid passing through a stretching surface. Recently, Mukhopadhyay[36] and Mukhopadhyay and Vajravelu[37] investigated the Maxwell fluid flow and heat transfer for an unsteady stretching surface.

Since no attention has been paid so far to the analysis of Casson fluid flow and heat transfer passing through a non-isothermal unsteady stretching surface, in this paper an attempt is made to fill the gap in the existing literature and to extend the work of Andersson *et al.*[21] for non-Newtonian Casson fluid and heat transfer. Similarity solutions are obtained and the reduced ordinary differential equations are solved numerically by using the shooting method. An exact solution of the momentum equation for the steady case is also obtained. The effects of unsteadiness parameter, Casson parameter, and Prandtl number on velocity and temperature fields of the fluid are investigated and analyzed with the help of their graphical representations.

2. Equations of motion

Consider laminar boundary-layer two-dimensional flow and the heat transfer of an incompressible, conducting non-Newtonian Casson fluid over an unsteady stretching sheet. The unsteady fluid and heat flows start at $t = 0$. The sheet emerges out of a slit at origin ($x = 0$, $y = 0$) and moves with non-uniform velocity $U(x,t) = cx/(1-\alpha t)$ where $c > 0$ and $\alpha \geq 0$ are constants with dimensions [time^{-1}], and c is the initial stretching rate.

The rheological equation of state for the isotropic and incompressible flow of a Casson fluid is

$$\tau_{ij} = \begin{cases} 2(\mu_{\rm B} + p_{\rm y}/\sqrt{2\pi})e_{ij}, & \pi > \pi_c, \\ 2(\mu_{\rm B} + p_{\rm y}/\sqrt{2\pi_c})e_{ij}, & \pi < \pi_c, \end{cases}$$

where $\pi = e_{ij}e_{ij}$ and e_{ij} is the (i,j)-th component of the deformation rate, so π is the product of the component of deformation rate with itself; $\pi_{\rm c}$ is a critical value of this product based on the non-Newtonian model; $\mu_{\rm B}$ is the plastic dynamic viscosity of the non-Newtonian fluid; $p_{\rm y}$ is the yield stress of the fluid.

The governing equations of such a type of flow are given in the usual notation by

$$\frac{\partial u}{\partial x} + \frac{\partial \upsilon}{\partial y} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \upsilon\frac{\partial u}{\partial y} = \nu\left(1 + \frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2}, \tag{2}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y} = \kappa\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_{\rm p}}\frac{\partial q_{\rm r}}{\partial y}, \tag{3}$$

when the viscous dissipation term in the energy equation is neglected (as the fluid velocity is low). Here, u and υ are the components of velocity respectively in the x and y directions, ν is the kinematic viscosity of the fluid, $\beta = \mu_{\rm B}\sqrt{2\pi_{\rm c}}/p_{\rm y}$ is the parameter of the Casson fluid, T is the temperature, κ is the thermal diffusivity of the fluid, $q_{\rm r}$ is the radiative heat flux, and $c_{\rm p}$ is the specific heat.

By using the Rosseland approximation for radiation,[38] we can write

$$q_{\rm r} = -\frac{4\sigma}{3k}\frac{\partial T^4}{\partial y}, \tag{4}$$

where σ is the Stefan–Boltzman constant, and k is the absorption coefficient.

Assuming that the temperature difference within the flow is such that T^4 may be expanded in a Taylor series, and expanding T^4 about T_∞ and neglecting higher orders, we obtain $T^4 \equiv 4T_\infty^3 T - 3T_\infty^4$. Therefore, equation (3) becomes

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + \upsilon\frac{\partial T}{\partial y} = \kappa\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma T_\infty^3}{3\rho c_{\rm p} k}\frac{\partial^2 T}{\partial y^2}. \tag{5}$$

