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ORIGINAL ARTICLE

A comparative analysis of magnetohydrodynamic non-Newtonian fluids flow over an exponential stretched sheet

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Abstract This study is dedicated to figure out the flow, thermal and concentration boundary layer nature of Casson and Carreau fluids over an exponential stretching surface with zero normal flux of nanoparticles having magnetic behavior. Moreover, consideration of nanoparticles which are passively control at the surface is physically more realistic condition (Buongiorno model). Adequate similarity transforms are invoked to put the flow governing equations in dimensionless form. Then after, the transformed equations are solved by means of an effective Runge-Kutta based shooting method. The influence of the selected flow managing parameters on the usual profiles viz. velocity, thermal and concentration are inspected comprehensively with the aid of plots. Numerical treatment for friction factor and reduced Nusselt number is presented in tabular form. It is noticed that Carreau fluid is highly affected by the Lorentz force when equated with the Casson fluid.

1. Introduction

The study of MHD is the relation between electric and magnetic properties. It has extensive applications in the manufacturing fields' likes, bearing, MHD generators, flow meter, pumps, etc. MHD boundary layer is noticed by many technical systems retaining plasma flow and liquid metal opposite to the magnetic fields. This type of force is called resistive force. Now, many researchers illustrated the study of MHD boundary layer flows past a stretching surface [1–5]. From the generalized Newtonian fluids we consider the viscosity model, such as Carreau rheological model. The characteristic of Carreau fluid can well rheology of assorted polymeric solution, namely poly ethylene oxide and one percent of methylcellulose tylose and 0.3 percentage of hydroxyethyl-cellulose incolorless solution. These polymeric solutions are generally used in capillary electrophoresis to increasing and separation of DNAs and Proteins [6–9].

The study of non-Newtonian fluids have multiple applications in industry and engineering. In particular separation of crude oil from petroleum products. Casson fluid is also consider as a non-Newtonian fluid. In 1859 Casson introduced the Casson fluid. It reveal the yield stress. When shear stress is small it acts like a solid otherwise it is a liquid. Paint, tomato sauce, Jelly, hone, vigorous fruit juice and soup are Casson

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fluid example. The heat transfer flow past a stretching sheet with radiation was illustrated by Pramanik [10] and noticed that rising values of Casson parameter enhances the surface stress. The MHD heat transfer Casson fluid past a stretching sheet in the presence of magnetic field analyzed by Hayat et al. [11] and Nadeem et al. [12]. Sulochana and Sandeep [13] discussed the convective MHD flow towards a stretching sheet with the slip effects. They concluded that raising values of magnetic field parameter depreciate Nusselt number and skin friction.

The study of MHD heat and mass transfer on Casson fluid past a stretching surface was studied by Nadeem et al. [14]. Gireesha et al. [15] provided the numerical solution for boundary layer MHD heat and mass transfer past a stretching sheet with chemical reaction effect. Sandeep [16] studied the effect of aligned magnetic filed on thin film flow of a nanofluid. Khan et al. [17] examined the magnetic field effect on MHD flow of a Carreau fluid with convective boundary condition. SathishKumar et al. [18] explained the MHDflow on heat and mass transfer towards a stretching surface with suction/injection effect. The numerical solution of entropy generation towards the radiation of MHD Carreau fluid flow past a stretching surface was explained by Bhatti et al. [19]. Bhatti et al. [20] examined the numerical solution of MHD Carreau fluid past a stretching surface with radiation effect. Squeezed flow and thermal analysis of Carreau fluid past a sensor surface with thermal conductivity was illustrated by Khan et al. [21]. Abdul Hakeem et al. [22] presented the influence of inclined Lorentz force on Casson fluid towards a stretching sheet. The researchers [23–25] analyzed the convective heat transfer in MHD flows. Hayat et al. [26] discussed the 2D MHD flow of Eyring- Powell fluid in the presence of Brownian motion and thermophoresis effects.

