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Mixed convective flow of MHD Carreau-Yasuda fluid over a moving vertical flat plate with couple Stress and non-Fourier heat flux

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Abstract

The present study investigates a steady, two-dimensional mixed convective flow of an electrically conducting Carreau-Yasuda non-Newtonian fluid over a vertically moving flat plate. Unlike conventional analyses that rely on Fourier's law, this work incorporates the non-Fourier (Cattaneo-Christov) heat flux model to account for finite thermal propagation speed, a critical factor in processes involving rapid heating or viscoelastic fluids. Additionally, the combined effects of a transverse magnetic field, couple stresses arising from fluid microstructures, and thermal radiation are examined. The Carreau-Yasuda rheological model is selected for its ability to accurately capture both shear-thinning and shear-thickening behaviours across a wide range of deformation rates. A set of appropriate similarity variables is employed to transform the coupled partial differential governing equations into a system of nonlinear ordinary differential equations. Numerical solutions are then obtained using the bvp4c solver in MATLAB, which implements a finite difference scheme with a collocation method. The key findings reveal that escalating the Weissenberg number, couple stress parameter, or magnetic field strength progressively diminishes the velocity profile due to heightened internal resistance and Lorentz drag. Conversely, the temperature field rises with increased thermal radiation but declines when either the Prandtl number or the thermal relaxation parameter is augmented the latter confirming the non-Fourier lag effect. Skin friction coefficient enhances with couple stress and Weissenberg number but reduces under stronger mixed convection. The Nusselt number improves for higher Prandtl and radiation parameters, whereas thermal relaxation suppresses heat transfer.

Keywords: MHD, bvp4c, thermal radiation, non-Newtonian fluid, mixed convection

Introduction

Huang ^[1] numerically analysed free convection of non-Newtonian fluids over a vertical permeable plate in a porous medium. The study incorporated non-Darcy flow, magnetohydrodynamic (MHD) effects, Soret/Dufour influences, and thermal radiation, solving the transformed governing equations using the Keller box method. Strengthening either the non-Darcy parameter reduces fluid velocity, which in turn lowers both the local Nusselt and Sherwood numbers. RamReddy *et al.* ^[2] examined the mixed convective flow of a power-law non-Newtonian fluid over an inclined plate embedded in a non-Darcy porous medium under a convective surface condition. The nonlinear Boussinesq approximation is incorporated to account for temperature- and concentration-dependent density variations, and the resulting equations are solved numerically using a successive linearization method combined with a local non-similarity technique. A key outcome is that increasing the Biot number enhances both the heat and mass transfer rates, whereas inclining the plate away from the vertical slows down the flow and lowers the Nusselt and Sherwood numbers. Maghsoudi *et al.* ^[3] analytically investigated the natural convective heat transfer of a non-Newtonian nanofluid flowing between two infinite vertical flat plates under the simultaneous influence of an applied magnetic field and thermal radiation, employing the Galerkin method alongside a numerical validation. The main findings indicate that boosting the magnetic field strength lowers the velocity distribution, wall friction coefficient, and Nusselt number, while the thermal radiation