2.1. Boundary conditions

The appropriate boundary conditions for the problem are given by

$$u = U(x,t), \quad \upsilon = \upsilon_{\rm w}(t), \quad T = T_{\rm w}(x,t) \ \text{ at } \ y = 0, \tag{6}$$

$$u \to 0, \ T \to T_\infty \ \text{ as } \ y \to \infty, \tag{7}$$

where $T_{\rm w}(x,t) = T_\infty + cx^2 T_0(1-\alpha t)^{-3/2}/(2\nu)$[21] with T_0, whose positive (negative) value refers to heating (cooling), being a reference temperature (slit temperature at $x = 0$); T_∞ is the constant free stream temperature; $\upsilon_{\rm w}(t) = -\upsilon_0/\sqrt{1-\alpha t}$ is the velocity of suction ($\upsilon_0 > 0$) or blowing ($\upsilon_0 < 0$). The expressions for $U(x,t), T_{\rm w}(x,t), \upsilon_{\rm w}(t)$ are valid for time $t < \alpha^{-1}$.

2.2. Method of solutions

Introducing $u = \partial\psi/\partial y$, $\upsilon = -\partial\psi/\partial x$ and $\theta = (T - T_\infty)/(T_{\rm w} - T_\infty)$ (ψ being stream function) and with the help of $\eta = \sqrt{c/\{\nu(1-\alpha t)\}}\, y$, $\psi = \sqrt{\nu c/(1-\alpha t)}\, x f(\eta)$, and

$$T = T_\infty + T_0 c x^2 (1-\alpha t)^{-3/2}/(2\nu)\ \theta(\eta),$$

the governing equations finally reduce to

$$A\left(\frac{\eta}{2}f'' + f\right) + f^2 - ff'' = \left(1 + \frac{1}{\beta}\right)f''', \tag{8}$$

$$\frac{A}{2}(\eta\theta + 3\theta) + 2f\theta - f\theta = \frac{1}{Pr}\left(1 + \frac{4}{3}N\right)\theta'', \tag{9}$$

where $A = \alpha/c$ is the unsteadiness parameter, $Pr = \nu/\kappa$ is the Prandtl number, and $N = 4\sigma T_\infty^3/(\kappa_1 k)$ is the radiation parameter, κ_1 is the thermal conductivity.

The boundary conditions (6) and (7) then become

$$f = 1, \quad f = S, \quad \theta = 1 \ \text{ at } \ \eta = 0 \tag{10}$$

and

$$f \to 0, \quad \theta \to 0 \ \text{ as } \ \eta \to \infty. \tag{11}$$

Here, $S = \upsilon_0/\sqrt{\nu c}$ is the suction/blowing parameter, $S\ (>0)$ corresponds to suction and $S\ (<0)$ corresponds to blowing.

Equations (8) and (9) along with boundary conditions (10) and (11) are solved numerically by using the shooting method.[39,40]

3. Exact solution for the steady case

The exact solution of Eq. (8) subject to the corresponding boundary conditions for the steady case, i.e., for $A = 0$, is given by

$$f(\eta) = \sqrt{1+\frac{1}{\beta}}\left(1 - \mathrm{e}^{-\eta/\sqrt{1+(1/\beta)}}\right).$$

This solution accords with the analytic result obtained by Bhattacharyya *et al.*[41] in the absence of an applied magnetic field (i.e., for $M = 0$) and suction/blowing (i.e., for $S = 0$).

4. Results and discussion

In order to validate the method used in this study and to judge the accuracy of the present analysis, comparisons of our results with the results available from Refs. [26] and [32] corresponding to the skin-friction coefficient $f''(0)$ for unsteady flow of viscous incompressible fluid are made (see Table 1) and show that they are in excellent agreement. Moreover, to verify the accuracy of the present numerical scheme, a comparison of the results corresponding to the stream function profiles $f(\eta)$ and velocity profiles with the exact results for steady motion ($A = 0$) is presented in Fig. 1 and shows that they are in excellent agreement.

Table 1. Values of $f''(0)$ for various values of unsteadiness parameter A for Newtonian fluid.

