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Dual solutions of Casson fluid flow over a stretching or shrinking sheet

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Abstract. The stagnation-point flow of an incompressible non-Newtonian Casson fluid over a stretching sheet in the presence of Soret and Dufour effects is investigated. The resulting partial differential equations are reduced to a set of nonlinear ordinary differential equations using similarity transformations and solved using the Matlab bvp4c package. A comparison is made with the results available in the literature and found to be in good agreement. Dual solutions for the velocity, temperature, concentration and skin friction were obtained for some special cases when the stretching parameter is negative. The effect of the Casson parameter on the skin friction, heat transfer and mass transfer rates is discussed.

Keywords. Casson fluid; stretching/shrinking sheet; Soret effect; Dufour effect.

1. Introduction

Boundary layer flow and heat transfer over a stretching sheet is significant due to its many applications in engineering processes such as in the extraction of polymer sheets, paper production, wire drawing and glass-fibre production. During the manufacturing process, a stretching sheet interacts with the ambient fluid both thermally and mechanically. The study of boundary layer flow caused by a stretching surface was initiated by Crane (1970) who gave an exact similarity solution in closed form. Mahapatra & Gupta (2001) reconsidered the steady stagnation point flow towards a stretching sheet taking different stretching and stagnation point velocities and observed two different kinds of boundary layer structure near the sheet. Recently, several papers on the dynamics of the boundary layer flow over a stretching surface have appeared in the literature (Dutta *et al* 1985; Kameswaran *et al* 2012, 2013). Mukhopadhyay (2013) has studied the effects of Casson fluid flow and heat transfer over a nonlinearly stretching surface. She found

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that temperature increases with an increase in nonlinear stretching parameter and the momentum boundary layer thickness decreases with an increase in Casson parameter.

When heat and mass transfer occur simultaneously in a moving fluid, the relationship between the fluxes and the driving potentials is complex. It has been observed that an energy flux can be generated not only by temperature gradients but also by concentration gradients. The energy flux caused by a concentration gradient is termed as the diffusion-thermo (Dufour) effect. On the other hand, mass fluxes can also be created by temperature gradients and this is termed as the thermal-diffusion (Soret) effect. Soret and Dufour effects have been utilized for isotope separation, in areas of hydrology, petrology, geosciences, etc. Srinivasacharya & RamReddy (2011) have investigated the Soret and Dufour effects on heat and mass transfer along a semi-infinite vertical plate embedded in a non-Darcy porous medium. Soret and Dufour effects on the magnetohydrodynamic (MHD) flow of a Casson fluid over a stretched surface were also studied by Hayat *et al* (2012a, b) and Nawaz *et al* (2012). Chamkha & Aly (2010) presented an analysis on heat and mass transfer in stagnation point flow of a polar fluid towards a stretching surface in porous media in the presence of Soret, Dufour and chemical reaction effects. Their study reveals that the velocity of fluid increased as the Soret number increased and the Dufour number decreased.

Casson fluids have a yield stress below which no flow occurs and a zero viscosity at an infinite rate of shear. The nonlinear Casson constitutive equation was derived by Casson (1959) and describes the properties of many polymers. At low shear rates when blood flows through small vessels, the blood flow is described by the Casson fluid model (McDonald 1974; Shaw *et al* 2009).

Non-Newtonian fluid flow generated by a stretching or shrinking sheet has many applications in industry. The flow of various non-Newtonian fluids over stretching or shrinking sheets was analysed by Liao (2003), Hayat *et al* (2008) and Ishak *et al* (2012). Stagnation point flow and heat transfer in a Casson fluid flow from a stretching sheet was studied by Mustafa *et al* (2012). An exact solution of the steady boundary layer flow of Casson fluid over a porous stretching or shrinking sheet was studied by Bhattacharyya *et al* (2011, 2013a, b). The effect of mass transfer on the magnetohydrodynamic flow of a Casson fluid flow over a porous stretching sheet was studied by Shehzad *et al* (2013). Hayat *et al* (2012a, b) studied the effects of mixed convection stagnation point flow of Casson fluid with convective boundary conditions. In their model, they showed that heat transfer characteristics depending on the embedded parameters.

The objective of this paper is to study the effect of the Casson parameter on the stagnation point flow of a Casson fluid over a permeable stretching or shrinking sheet subject to Soret and Dufour effects. We determine the dual fluid property solutions in the case when the surface is shrinking.

