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ORIGINAL ARTICLE

Computational modeling of magnetohydrodynamic non-Newtonian fluid flow past a paraboloid of revolution

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KEYWORDS

Magnetohydrodynamic (MHD);
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Casson fluid;
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Abstract Flow and heat transfer behavior of magnetohydrodynamic Carreau and Casson fluids past an upper part of the paraboloid of revolution with space dependent internal heat source/sink is investigated theoretically. The buoyancy induced on the flow is considered in such way that the surface is neither vertical/horizontal nor wedge/cone. The equations that govern the flow are transformed using suitable similarity variables and solved numerically by employing R-K-F integration scheme. Graphical results are obtained to discuss the behavior of flow and temperature fields for various parameters of interest. Also the wall friction is computed and heat transfer coefficient is reduced. It is found that the boundary layers of temperature and velocity distributions are non-uniform for Carreau and Casson flows. Impact of drag force is high on Casson flow when equated with Carreau fluid.

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1. Introduction

MHD flow has more tendencies in aeronautical engineering, solar collectors, modern science and technology. Hydromagnetic flows have an important role in the field of planetary and magnetospheres. The concepts of MHD flows are used in many industrials in the production of heat exchangers, pumps and oil purification [1]. Unsteady Casson fluid flow past a moving flat plate was analytically (homotopy analysis method) studied by Mustafa et al. [2]. Abbasi et al. [3] illustrated the effects of MHD and internal heat source on Maxwell nanofluid flow past a stretched sheet and mentioned that the coefficients of heat generation develop the flow field. Radiative Casson flow over a surface with stretched velocity was discussed by Pramanik [4] and concluded that temperature increases when radiations increase. Miller [5,6] illustrated the boundary layer flow over paraboloid revolution and presented the downstream solution for viscous flow. Animasaun and Makinde [7] studied the magnetohydrodynamic nanofluid flow over a paraboloid of revolution with thermal radiation and concluded that Prandtl number boosts the heat transfer rate.

The feature of magnetic field and heat transfer of Carreau fluid was numerically illustrated by Hayat et al. [8]. Sulochana et al. [9] numerically discussed the Carreau flow over a stretching surface with Brownian momentum. In this study they used

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Nomenclature

A, b	non-negative constants
m	velocity power index
N	exponential parameter
C_f	skin friction coefficient
f, F	dimensionless velocities
Pr	Prandtl number
We	Weissenberg number
Gr	Grashof number
Nu_x	local Nusselt number
M	magnetic field parameter
S	heat source parameter
T	fluid temperature
Q_0	heat generation/absorption coefficient
B_0	magnetic field strength $(Teslas - T)$
k	thermal conductivity of the fluid (W/m K)
T_w	Surface fluid temperature (K)
T_∞	free stream temperature (K)
x, y	cartesian coordinates (m)
u, v	flow component along x and y directions m/s

Greek symbols

σ	fluid electrical conductivity
β	Casson parameter
ζ	similarity independent variable
θ, Θ	non-dimensional temperature
ξ	stream function
α	thermal diffusivity (m^2/s)
υ	kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^3)
c_p	specific heat capacity (J/(m^3 K))