A	Sharidan *et al.*[26]	Chamakha *et al.*[32]	Present study
0.8	–1.261042	–1.261512	–1.261479
1.2	–1.377722	–1.378052	–1.377850

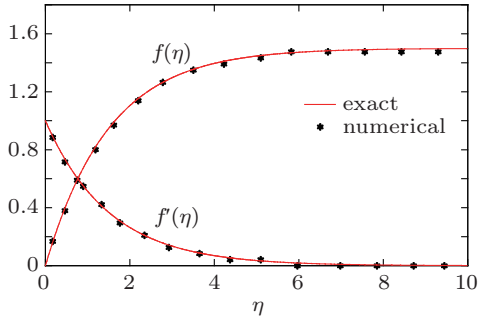


Fig. 1. (color online) Variations of stream function and velocity with η for steady motion.

In order to study the behavior of velocity and temperature fields for a Casson fluid, a comprehensive numerical computation is carried out for various values of the parameters that describe the flow characteristics, and the results are shown in Figs. 2–5.

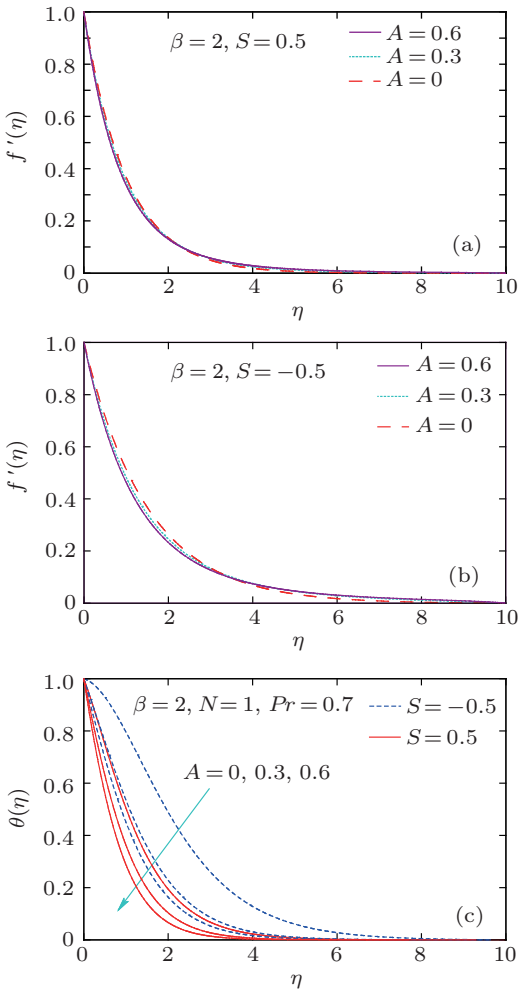


Fig. 2. (color online) Velocity profiles for variable unsteadiness parameter A in the presence of suction (a), blowing (b), and the temperature profiles in the presence of suction and blowing (c).

Figure 2(a) exhibits the velocity profiles for several values of unsteadiness parameter A in the presence of suction. It is seen that the velocity along the sheet decreases initially with the increase in unsteadiness parameter A and this implies an accompanying reduction of the thickness of the momentum boundary layer near the wall. However, away from the wall, fluid velocity increases as unsteadiness increases, i.e., away from the wall, the velocity field and the corresponding boundary layer are found to increase with the values of A increasing ($A = 0$ indicates the steady case). The same nature of velocity field due to unsteadiness is noted in the presence of blowing also (Fig. 2(b)). However, the effect of unsteadiness is more pronounced in the case of blowing than in the case of suction. Figure 2(c) represents the effects of unsteadiness parameter on the temperature distribution in the presence of

suction/blowing. From this figure, it is noticed that the temperature at a particular point decreases significantly as the unsteadiness parameter increases. The rate of heat transfer (from the sheet to the fluid) decreases with the value of A increasing. As the unsteadiness parameter A increases, less heat is transferred from the sheet to the fluid; hence, the temperature $\theta(\eta)$ decreases (Fig. 2(c)). Since the fluid flow is caused solely by the stretching sheet and the sheet surface temperature is higher than free stream temperature, the velocity and temperature decrease as η increases. It is important to note that the rate of cooling is much faster for higher values of unsteadiness parameter whereas it may take a longer time for cooling during steady flows.