2. Mathematical formulation

Consider steady, incompressible two-dimensional flow of a Casson fluid near the stagnation point on a permeable stretching or shrinking sheet. The Cartesian coordinates x and y are along the surface and normal to it, u and v are the respective velocity components. The flow is generated by the stretching or shrinking of the sheet, caused by the simultaneous application of two equal forces along the x-axis. Keeping the origin fixed, the surface is stretched or shrunk with a linear velocity $u_w(x) = cx$, where c is a constant with $c > 0$ for a stretching sheet, $c < 0$ for a shrinking sheet and $c = 0$ for a static sheet. We assume that the rheological equation of state for an isotropic and incompressible flow of a Casson fluid can be written as (Nakamura & Sawada 1988)

$$\tau_{ij} = \begin{cases} (\mu_B + \tau_y/\sqrt{2\pi})2e_{ij} & \pi > \pi_c \\ (\mu_B + \tau_y/\sqrt{2\pi_c})2e_{ij} & \pi < \pi_c \end{cases}, \tag{1}$$

where μ_B is plastic dynamics viscosity of the Casson fluid, τ_y is the yield stress of fluid, π is the product of the component of deformation rate with itself, namely, $\pi = e_{ij}e_{ij}$, e_{ij} is the (i, j)th component of the deformation rate, and π_c is the critical value π. The momentum, temperature and concentration equation under the above assumptions are written as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{2}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = u_e\frac{du_e}{dx} + \nu\left(1 + \frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} + g\beta_T(T - T_\infty), \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_m\frac{\partial^2 T}{\partial y^2} + \frac{D_m K_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2}, \tag{4}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + \frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2}. \tag{5}$$

The boundary conditions for equations (2)–(5) are given in the form:

$$u = u_w(x) = cx, \quad v = 0, \quad T = T_w(x) = T_\infty + bx, \quad C = C_w(x) = C_\infty + dx, \quad \text{at} \quad y = 0,$$
$$u \to u_e(x) = ax, \quad T \to T_\infty, \quad C \to C_\infty, \quad \text{as} \quad y \to \infty, \tag{6}$$

where the ambient fluid moves with a velocity $u_e(x) = ax$, a is a constant, $\beta = \mu_B\sqrt{2\pi_c}/\tau_y$ is the Casson parameter, g is the acceleration due to gravity, β_T is the coefficient of thermal expansion, T is the fluid temperature, T_∞ is uniform ambient temperature, α_m is the effective thermal diffusivity, D_m is the effective solutal diffusivity of the medium, K_T is the thermal diffusion ratio, C_s is the concentration susceptibility, C_p is the specific heat capacity, T_m is the mean fluid temperature. The continuity equation (2) is satisfied by introducing a stream function $\psi(x, y)$ such that

$$u = \frac{\partial \psi}{\partial y} \quad \text{and} \quad v = -\frac{\partial \psi}{\partial x},$$

where $\psi = (a\nu)^{\frac{1}{2}}xf(\eta)$, $f(\eta)$ is the dimensionless stream function and $\eta = (a/\nu)^{\frac{1}{2}}y$. The velocity components are given by

$$u = axf'(\eta) \quad \text{and} \quad v = -(a\nu)^{\frac{1}{2}}f(\eta). \tag{7}$$

The temperature and concentration are represented as

$$T = T_\infty + \Delta T\theta(\eta) \quad \text{and} \quad C = C_\infty + \Delta C\phi(\eta), \tag{8}$$

where $\theta(\eta)$ and $\phi(\eta)$ are the dimensionless temperature and dimensionless concentration. On using equations (7) and (8), equations (2)–(5) transform into the following two-point boundary value problem

$$\left(1+\frac{1}{\beta}\right) f'''(\eta)+f(\eta)f''(\eta)-f'^{2}(\eta)+1+\lambda\theta(\eta)=0, \tag{9}$$

$$\frac{1}{Pr}\theta''(\eta)+f(\eta)\theta'(\eta)-f'(\eta)\theta(\eta)+D_f\phi''(\eta)=0, \tag{10}$$

$$\frac{1}{Sc}\phi''(\eta)+f(\eta)\phi'(\eta)-f'(\eta)\phi(\eta)+Sr\theta''(\eta)=0, \tag{11}$$

