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FLOW AND HEAT TRANSFER OF RADIATIVE CASSON/CARREAU LIQUID FLOW ALONG A NONLINEARLY EXTENDING SURFACE

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Abstract:

The chief drive of the contemporary article is to inspect the thermophysical physiognomies of radiative Casson/Carreau liquid flow along a nonlinearly extending sheet witha non-uniform thermal rise/falleffects.The prime novelty of this study is to determine the enhanced thermal transmission features of Casson/Carreau fluid. Simultaneous solutions are exhibited for Casson fluid and Carreau fluid cases graphically. The arisingperiphery layer expressions are converted into nonlinear ODE's using relevant dimensionless transfigurations. Further, the attained expressions areunravelled by employingthe bvp5c MATLAB script. Moreover, the impact of various physical factors over the flow fields is conferred and displayed through graphs. Along with this, the numerical results of frictional drag, thermal transport is inspected as well as tabulated for the two liquids Casson and Carreau separately. The significant outcome of the study is that the thermal transport rateismore prominent in the Carreau liquid case than the Casson fluid case. Furthermore, improvement in the radiative flux boosts the thermal boundary layer rigidity.

Keywords: Non-Newtonian, Casson/Carreau liquid, MHD, Thermal radiation.

Introduction

The Rheological properties and massive applications of non-Newtonian liquids in chemical and plastic processing industries, mining industries, lubrication, and biomedical flows have triggered many researchers to perform the study on these fluids. Non-Newtonian liquids are the ones that disagree with Newton's laws of viscosity. Williamson, Oldroyd-B, Casson, and Carreau are some such important fluids. Three-phase Casson-Carreau liquids in the presence of diverse thermophysical features, considering heterogeneous and homogeneous responses over the stretching surface are analyzed by Raju et al. [1]. A relative study of homogeneous and heterogeneous reactions of three-dimensional Casson-Carreau fluids is performed by Gireesha et al. [2]. They noticed that the flow rate of Carreau liquid is less prominent in comparison to Casson liquid for numerous values of the magnetic field parameters. Later, electrically conducting Casson/Carreau liquid stream considering multiple slips over an unsteady elongated sheet is studied by Raju et al. [3]. They determined that the thermal boundary layer rigidity of Casson liquid is less in comparison to Carreau liquid. Later, Kumaran et al. [4] elucidated the sway of the thermal rise/fall parameter of the MHD Casson and Carreau fluid stream across a revolving paraboloid. The influence of the thermal rise/fall parameter upon MHD Casson-Carreau liquid in the presence of dust, as well as nanoparticles of graphene, is investigated by Santhosh et al.[5]. The features of viscid dissipation, also the radiation heat parameter on 2-D unsteady Casson-Carreau fluid flow using the Buongiorno model is examined by Emran et al. [6]. Further, the two-dimensional Casson-Carreau fluids embedded with dust particles considering the convective conditions over the stretching sheet are examined by Mahantesh et al. [7]. Kumar et al. [8] obtained the comparative study of Casson-Carreau nanofluids suspended in a Darey-Forchheimer medium accommodating thermal diffusion and diffusion thermos effects. Sulochana et al. [9] piloted a mathematical analysis to investigate the boundary layer analysis on the MHD flow of Casson and Carreau hybrid-nanoliquid through an incessant moving needle with considering radiation.

MHD is the physical phenomenon that deals with the study of magnetic possessions and the conductance of electrically influencing liquids in the presence of exterior magnetic field. It has gained much importance due to its application in various fields like fluid pumping, power generation, biomedical, and many more. Sarpakaya [10] was the first to work on the MHD flow of non-Newtonian liquids. Momentum and thermal transport physiognomies of MHD Maxwell, Jeffery, and Oldroyd-B nanoliquids across a straightened sheet considering thermal radiation and suction effects are elucidated by Sandeep et al. [11]. The outcome of their study statesthat the Jeffery nanoliquid has a better thermal transport rate than the other two nanofluids considered. The unsteady laminar boundary layer flow of electically conducting fluids across the widened sheet in the occurrence of heat generation and thermal radiation is performed by Ahmed et al. [12]. Further, Iskander et al. [13] obtained the simultaneous solutions for Newtonian and non-Newtonian fluid flows considering the Joule heating, and Buongiorno slip effect. They determined that the thermal transfer rate in normal fluids is less compared to Casson fluid. Also, declared that the Buongiorno slip controls the thermal boundary layer and concentration attributesLater Jian-Cun Zhou et al. [14] explained the magnetohydrodynamic Casson fluid flow in the manifestation of an uneven heat source considering radioactive slip. Heat along with mass transport characteristics of Williamson nanofluid under the existence of heat generation/absorption is illustrated by Yi-Xia Li et al. [15]. They exposed that the rate of thermal transport declines upon increasing the Buongiorno slip effect. Further impact of Joule heating and heat generation on unsteady two-phase deflection point flow of MHD Casson liquidover elongated and shrinking sheets under the attendance of mixed convection, slip condition, and convection condition is elucidated by Riaz et al. [16]. Entropy generation of Newtonian/non-Newtonian liquids with inclined magnetohydrodynamic slip considering permeable media is deliberated by Praveen et al. [17]. Moreover, Abdulmajeed [18] performed, a statisticalanalysis to study the thermophysical attributes of hybrid nano Williamson liquid.vicinity.

Periphery layer flow across a straightened sheet is emerging as an important part of research because of countless applicability in industries like fiber spinning, and glass bowling. The impact of viscid dissipation, nonuniform thermal rise/fall, andJoule heating on micropolar fluid flow across an extendableexterior is scrutinized by Anantha et al. [19]. They revealed that

Eckart number and radiation heat constraint upsurge the thermal conductivity. Later, theinfluence of thermal conductivity and variedviscidnessof electrically conducting Carreau liquid past an extendableregion is analyzed by Abbas et al. [20]. Entropy generation of two-phase Carreau liquid across a widened sheet in an existence of radiation heat is demonstrated by Rabeeah et al. [21]. An impact of suction and radiation parameters considering convective boundary conditions on two-phase MHD Casson hybrid nanofluid over linear stretching and shrinking sheets is analyzed by Mousavi et al. [22]. Later, the influence of Soret and Dufour's effects on Casson fluid flow across an elongating surface in the attendance of convective-diffusive conditions is observed by Venkata Ramadu et al.[23]. However, a numerical study is carried out by Rehaman et al. [24] to detect the impression of buoyancy parameter along with the radiation effect on micropolar nanofluid past anextended sheet. They discovered that the enhancement of the numerical values of the buoyancy parameter enriches the velocity profile. Heat and mass transport characteristics of hybrid nanofluid across a power law velocity elongating sheet using the darcy-forchhimer ideal is studied by Sulochana et al. [25].