The effects of Casson parameter β on velocity and temperature profiles for steady/unsteady motion in the case of a non-porous sheet are clearly exhibited in Figs. 3(a)–3(b), respectively. For steady motion and unsteady motion, the same type of behavior of velocity with the increase in β is noted. The effect of an increasing value of β is to reduce the velocity and hence the boundary layer thickness decreases (Fig. 3(a)). It is observed that velocity and the associated boundary layer thickness each are a decreasing function of β. The velocity curves in Fig. 3(a) show that the rate of transport considerably reduces with the value of β increasing. The effect of increasing β leads to an enhancement of the temperature for both steady and unsteady motion (Fig. 3(b)). This effect is more pronounced for steady motion. The thickening of the thermal boundary layer occurs due to the increase in elasticity stress parameter. It can also be seen from Fig. 3(a) that the momentum boundary layer thickness decreases as β increases, and hence induces an increase in the absolute value of the velocity gradient at the surface. On the other hand, figures 3(c) and 3(d) exhibit the natures of velocity and temperature profiles respectively for unsteady motion in the presence of suction/blowing. In addition, as the value of Casson parameter increases, the fluid velocity decreases (Fig. 3(c)), while the temperature increases (Fig. 3(d)).

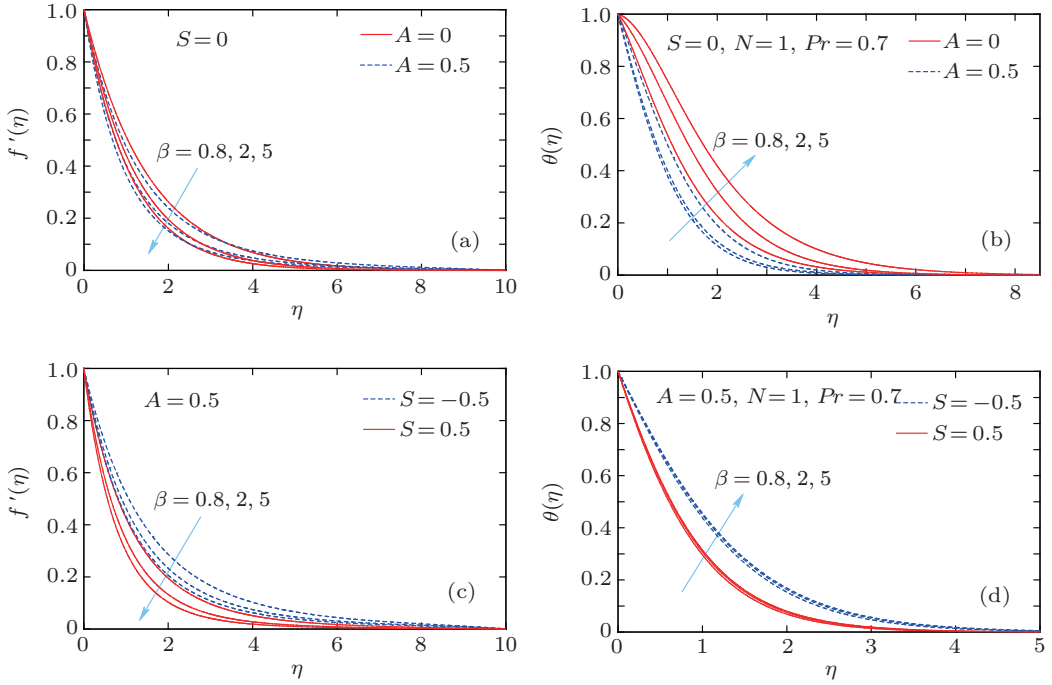


Fig. 3. (color online) Velocity (a) and temperature (b) profiles for variable values of Casson parameter β for steady/unsteady motion in the absence of suction/blowing, and velocity (c) and temperature (d) profiles for variable values of Casson parameter β for unsteady motion in the presence of suction/blowing.