R-K method with shooting system. By using R-K Fehlberg integration scheme, the laminar 2D MHD flow of Carreau fluid past a heated sheet was discussed by Khan et al. [10]. Further, Khan et al. [11] studied the steady 2D MHD flow of incompressible Carreau fluid past a stretching sheet and found that rising values of Biot number increase the thickness of the thermal field. The chemical reaction impact on 3D Couette flow between two vertical plates with sinusoidal fluid was studied by Ahmed et al. [12] and highlighted that the magnetic parameter improves the x-direction component and minimizes the z-direction component. Mukhopadhyay et al. [13] analyzed the unsteady 2D radiative flow past a stretching sheet in the presence of non-Newtonian fluid. Nonlinear radiative flow between parallel plates was studied by Sathishkumar et al. [14]. Nadeem et al. [15] analytically discussed the MHD Casson fluid flow past a permeable stretching surface by using ADM. Raju and Sandeep [16] studied the 3D MHD laminar flow of Casson and Carreau fluids over a stretching sheet with thermal radiation. Georgiou [17] discussed the influence of Poiseuille flow on Carreau fluid under the slip conditions and observed a fall in the wavelength for rising the slip. Nandy [18] studied the Casson flow past a stretching surface and concluded that improving the non-dimensional heat slip effects depreciate the flow profile. Hayat et al. [19] discussed the influence of peristaltic flow on Carreau fluid with magnetic field. Akbar et al. [20] studied the influence of velocity on dissipative MHD flow of Casson fluid under the magnetic field. Makinde and Animasaun [21] studied the chemically reacting MHD flow past an upper paraboloid revolution. In this study they used R-K method to solve numerically. The effects of magnetic field chemically reacting Casson fluid past a porous surface were studied by Arthur et al. [22]. Falkner-Skan flow of Casson fluid past a wedge was theoretically investigated by Raju and Sandeep [23]. Convective heat transfer magnetohydrodynamic flow past a non-uniform stretching surface was studied by Anjalidevi et al. [24]. Animasaun and Sandeep [25] developed a buoyancy model for alumina-water nanofluid flow over a revolving paraboloid. The researchers [26–28] studied the free convective heat transfer of MHD flow. The behavior of 2D insecure MHD Casson fluid flow toward a flat plate was studied by Jasmine Benazir et al. [29]. Rushi Kumar et al. [30] discussed the influence of chemical reaction on magnetohydrodynamic convection fluid flow past a vertical cone in the presence of electrical conductivity. The unsteady magnetohydrodynamic and thermal radiation effect on vertical wavy plate in the presence of cross diffusion was studied by Prakash et al. [31]. The influences of cross diffusion on magnetohydrodynamic viscoelastic fluid flow past a vertical cone in the presence of non-Darcy preamble medium were studied by Rushi Kumar and Sivaraj [32].

In all the above investigations researchers focused on analyzing the heat transfer behavior of magnetohydrodynamic flows by assuming one or two physical effects with the routine physical models. But in this paper, we investigated the momentum and thermal transport of magnetohydrodynamic Carreau and Casson fluids over revolving paraboloid by assuming the exponential heat source/sink. Additionally we presented a comparative analysis between Casson and Carreau fluids. Numerical solutions are obtained by making use of R-K-F integration scheme. Results are illustrated with the help of plots and tables.

2. Problem formulation

Consider a steady magnetohydrodynamic 2D flow of Carreau and Casson fluids past a non-melting upper part of the revolving paraboloid. The flow is confined over the region $A(x+b)^{\frac{m-1}{2}} \leqslant y < \infty$ (here A and b are non-negative and $m < 1$) and the revolving paraboloid is stretched with the velocity $U_w = U_0(x+b)^m$. Here horizontal surface is located along x-direction and y-axis is perpendicular to it. A uniform magnetic field of strength $B(x) = B_0(x+b)^{\frac{m-1}{2}}$ is applied in the flow direction as displayed in Fig. 1. The temperature near the surface is considered as $T_w(x) = A(x+b)^{\frac{1-m}{2}}$ (here "m" is velocity power index and "b" is stretching parameter). Induced magnetic field is neglected in this study. Buoyancy effects along with viscous dissipation and exponential heat source

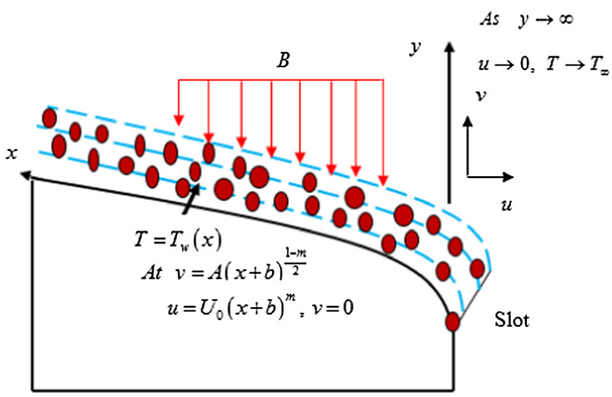

Figure 1 Flow geometry of the problem.

effects are incorporated in the model, with the above assumptions and followed by the researchers Refs. [24,25].

