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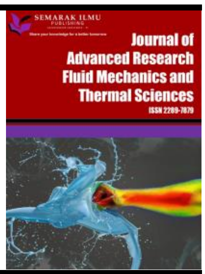

MHD Mixed Convective Non-Newtonian Stagnation Point Flow Over an Inclined Stretching Sheet: Numerical Simulation

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ABSTRACT

This paper includes numerical simulation upon MHD mixed convective heat transfer properties of stagnation point flow across an angled stretched sheet. Boundary value problem is solved using similarity transformation approach with shooting technique. The impact of different corporeal constraints like mixed convection parameter (λ), thermal radiation parameter (R_d), chemical reaction parameter (γ), Brownian motion (N_b)and thermophoresis (N_t), Casson parameter (β) upon velocity and temp profile as well as skin-friction coefficient C_f , Nusselt number Nu_x , Sherwood number Sh_x on velocity, temp concentration profile are shown graphically. Casson parameter increases velocity and diminishes temperature profile. Chemical reaction term decreases Sherwood number and increases concentration profile.

1. Introduction

Non-Newtonian fluids have been closely related with its viscosity that plays key role in boundary layer flows in many industrial applications such as chemical processing units, food processing and polymer solutions etc [1]. Due to increased usage of non-Newtonian fluids in many domains it is very important to understand physics of these fluids within boundary layer region. Significant number of studies can be found in literature exploring boundary layer flows of non-Newtonian fluids using different rheological models. Sakiadis [2-4] successfully demonstrated these type of flows over different geometries in his initial works. Later many researchers extended this model under various physical conditions. Rajagopal e*t al*., [5] discussed about viscoelastic fluid flow upon stretched surface. Siddappa and Subhas [6] scrutinized non-Newtonian boundary layer flows. Due to technological revolution over the period of time many advanced problems are considered in non-Newtonian fluid flows with respect variety of geometries. Non-Newtonian fluid flow with

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convective condition in non-uniform channel is studied by Gudekote *et al*., [7]. The major complexity in modelling non-Newtonian fluid flows is governing equations, because a single equation can't exhibit all properties hence different non-Newtonian models are use in literature among them Casson rheological model is widely used to understand which discloses the yield stress. Ibrahim *et al.,* [8] researched regarding mixed convection Casson fluid flow upon stretch surface having chemical reaction impacts. Khan *et al.,* [9] reported Casson fluid flow over stretching sheet having convective & slippery boundary circumstances. Khan *et al.,* [10] researched about hydromagnetic Casson liquid flow over stretching sheet having inclined magnetic field, thermophoresis impacts and Brownian motion. Role of no linear thermal radiation upon Casson stagnation point flow is explained by Ananta Kumar *et al.,* [11]. Concurrent impacts of mixed convection and thermal radiating into boundary layer flow over a stretching surface is scrutinized by Mehmood *et al.,* [12]. Entropy analysis of Casson fluid stagnation point flow is examined with Afridi *et al.,* [13] past non-isothermal stretching surface and joule heating effect. Apart from these some more article on mixed convection Casson fluid flow can be found in literature [14-19]. Effect of variable viscosity of peristaltic flow with porous channel geometry is reported by Vaidya *et al*., [20]. Casson fluid flow in an inclined tube with slip condition is examined by Gudekote and Rajashekhar [21] and another work with elastic tube configuration and slip condition is reported by Gudekote *et al.,* [22]. Baliga *et al*., [23] studied Herschel-Bulkley fluid through an inclined tube. Some more recent works on non-Newtonian fluid and applications can be found in research works [24–26].