Radiation is the method where energy is dissipated from a heated region in every direction. It occurs when the energy difference is greater in surface temperature and ambient surface. The wire coating procedureis the use of coating material for 3rd-grade non-Newtonian liquid under the existence of radiation heat is exemplified by Khan et al. [26]. Their study illustrated that an upsurge in the heat radiation parameter increases the velocity/temperature of the dissolve polymer thus increasing the coating process. The stimulus of radiation heat on entropy analysis for unsteady Casson nanoliquid flow over the enlarging vertical plate is elucidated by Shit et al. [27]. The consequence of radiation on non-Newtonian liquid flow thru the Riga plate is analyzed by Mallawi et al. [28]. Later, the bioconvective phenomenon considering multiple slip effect, for Casson and Maxwell fluids under the attendance of the thermal radiation parameter is elucidated by Anil Kumar et al. [29]. They concluded that the upliftment of the radiation upsurges the temperature. Further, Muhammed et al. [30] employed the Cattaneo-Christove model and revised the nanofluid model to study the sway of thermal radiation on chemically reactive Maxwell nanofluid. An impression of thermal radiation on a convective micropolar hybrid nanofluid considering suction/injection, joule heating, and viscous dissipation parameter is explored by Priya et al. [31].

With the inspiration of the early research, in the present framework, we have tried to study the thermofluid features of Casson and Carreau fluids which are highly industrial applications. The flow is generated by a nonlinear extending surface. Dual solutions are presented to analyze the flow characteristics of the fluids. The bvp5c Matlab package is used to resolve the ODE's. Further, the consequences of the pertinent governing factors on flow fields along with local-Nusselt number, friction-drag coefficient are demonstrated pictorially[34].

2.Mathematical formulation

A 2Dtime-independentmagnetohydrodynamic (MHD) flow past a nonlinearly elongated sheet under the attendance of nonumiform heat rise/falland radiativeheat is considered for the current study.Here $U_w = ax^{\delta}$ denotes variable stretching velocity, $B(x) = B_0 x^{2\delta-1}$ represents a magnetic fieldof the fluid.Variable surface temperature is given by $T_w = T_\infty + bx^{2\delta-1}$.

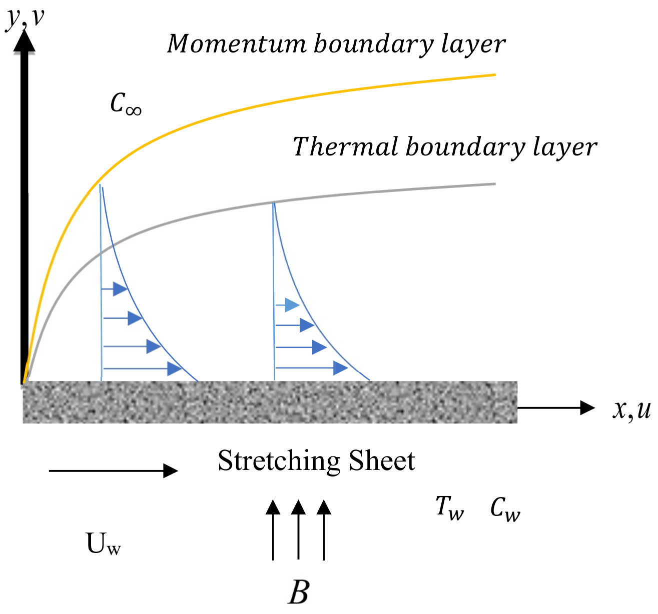

Fig. 1: Flow configuration

The governing equations are

$$u_x + v_y = 0, \quad (1)$$

$$\left(uu_x + vu_y\right) = \frac{\mu_f}{\rho_f}\left\{\left(1+\frac{1}{\beta}\right)u_{xx} + \frac{3(\delta-1)}{2}\Gamma^2 u_y^2 u_{yy}\right\} - \frac{\sigma_f B^2(x) u}{\rho_f}, (2)$$

$$\left(\rho C_p\right)_f \left(uT_x + vT_y\right) = \alpha_f T_{yy} + q''' - \frac{16\sigma^* T_\infty^3}{3k^*}\left(T_{yy}\right), (3)$$

and the pertinent boundary restrictions are

$$\left.\begin{array}{l} u = U_w(x) = ax^\delta, v = 0, T = T_w = T_\infty + bx^{2\delta-1} \text{ at } y = 0 \\ u \to 0, T = T_\infty \text{ as } y \to \infty \end{array}\right\}, (4)$$

Here x and y are the directionsalongsideand vertical to the sheet respectively. u is the horizontal and v represents vertical velocity along xy – direction. μ_f - coefficient of viscosity, $\left(\rho C_p\right)_f$ - heat capacitance, ρ_f -density, β_f - thermal expansion, $\alpha_f = \frac{k_f}{\left(\rho C_p\right)_f}$ is thermal diffusivity. q_r is radiative heat flux,and $\beta = \frac{\mu_{B\sqrt{2\pi_c}}}{\tau_0}$ is theCasson parameter.

The irregular heat rise/fall parameter q''' is outlined as,

$$q''' = \frac{(T_w - T_\infty) k_f U_w}{\nu_f}\left\{A^* f' + B^* \frac{(T - T_\infty)}{(T_w - T_\infty)}\right\}, \qquad (5)$$

Roseland approximationis given by,

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

By the use of Taylor's series about T_∞ (the ambient temperature) and ignoring greater order terms, T^4 can be expressed as

$$T^4 \cong 4T_\infty{}^3 T - 3T_\infty{}^4, (7)$$

The governing nonlinear ODEs are

$$f'''\left\{\left(1+\frac{1}{\beta}\right)+\frac{3(\delta-1)}{2}Wef''^2\right\}+ff''-\frac{2\delta}{\delta+1}f'^2-Mf'=0, (8)$$

$$\left(1+\frac{4}{3}R\right)\theta''+\Pr f\theta'+A^*f'+B^*\theta=0, (9)$$

Where $\rho_f,\ \mu_f, \left(\rho C_p\right)_f, \sigma_f, k_f, \beta_f$ are respectively the density,effective viscosity, thermal conductivity,electrical conductivity,and thermal conductivity, thermal expansion coefficient.