Figures 4(a) and 4(b) display the effects of suction/blowing parameter S on velocity and temperature profiles respectively. With the value of S increasing, both fluid velocity and temperature decrease. Actually, velocity decreases significantly as suction increases ($S > 0$) whereas fluid velocity is found to increase with blowing (Fig. 4(a)). It is observed that when the wall suction ($S > 0$) is considered, this causes a decrease in boundary layer thickness and the velocity field is reduced. Here, $S = 0$ represents the case of a non porous stretching sheet. The opposite behavior is noted for blowing ($S < 0$). The physical explanation for such a behavior is that when stronger blowing is provided, the heated fluid is pushed farther from the wall and, due to less influence of the viscosity, the flow is accelerated. This effect acts to increase maximum velocity within the boundary layer. The same principle operates but in the reverse direction in the case of suc-

tion. Figure 4(b) presents the temperature profiles for variable suction/blowing parameter S. It is seen that temperature decreases as suction increases, whereas it increases due to blowing (Fig. 4(b)). The effect of suction is to make the velocity and temperature distributions more uniform within the boundary layer. The imposition of fluid suction at the surface has a tendency to reduce both the hydrodynamic and thermal thickness values of the boundary layer where viscous effects dominate. This has the effect of reducing both the fluid velocity and the temperature. On the other hand, the thermal boundary layer thickness increases with injection, which causes a decrease in the rate of heat transfer (Fig. 4(b)).

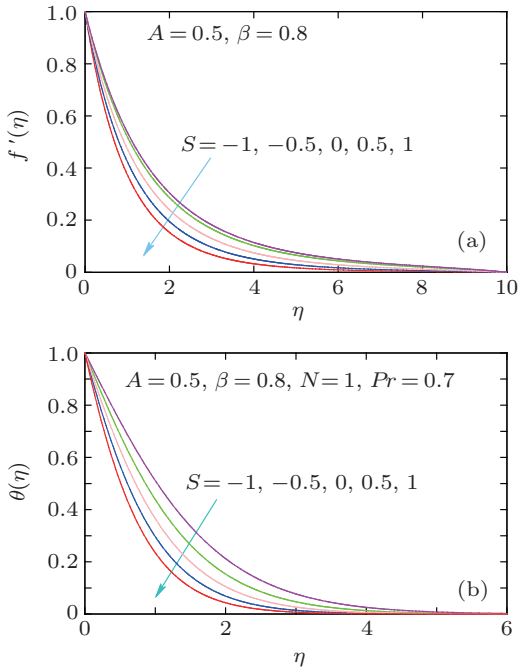


Fig. 4. (color online) Velocity (a) and temperature (b) profiles for variable values of suction/blowing parameter S for unsteady motion.

Figure 5(a) displays the effect of radiation parameter N on temperature field for an impermeable stretching surface. With the increase of radiation parameter N, the temperature at a point in the boundary layer increases (Fig. 5(a)) for both steady and unsteady motion. Figure 5(b) exhibits the radiation effect on temperature field in the presence of suction/blowing. Here also, temperature increases with the augment of η for increasing values of radiation parameter N. This supports the physical fact that the thermal boundary layer thickness increases as N increases. The effect of radiation in the thermal boundary layer Eq. (5) is equivalent to an increased thermal diffusivity. $Pr/(1+4N/3)$ in Eq. (10) can be considered as an effective Prandtl number which reduces as the value of N increases. This can be explained as follows.

An increase in the value of $N = 4\sigma T_\infty^3/(\kappa_1 k)$ for given κ_1 and T_∞ means a decrease in Rosseland radiation absorptivity k. According to Eq. (3) and the expression of q_r, the divergence of the radiative heat flux $\partial q_r/\partial y$ increases as k decreases which in turn causes the rate of radiative heat transfer to the fluid to increase, thereby increasing the fluid temperature.