$$f(0)=0, \quad f'(0)=\frac{c}{a}, \quad f'(\infty)\rightarrow 1, \tag{12}$$

$$\theta(0)=1, \quad \theta(\infty)\rightarrow 0, \tag{13}$$

$$\phi(0)=1, \quad \phi(\infty)\rightarrow 0, \tag{14}$$

where the primes denote differentiation with respect to η. The non-dimensional constants in equations (9) – (14) are the buoyancy or free convection parameter λ, Prandtl number Pr, Dufour parameter D_f, Schmidt number Sc, Soret parameter Sr and the velocity ratio parameter c/a. These are defined as

$$\lambda = \frac{g\beta_T b}{a^2}, \quad Pr=\frac{\nu}{\alpha_m}, \quad D_f=\frac{D_m K_T(C_w-C_\infty)}{C_s C_p \nu (T_w-T_\infty)}, \quad Sc=\frac{\nu}{D_m},$$
$$Sr = \frac{D_m K_T(T_w-T_\infty)}{T_m \nu (C_w-C_\infty)}.$$

3. Skin friction, heat and mass transfer coefficients

The quantities of practical interest in this study are the skin friction C_f. The shearing stress at the surface of the wall τ_w is given by

$$\tau_w=\left(\mu_B+\frac{\tau_y}{\sqrt{2\pi_c}}\right)\left[\frac{\partial u}{\partial y}\right]_{y=0}=\left(\mu_B+\frac{\tau_y}{\sqrt{2\pi_c}}\right)\left(\frac{a^3}{\nu}\right)^{1/2} x f''(0). \tag{15}$$

The skin friction coefficient is defined as

$$C_f=\frac{\tau_w}{\rho\, u_e(x)^2} \tag{16}$$

and using equation (15) in the equation (16), we obtain

$$C_f Re_x^{\frac{1}{2}}=\left(1+\frac{1}{\beta}\right) f''(0). \tag{17}$$

The heat transfer rate at the surface flux at the wall is given by

$$q_w = -k\left[\frac{\partial T}{\partial y}\right]_{y=0} = -k\,(T_w - T_\infty)\left(\frac{a}{\nu}\right)^{\frac{1}{2}}\theta'(0)\,. \tag{18}$$

The local Nusselt number is defined as

$$Nu_x = \frac{xq_w}{k\,(T_w - T_\infty)}. \tag{19}$$

Using equation (18) in equation (19), the dimensionless Nusselt number can be represented as below

$$\frac{Nu_x}{Re_x^{\frac{1}{2}}} = -\theta'(0)\,. \tag{20}$$

The mass flux at the surface of the wall is given by

$$q_m = -D_s\left[\frac{\partial C}{\partial y}\right]_{y=0} = -D_s\,(C_w - C_\infty)\left(\frac{a}{\nu}\right)^{\frac{1}{2}}\phi'(0)\,. \tag{21}$$

The local Sherwood is defined as

$$Sh_x = \frac{xq_m}{D_s(C_w - C_\infty)}. \tag{22}$$

Using (21) in (22) the dimensionless Sherwood number obtained as

$$\frac{Sh_x}{Re_x^{\frac{1}{2}}} = -\phi'(0)\,, \tag{23}$$

where $Re_x = xu_e(x)/\nu$ is the local Reynolds number.

4. Results and discussion

The system of ordinary differential equations (9)–(11) subject to the boundary conditions (12)–(14) were solved using the Matlab bvp4c ODE solver. To benchmark the numerical results, we have compared our results for the skin friction coefficient with those reported by Bhattacharyya

Table 1. Comparison of $f''(0)$ values with Bhattacharyya (2011) and Ishak *et al* (2010) for $\lambda = Pr = Df = Sc = Sr = 0$ and $\beta = 10^8$.

	Present study		Bhattacharyya (2011)		Ishak *et al* (2010)	
c/a	1st solution	2nd solution	1st solution	2nd solution	1st solution	2nd solution
−0.25	1.4022408		1.4022405		1.402241	
−0.50	1.4956698		1.4956697		1.495670	
−0.75	1.4892982		1.4892981		1.489298	
−1.00	1.3288169	0	1.3288169	0	1.328817	0
−1.15	1.0822312	0.1167021	1.0822316	0.1167023	1.082231	0.116702
−1.20	0.9324734	0.2336497	0.9324728	0.2336491	0.932474	0.233650
−1.2465	0.5842817	0.5542962	0.5842915	0.5542856	0.584295	0.554283

Table 2. Critical c/a value for different Casson parameter β.