The usage of external magnetic field on stretching sheet boundary layer flows is investigated by several scholars due to its wide range of applications. Magnetic field is applied to control momentum and heat transport phenomena in boundary layer flows. Nagantran *et al*., [27] discussed time dependent stretching shrinking stagnation point flow of special non-Newtonian models. Aly [28] portrayed role of magnetic field and radiation in stagnation point flow of Casson fluid embedded in porous media. Reddy *et al.,* [29] presented magnetohydrodynamic fluid flow under zero mass flux boundary condition. Recently Kumar *et al*., [30] researched entropy generation of viscoelastic non-Newtonian stagnation point flow over stretch sheet. Report on Williamson nanofluid over stretching sheet intensifies role of magnetic field which was illustrated by Rajput *et al*., [31]. Most recently Verma *et al*., [32] examined Sorret and DuFour effect upon stagnation point flow past moving surface. Even though many articles published on stagnation point flow of non-Newtonian models past stretching shrinking sheets, most of authors considered geometry as either horizontal or vertical. But inclined stretch sheet problems have wide range application in many industries and very few articles can be seen in literature focusing inclined stretching sheet stagnation point flow of non-Newtonian fluid. Hence the main goal of current study is examining mass & heat transport phenomena of Casson fluid upon persuaded stretch surface by extending article Gupta *et al*., [33] by including Casson rheological model.

2. Problem Statement and Governing Equations

We thought of Casson fluid flowing steadily in 2D along an inclining stretching sheet near the stagnation point of a magnetohydrodynamic (MHD). A homogenous intensity of magnetic field B_0 is occupied as into plane parallel to surface. We presumed as stretching velocity $U_w(x)=ax$ & free stream velocity $U_\infty(x)=bx$ being presumed to be into orientation of x-axis. Assuming vertical stretch sheet is oriented at ω angle. Temperature T & nanoparticle concentration C. Temperature & concentration of fluid over a sheet are T_w and C_w correspondingly. Ambient fluid temp at the wall & concentration T_∞ & C_∞ correspondingly as y tends to infinity at stretch sheet. Magnetic Reynold's number is presumed as very smaller & induced magnetic field and pressure gradient is neglected.

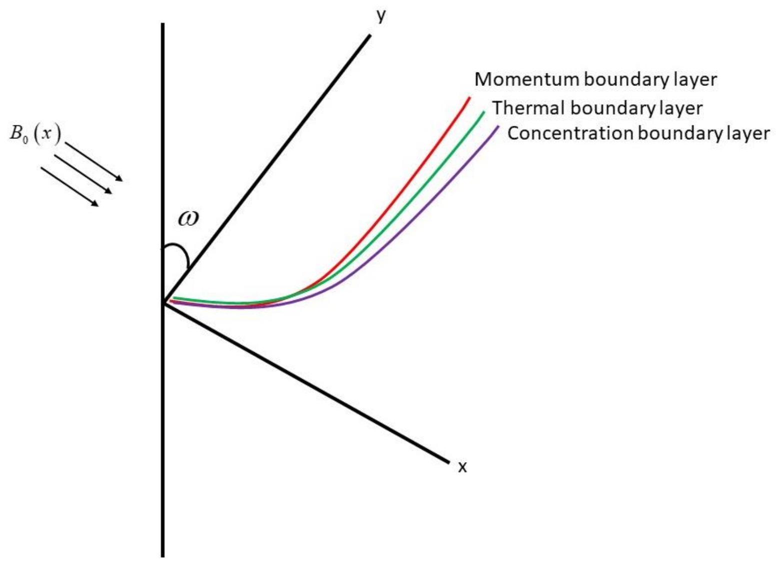

Fig. 1. Physical representation of the fluid flow

The following the works of Gupta *et al.*, [33], the boundary layer equations of continuity, momentum, energy and concentration.

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U_\infty\frac{dU_\infty}{dx}+\nu\left(1+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2}-\frac{\sigma_{nf}}{\rho_f}B_0^2(U_\infty-u)$$
$$+\left[(C-C_\infty)(T-T_\infty)\beta-\frac{(\rho_{nf}-\rho_f)(C-C_\infty)}{\rho_p}\right]g\cos\omega \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\left(\frac{\partial T}{\partial y}\right)=\alpha\left(\frac{\partial^2 T}{\partial y^2}\right)+\tau\left\{D_B\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}\right)+\left(\frac{D_T}{T_\infty}\right)\left[\left(\frac{\partial T}{\partial y}\right)^2\right]\right\}-\frac{1}{(\rho c)_p}\frac{\partial}{\partial y}(q_r) \tag{3}$$