The under laying dimensionless similarity transmutations are used to reduce the equations (2) - (4) into dimensionless ODE.

$$\zeta=\sqrt{\frac{(\delta+1)u}{2\nu x}}y,\ \psi(x,y)=\sqrt{\frac{2\nu u x}{(\delta+1)}}f(\zeta),\ \theta(\zeta)=\frac{T-T_\infty}{T_w-T_\infty}, (10)$$

Here $\zeta(x,y)$, represents the similarity variable, ν representsthe kinematic viscosity of a fluid $\theta(\eta)$ is the dimensionless temperature and $\psi(x,y)$ represents for stream function demarcated as

$$u=\frac{\partial\psi}{\partial y},\quad v=-\frac{\partial\psi}{\partial x}, \qquad (11)$$

Subject to the following non-dimensional conditions

$$\left.\begin{aligned} &f(\zeta)=0,\ f'(\zeta)=1,\ \theta(\zeta)=1\ \text{ at } \zeta=0\\ &f'(\zeta)=0,\ \theta(\zeta)=0,\ \text{ as } \zeta\to\infty,\end{aligned}\right\}, \quad (12)$$

Here M, δ, R, $\Pr$, We, A^* and B^* is symbolizes the magnetic field,power-law index,radiation, Prandtl number,Weissenberg number, nonuniform heat source/sink respectively.They are stated as

$$\left.M=\frac{\sigma_f B_0{}^2}{\rho_f a},\ R=-\frac{4\sigma^* T^3{}_\infty T}{k_f k^*{}_f}, \Pr=\frac{\nu_f}{\alpha_f},\ , We=\frac{a^{\frac{3}{2}}x\Gamma}{\sqrt{\upsilon}},\right\}, (13)$$

The C_f and Nu_x are defined as

$$C_f = \frac{\tau_w}{\rho_f {u_w}^2} \quad \text{and} \quad \mathrm{Nu}_x = \frac{x q_w}{k_f \left(T_w - T_\infty\right)}, \tag{14}$$

where

$$\tau_w = \mu_f \left(\frac{\partial u}{\partial y}\right)_{y=0}, \quad \text{and} \quad q_w = \left.\left[-\left(1+R\right)\left(\frac{\partial T}{\partial y}\right)\right]_{y=0},\right\}, \tag{15}$$

Usingthe nondimensional variables, we get

$$\left(\mathrm{Re}^x\right)^{\frac{1}{2}} C_{f_x} = \left\{\left(1+\frac{1}{\beta}\right) f''(0) + \frac{3(\delta-1)}{2} We^2 \left(f''(0)\right)^3\right\}\left(\frac{\delta+1}{2}\right)^{\frac{1}{2}}, \tag{16}$$

$$\left(\mathrm{Re}_x\right)^{-\frac{1}{2}} Nu_x = -\left(\frac{\delta+1}{2}\right)^{\frac{1}{2}} . \left(1+\frac{4}{3}R\right)\theta'\left(0\right) \tag{17}$$

where $\mathrm{Re}_x = x u_x\left(x\right)/\nu_f$.

Results and discussions

The present framework portrays the impacts of parameter on velocity, temperature along with wall friction C_{fx} and Nusselt number Nu_x. The dual solutions for both Casson and Carreau fluids are displayed through graphs and tables.We considered $M = 2, R = 0.5, We = 0.3, \delta = 2, A^* = B^* = 0.5, \beta = 0.1$ and these are kept constant during the entire study and others are varied as indicated in figures and tables

Plots2-3depict the impact of M occurring on $f'(\zeta)$ and $\theta(\zeta)$.Clearly from the above plots we notice that, an upturn in M decelerates the velocity profiles and accelerates thermal profiles. Physically, this happensowing to the development of Lorentz force which causes resistance to the flowing stream. The study exposes that the magnetic force assimilates an additional layer of resistance to the stream, slowing the flow of fluid and increasing the thermal description of the fluid.Figs. 4–5 represents the sway of δ on $f'(\zeta)$ and $\theta(\zeta)$. It isevident that advanced values of δ deteriorate $f'(\zeta)$ and proliferate $\theta(\zeta)$.

Plot6interprets the effect of R on thermal field and depicts that the hike in radiation parameter enhances the thermal description.It is becausemainly, thermal emission includes an exterior heat energy thatsums up the movements of conductive particles leading to rise in the thermal profile. Figs. 7 – 8 are sketched to embarkthe consequence of A^* and B^* on thermal profile.We perceive from the graph that the upgradation of A^* and B^* improves the heat transferal capacity of the fluids. The positive values of A^* and B^* are responsible factors of heat generators, theydischargeenergy to fluid causingthe raise inthermal conductivity of the fluid.

Figs. 9–10 display the influence of β uponthe dimensionless $f'(\zeta)$ and $\theta(\zeta)$ distributions. An escalation in β deteriorates the velocity field as the viscosity of the momentum boundaryfilm is enlarged by the growth of the value of β.At the same time,it upgrades the temperature curves. Figs.11 – 12 are put forth to demonstrate the stimulus of We upon the $f'(\zeta)$ and $\theta(\zeta)$. The escalation in We depletes the velocity distribution and improves the energy profiles. Physically, We is proportionate to the ratio of time constant towards viscosity, which is larger for increasing values of We ,as a result, there is advancement in the temperature of the fluid.

Figs. 13 – 14 are outlined to show the influence A^* and B^* on Nusselt number. From the figurewe observe that the thermal transfer is significantly more in the Carreau fluid than in the Casson fluid. Fig. 15pictures the power of R on rate of therma transport. Interestingly, the thermal transfer capability is significantly higher in Carreau fluid than in Casson fluid for increasing values of R. Table 1 is formulated to show the disparities in frictionaldrag factor C_{fx} considering the physical parameters M , δ , β , We for both Casson and Carreau fluid flows. It followsfrom the table that, escalating values of M , δ marks the retardation of thermal transfer whereas a hike in β , We , will boost the heat transportrate forCasson as well asCarreau fluids. Table 2 portrays the responses of Nu_x on a few selected physical parameters like, M , δ , R , A^* , B^* , β , We .It is analyzed that enhancement of M , A^* , B^* deteriorates $-\theta'(0)$ and upgradation of δ , R , β , We upgrades Nu_x for both fluid flows. Table 3 portrays the validation of the results for local Nusselt number under the impact of power-law index parameter with the previously published literature and we found an excellent agreement between them.