parameter has a minimal effect on velocity but increases skin friction and reduces the Nusselt number. Besthapu *et al.* [4] focused on the magnetohydrodynamic stagnation-point flow of a Casson nanofluid past a convectively heated nonlinear stretching surface, incorporating the effects of thermal radiation, velocity slip, and a porous medium. The governing partial differential equations are transformed into ordinary differential equations via similarity variables and then solved numerically using the Keller-box method. The results reveal that the thermophoresis parameter enhances both temperature and nanoparticle concentration, whereas the velocity slip parameter reduces the surface velocity but increases the temperature profile. Bahmani and Kargarsharifabad [5] numerically investigated the magnetohydrodynamic free convection of non-Newtonian power-law fluids over a horizontal plate subjected to uniform heat flux. A lower generalized Prandtl number leads to higher skin friction and wall temperature, while the influence of the power-law index depends strongly on the Prandtl number: at high Prandtl numbers, decreasing the index (shear-thinning behaviour) increases wall friction and thermal layer thickness but lowers the Nusselt number, with the opposite trend observed at low Prandtl numbers. Wahab *et al.* [6] inspected the magnetohydrodynamic flow of a non-Newtonian Powell-Eyring nanofluid over a nonlinear stretching sheet, incorporating temperature-dependent viscosity and thermal conductivity, double stratification, binary chemical reaction, activation energy, and zero nanoparticle mass flux at the surface. Chang *et al.* [7] studied the unsteady flow and heat transfer of a non-Newtonian power-law fluid over an oscillating flat plate. The oscillation frequency is found to strongly influence both the velocity and thermal fields, while the power-law index has little effect on the dimensionless velocity distribution but significantly alters the temperature field. Verma *et al.* [8] investigates the forced convective boundary layer flow of a non-Newtonian Eyring-Powell nanofluid over a moving flat plate embedded in a Darcy porous medium under a parallel free-stream. A key finding is that dual velocity, temperature, and concentration solutions exist when the plate and free-stream move in opposite directions, but the lower branch is unstable while the upper branch is stable. Dawar *et al.* [9] investigated the magnetohydrodynamic stagnation-point flow of a water-based hybrid nanofluid containing ferrous and graphene oxide nanoparticles over a non-isothermal flat plate, incorporating thermal radiation and assuming a laminar incompressible tangent hyperbolic non-Newtonian behaviour. Key findings indicate that a higher Weissenberg number, linked to longer relaxation time, lowers the velocity but increases the temperature. Tauvijirrahman *et al.* [10] compared the performance of Newtonian and non-Newtonian fluids in a heterogeneous slip/no-slip journal bearing system using coupled CFD and two-way fluid-structure interaction simulations that account for cavitation and turbulence. Later, several authors [11 - 19] discussed various non-Newtonian fluid flows across different geometries.

Despite extensive research on non-Newtonian fluid flows over various geometries, a critical research gap persists in the simultaneous integration of Carreau-Yasuda rheology, couple stress effects, and non-Fourier heat flux under magnetohydrodynamic mixed convective conditions over a moving vertical flat plate. Most existing studies either rely on the simpler power-law or Casson models, or they adhere to Fourier's law which assumes infinite thermal propagation speed an assumption that fails for viscoelastic fluids with

microstructural relaxation. Furthermore, the combined influence of couple stresses (arising from particle rotation or polymer chain interactions) and the Cattaneo-Christov thermal relaxation has remained unexplored for Carreau-Yasuda fluids. The present study fills this void by proposing a comprehensive mathematical model that captures shear-thinning/thickening behavior, internal micro-structural resistance, finite heat propagation speed, and electromagnetic damping simultaneously. The significance of this work lies in its ability to predict flow and heat transfer more realistically than conventional Fourier-based models, especially in scenarios involving rapid thermal transients or fluids with complex microstructures. Practical applications of this investigation are manifold: polymer extrusion where melt exhibits both elasticity and thermal lag, coating processes involving magnetic non-Newtonian paints, enhanced oil recovery using viscoelastic polymer solutions under applied magnetic fields, thermal management of smart fluids in electronic cooling, and biomedical devices handling blood or synovial fluid (which display both couple stress and non-Newtonian traits) under external magnetic guidance.

2 Formulation of the problem

In this study, a steady flow of Carreau-Yasuda fluid over a moving vertical flat plate in the presence of couple stress, magnetic field, and non-Fourier heat flux is considered. The following simplifying assumptions are adopted to formulate the problem, as illustrated schematically in Fig. 1:

- The flow is assumed steady, two-dimensional, and laminar, which is valid for moderate Reynolds numbers typical of viscoelastic boundary layer flows over flat plates.
- The heat generated due to internal fluid friction is assumed negligible compared to conductive and radiative heat transfer, which is reasonable for low-velocity non-Newtonian flows.
- A uniform magnetic field of strength B_0 is applied perpendicular to the flow direction.
- Instead of the classical Fourier law (which assumes infinite thermal propagation speed), the non-Fourier model incorporates a finite thermal relaxation time, accounting for the lag between the temperature gradient and the resulting heat flux.
- The plate is maintained at a constant temperature T_w , which is higher than the ambient fluid temperature T_∞ to facilitate mixed convection.