Associated boundary conditions are

$$u=U_w(x)=ax, v=0, T=T_w, C=C_w \text{ at } y=0 \tag{4}$$

$$u\to U_\infty(x)=bx, v=0, T\to T_\infty, C\to C_\infty aty\to\infty \tag{5}$$

Introducing the following similarity transformation, we obtain governing equations as shown in Eq. (6) until Eq. (8)

$$\psi = x\sqrt{(a\nu)}\, f(\eta), \eta = \sqrt{\frac{a}{\nu}}\, y, \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty},$$

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

$$\left(1 + \frac{1}{\beta}\right) f''' + ff'' - f'^2 + A^2 + \lambda(\theta - N_r\phi)\cos\omega - M(f' - A) = 0 \tag{6}$$

$$\left(1 + \frac{4}{3}R_d\right)\theta'' + \Pr(f\theta' + N_b\theta'\phi' + N_t\theta'^2) = 0 \tag{7}$$

$$\phi'' + Le(f\phi' - \gamma\phi) + \frac{N_t}{N_b}\theta'' = 0 \tag{8}$$

By corresponding boundary conditions are

$$f(0) = 0, f'(0) = 1, \theta(0) = 1, \phi = 1 \text{ at } \eta = 0$$

$$f'(\infty) \to A, \theta(\infty) \to 0, \phi \to 0 \quad \text{at } \eta \to \infty \tag{9}$$

$M = \dfrac{\sigma_{nf} B_0^{\,2}}{\rho_f a}$, $N_b = \dfrac{\{\tau D_B(C_w - C_\infty)\}}{\nu}$, $N_t = \dfrac{\{(\tau D_T)(T_w - T_\infty)\}}{\nu T_\infty}$ $Le = \dfrac{\nu}{D_B}$ $Gr = \dfrac{\beta_T g(T_w - T_\infty)}{\nu^2} x^3$ $Gr^* = \dfrac{\beta_C g(C_w - C_\infty)}{\nu^2} x^3$, $\gamma = \dfrac{\nu x k_1}{U_w}$ is chemical reaction parameter, $A = \dfrac{b}{a}$ is velocity ratio parameter, $Nr = \dfrac{(\sigma_{nf} - \rho)(C_w - C_\infty)}{\beta\rho_p(1 - C_\infty)(T_w - T_\infty)}$ stands for the buoyancy ratio. $R_d = \dfrac{4\sigma^* T_\infty^3}{3K^* k}$ is radiation parameter. k_1 is chemical reaction. β_T, β_C are thermal expansion coefficient & concentration extension coefficient correspondingly.

Coefficient of Skin Friction, Local Nusselt Number, and Sherwood Number are physical quantities of interest for this problem and given as

$$C_f = \frac{\tau_w}{\rho_f u_w^2(x)}, Nu_x = \frac{xq_w}{k(T_w - T_\infty)}, Sh_x = \frac{xq_m}{D_B(C_w - C_\infty)} \tag{10}$$

Into aforementioned equation τ_w is Stress with stretching surface, q_w is wall heat flux, q_m is mass heat flux, k is the thermal conductivity which are stated as

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, q_w = -\alpha\left(\frac{\partial T}{\partial y}\right)_{y=0}, q_m = -D_B\left(\frac{\partial C}{\partial y}\right)_{y=0} \tag{11}$$

Using variables with no dimensions, we get the following in Eq. (12)

$$\sqrt{\mathrm{Re}_x} C_f = -\left(1+\frac{1}{\beta}\right) f''(0), \frac{Nu_x}{\sqrt{\mathrm{Re}_x}} = -\left(1+\frac{4}{3}R_d\right)\theta'(0), \frac{Sh_x}{\sqrt{\mathrm{Re}_x}} = -\phi'(0) \tag{12}$$

3. Result and Discussions

The equations for velocity, energy, and density after transformation. Eq. (6) until Eq. (8) are solved numerically utilizing shooting approach, corresponding boundary constraints specified in Eq. (9). We were able to plot the profiles of speed, temperature, and concentration for a variety of input values.

In Figure 2, we see the effect of the velocity ratio on the momentum profile, and in Figure 3 and Figure 4, we see impact ratio upon temperature profile & concentration profile. Casson's parameter upon temperature and velocity profiles are depicted into Figure 5 and Figure 6 correspondingly. Chemical concentration reaction diagram is shown in Figure 7. Thermophoresis on a temperature and concentration profile are shown in Figure 8 and Figure 9. Brownian motion on a temperature profile is shown as in Figure 10 and a concentration profile as in Figure 11.