The effect of thermal radiation on MHD flow of viscous fluid over a stretching cylinder was investigated by Khan et al. [27]. Khan et al. [28] presented the impact of homogeneous-heterogeneous reaction on Maxwell fluid flow past a moving sheet. The impact of Joule heating and viscous dissipation on MHD boundary layer flow of Casson fluid past a stretching cylinder was studied by Tamoor et al. [29]. Hayat et al. [30] presented the MHD boundary value flow of a viscous fluid past a stretching cylinder with nonlinear thermal radiation. The effect of thermophoresis and Brownian motion on heat and mass transfer of viscous fluid over a cylinder was studied by Hayat et al. [31]. Waqas et al. [32] discussed the MHD mixed convection flow of a micropolar fluid over a stretching surface with viscous dissipation and Joule heating effects. The effect of Cattaneo-Christov heat flux model on heat transfer of a Jaffrey fluid over a stretching surface was explained by Hayat et al. [33,34] and found that for larger value of the Schmidt number depreciate the concentration field. The numerical study of heat transfer of nanofluid flow through a channel with velocity slip condition was investigated by Khan et al. [35]. Ahmed et al. [36] discussed the impact of thermal radiation on MHD heat transfer flow past porous channel and solved numerically by Galerkin's method. The 3D MHD squeezing flow of nanofluid over a stretching wall and plate with magnetic fields effects was studied by Khan et al. [37–43].

In this article, we studied the effect Brownian moment and thermophoresis on the MHD Carreau and Casson fluids flows towards a stretching surface with magnetic field effect. We presented the dualsolutions for the Casson and Carreau cases. The resulting non-linear PDE were changed into the set of ODE and solved by Runge-Kutta with shooting method. The effect of various parameters on flow, thermal and concentration fields, along with skin friction and reduced Nusselt numberare investigated through tables and graphs.

2. Formulation of the problem

Consider a steady, 2D incompressible flow on Carreau and Casson fluid flows towards an exponential stretching surface. The x-axis taken through a stretching sheet in the flow direction and y- axis is normal to the surface. The exponential stretching sheet is assumed in x-axis with in velocity $U_w = Ue^{Nx/L}$ elucidateat $y = 0$, where N is the exponential parameter and L is the characteristic length. It is assumed that the present model deals with the Casson flow when $n = 1$ and Carreu flow when $\beta \to \infty$. Thermophoresis and Brownian motion effects are considered with effective passive controlled Buongiorno model. The magnetic field B_0 is applied in the flow direction as depicted in Fig. 1.

According to the assumptions stated above, the governing boundary layer equation can be defined as follows [12,17]:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\left(1+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} + \upsilon\frac{3(n-1)\Gamma^2}{2}\left(\frac{\partial u}{\partial y}\right)^2\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2(x)}{\rho_f}u \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \tau\left\{D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y} + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_B\frac{\partial^2 C}{\partial y^2} + \left(\frac{D_T}{T_\infty}\right)\frac{\partial^2 T}{\partial y^2} \tag{4}$$

Here u, v represents the velocities components in the x, y-direction respectively, ρ_f – fluid flow density, υ – kinematic viscosity, σ – electrical conductivity, Γ – material constant, T – Temperature, $\alpha = \frac{k}{(\rho C)_f}$ is thermal diffusivity, β – Casson

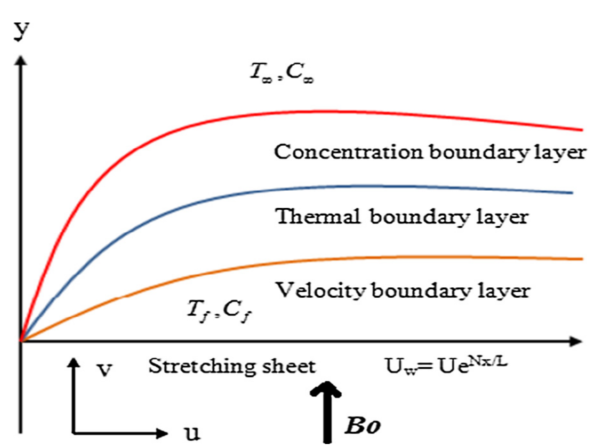

Fig. 1 Physical model.

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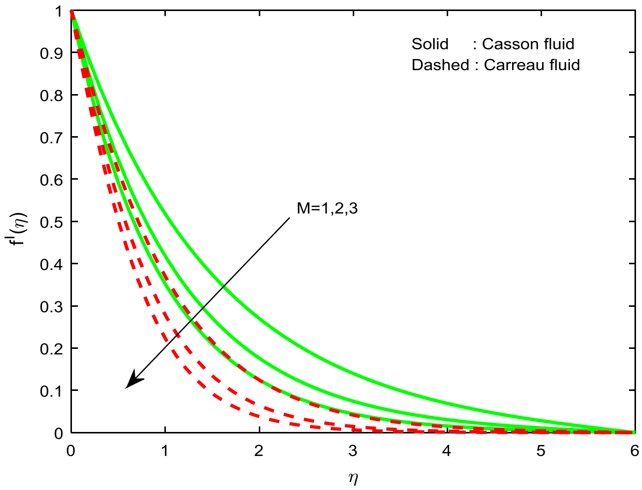

Fig. 2 Effect of M on velocity fields.