With these assumptions, the governing equations and boundary conditions for this study are presented as below:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\mu}{\rho} \frac{\partial^2 u}{\partial y^2} + \frac{\mu}{\rho} \gamma^d \left(\frac{n-1}{d} \right) (d+1) \left(\frac{\partial u}{\partial y} \right)^d \frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2}{\rho} (u - U_\infty) - \frac{\gamma_0}{\rho} \frac{\partial^4 u}{\partial y^4} + g \beta_T (T - T_\infty) \quad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{\rho C_p} \left(k + \frac{16\sigma^* T^3}{3k^*} \right) \frac{\partial^2 T}{\partial y^2} - \kappa \left(u^2 \frac{\partial^2 T}{\partial x^2} + 2uv \frac{\partial^2 T}{\partial x \partial y} + v^2 \frac{\partial^2 T}{\partial y^2} + \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) \frac{\partial T}{\partial x} + \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) \frac{\partial T}{\partial y} \right) \quad (3)$$

$$\begin{aligned} \text{at } y = 0: u &= \lambda U_\infty, v = 0, \frac{\partial^2 u}{\partial y^2} = 0, T = T_w, \\ \text{as } y \rightarrow \infty: u &\rightarrow U_\infty, \frac{\partial u}{\partial y} \rightarrow 0, T \rightarrow T_\infty. \end{aligned} \quad (4)$$

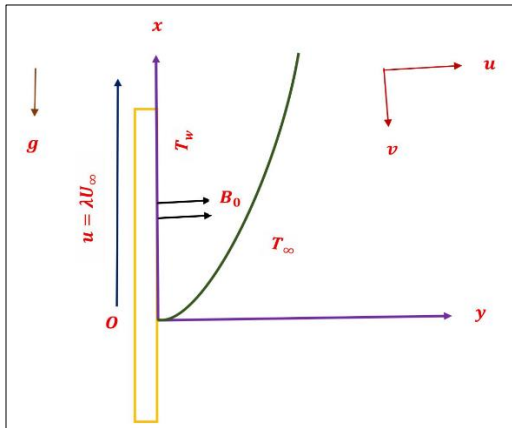


Fig 1: Schematic representation of the present study

Rosli *et al.* [20] presented the following similarity transformations to convert the governing equations into a set of nonlinear ordinary differential equations:

$$u = U_\infty f'(\eta), v = -\frac{1}{2} \sqrt{\frac{\nu U_\infty}{x}} (f(\eta) - \eta f'(\eta)), \eta = \sqrt{\frac{U_\infty}{\nu x}} y, \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}. \quad (5)$$

Terms in (5) clearly satisfies eqn. (1) and transform the eqns. (2) - (4) as below:

$$\left(1 + (n-1) \frac{d+1}{d} We^d f'^{nd}\right) f'''' + \frac{1}{2} f f'' - M(f' - 1) + \delta \theta - Cs f' = 0 \quad (6)$$

$$\frac{1}{Pr} \theta'' + \frac{R}{Pr} \theta' - \frac{\Gamma}{4} (f^2 \theta'' + 3 f f' \theta') + \frac{1}{2} f \theta' = 0 \quad (7)$$

$$\begin{cases} \text{at } \eta = 0: f(\eta) = 0, f'(\eta) = \lambda, f''(\eta) = 0, \theta(\eta) = 1, \\ \text{as } \eta \rightarrow \infty: f'(\eta) \rightarrow 1, f''(\eta) \rightarrow 0, \theta(\eta) \rightarrow 0. \end{cases} \quad (8)$$

where

$$\begin{aligned} M &= \frac{\sigma B_0^2 x}{\rho U_\infty}, We = \gamma U_\infty \sqrt{\frac{U_\infty}{\nu x}}, Cs = \frac{\gamma_0 U_\infty}{\rho \nu^2 x}, Pr = \frac{\mu C_p}{k}, R = \frac{16 \sigma^* T_\infty^3}{3 k k^*}, \\ \delta &= \frac{Gr}{Re_x^2}, Gr = \frac{g \beta_T (T_w - T_\infty) x^3}{\nu^2}, Re_x = \frac{x U_\infty}{\nu}, \Gamma = \frac{\kappa U_\infty}{x}. \end{aligned}$$

Skin friction coefficient and Nusselt numbers in dimensional form can be stated as the following:

$$Cf = \frac{\tau_w}{\rho U_\infty^2} \Big|_{y=0}, \tau_w = \mu \frac{\partial u}{\partial y}, Nu = -\frac{x q_w}{k (T_w - T_\infty)} \Big|_{y=0}, q_w = \left(k + \frac{16 \sigma^* T_\infty^3}{3 k^*} \right) \frac{\partial T}{\partial y}. \quad (9)$$

By employing (5), the terms in (9) can be succinctly redeveloped as:

$$\sqrt{Re_x} Cf = f''(0), \sqrt{\frac{1}{Re_x}} Nu = -(1 + R) \theta'(0).$$

3 Results and discussion

Equations (6 - 7) subject to the conditions (8) were solved using the bvp4c solver in MATLAB.