The governing equations with stream function ξ are as follows:

$$\frac{\partial^2 \xi}{\partial x \partial y} - \frac{\partial^2 \xi}{\partial y \partial x} = 0, \tag{1}$$

$$\frac{\partial \xi}{\partial y}\frac{\partial^2 \xi}{\partial x \partial y} - \frac{\partial \xi}{\partial x}\frac{\partial^2 \xi}{\partial y^2} = \upsilon\left(\left(1+\frac{1}{\beta}\right)\frac{\partial^3 \xi}{\partial y^3} + \frac{3(n-1)}{2}\Gamma^2 \frac{\partial^3 \xi}{\partial y^3}\left(\frac{\partial^2 \xi}{\partial y^2}\right)^2\right) + (T - T_\infty)\frac{\partial}{\partial x}\left(g\beta x \frac{m+1}{2}\right) - \frac{\sigma B^2(x)}{\rho}\frac{\partial \xi}{\partial y}, \tag{2}$$

$$\frac{\partial \xi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial \xi}{\partial x}\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{Q(x)(T_w - T_\infty)}{\rho c_p} e^{\left(-Ny\left(\frac{m+1}{2}\right)^{0.5}\left(\frac{U_0}{\upsilon}\right)^{0.5}(x+b)^{\frac{m-1}{2}}\right)} + \frac{\upsilon}{c_p}\left(\frac{\partial^2 \xi}{\partial y^2}\right)^2, \tag{3}$$

with the conditions

$$u = U_w, \quad v = 0, \quad T = T_w(x) \quad at \quad y = A(x+b)^{\frac{m-1}{2}};$$
$$u \to 0, \quad T \to T_\infty \quad \text{as} \quad y \to \infty. \tag{4}$$

Here, the continuity Eq. (1) will satisfy with the stream function $\xi(x, y)$ and the similarity transformations are given by

$$\left.\begin{aligned} &\zeta = y\left(\tfrac{m+1}{2}\tfrac{U_0}{\upsilon}\right)^{0.5}(x+b)^{\frac{m-1}{2}},\ u = \tfrac{\partial \xi}{\partial y}, \\ &\xi(x,y) = f(\zeta)\left(\tfrac{2}{m+1}\right)^{0.5}(\upsilon U_0)^{0.5}(x+b)^{\frac{m-1}{2}},\ v = -\tfrac{\partial \xi}{\partial x}, \\ &\Theta(\zeta) = \tfrac{T - T_\infty}{T_w(x) - T_\infty},\ Q(x) = (x+b)^{m-1}, \end{aligned}\right\} \tag{5}$$

By making use of Eq. (5), Eqs. (2)–(4) transformed as

$$\left(1+\frac{1}{\beta}\right)F''' - \frac{2m}{m+1}F'^2 + FF'' + 0.75(n-1)(m+1)WeF'''F''^2 - \frac{2M}{m+1}F' + Gr\theta = 0, \tag{6}$$

$$\Theta'' + PrF\Theta' - Pr\frac{1-m}{1+m}F'\Theta + PrS\frac{2}{m+1}e^{(-N\zeta)} = 0, \tag{7}$$

where $F(\zeta)$ and $\theta(\zeta)$ are dimensionless stream function and dimensionless temperature with

$$\left.\begin{aligned} &We = \tfrac{\Gamma^2(x+b)^{3m-2}}{\nu},\ M = \tfrac{\sigma B_0^2}{U_0},\ Gr = \tfrac{g\beta(T_w - T_\infty)}{U_0^2(x+b)^{2m-1}}, \\ &S = \tfrac{Q_0}{(\rho c_p)U_0},\ Pr = \tfrac{(\rho c_p)\upsilon}{k} = \tfrac{\nu}{\alpha},\ U_w = U_0(x+b)^m, \end{aligned}\right\} \tag{8}$$

As per the formulation of the problem y is not an initial point of the slot, and from this Eq, (4) is not imposed at $y = 0$. So by substituting the $y = A(x+b)^{\frac{1-m}{2}}$ is the minimum value of y in the domain into ζ as $\chi = A\left(\frac{(m+1)U_0}{2\vartheta}\right)^{0.5}$. Now the suitable scale of the boundary layer flow is $\zeta = \eta$ and the transformed boundary conditions are specified as

$$\frac{dF}{d\chi} = 1,\ F(\chi) = \frac{1-m}{m+1}\chi,\ \Theta(\chi) = 1 \text{ at } \chi = 0,$$
$$\frac{dF}{d\chi} \to 0,\ \Theta \to 0 \text{ as } \chi \to \infty. \tag{9}$$

For suitable transformation of the domain from $[\chi, \infty)$ to $[0, \infty)$, we consider $f(\eta) = f(\zeta - \chi)$ and $\theta(\eta) = \theta(\zeta - \chi)$.