	$\beta = 3.5$	$\beta = 4.0$	$\beta = 4.5$
$(c/a)_{crit}$	-1.25182704	-1.25182390	-1.25181905

(2011) and Ishak *et al* (2010) in table 1. The results are in very good agreement thereby lending confidence as to the accuracy of the present method.

This investigation confirms that the existence and uniqueness of solution depends on the stretching ratio parameter. We found that for a stretching sheet, solutions of equations (9)–(11) may be found for all values of c/a, while for a shrinking surface, solutions exist only for $c/a > (c/a)_{crit}$, where $(c/a)_{crit}$ is a critical value of c/a which depends on other parameters. There are no solutions when $c/a < (c/a)_{crit}$. Dual solutions of the fluid properties appear when $(c/a)_{crit} < c/a < -1$. The critical value $(c/a)_{crit}$ for different Casson parameters is given in table 2. It is evident that the critical value of c/a is not significantly influenced by the Casson parameter β within the chosen range.

In the absence of Soret and Dufour effects, for a particular values of other parameters, in order to validate our results, we have compared the results of heat transfer $-\theta'(0)$ for various values of c/a (table 3.) with those of Wang (2008) and found that the results are excellent in agreement. It can also be noticed that for the values of $c/a < 0$ heat transfer decreases and increases for $c/a > 0$.

Table 4 shows that the values of heat transfer coefficient for different c/a and β. It is observed that heat transfer rate increases with an increase in ratio of c/a.

The dual solution is of the skin friction, heat transfer and mass transfer coefficients for different values of the Casson parameter are shown in figure 1. The Casson parameter β is inversely proportional to the yield stress, hence a decrease in the Casson parameter indicates an increase in the yield stress. With an increase in β, the skin friction coefficient increases in the case of the first solution but is reduced in the second solution. It is interesting to note that the values of the heat transfer rate (Nusselt number) and mass transfer rate (Sherwood number) coincide when plotted against the stretching ratio parameter c/a as shown in figure 1(b). An increase in the Casson parameter enhances both the heat and mass transfer rates. This is because the thermal and concentration boundary layer thicknesses decrease with β causing the temperature and concentration gradients at the surface to increase.

Two velocity and temperature solutions were obtained when $c/a < -1$. These solutions are shown in figure 2 for three different values of $c/a = -1.23, \; -1.24, \; -1.25$. As observed by Merkin (1985), Merrill *et al* (2006), Paullet & Weidman (2007), Postelnicu & Pop (2011), the

Table 3. Comparison of $-\theta'(0)$ with Wang for particular value of c/a.

c/a	Present study	Wang (2008)
-0.25	0.6685728	0.66857
-0.5	0.5014476	0.50145
-0.75	0.2937625	0.29376
0	0.8113013	0.811301
0.1	0.8634517	0.86345
0.2	0.9133028	0.91330
0.5	1.0514584	1.05239
1	1.2533141	1.25331

Table 4. Heat transfer coefficient $-\theta'(0)$ for different values of c/a and β for fixed values of $\lambda = 0.01 = Pr = Df = Sc = Sr = 0.1$.

	$\beta = 3.5$		$\beta = 4.0$		$\beta = 5$	
c/a	1st solution	2nd solution	1st solution	2nd solution	1st solution	2nd solution
−1.25	0.0291102	0.0583329	0.0324337	0.0613653	0.0371985	0.0657208
−1.20	0.053657	0.1128705	0.0494951	0.1154347	0.0435444	0.1191202
−1.10	0.2132429	0.1549802	0.2067033	0.1571813	0.1974351	0.1603466
−1.00		0.1822328		0.1841972		0.1870228

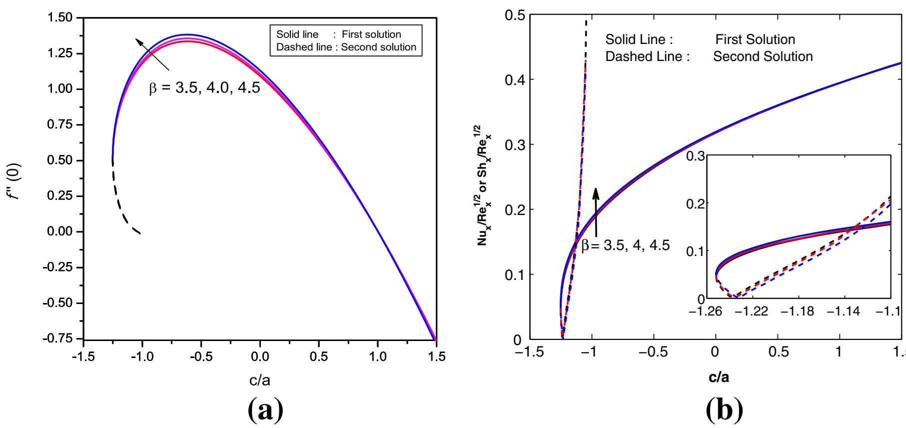

Figure 1. Effects of the stretching rate c/a on the (**a**) skin friction and (**b**) heat transfer/mass transfer rates when $\lambda = 0.01$, $Pr = D_f = Sc = Sr = 0.1$.