Figure 2 depicts velocity graph for several values of velocity ratio parameter A. By fixing other parameter and varying values we have noticed enhanced. When A is increased, free stream velocity increases. Its thermal boundary layer is narrower because of free stream velocity is higher. There is rise in flow velocity and a reduction into boundary layer thickness with increasing A so when free stream velocity is higher compared velocity of stretch sheet. In addition, whenever stream velocity is smaller than stretch velocity, flow velocity & thickness of boundary layer are both reduced. When A>1, boundary layer structure is present in flow, & thickness of boundary layer reduced with increasing. If A<1, boundary layer thins even as flow does have an inverted boundary structure; this happens when A is less than one because the boundary layer is thinner at larger values. No boundary layer thickness of Casson nanofluid exists close to sheet so when stretching sheet velocity is equal to free stream velocity.

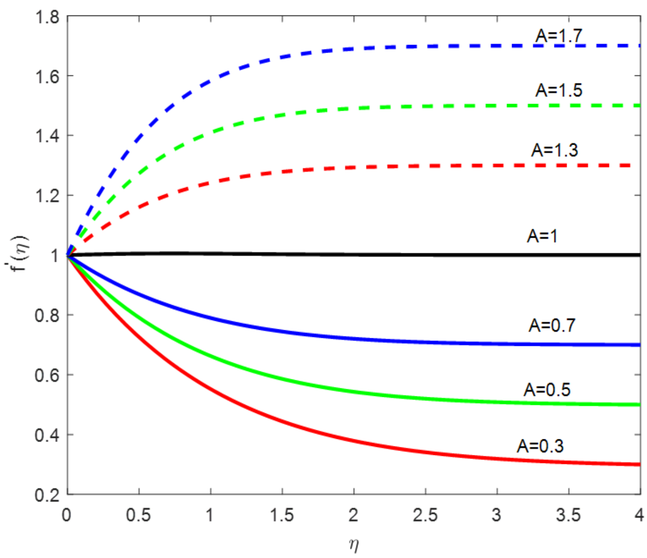

Fig. 2. Impact of velocity ratio upon momentum profile

Any change in values of velocity ratio constraint is depicted into Figure 3 having impact upon temp profile. Thickness of thermal boundary layer is found to decrease with increasing velocity ratio. In addition, absolute value of surface temperature gradient rises as A rises. Consequently, local Nusselt number $-\theta'(0)$ upon surface rises.

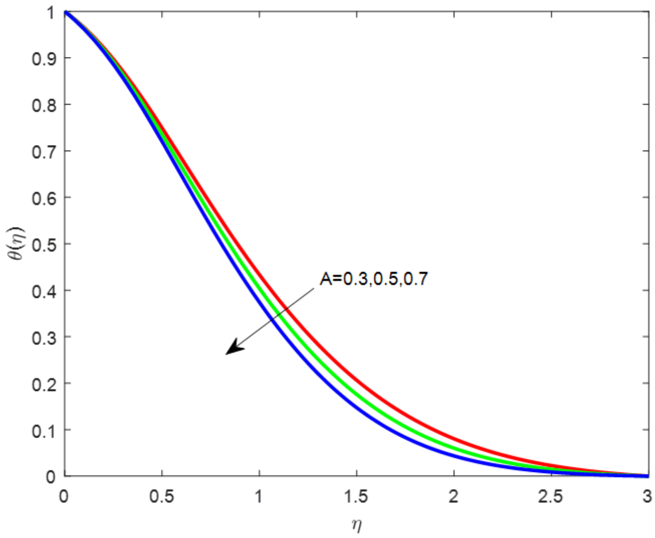

Fig. 3. Impact of velocity ratio upon temperature profile

The impact of relative velocity upon that concentration graph is seen into Figure 4. Thickness of concentration boundary layer decreases as A increases. The graph also makes it clear that as A rises, so does temperature gradient upon that plate's surface. When a result, as the value of grows, the surface mass transfer rate (represented by local Sherwood number $-\phi'(0)$,) also increases. The rate of mass transfer between nanofluids may rise when velocity ratio parameter is increased, which might explain why this is the case.