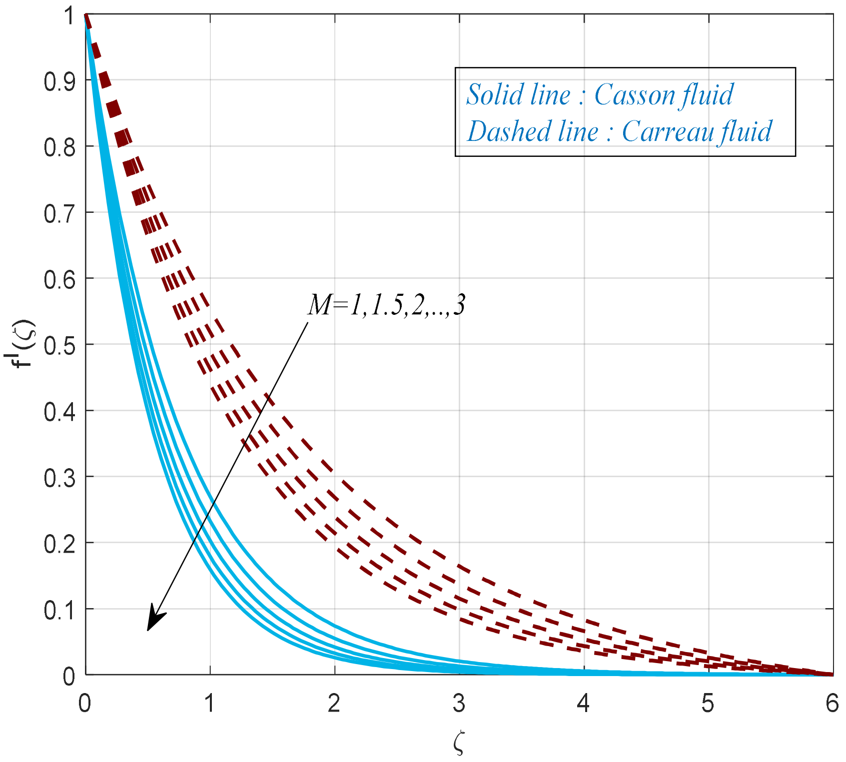

Fig. 2 Preeminence of M over $f'(\zeta)$

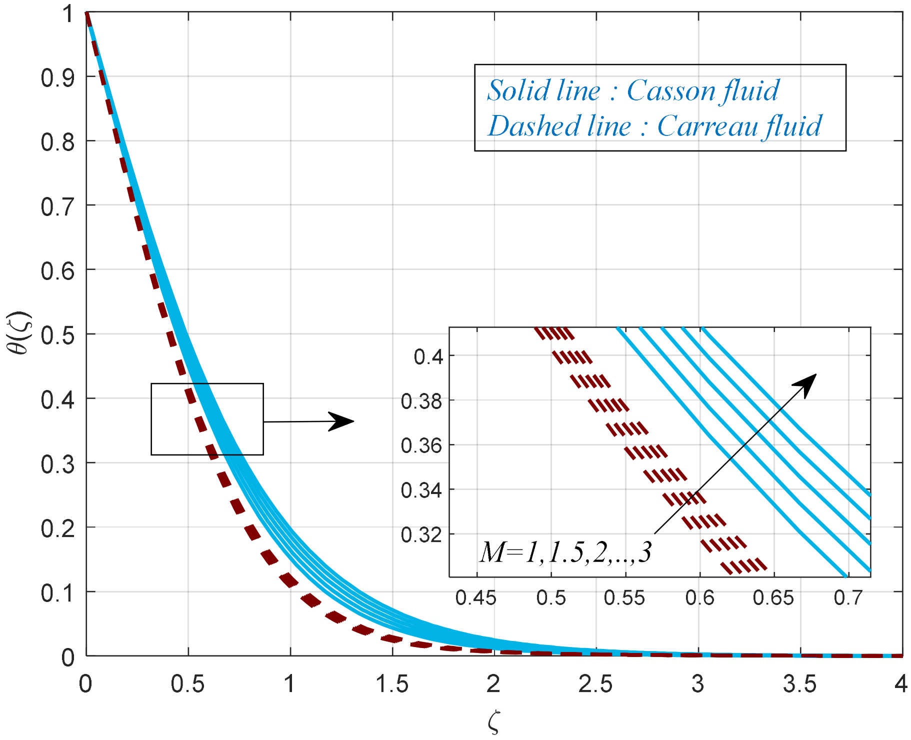

Fig. 3 Preeminence of M over $\theta(\zeta)$

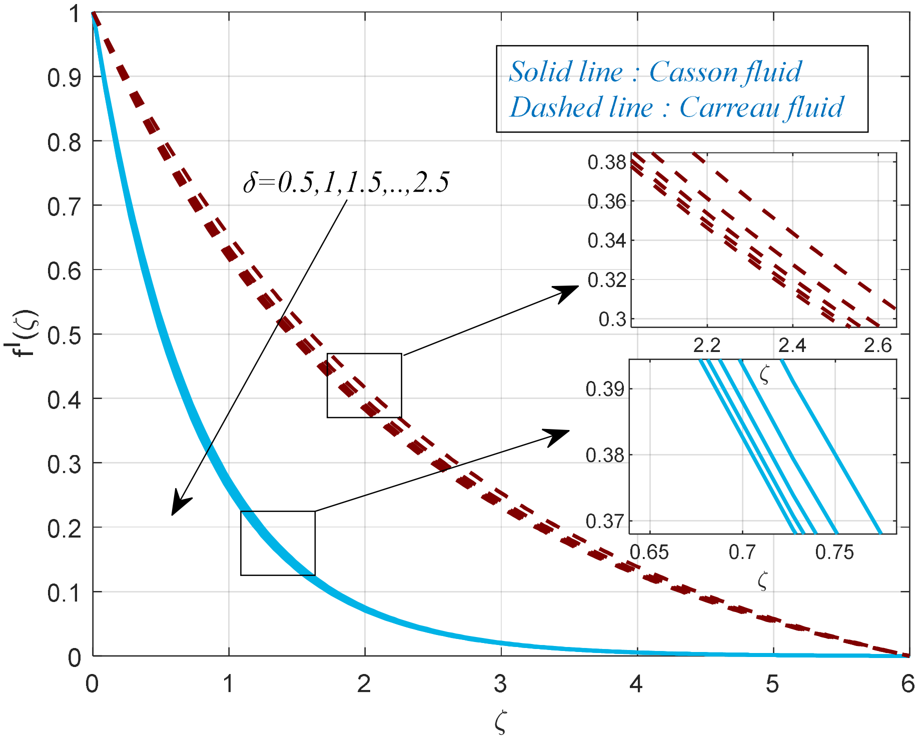

Fig. 4 Preeminence of δ over $f'(\zeta)$

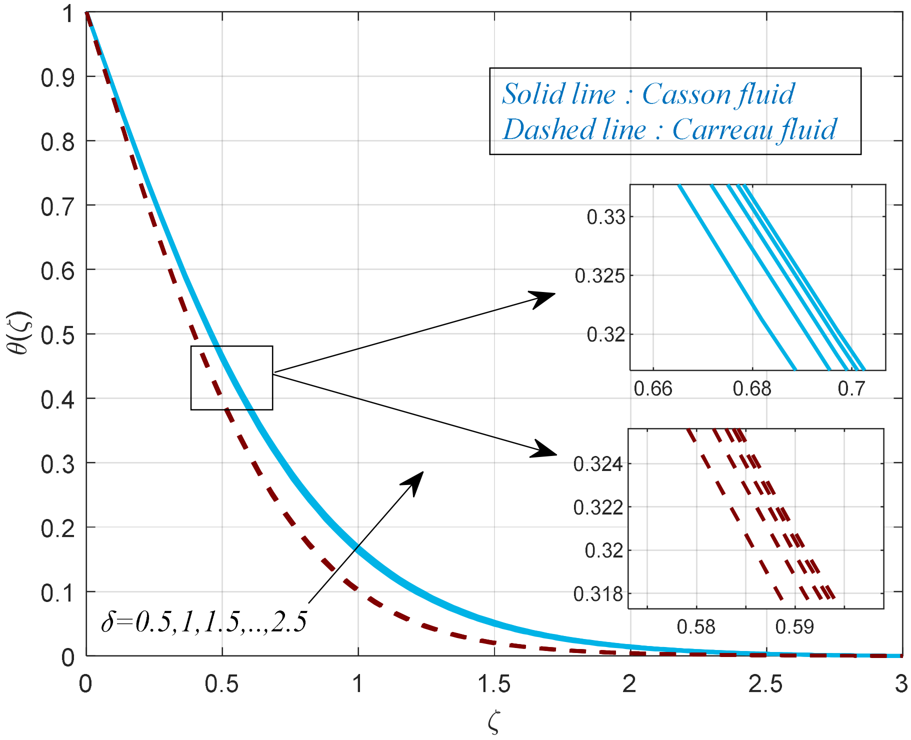

Fig. 5 Preeminence of δ over $\theta(\zeta)$

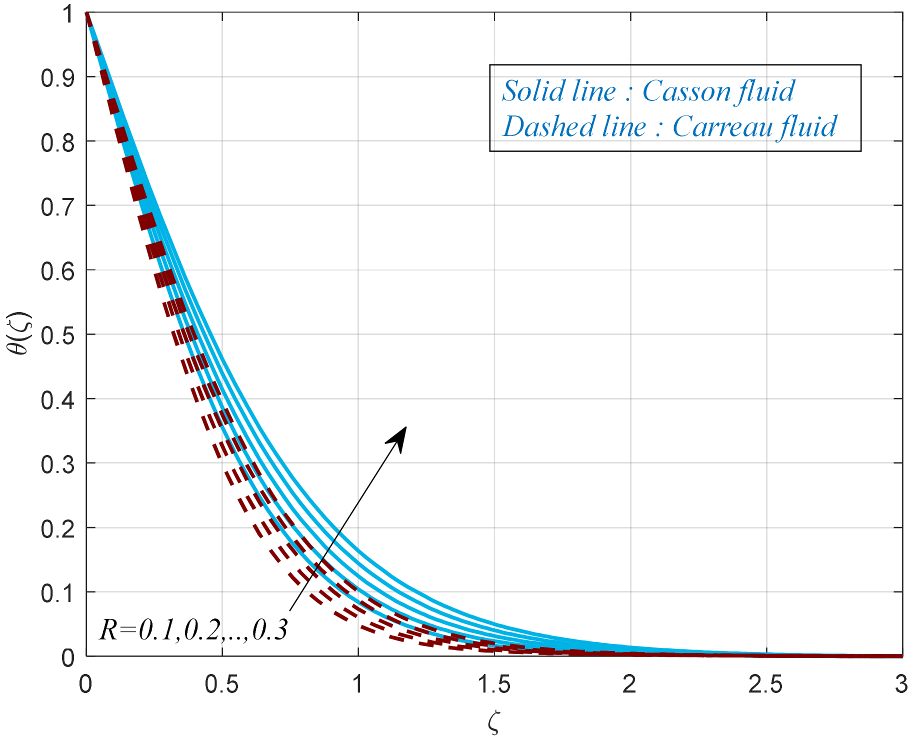

Fig. 6 Preeminence of R over $\theta(\zeta)$

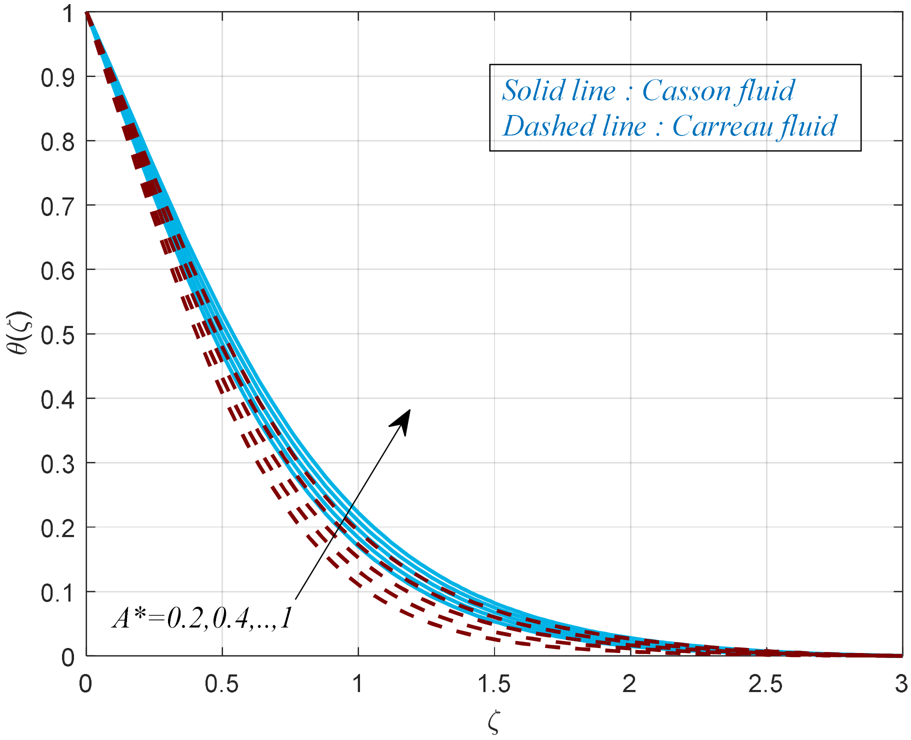

Fig. 7. Preeminence of A^* over $\theta(\zeta)$

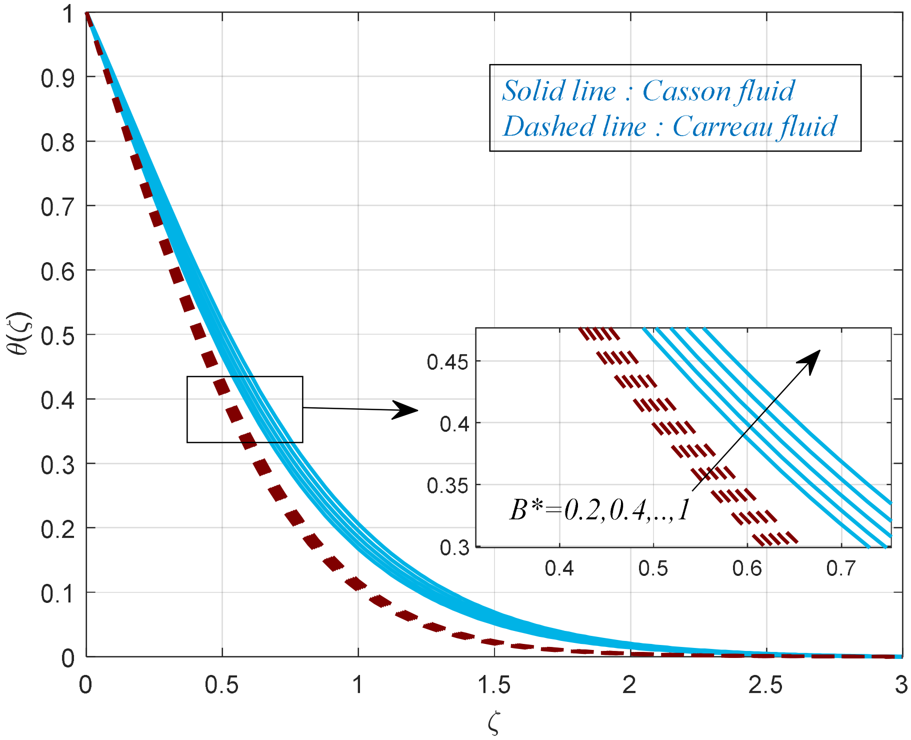

Fig.8. Preeminence of B^* over $\theta(\zeta)$

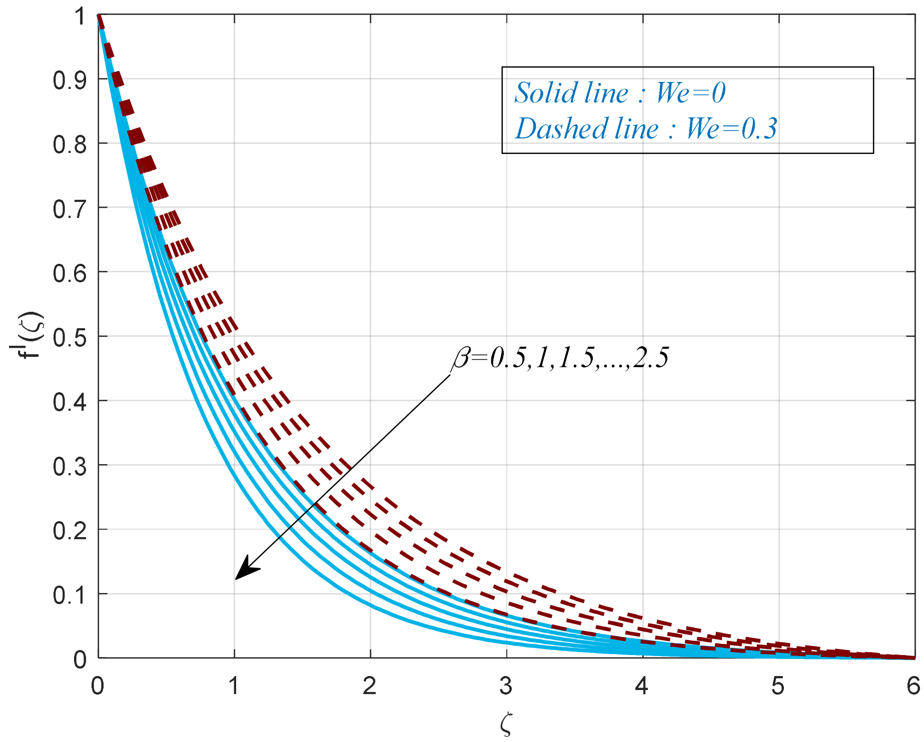

Fig. 9 Preeminence of β over $f'(\zeta)$

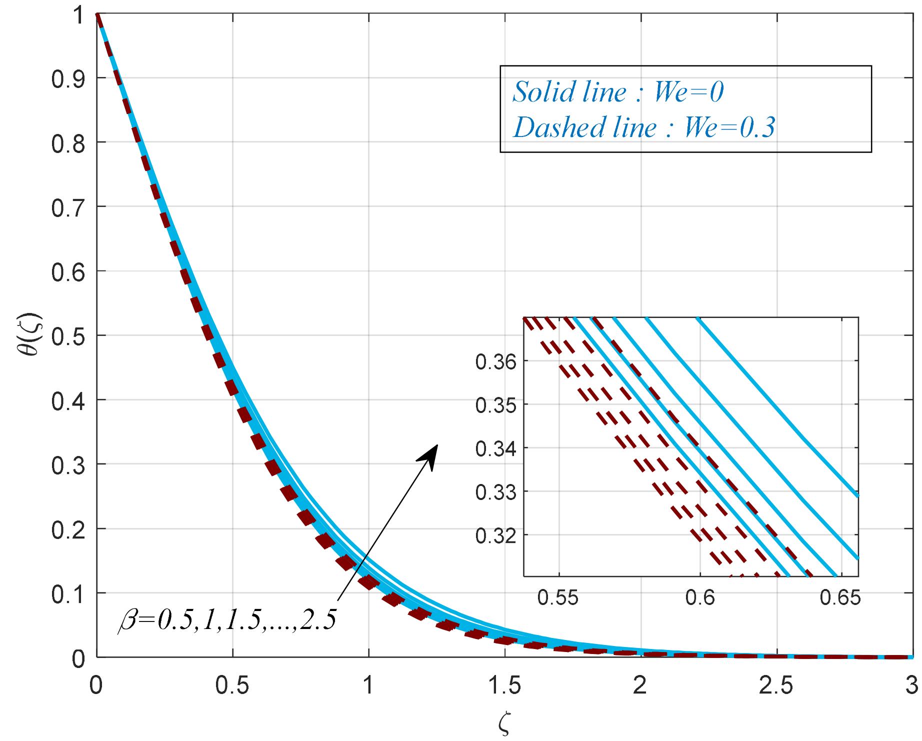

Fig. 10 Preeminence of β over $\theta(\zeta)$