$$\left(1+\frac{1}{\beta}\right)f''' - \frac{2m}{m+1}f'^2 + ff'' + 0.75(n-1)(m+1)Wef'''f''^2 - \frac{2M}{m+1}f' + Gr\theta = 0, \tag{10}$$

$$\theta'' + Prf\theta' - Pr\frac{1-m}{1+m}f'\theta + PrS\frac{2}{m+1}e^{(-N\eta)} = 0, \tag{11}$$

With boundary conditions

$$f' = 1,\ f = \chi\frac{1-m}{m+1},\ \theta = 1,\ \text{at } \eta = 0.\ f' \to 0,$$
$$\theta \to 0 \text{ as } \eta \to \infty, \tag{12}$$

Physical quantities of engineering interest, wall friction C_{fx} and reduced Nusselt number Nu_x is defined as

$$C_{fx} = \left(1+\frac{1}{\beta}\right)\frac{\tau_w}{\rho(U_w)^2}\left(\frac{m+1}{2}\right)^{-0.5},$$
$$Nu_x = \frac{(x+b)q_w}{k(T_w - T_\infty)}\left(\frac{m+1}{2}\right)^{-0.5}, \tag{13}$$

where τ_w the shear stress and q_w is the heat flux

$$C_f Re_x^{1/2} = \left[\left(1+\frac{1}{\beta}\right)f''(0) + \frac{(n-1)We}{2}(f''(0))^3\right],$$
$$Nu_x Re_x^{-1/2} = -\theta'(0), \tag{14}$$

where $Re_x = \frac{U_w(x+b)}{\upsilon}$ is the local Reynolds number.

3. Results and discussion

The solution for the B.V.P represented by Eqs. (10) and (11) has been constructed through the effective numerical process namely R-K-F integration scheme (see Ref. [28]). Following the problem solution, we focused on determining the impacts of distinct flow regulating quantities on fluid velocity and temperature with the support of computer produced plots. The results are acquired for both contexts viz. (i) Casson fluid and (ii) Carreau fluid flows by proceeding with $\beta = 0.5, n = 1$ and $\beta \to \infty, n = 1.5$ respectively. The results are acquired by giving the values of flow parameters $N = 0.1$, $M = 1$, $m = 0.5$, $Gr = 0.5$¸ $We = 2$, $Pr = 6.8$ as input for the complete production of results unless otherwise noted in plots and tabular forms. The results are elaborated via Figs. 2–10 and Tables 1 and 2.

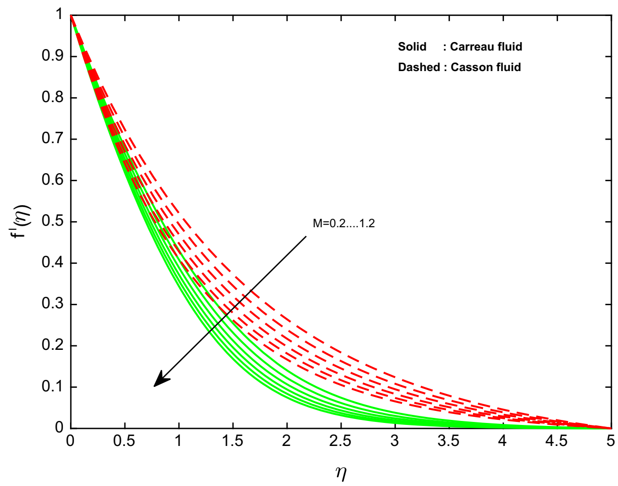

Figure 2 Influence of M on $f'(\eta)$.

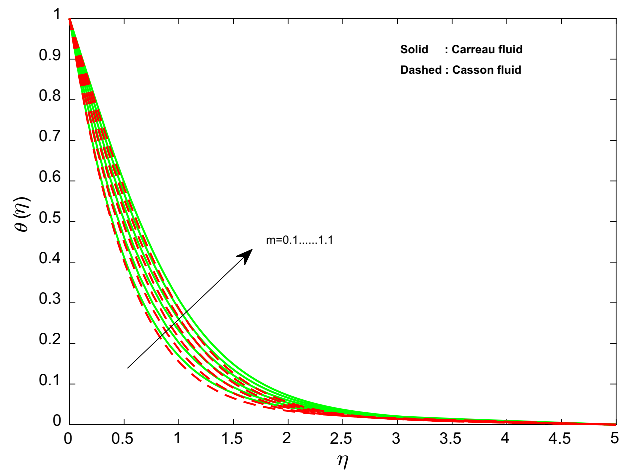

Figure 5 Influence of m on $\theta(\eta)$.