An increase in the Weissenberg number decreases the fluid velocity because it strengthens the non-Newtonian behaviour of the fluid (see Fig. 2). This parameter controls the transition between different viscosity levels; a higher value enhances the fluid's resistance to flow by increasing its effective viscosity under the prevailing shear rates. Physically, the fluid becomes "thicker" and more resistant to deformation, which slows down the overall motion of the fluid layers. Fig. 3 illustrates that an increase in the couple stress parameter decreases the fluid velocity because it enhances the internal twisting resistance (couple stresses) arising from the fluid's microscopic particles or polymer chains. These extra resistances act like microscopic brakes that oppose the rotation and smooth sliding of fluid layers, effectively increasing the fluid's resistance to flow. As a result, the fluid behaves as if it is thicker, leading to a noticeable reduction in velocity. Fig. 4 displayed that an increase in the magnetic field parameter decreases the fluid velocity due to the strong Lorentz force generated by the interaction between the magnetic field and the electrically conducting fluid. This force acts as a resistive drag that opposes the fluid motion, slowing down the flow. Physically, it is like applying an invisible magnetic brake that pulls the fluid particles in the opposite direction of flow. As a result, the fluid velocity declines significantly. It is observed from Fig. 5 that an increase in the Prandtl number decreases the fluid temperature because Prandtl number represents how quickly heat spreads compared to momentum. A higher *Pr* means the fluid has relatively low thermal diffusivity, so heat conducts slowly into the fluid. The thermal boundary layer becomes thinner and the temperature drops more rapidly away from the hot surface. As a result, the overall temperature of the fluid declines. An increase in the thermal radiation parameter leads to a rise in the fluid temperature because it enhances the radiative heat transfer within the fluid (see Fig. 6). Physically, higher thermal radiation allows the fluid to absorb and emit more thermal energy in the form of electromagnetic waves, adding extra heat to the system. This additional radiative heating thickens the thermal boundary layer and increases the overall temperature distribution. Fig. 7 illustrates that an increase in the thermal relaxation parameter decreases the fluid temperature because it introduces a time lag (finite speed) in heat propagation within the fluid. In simple terms, the fluid does not respond instantly to temperature changes higher relaxation means heat takes longer to transfer through the material. This delay causes less heat accumulation inside the fluid, leading to a reduction in overall temperature.