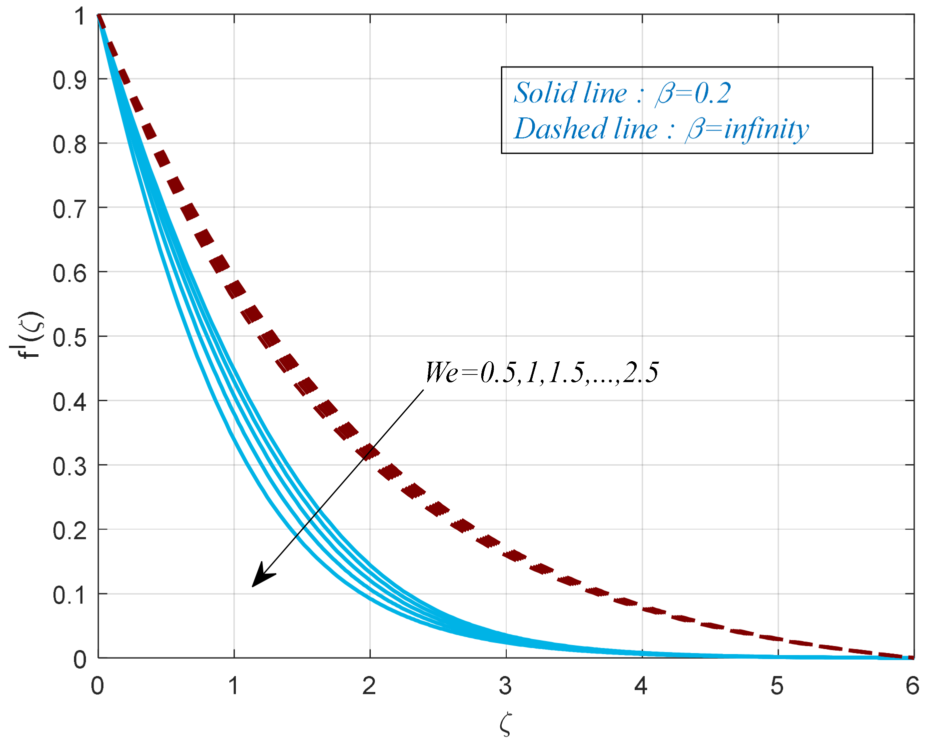

Fig. 11 Preeminence of *We* over $f'(\zeta)$

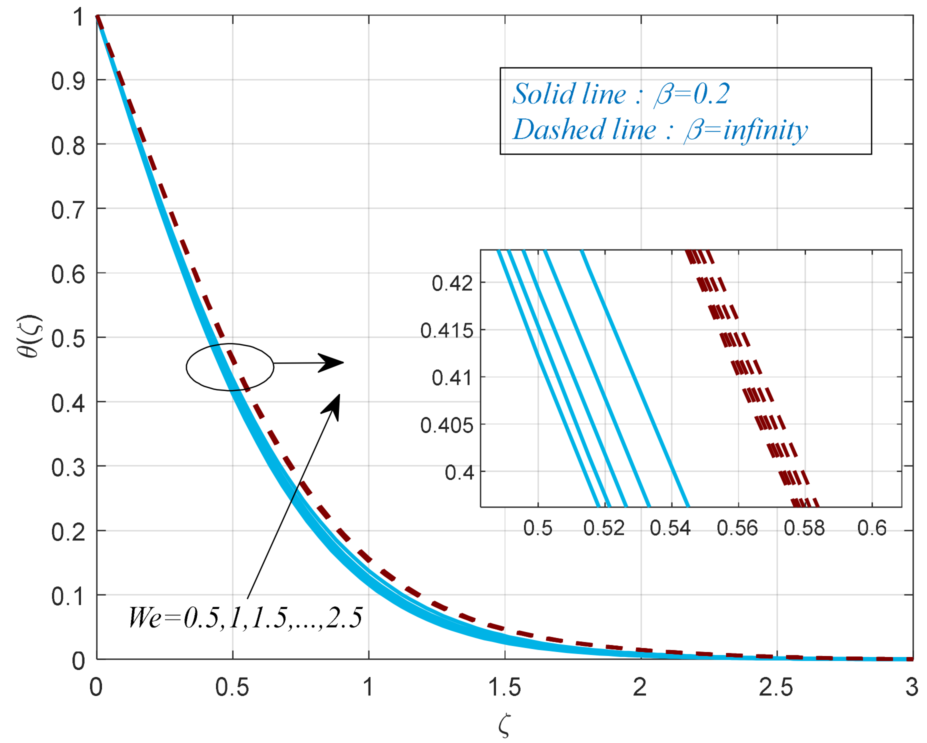

Fig. 12 Preeminence of *We* over $\theta(\zeta)$

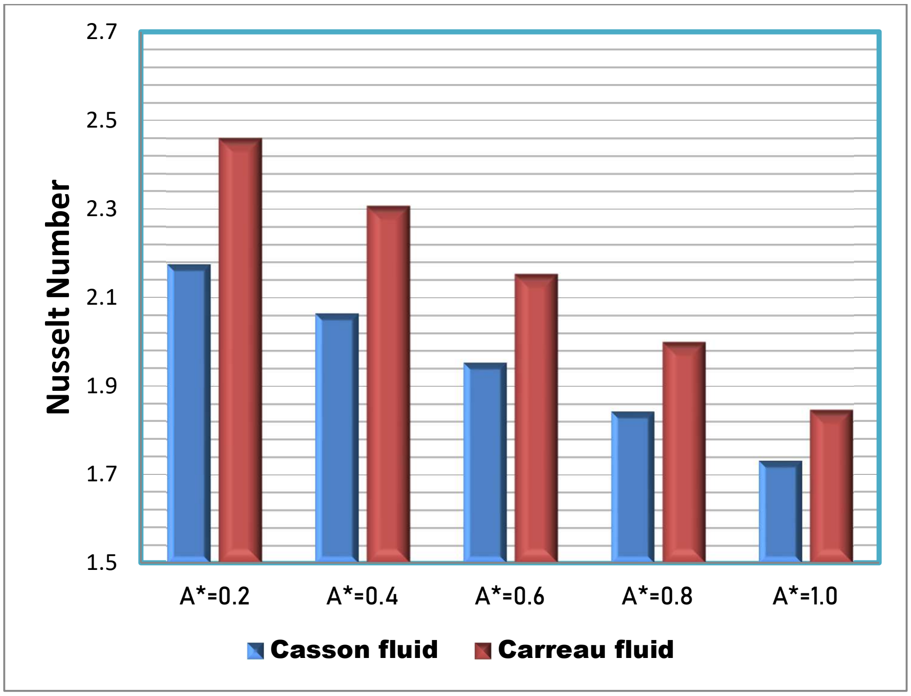

Fig. 13 Preeminence of A^* over Nu_x

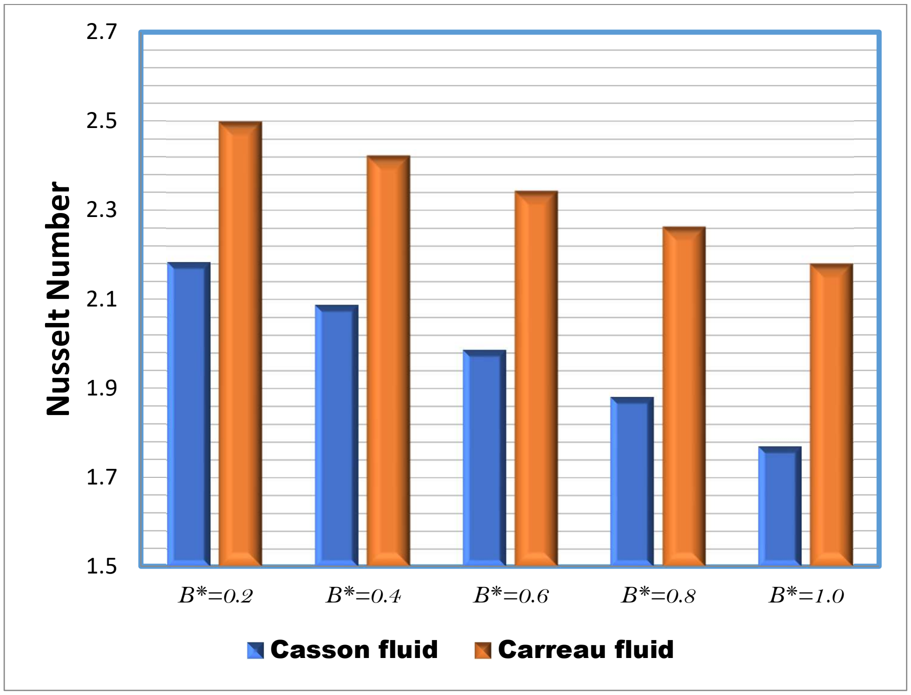

Fig.14 Preeminence of B^* over Nu_x

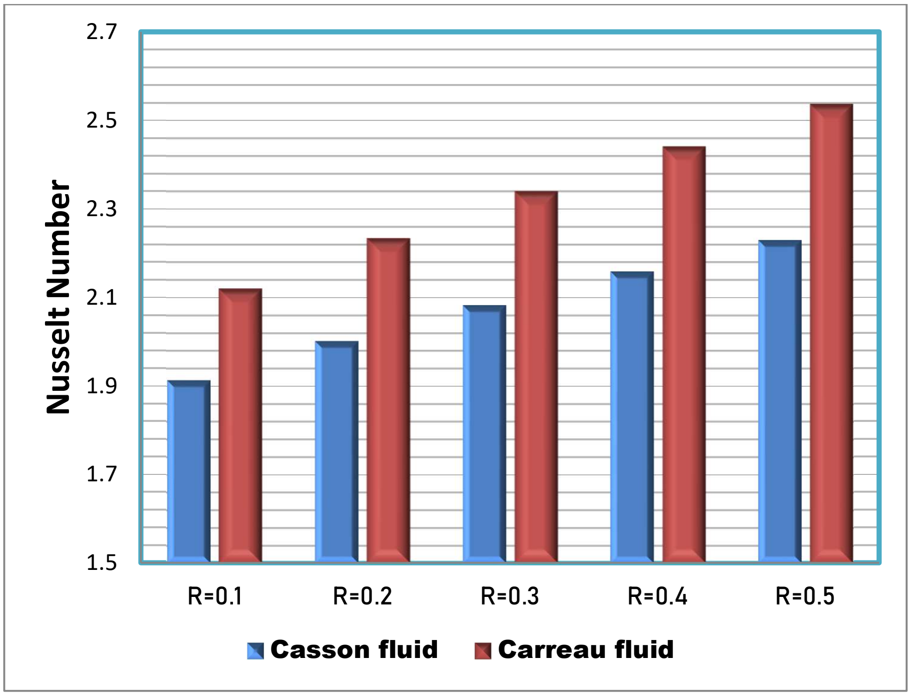

Fig.15. Preeminence of R over Nu_x

Table 1: Assessment of the values of $f''(0)$ for the liquids Casson and Carreau

M	δ	β	We	$f''(0)$	
				Casson liquid	Carreau liquid
1				-4.849275	-0.898266
1.5				-5.717303	-1.025961
2				-6.597625	-1.154420
	0.5			-5.956801	-0.555273
	1.0			-7.748300	-0.702059
	1.5			-9.772207	-0.866380
		0.5		-4.872294	-3.054928
		1.0		-2.924528	-1.869027
		1.5		-2.172642	-1.426755
			0.5	-6.196270	-1.002942