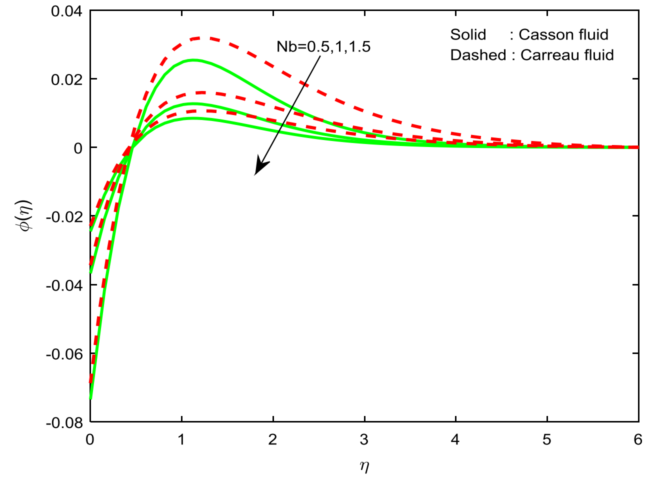

Fig. 5 Effect of Nb concentration fields.

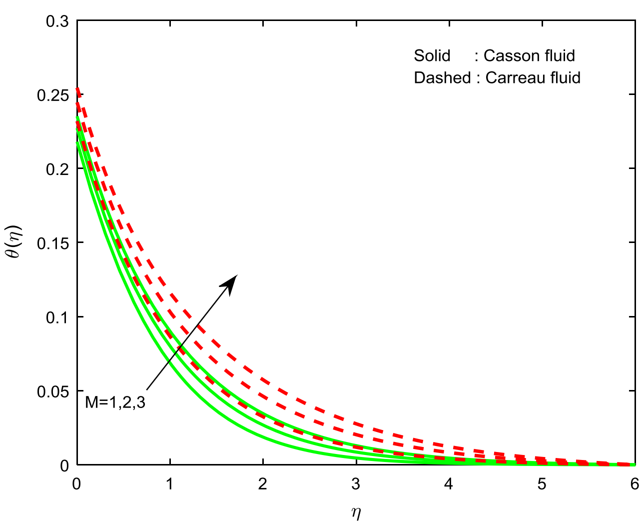

Fig. 3 Effect of M on temperature fields.

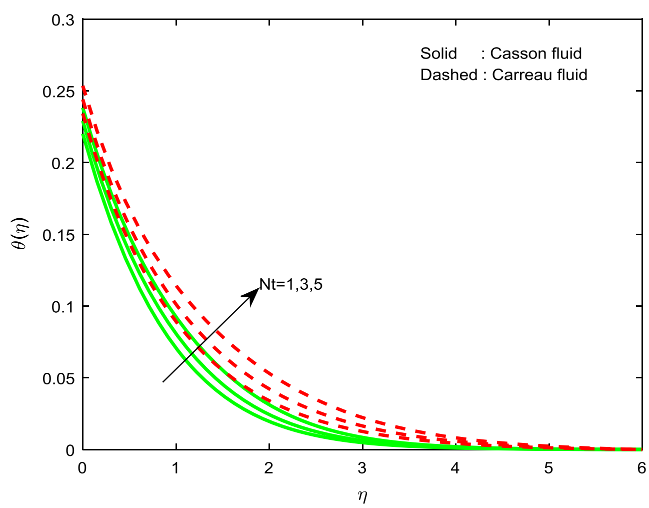

Fig. 6 Effect of Nt on temperature fields.