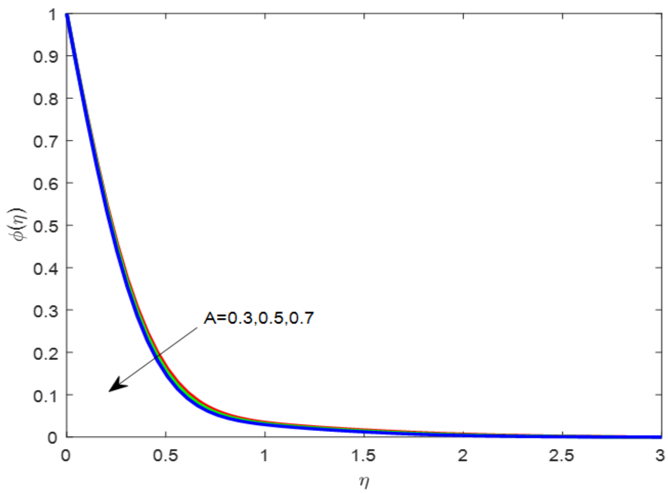

Fig. 4. Impact of velocity ratio upon momentum profile

The influence of Casson parameter upon that velocity graph with varying β is seen in Figure 5. As β increases, its seen as the velocity profile flattens out. As β rises, yielding stress drops, causing thickness of momentum boundary layer to grow, which in turn increases surface velocity gradient.

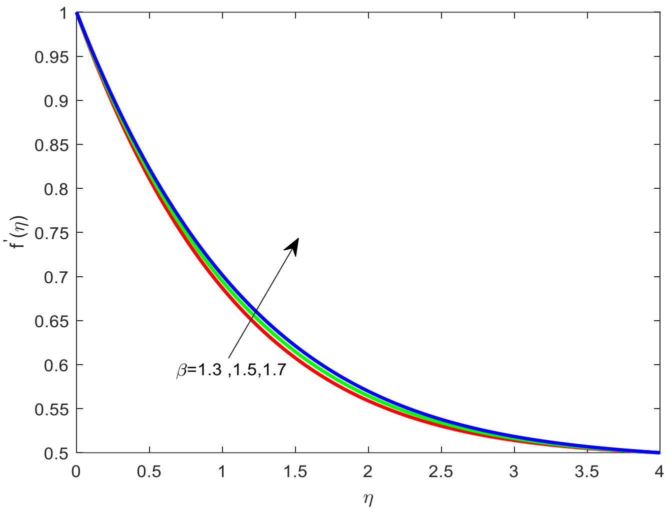

Fig. 5. Impact of Casson parameter upon momentum velocity profile

Impact of Casson parameter β upon that fluid's temperature profile is shown graphically in Figure 6. This is because as Casson parameter β increases, also temperature at sheet's border. The result was a rise in fluid's average temperature, which in turn caused thickness of boundary layer to shrink.

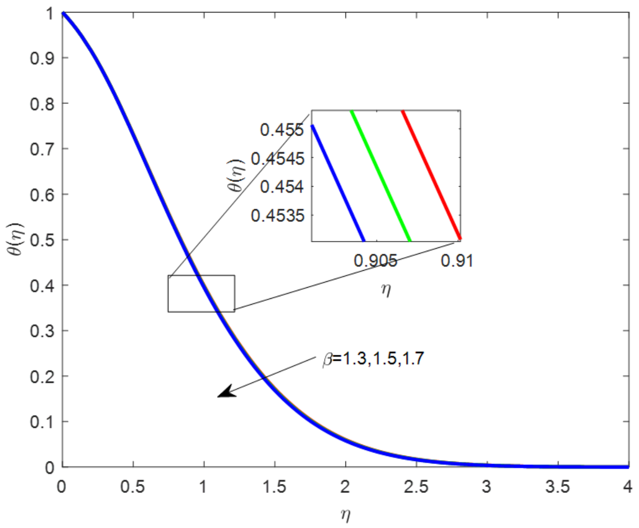

Fig. 6. Impact of Casson parameter upon temperature profile

The impact of chemical reaction γ upon that concentration profile is seen in Figure 7. The particle concentration in the fluid rises as a result of this characteristic. Volume decrease of nanoparticles results from an increase into amount of intermolecular mass transport as result of a chemical reaction.