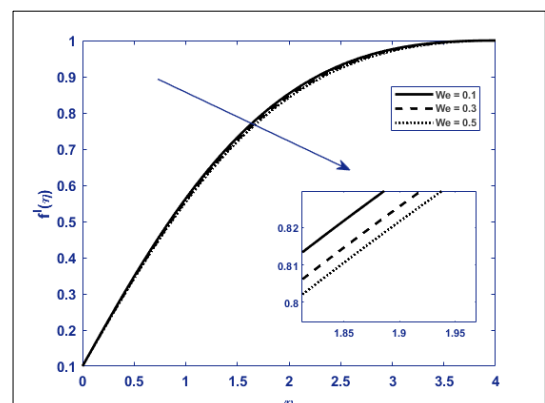


Fig 2: Influence of Weissenberg number on velocity profile

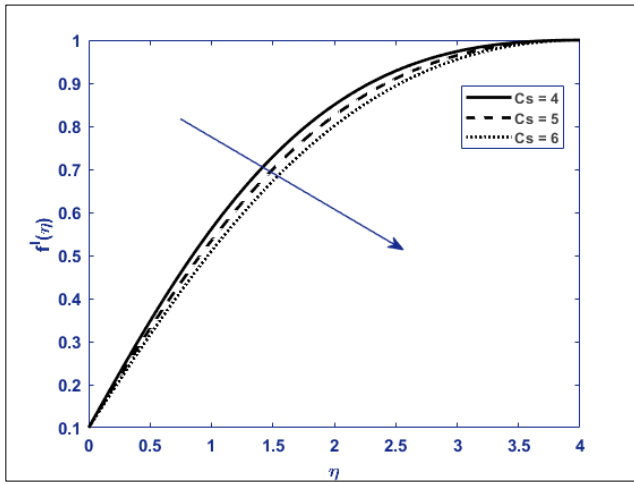


Fig 3: Influence of couple stress parameter on velocity profile

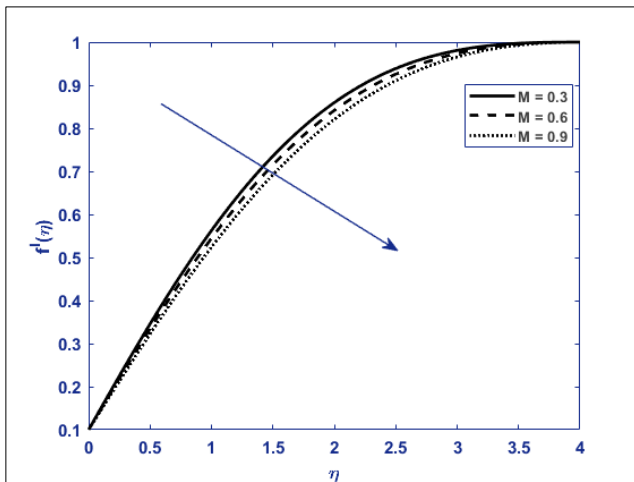


Fig 4: influence of magnetic field parameter on velocity profile

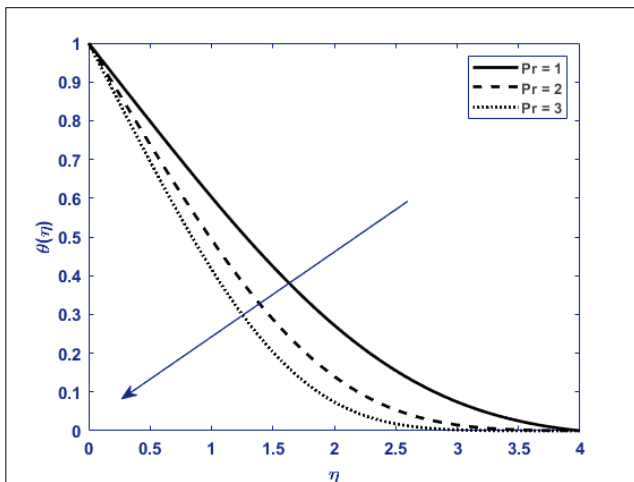


Fig 5: Influence of Prandtl number on temperature profile

Based on Table 1, the skin friction coefficient increases with the couple stress parameter because a higher couple stress strengthens the fluid's resistance to rotational motion and internal micro-structure deformation, which enhances the shear stress at the wall. Similarly, Cf increases with the Weissenberg number due to the elastic nature of the

viscoelastic fluid; larger We means longer stress relaxation times, causing the fluid to resist deformation more and thereby increasing drag. In contrast, Cf decreases with the mixed convection parameter δ because a higher δ implies stronger buoyancy forces relative to inertial forces, which can accelerate the flow in the boundary layer, reduce the velocity gradient at the wall, and consequently lower the skin friction. Based on Table 2, the Nusselt number Nu increases with the Prandtl number Pr because a higher Prandtl number enhances the ratio of momentum diffusivity to thermal diffusivity, leading to a thicker momentum boundary layer relative to the thermal boundary layer, which steepens the temperature gradient at the wall and improves heat transfer. Similarly, Nu increases with the thermal radiation parameter R since stronger radiation contributes additional energy transfer within the fluid, effectively augmenting the total heat flux at the surface. In contrast, Nu decreases with the thermal relaxation parameter Γ ; this occurs because a larger relaxation time implies a delayed response of the heat flux to the temperature gradient (non-Fourier effect), which reduces the effective thermal conductivity near the wall and consequently weakens the rate of heat transfer.