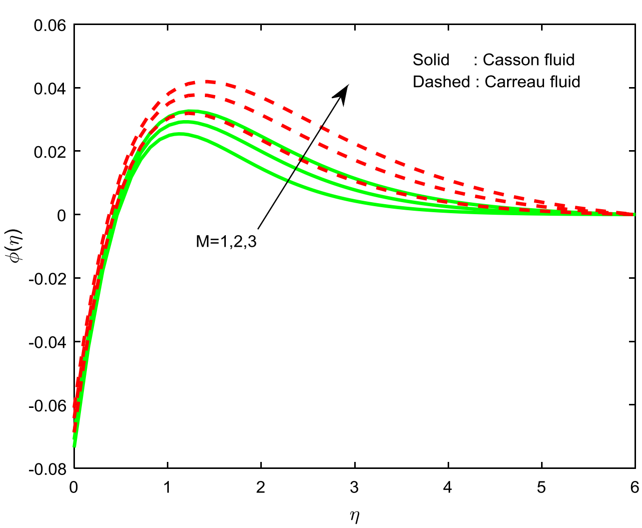

Fig. 4 Effect of M on concentration fields.

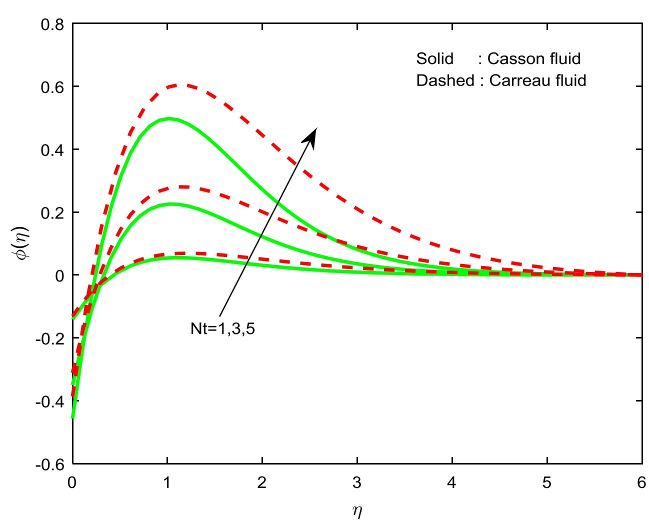

Fig. 7 Effect of Nt on concentration fields.

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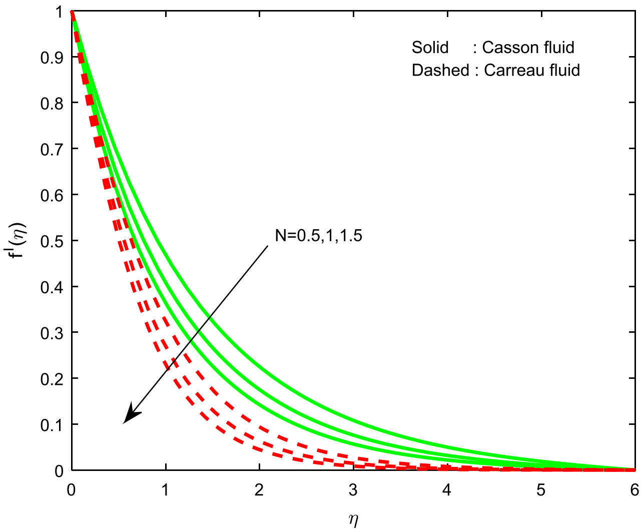

Fig. 8 Effect of N on velocity fields.

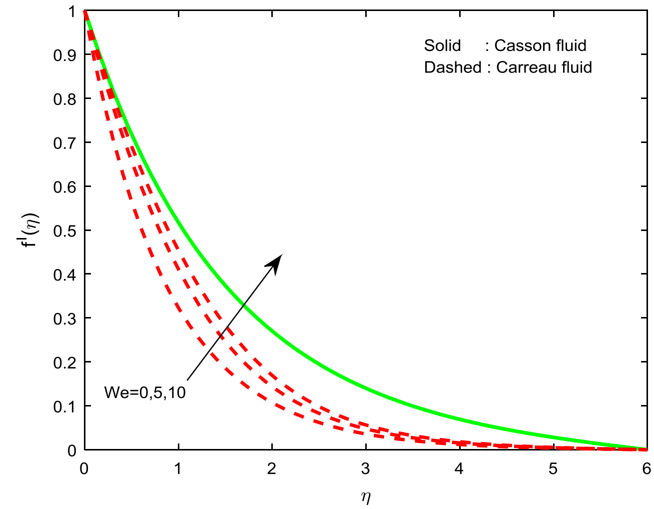

Fig. 11 Effect of We on velocity profile.