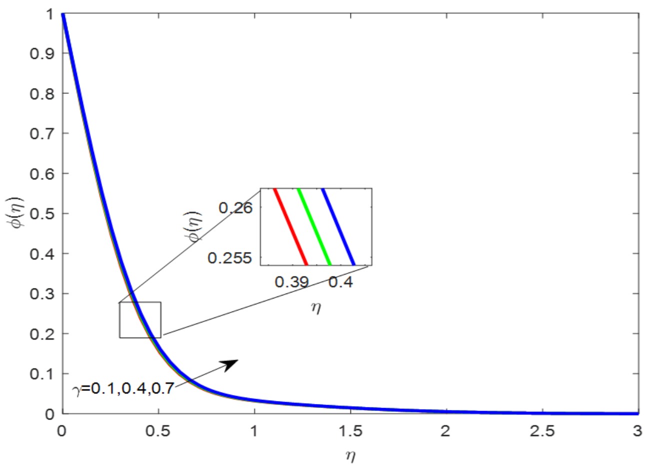

Fig. 7. Impact of chemical reaction parameter upon concentration

In Figure 8 and Figure 9, we see impact of changing thermophoresis variable N_t upon that resulting temperature and concentration curves. Fluid temperature is shown to rise in step with the thermophoresis parameter N_t. As N_t increases, a similar pattern emerges in the concentration profile.

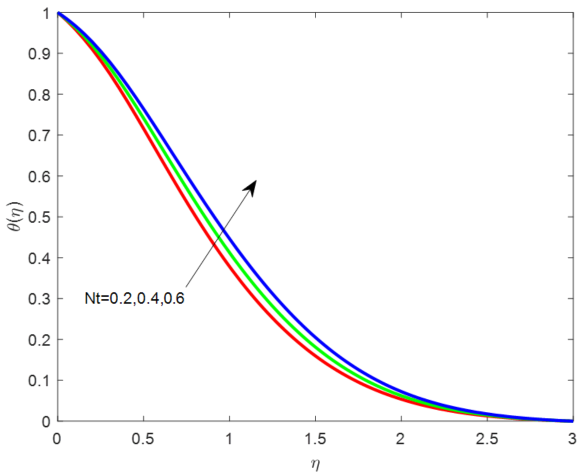

Fig. 8. Impact of thermophoresis upon temperature profile

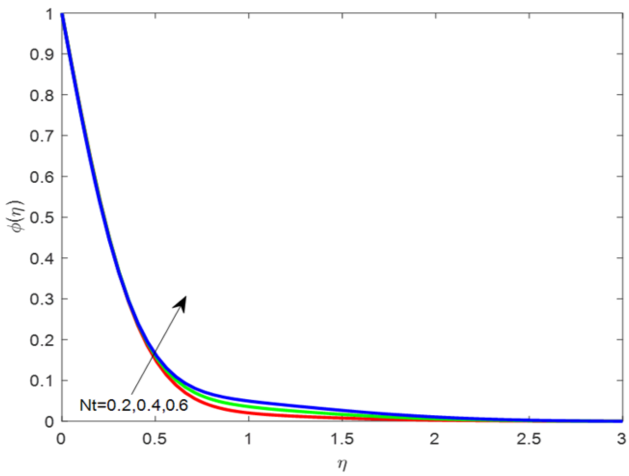

Fig. 9. Impact of thermophoresis upon concentration profile

It's worth noting that thermophoresis has a far larger impact on Newtonian fluid than on non-Newtonian fluid. For small Prandtl P_r and Lewis numbers L_e, the boundary layer may be warmed via thermophoresis. It may be deduced that when N_t lowers, so does rate of mass and heat transmission.

The concentration and temperature patterns for different Brownian motion parameters are shown in Figure 10 and Figure 11, correspondingly (N_b). Its known which dimension temp $\theta(\eta)$ rises as Brownian motion parameter (N_b) rises, but we found the converse to be true for concentration profiles. Temperature of boundary layer rises with rise in Brownian motion parameter (N_b) because of accompanying increase into the mass diffusivity.