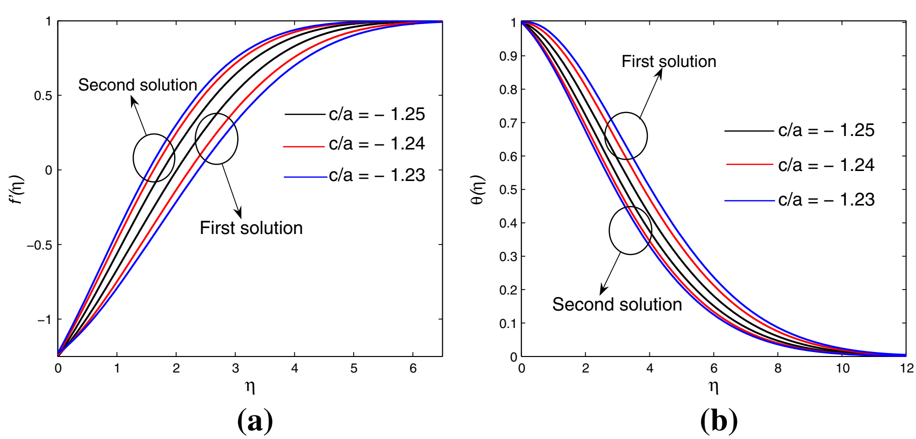

Figure 2. Effects of the stretching rate c/a on the (**a**) velocity and (**b**) temperature solutions when $\beta = 3.1$, $\lambda = 0.01$, $Pr = D_f = Sc = Sr = 0.1$.

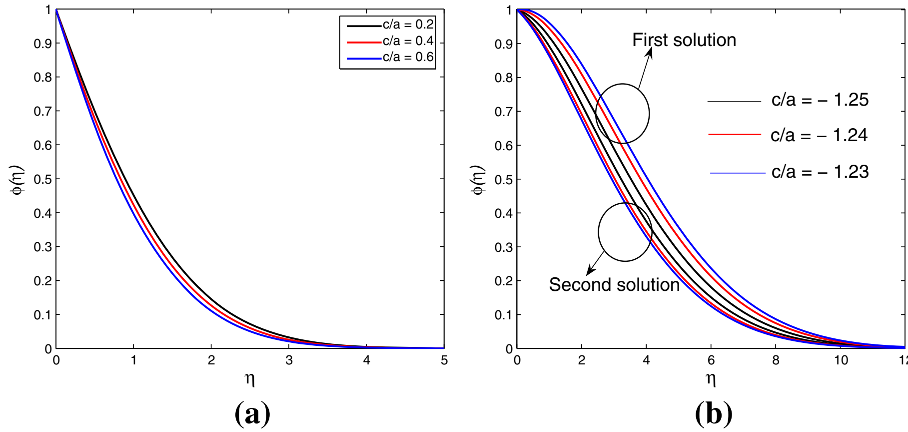

Figure 3. Effects of the stretching rate c/a on (**a**) the concentration when $\beta = 0.5, \lambda = 1, Pr = 0.7, D_f = 0.5, Sc = Sr = 0.8$ and (**b**) dual concentration solutions when $\beta = 3.1, \lambda = 0.01, Pr = D_f = Sc = Sr = 0.1$.

first solution is stable and physically realizable, while the second solution is unstable. Although the second solution seems to be deprived of physical significance, it is interesting in the theory of nonlinear differential equations since a similar equation may appear in other situations where the solution could have physical significance. As the shrinking ratio increases, the free stream velocity decreases reducing both the momentum and thermal boundary layer thicknesses.

The effect of the stretching ($c/a > 0$) and shrinking ($c/a < 0$) ratios on the concentration profiles are shown in figure 3. With an increase in the stretching ratio, the velocity of the fluid increases which in turn reduces the concentration layer thickness. In the case of a shrinking sheet we obtain dual solutions. For the first solution, the concentration boundary layer thickness increases with increase c/a while for second solution in figure 3(b), the concentration profiles decrease with the shrinking ratio.