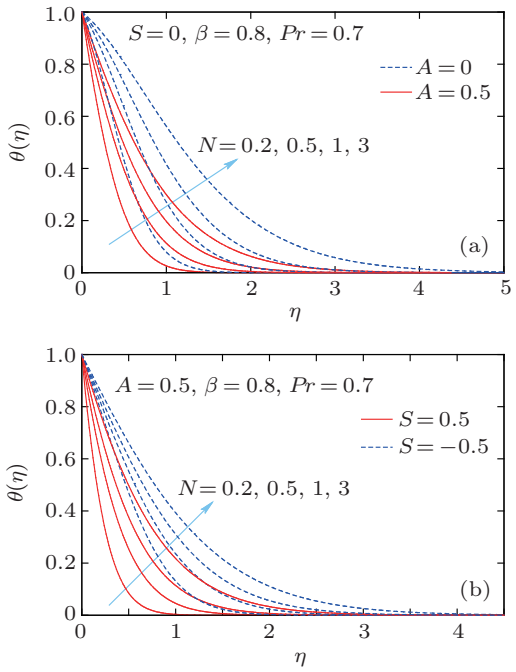


Fig. 5. (color online) Temperature profiles for variable values of radiation parameter N for (a) steady/unsteady motion in the absence of suction/blowing and (b) unsteady motion in the presence of suction/blowing.

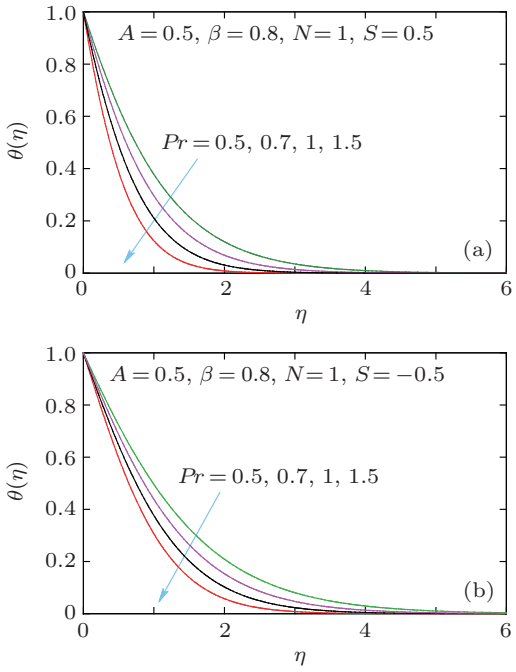


Fig. 6. (color online) Temperature profiles for variable values of Prandtl number Pr in the presence of suction (a) and blowing (b).

The behaviors of the temperature profiles for the variation of Prandtl number in presence of suction, and in presence of blowing can be found from Figs. 6(a) and 6(b) respectively. It

is noted that the temperatures decrease with Pr increasing for the cases of suction and blowing (Figs. 6(a) and 6(b)). The effect is more pronounced in case of suction than in case of blowing. Moreover, the thermal boundary layer thickness decreases as Prandtl number increases. The wall temperature gradients are negative for all values of Prandtl number, which means that the heat is always transferred from the surface to the ambient fluid. An increase in Prandtl number reduces the thermal boundary layer thickness. Prandtl number signifies the ratio of momentum diffusivity to thermal diffusivity. Fluids with lower Prandtl number will possess higher thermal conductivities (and thicker thermal boundary layer structures) so that heat can diffuse faster from the sheet than for the case of higher Pr fluids (thinner boundary layers). Hence, Prandtl number can be used to increase the rate of cooling in flows. The boundary layer is reached much faster in the case of suction than in the case of blowing.

Furthermore, the effects of unsteadiness parameter A and Casson parameter β on velocity gradient at the wall and heat transfer coefficient for impermeable sheet are presented in Figs. 7(a) and 7(b). The magnitude of velocity gradient at the wall, i.e., $|f''(0)|$ decreases as both the unsteadiness parameter A and the Casson parameter β increase, but the magnitude of heat transfer rate at the surface i.e., $|\theta'(0)|$ decreases as β increases, and increases with the value of A increasing. A drop in the value of $|f''(0)|$ as investigated in this paper, has an important implication that in free coating operations, elastic properties of the coating formulations may be beneficial to the whole process. This means that less force may be necessary to pull a moving sheet at a given withdrawal velocity, or equivalently, higher withdrawal speeds can be achieved for a given driving force affecting an increase in the rate of production.