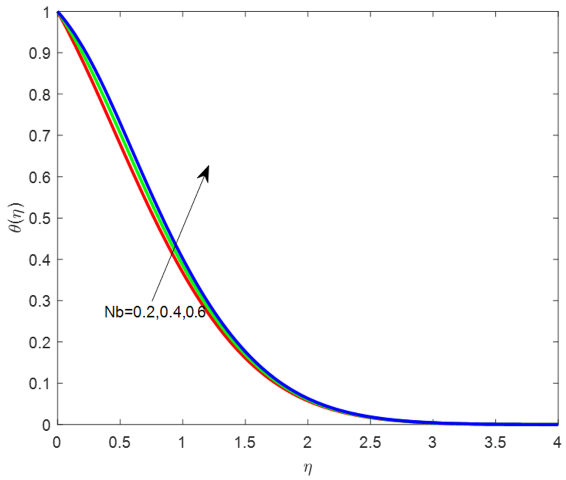

Fig. 10. Impact of Brownian motion upon temperature

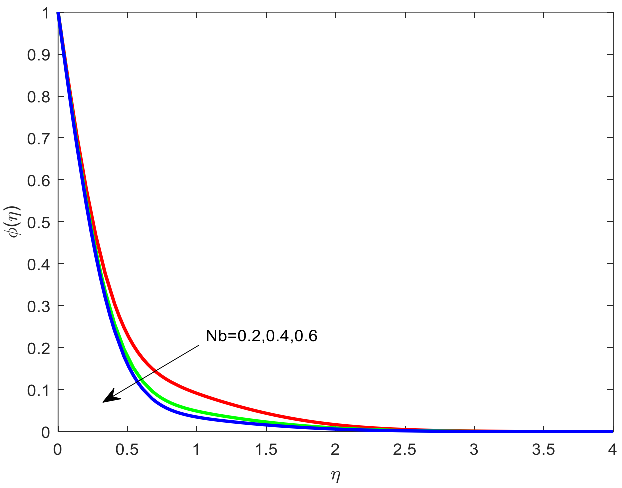

Fig. 11. Impact of Brownian motion upon concentration

Table 1 shows the key physical values namely skin friction coefficient, Nusselt number and Sherwood number for different physical parameters.

Table 1
Computation of the skin friction coefficient, Nusselt and Sherwood numbers

M	γ	β	λ	A	Le	Nt	Nb	Cf_x	Nu_x	Sh_x
0.5								0.979823	0.452057	2.446418
1.0								1.084144	0.448494	2.435190
1.5								1.180084	0.445386	2.425106
	0.1							0.935265	0.453637	2.451295
	0.4							0.935447	0.454693	2.390790
	0.7							0.935634	0.455790	2.328996
		1.3						0.935265	0.453637	2.451295
		1.5						0.906820	0.452567	2.448152
		1.7						0.884556	0.451691	2.445557
			0.1					0.935265	0.453637	2.451295
			0.2					0.909221	0.454931	2.454929
			0.3					0.883324	0.456207	2.458522
				0.3				1.218510	0.433324	2.406393
				0.4				1.084690	0.443363	2.428193
				0.5				0.935265	0.453637	2.451295
					2			0.953387	0.577609	0.946697
					3			0.947579	0.535638	1.233957
					5			0.941502	0.493720	1.673145
						0.2		0.941300	0.771916	2.296613
						0.4		0.937590	0.611515	2.418006
						0.6		0.935653	0.481849	2.447981
							0.2	0.936016	0.498352	2.425452
							0.4	0.935004	0.439914	2.460685
							0.6	0.933906	0.390254	2.500826

4. Conclusions

Theoretical study upon non-Newtonian fluid flow upon inclined stretch sheet is discussed using shooting method. Casson rheology model has been used to explain fluid behaviour and few significant observations of our research

i. Casson parameter reduces Nusselt number & skin friction coefficient.
ii. Mixed convection parameter rises Nusselt number and Sherwood number.
iii. Heat transfer rate increased with respect to velocity ratio parameter.
iv. Temperature distribution increases with Brownian motion and thermophoresis parameter.

5. Scope and Future Work

The results obtained in this study will be used to analyse the heat and mass transport phenomena in many non-Newtonian fluid flow industrial applications. This work can be extended in future with some other geometries and physical conditions.

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