The influence of the Casson parameter on the velocity, temperature and concentration profiles is shown in figures 4 and 5 when $c/a = -1.25$. The magnitude of the velocity is greater in the

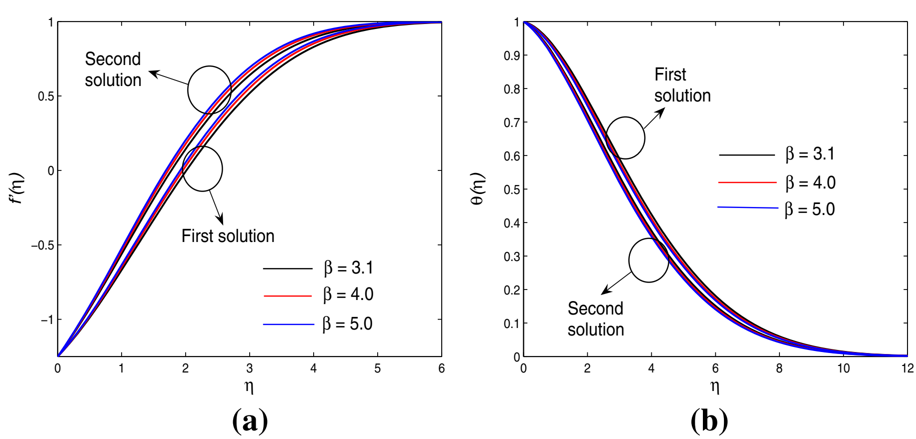

Figure 4. Effects of the Casson parameter on the (**a**) velocity and (**b**) temperature profiles when $\lambda = 0.01, Pr = D_f = Sc = Sr = 0.1, c/a = -1.25$.

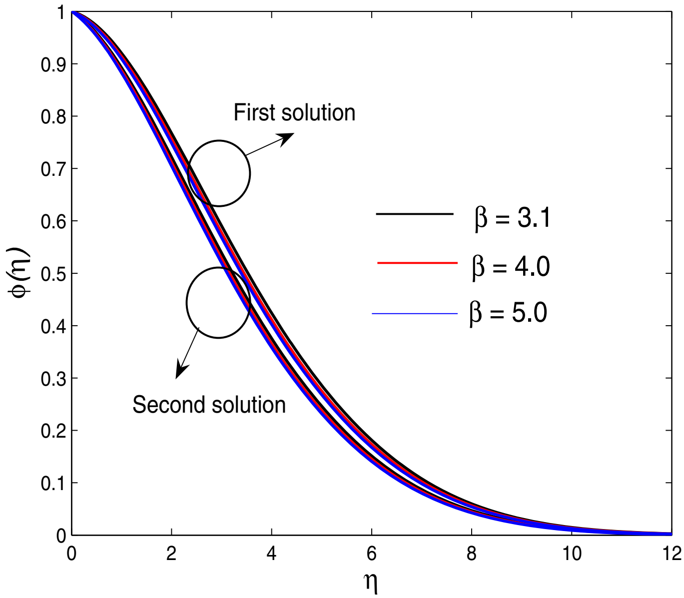

Figure 5. Effects of the Casson parameter on the concentration profiles when $\lambda = 0.01$, $Pr = D_f = Sc = Sr = 0.1$, $c/a = -1.25$.

case of a Casson fluid when compared with a viscous fluid. Hence in general, with an increase in β, the velocity of the fluid decreases for a stretching sheet. However, for a shrinking sheet the opposite is true and the velocity profiles increase with β. Consequently, the thermal and concentration boundary layer thicknesses decrease with an increase in β in the case of a shrinking sheet.

5. Conclusions

The Soret and Dufour effects on a Casson fluid are investigated about a stagnation point on a stretching sheet. The momentum, temperature and concentration equations are written as a system of ordinary differential equations using a suitable similarity transformation and then solved numerically using the Matlab bvp4c package. Two solutions were obtained when $c/a < -1$. We have shown that Dufour number enhances the velocity and temperature throughout the boundary layer. The concentration boundary layer thickness is enhanced by an increase in the Soret number. The shrinking ratio reduces the velocity of the fluid but enhances the concentration layer thickness in the case of the first solution. The skin friction and heat and mass transfer rates increase with the Casson parameter.

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