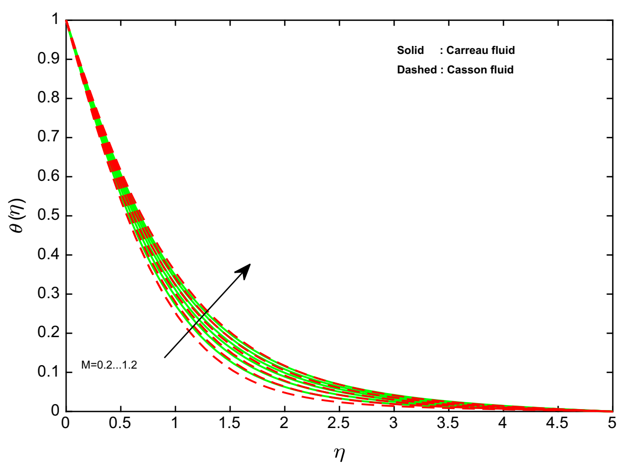

Figure 3 Influence of M on $\theta(\eta)$.

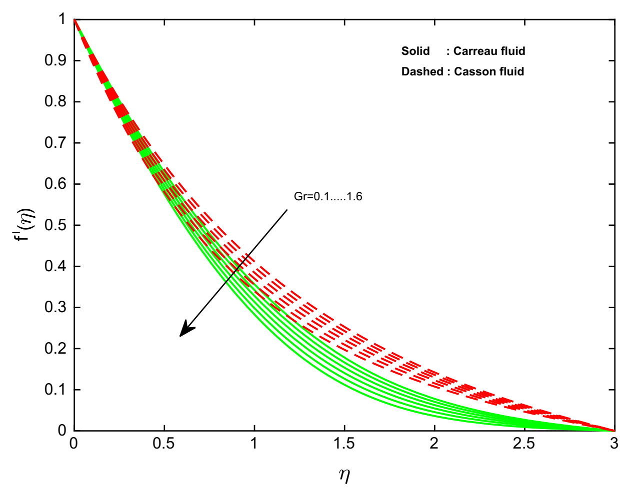

Figure 6 Influence of Gr on $f'(\eta)$.

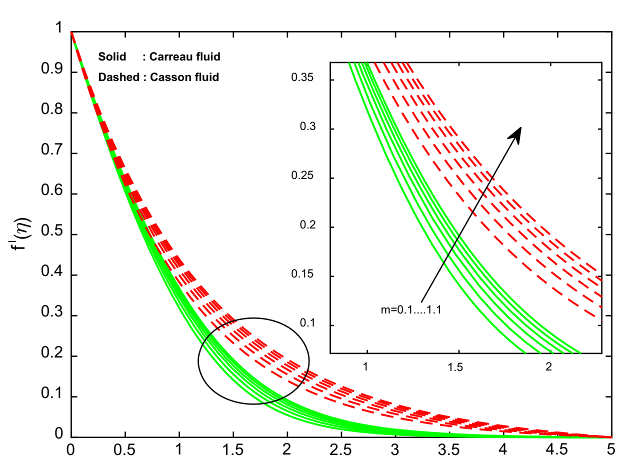

Figure 4 Influence of m on $f'(\eta)$.

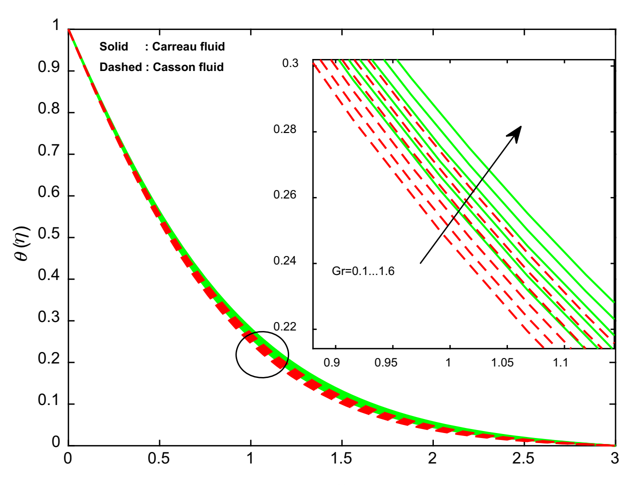

Figure 7 Influence of Gr on $\theta(\eta)$.