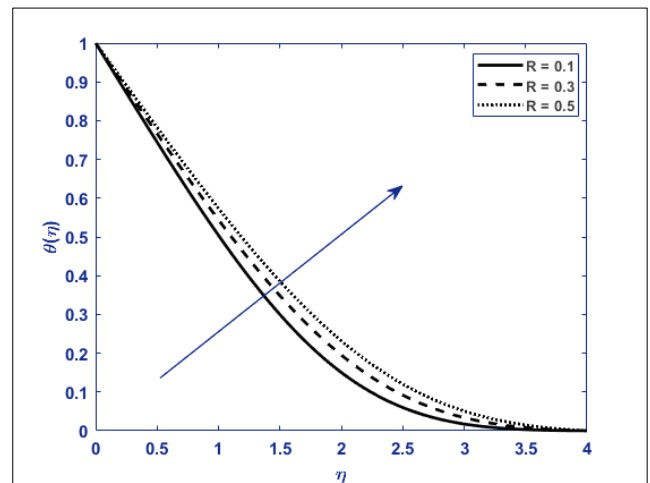


Fig 6: Influence of thermal radiation parameter on temperature profile

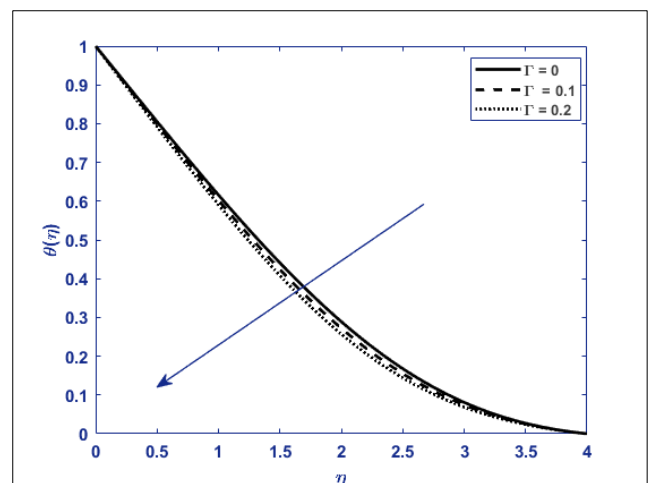


Fig 7: Influence of thermal relaxation parameter on temperature profile

Table 1: Influence of couple stress parameter, Weissenberg number and mixed convection parameters on Cf

Cs	We	δ	Cf
3.5			0.490397
4			0.499815
4.5			0.510517
5			0.522799
5.5			0.537066
	0.1		0.562309
	0.2		0.565413
	0.3		0.569203
	0.4		0.574154
	0.5		0.581625
		0.5	0.769799
		1	0.722714
		1.5	0.674452
		2	0.624951
		2.5	0.574154

Table 2: Influence of Prandtl number, thermal radiation parameter and thermal relaxation parameters on Nu

Pr	R	Γ	Nu
0.5			0.362822
1			0.44518
1.5			0.517
2			0.578308
2.5			0.631222
	0		0.418583
	0.05		0.548718
	0.1		0.675342
	0.15		0.800921
	0.2		0.926123
		0	0.459377
		0.05	0.452409
		0.1	0.44518
		0.15	0.437666
		0.2	0.429851

4 Conclusions

The present study numerically investigated the steady mixed convective flow of an electrically conducting Carreau-Yasuda non-Newtonian fluid over a moving vertical flat plate. The mathematical model uniquely integrated the effects of couple stresses (arising from fluid microstructural rotations), a transverse magnetic field (inducing Lorentz drag), thermal radiation (Rosseland approximation), and non-Fourier (Cattaneo-Christov) heat flux accounting for finite thermal propagation speed. The key findings of the study are summarized below:

- Increasing the Weissenberg number strengthens the non-Newtonian shear-thinning or shear-thickening response, enhancing effective viscosity and thereby reducing fluid velocity. Similarly,
- A higher couple stress parameter introduces additional internal resistance against rotational motion of micro-elements, acting as microscopic brakes that decelerate the main flow.
- The temperature profile decreases with increasing Prandtl number because higher Pr implies lower thermal diffusivity, thinning the thermal boundary layer. In contrast, enhanced thermal radiation thickens the thermal layer and elevates temperatures by supplying additional radiative energy.
- The thermal relaxation parameter uniquely reduces temperature due to the finite lag in heat propagation, a

purely non-Fourier signature absent in classical Fourier models.

- Skin friction coefficient increased with the rise in both the couple stress parameter and Weissenberg number, as both enhance the fluid's resistance to deformation at the wall. However, the same decreased under stronger mixed convection, since buoyancy forces accelerate near-wall flow, reducing the velocity gradient at the surface.
- Nusselt number improves with higher Prandtl number and thermal radiation parameter, attributed to steeper wall temperature gradients and augmented radiative heat flux, respectively. Conversely, Nu declines with increasing thermal relaxation parameter, confirming that finite-speed heat propagation reduces effective thermal conductivity near the heated plate.

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