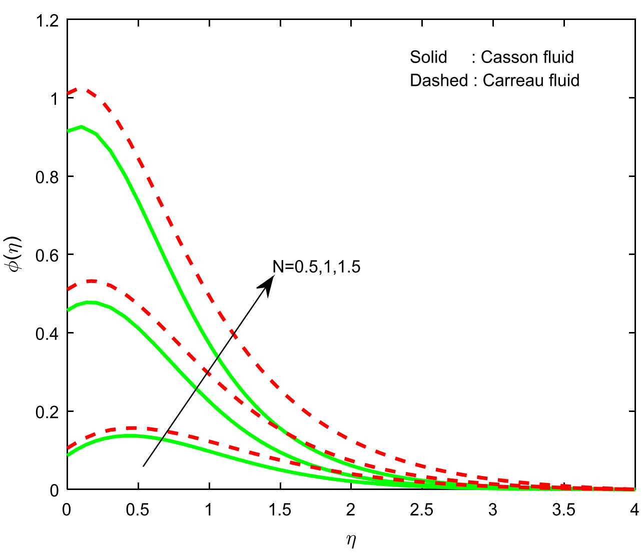

Fig. 9 Effect of N on concentration fields.

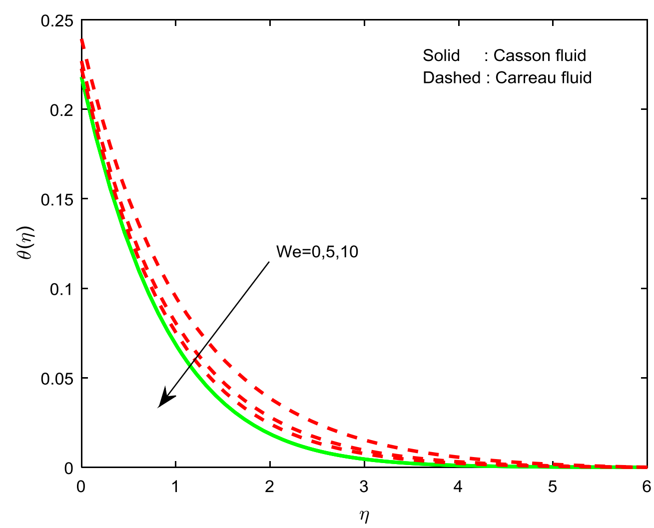

Fig. 12 Effect of We on temperature fields.

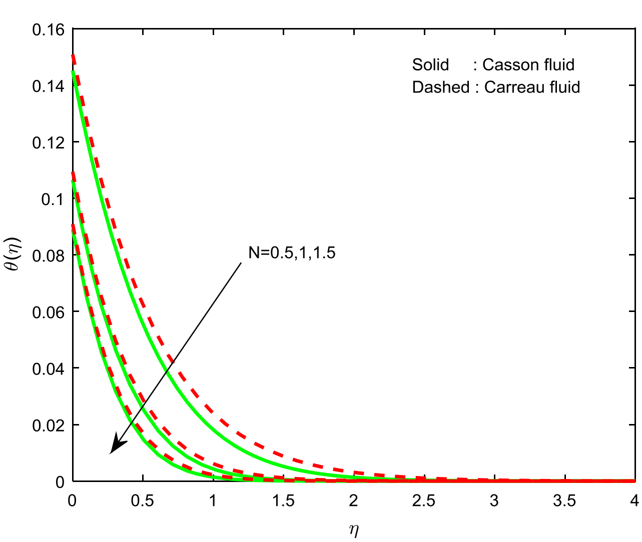

Fig. 10 Effect of N on temperature profiles.

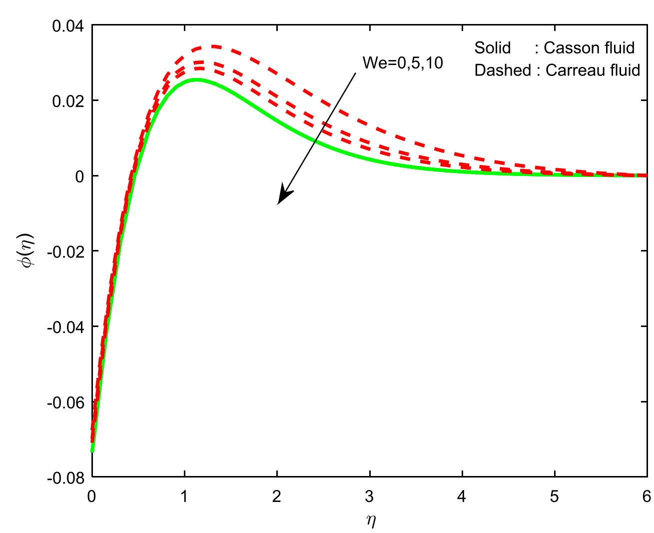

Fig. 13 Effect of We on concentration profiles.