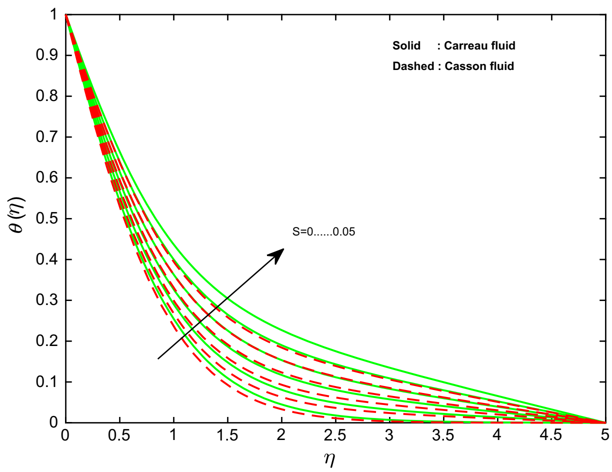

Figure 8 Influence of S on $\theta(\eta)$.

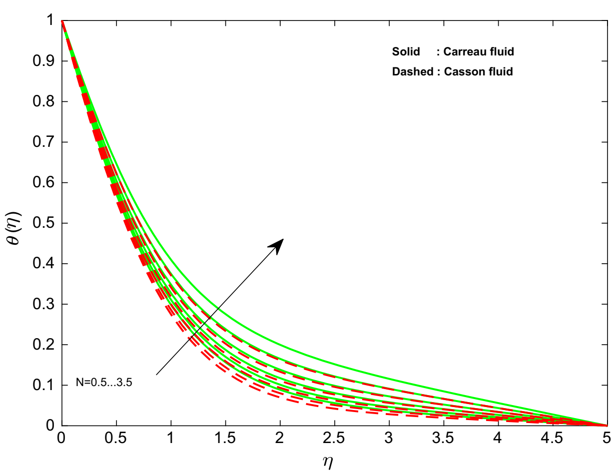

Figure 9 Influence of N on $\theta(\eta)$.

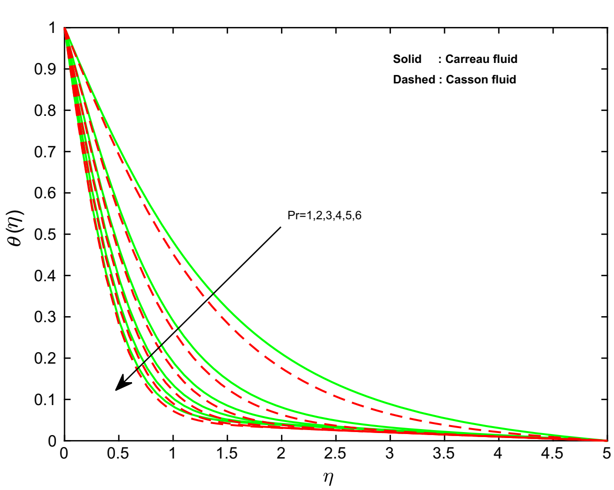

Figure 10 Influence of Pr on $\theta(\eta)$.

Table 1 Validation of the current results with Animasaun and Sandeep [25] when $\phi = 0, \beta \to \infty, n = 1$.

m	$f''(0)$ Animasaun and Sandeep [25]	$f''(0)$ Current values
0.1	−0.8671009	−0.8671009201
0.2	−0.8624053	−0.8624053101
0.3	−0.8584863	−0.8584863213
0.4	−0.8481543	−0.8481543109

Figs. 2 and 3 display the impact of magnetic field on thermal and flow fields of Carreau and Casson fluids. We noticed that rising the magnetic field influence depreciates the flow field and enhances the thermal field. Physically, boosting the magnetic field develops the resistive type drag force (Lorentz force) which works opposite to the flow field. This reverse force is capable to decrease the flow and increase the temperature field. It is also observed that the impact of magnetic effect is high on Carreau flow when equated with the Casson flow.