			1.0	-5.352552	-0.940010
			1.5	-4.888232	-0.894281

Table 2: Assessment of the values of $-\theta'(0)$ for the liquids Casson and Carreau

M	δ	R	A^*	B^*	β	We	$-\theta'(0)$	
							Casson liquid	Carreau liquid
1							2.282869	2.502536
1.5							2.230924	2.480293
2							2.183434	2.459382
	0.5						1.751384	1.972780
	1.0						2.003891	2.263921
	1.5						2.228647	2.522274
		0.1					1.913052	2.119994
		0.2					2.001019	2.233274
		0.3					2.082446	2.339823
			0.2				2.174242	2.459468
			0.4				2.063448	2.305932
			0.6				1.952653	2.152395
				0.2			2.182868	2.498479
				0.4			2.086473	2.421627
				0.6			1.985901	2.342896
					0.5		2.282432	2.406776
					1.0		2.341662	2.443087
					1.5		2.381259	2.467650
						0.5	2.352334	1.988041
						1.0	2.397071	1.995380
						1.5	2.423887	2.000893

Table 3: Validation of present results for $-\theta'(0)$ with the published literature.

δ	Jafar et al. [33]	Hady et al. [32]	Present Result
0.75	3.1231	3.123518	3.123347
1.5	3.5660	3.566532	3.566425
7.0	4.1846	4.184386	4.184465

Conclusions

An examination is carried out to inspect the characteristics of MHD non-Newtonian Casson and Carreau liquid flows across an elongated sheet consideringthe impression of the parameters like thermal radiation, Weissenberg number, chemical reactionwhich affects the fluid dynamics in the flow regime. Simultaneous solutions are presented for Casson and Carreau fluids. Pertaining dimensionless transmutations are considered to transform the nonlinear PDE'S to nonlinear ODE'S.

- A proliferation of the magnetic field dejects the velocity profile, rate of heat and mass transfer.
- Carreau liquid possesses more conductive properties than Casson.
- Improvement in radiation parameter enhances the thermal transmission of Carreau liquid.
- An acceleration in the Casson parameter β controls the fluid flows and but elevates the temperature profiles.
- Progressive values of A^* and B^* perform as heat generators.
- Intensification of We dissipates the flow profile and recovers the thermal contour.
- Intensification of M, δ results in the hindrance of thermal transmissionwhereas escalation of β, We, enhances the thermal transmission for both Casson and Carreau fluids.
- The amelioration of M, A^*, B^* decreases $-\theta'(0)$ and amplification of δ, R, β, We increases $-\theta'(0)$ for both fluid flows.

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