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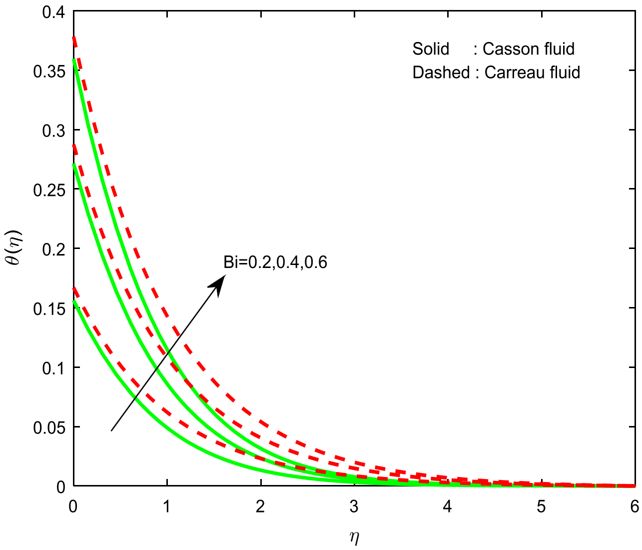

Fig. 14 Effect of Bi on temperature fields.

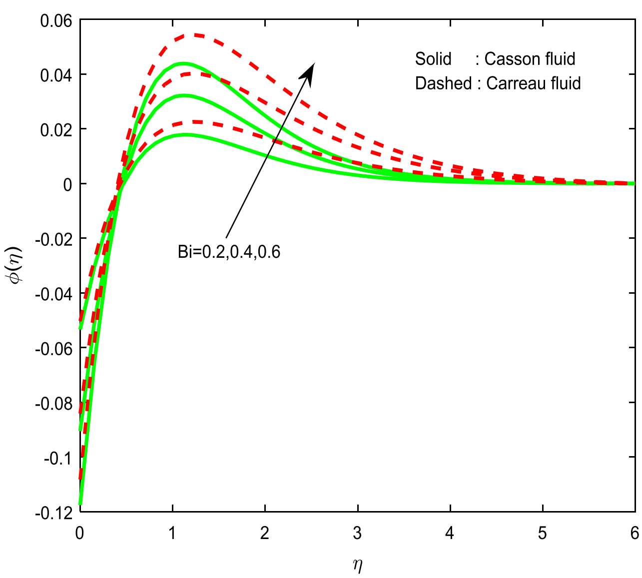

Fig. 15 Effect of Bi on concentration fields.

parameter, C – concentration of fluid, $(\rho c)_p$ – heat capacity of the pressure, $(\rho c)_f$ – fluid heat capacity, $\tau = \frac{(\rho c)_p}{(\rho c)_f}$ – nanoparticle to base fluid heat capacity ratio, T_∞ – temperature away from the fluid, D_B – coefficient Brownian diffusion and D_T – coefficient thermophoresis diffusion. Here applied magnetic field is $B(x) = B_0 e^{Nx/2L}$, B_0 being constant.

The relevant boundary conditions for the physical problem are given by:

$$u = U, v = 0, -k\frac{\partial T}{\partial y} = h_f(T_f - T), D_B\frac{\partial C}{\partial y} + \frac{D_T}{T_\infty}\frac{\partial T}{\partial y} = 0 \text{ at } y = 0$$

$$u \to 0, v \to 0, T = T_\infty, C = C_\infty \text{ as } y \to \infty \quad (5)$$

Introducing the similarity variables as:

$$u = U_w = Ue^{\frac{Nx}{L}} f'(\eta), v = -\sqrt{\frac{\upsilon U}{2L}} e^{Nx/2L}\{f(\eta) + \eta f'(\eta)\},$$
$$\eta = y\sqrt{\frac{U}{2\upsilon L}} e^{Nx/2L} \quad (6)$$