Figs. 4 and 5 depict the flow and thermal distribution for different values of velocity power index m. It is clear that the flow and temperature profiles increase with rising values of m. This may happen due to the fact that increasing the power law index enhances the linearity of the channel. These causes to decline the buoyancy force acting on the flow and encourage the momentum and thermal fields. It is evident that the flow field of Carreau fluid and thermal field of Casson fluid are highly influenced with the variation in power law index. This may happen due to the viscosity variations of both fluids. It is evident from Figs. 6 and 7 that rising values of Grashof number encourage the temperature field and decrease the velocity profile of both fluids. Physically, boosting values of Grashof number enhance the buoyancy force of the flow field.

Figs. 8 and 9 display the impact of heat source and exponential parameters on thermal field. We noticed a hike in thermal distribution of both fluids for boosting values of heat source and exponential parameters. This obeys the general physical nature of the heat source parameter that increasing the internal heat improves the thermal conductivity of the fluid molecules and hence the temperature field. Fig. 10 displays the effect of Prandtl number on thermal field of both Carreau and Casson fluids. It is clear that rising values of Pr depreciate the temperature profiles of both fluids.

Validation of the obtained results with the published results for special case (in the presence of radiation) is performed in Table 3 and found a favorable agreement. Tables 2 and 3 show that variation of wall friction and heat transfer for various values of magnetic field parameter, power law index, Grashof number, heat source, exponential parameter and Prandtl number. Rising values of magnetic field, Grashof number, heat source, and exponential parameter decrease the flow and heat transfer rates. But opposite to Prandtl number, rising values of velocity power index enhance the skin friction and depreciate Nusselt number. Table 4 depicts the validation of the numerical technique by comparing with the other techniques.

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

M	m	Gr	S	N	Pr	$f''(0)$	$-\theta'(0)$
0.2						−0.717886	1.052121
0.4						−0.754369	1.041004
0.6						−0.786789	1.030968
	0.1					−0.892425	1.697438
	0.3					−0.873138	1.439752
	0.5					−0.858681	1.240929
		0.1				−0.843481	1.030627
		0.4				−0.872540	1.023252
		0.7				−0.900754	1.015708
			0			−0.842372	1.042440
			0.01			−0.843109	0.984221
			0.02			−0.843850	0.925752
				0.5		−0.842821	1.006914
				1.1		−0.842949	0.996807
				1.6		−0.843114	0.983819
					1	−0.846526	0.627423
					2	−0.843109	0.984221
					3	−0.841426	1.264814

Table 3 Variation in $f''(0)$ *and* $-\theta'(0)$ for Casson fluid.

M	m	Gr	S	N	Pr	$f''(0)$	$-\theta'(0)$
0.2						−0.647071	1.088732
0.4						−0.701674	1.076239
0.6						−0.752782	1.064473
	0.1					−0.928723	1.719803
	0.3					−0.895916	1.465377
	0.5					−0.872036	1.268598
		0.1				−0.861412	1.048631
		0.4				−0.906649	1.040763
		0.7				−0.952574	1.032571
			0			−0.845945	1.068953
			0.01			−0.846883	1.016634
			0.02			−0.847824	0.964202
				0.5		−0.846516	1.037018
				1.1		−0.846679	1.027939
				1.6		−0.846889	1.016274
					1	−0.851590	0.662346
					2	−0.846883	1.016634
					3	−0.844565	1.294406

Table 4 Validation of the numerical technique for $-\theta'(0)$ in Casson case.

M	*bvp4c*	*bvp5c*	*RKS*	*RKF*
0.2	1.088732341	1.088732342	1.088732341	1.088732
0.4	1.076239237	1.076239234	1.076239236	1.076239
0.6	1.064473524	1.064473523	1.064473522	1.064473

4. Conclusions

Numerical investigation is carried out for analyzing the low and heat transfer behavior of magnetohydrodynamic Carreau and Casson fluids past an upper part of the revolving paraboloid with space dependent internal heat source/sink investigated theoretically. The buoyancy induced on the flow is considered in such way that the surface is neither vertical/horizontal nor wedge/cone. The equations govern the flow transformed using suitable similarity variables and solved numerically by employing R-K-F scheme. Numerical findings are as follows:

- The effect of Lorentz force is high on Casson fluid when compared with the Carreau fluid.
- Heat transfer rate is high in Casson flow when equated with the Carreau flow.
- Buoyancy force acts on parabolic flow having tendency to regulate the momentum boundary layer.

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- The impact of buoyancy force is high on Casson flow when compared with the Carreau flow.
- Increasing the exponential internal heat source enhances the thermal field.
- Thermal and flow fields are non-uniform for Casson and Carreau flows.

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