Figure 7(c) exhibits the nature of velocity gradient at the wall with Casson parameter β for three values of suction/blowing parameter S. It is found that $[-f''(0)]$ increases as β increases and it is higher for suction than that for blowing. From this figure it is very clear that $f''(0)$ is negative here. Physically, a negative sign of $f''(0)$ implies that surface exerts a dragging force on the fluid and a positive sign implies the opposite scenario. Figure 7(d) displays the nature of heat transfer coefficient $[|\theta'(0)|]$ against the radiation parameter N. The increase of radiation parameter N leads to the increase of the heat transfer coefficient. Wall temperature gradient $[|\theta'(0)|]$ increases with blowing but decreases with suction (Fig. 7(d)).

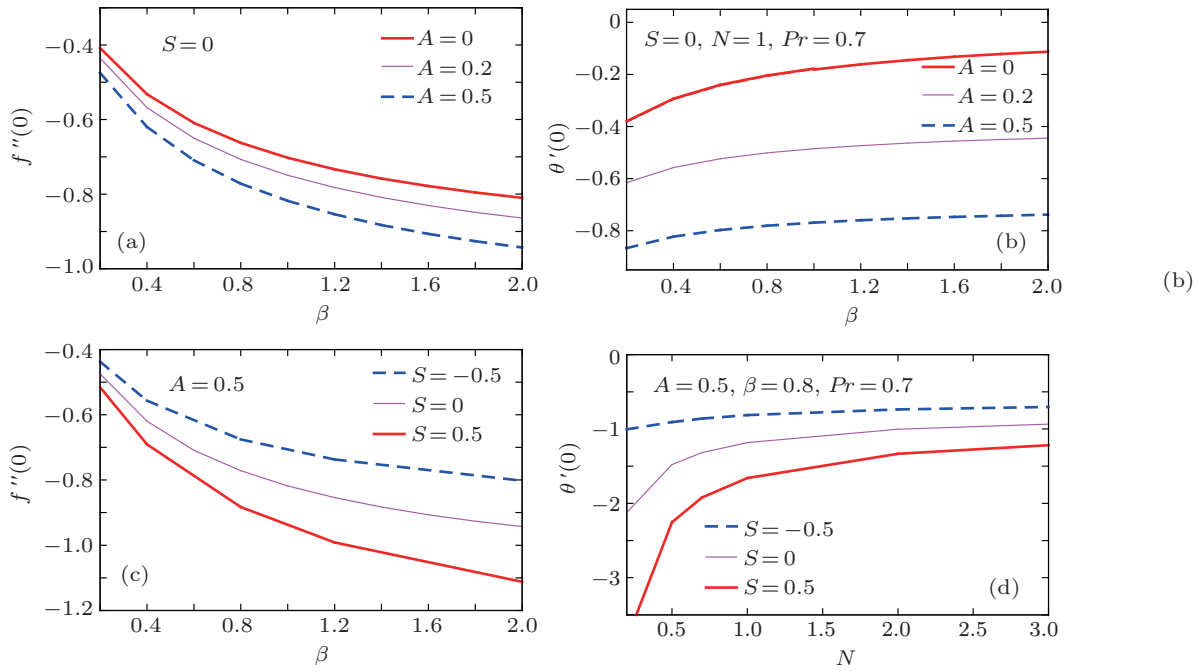


Fig. 7. (color online) Variations of $f''(0)$ (a) and heat transfer coefficient (b) with Casson parameter β for three values of unsteadiness parameter A; variation of $f''(0)$ with Casson parameter β (c) and heat transfer coefficient with radiation parameter N (d) for three values of suction/blowing parameter S.

5. Conclusions

The present study provides the numerical solutions for the unsteady boundary layer flow of a Casson fluid and heat transfer over a permeable stretching surface in the presence of thermal radiation. Fluid velocity decreases initially due to the increase in unsteadiness parameter. Temperature also decreases significantly in this case. The effect of increasing values of the Casson parameter is to suppress the velocity field whereas the temperature is enhanced as the Casson parameter increases. The Prandtl number can be used to increase the rate

of cooling in a flow. The temperature increases as the value of the radiation parameter increases. This phenomenon is ascribed to a higher effective thermal diffusivity. Momentum boundary layer thickness decreases as the Casson parameter increases but the thermal boundary layer thickness increases in this case.

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