And upon substituting Eq. (6) in Eqs. (2)–(4) reduced to:

$$\left(1 + \frac{1}{\beta}\right)f''' + N(ff'' - 2f'^2) + \frac{3(n-1)We}{2} f''' f''^2 - Mf' = 0 \quad (7)$$

$$\theta'' + PrN(f\theta' - f'\theta) + Nb\theta'\phi' + Nt\theta'^2 = 0 \quad (8)$$

$$\phi'' + ScN(f\phi' - f'\phi) + \frac{Nt}{Nb}\theta'' = 0 \quad (9)$$

with boundary conditions being

$$f(0) = 0, f'(0) = 1, \theta'(0) = -Bi(1 - \theta(0)), Nb\phi'(0) + Nt\theta'(0) = 0 \quad (10)$$

$$f'(\eta) \to 0, \theta(\eta) \to 0, \phi(\eta) \to 0 \text{ as } \eta \to \infty \quad (11)$$

where $M = \frac{2\sigma B_0^2 L}{U\rho}$ – magnetic parameter, $We = \frac{U^3 e^{3x/L}\Gamma^2}{\upsilon L}$ – Weissenberg number, $Sc = \frac{\upsilon}{D_B}$ is Schmidt number, $Pr = \frac{\upsilon}{\alpha}$ is Prandtl number, $Nt = \frac{D_T(T_f - T_\infty)(\rho c)_p}{T_\infty \upsilon(\rho c)_f}$ is the thermophoresis parameter, $Nb = \frac{D_B C_\infty (\rho c)_p}{\upsilon(\rho c)_f}$ is the Brownian motion is parameter. Physical quantity of interest are local Nusselt number and local Skin friction coefficient are given by

$$C_f = \frac{\tau_w}{\rho U_w^2} \text{ where}$$
$$\tau_w = \left(1 + \frac{1}{\beta}\right)\left(\frac{\partial u}{\partial x}\right) + \frac{(n-1)\Gamma^2}{2}\left(\frac{\partial u}{\partial y}\right)^3,$$
$$Nu_x = \frac{xq_w}{k(T_f - T_\infty)} \quad (12)$$

where k - thermal conductivity and q_w, q_m are the heat and mass fluxes are given by

$$q_w = -k\left(\frac{\partial T}{\partial u}\right)_{y=0} \quad (13)$$

In Eqs. (12) and (13), substuting Eq. (6) we get

$$\sqrt{Re}C_f = \left(1 + \frac{1}{\beta}\right)f''(0) + \frac{(n-1)We^2}{2}(f'(0))^3, \sqrt{\frac{2}{Re}}Nu_x = -\theta'(0) \quad (14)$$

where $Re = \frac{U_w L}{\upsilon}$ local Reynolds number.

3. Solution procedure

The numerical solution of the governing system of coupled ODEs (8)–(10) under the boundary restrictions Eq. (11) is obtained with the assist of Runge–Kutta based shooting technique with step size as $\eta = 0.001$ and relative error as 10^{-6}. Set of nonlinear ordinary differential equations are of third order in f second order in θ and ϕ are first reduced into a system of simultaneous ordinary equations as shown below. In order to solve this system using Runge-Kutta with shooting method, one should require three more missed initial conditions. However, the values of $f'(\eta)$, $\theta(\eta)$ and $\phi(\eta)$ are known when

Table 1 Variation in physical quantities $f''(0)$ and $-\theta'(0)$ for Casson fluid.

M	Nb	Nt	N	We	Bi	$f''(0)$	$-\theta'(0)$
1						−0.667199	0.234613
2						−0.881896	0.231852
3						−1.054049	0.229459
	0.5					−0.667199	0.234613
	1					−0.667199	0.234613
	1.5					−0.667199	0.234613
		1				−0.667199	0.233988
		3				−0.667199	0.231301
		5				−0.667199	0.228529
			0.5			−0.781292	0.256502
			1			−0.940860	0.268056
			1.5			−1.076868	0.273297
				0		−0.667199	0.234613
				5		−0.667199	0.234613
				10		−0.667199	0.234613
					0.2	−0.667199	0.168751
					0.4	−0.667199	0.291399
					0.6	−0.667199	0.384186

Table 2 Variation in physical quantities $f''(0)$ and $-\theta'(0)$ for Carreau fluid.

M	Nb	Nt	N	We	Bi	$f''(0)$	$-\theta'(0)$
1						−0.908595	0.230444
2						−1.104862	0.226645
3						−1.243470	0.223682
	0.5					−0.908595	0.230444
	1					−0.908595	0.230444
	1.5					−0.908595	0.230444
		1				−0.908595	0.229744
		3				−0.908595	0.226809
		5				−0.908595	0.223951
			0.5			−1.018291	0.254756
			1			−1.158125	0.267185
			1.5			−1.267354	0.272744
				0		−1.153748	0.228205
				5		−0.787228	0.231919
				10		−0.692572	0.233194
					0.2	−0.908595	0.166596
					0.4	−0.908595	0.284964
					0.6	−0.908595	0.373002

Table 3 Validation of the values of $-\theta'(0)$ for various different of Prandtl number when $We = 0$ and $\beta \to \infty$.

Pr	Magyari and Keller [25]	Present study
0.5	−0.330493	−0.33049321
1	−0.549643	−0.54964320
3	−1.122188	−1.12218832
5	−1.521243	−1.52124342

$\eta \to \infty$. These end conditions are used to obtain the unknown initial conditions at $\eta = 0$ using shooting technique.

4. Results and discussion

The transformed set of ODE's Eqs. (7)–(9), subject to the Eqs. (10) and (11) are solved with the help of R-K based shooting technique. We illustrated the effect of several physical parameters namely, magnetic field parameter, Brownian moment parameter, exponential parameter, thermophoresis parameter, Biot number and Weissenberg number on velocity, thermal and concentration fields. In this study, we examined the pertinent values as $Pr = 6.8$, $M = 1$, $Nb = Nt = 0.5$, $Sc = 1$, $N = 0.2$, $We = 2$, $Bi = 0.3$. We also computed the wall friction along with reduced Nusselt number.

Figs. 2–4 show the velocity, thermal and concentration fields while changing magnetic field values. It is noticed that velocity field depreciate with rising values of M and opposite trend is founded in thermal and concentration profiles. Generally, increasing magnetic field produced the resistive force to the flow, such flow is known as Lorentz force. These negative forces depreciate the velocity profiles and enhance the concentration and thermal bounder layers.

Fig. 5 depicts the variation in concentration profiles as results of changes in Nb. It is found that increasing values of

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Nb depreciate the concentration field of both fluids. Physically, an increase in Brownian motion, the random movement of molecules enhances, his result in increases in the temperature profiles. Figs. 6 and 7 reveal the variation on *Nt* on thermal and concentration profiles. It is noticed that rising values of *Nt* enhancing both thermal and concentration profiles.

Figs. 8–10 presented the variation of exponential parameter on flow, thermal and concentration fields. It is clear that increasing the exponential parameter decreases both velocity and thermal boundary layer thickness. A reverse action is observed in concentration profiles. Generally, increasing values of exponential parameter depreciate the momentum, thermal boundary layer thicknesses. Figs. 11–13 are plotted the effect of *We* on the velocity, thermal and concentration fields. Physically, Weissenberg number is directly correlative with time constant and inversely correlative with viscosity. The time constant to viscosity ratio is larger for increasing the values of Weissenberg number. For this reason Weissenberg number enhances the velocity profiles and declines thermal and concentration fields.

Figs. 14 and 15 displayed the variation on Biot number on thermal and concentration fields. It is clear that increasing values of Biot number increases both temperature and concentration fields. Physically, higher values of Biot number causes to increase in the temperature difference. Tables 1 and 2 demonstrate the modification in friction factor and reduced Nusselt number of Casson and Carreau fluids for different values of pertinent parameters. It is found that rising values of thermophoresis parameter depreciate the heat transfer rate of both fluids. Converse action has been noticed for values of the Biot number and exponential parameter. But values of exponential parameter depreciate the friction factor. Weissenberg number and Brownian motion does not show notable variation in friction factor and Nusselt number. Table 3 displays the contrast of the current result with the pertained results. We found that there is an eminent agreement of the present solutions with the existed solution.

5. Conclusions

Theoretical investigation is carried out for analyzing the thermal and concentration behavior of Casson and Carreau fluids. Passively control of nanoparticles at the surface is physically more realistic condition. So, we considered Buongiorno model. Adequate similarity transforms are invoked to put the flow governing equations in dimensionless form. Then after, the transformed equations are solved by means of an effective R-K based shooting method. Dual solutions are presented for both fluid cases.

The numerical findings are as follows:

- Thermal and concentration transport of Casson fluid is comparatively higher than Carreau fluid.
- Biot number effectively enhances the heat transfer rate of both Carreau and Casson fluids.
- Brownian moment and thermophoresis parameters works like controlling parameters of thermal and concentration boundary layers.
- Carreau fluid is highly affected by the Lorentz force when equated with Casson fluid.
- Exponential parameter effectively enhances the heat transfer rate of both fluids.

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