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Magnetohydrodynamic Williamson fluid flow over an angled wedge with Cattaneo-Christov heat flux and couple stress: An irreversibility analysis

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Abstract

This study investigates the steady-state magnetohydrodynamic (MHD) flow of a Williamson non-Newtonian fluid over an angled wedge, incorporating the Cattaneo-Christov heat flux model to account for thermal relaxation effects. The analysis includes the influence of couple stress, thermal radiation, and heat source. The governing partial differential equations are transformed into a system of ordinary differential equations using appropriate similarity transformations and solved numerically using the bvp4c solver in MATLAB. The effects of key parameters on velocity, temperature, entropy generation, skin friction coefficient, and Nusselt number are examined in detail. Results indicate that the velocity field diminishes with increasing Weissenberg number, couple stress parameter, and magnetic field parameter. The temperature profile rises with higher heat source and thermal radiation parameters but decreases with an increasing thermal relaxation parameter. Entropy generation intensifies with higher Brinkman number and thermal radiation parameter. The skin friction coefficient is enhanced by both couple stress and Weissenberg numbers. Notably, the Nusselt number increases with the thermal relaxation parameter but decreases with the heat source parameter, as internal heat generation reduces the thermal gradient near the wall. This study provides valuable insights for thermal management applications involving non-Newtonian fluids with complex heat transfer mechanisms.

Keywords: Non-Newtonian fluid, thermal radiation, bvp4c solver, heat source, entropy generation

1. Introduction

The Cattaneo-Christov heat flux model holds considerable significance in fluid flow analysis as it addresses a key limitation of the classical Fourier's law by incorporating thermal relaxation time, thereby accounting for the finite speed of heat propagation. This modification makes it particularly suitable for studying processes involving rapid heating, micro-scale energy transport, and high-temperature gradients where conventional models fall short. In practical applications, this framework proves valuable in optimizing thermal management systems such as advanced cooling of electronic components, polymer processing, laser material treatment, and energy-efficient heat exchangers. By providing a more realistic description of heat transfer behavior in non-Newtonian and hybrid nanofluids, the model supports the development of more accurate design strategies in industrial manufacturing, biomedical devices, and renewable energy systems where precise thermal control is essential. Alebraheem and Ramzan ^[1] investigated the heat and mass transfer behaviour of a Casson nanofluid containing gyrotactic microorganisms flowing past a swirling cylinder, incorporating the Cattaneo-Christov heat flux model along with magnetohydrodynamic effects, chemical reaction, and zero mass flux condition. Elevated values of the magnetic parameter enhanced both components of surface drag force while increasing the Brownian motion and Reynolds number led to a reduction in fluid concentration. Reddy *et al.* ^[2] numerically investigated the two-dimensional flow of an incompressible hybrid dusty fluid through a Darcy-Forchheimer porous medium over a stretching sheet, incorporating the Cattaneo-Christov heat flux model and carbon nanotube properties using the RKF-45 method. Heat transfer performance was observed to be more pronounced in the dusty fluid compared to

the hybrid nanofluid, with elevated radiation parameters significantly enhancing the cooling process. Reddy *et al.* [3] investigated the Darcy-Forchheimer flow of a Prandtl non-Newtonian nanofluid over a moving sheet, incorporating the Cattaneo-Christov heat flux model, thermal radiation, viscous heating, and zero-mass flux boundary conditions, and obtained numerical solutions using the Runge-Kutta method. Higher values of the elastic and Prandtl parameters significantly enhanced the velocity field, while increasing the inertia and porosity parameters reduced it. Turkyilmazoglu [4] analytically investigated the heat transfer enhancement characteristics of the Cattaneo-Christov heat flux model compared to the classical Fourier law, deriving closed-form expressions for temperature and Nusselt number and establishing the conditions under which the non-Fourier model promotes increased heat transfer rates. The analytical derivations demonstrated that for a bounded vertical velocity function, the Cattaneo-Christov model enhances the Nusselt number when the thermal relaxation parameter satisfies specific conditions related to the Prandtl number and the flow field. Hussain *et al.* [5] analytically investigated the stagnation point flow of a Jeffery fluid over a stretching cylinder using the Cattaneo-Christov heat flux model, incorporating double stratification, heat generation, and thermal relaxation effects, and obtained series solutions via the homotopy analysis method. Increasing the curvature parameter and Deborah number (retardation time) enhanced the velocity field, while larger relaxation time parameters reduced it. Later, various researchers [6-13] discussed various fluid flows across different geometries by considering Cattaneo-Christov heat flux model.

Williamson fluid, as a shear-thinning non-Newtonian model, holds significant importance in fluid mechanics due to its ability to accurately capture the viscosity reduction behaviour under increasing shear rates, a characteristic commonly observed in many industrial and biological materials. This makes it particularly valuable for applications involving polymer processing, coating flows, food processing, and the transport of drilling muds in petroleum engineering, where precise control of flow behaviour is critical. In biomedical contexts, Williamson fluid models help simulate blood flow in arteries and microchannels, aiding in the design of medical devices and drug delivery systems. Its compatibility with advanced thermal and mass transport frameworks, such as the Cattaneo-Christov heat flux model and Darcy-Forchheimer porous media, further extends its utility in heat exchanger optimization, solar thermal systems, and enhanced oil recovery processes where combined momentum and heat transfer analysis is essential. Priyadarshini *et al.* [14] numerically investigated the magnetohydrodynamic flow of a Williamson non-Newtonian nanofluid containing gyrotactic microorganisms over a symmetrically stretching sheet, incorporating thermal radiation, Brownian motion, thermophoresis, and activation energy effects, and complemented their analysis with multiple linear regression machine learning predictions. Velocity profiles diminished with increasing magnetic field strength but rose with higher Williamson fluid parameters. Obalalu *et al.* [15] numerically analyzed the three-dimensional hydromagnetic flow of a Williamson non-Newtonian fluid over an inclined stretching sheet, incorporating Hall current, solar radiation, chemical reaction, activation energy, and heat generation or absorption effects using the Galerkin Weighted Residual Method. Pooja *et al.* [16] numerically investigated the magnetohydrodynamic flow of a Williamson fluid over a stretching cylinder embedded in a porous medium, incorporating homogeneous and heterogeneous reactions, thermal radiation, heat generation or absorption, and buoyancy effects, solving the transformed ordinary differential equations using the Runge-Kutta-Fehlberg 4-5th order method. Later, different researchers [17-19] discussed various Williamson fluid flows across different geometries.

Despite the growing body of literature on non-Newtonian fluid flows with advanced thermal models, the combined influence of couple stress, thermal radiation, and the Cattaneo-Christov heat flux model on Williamson fluid flow over an angled wedge remains largely unexplored. Existing studies have primarily focused on simpler geometries or conventional Fourier heat conduction, leaving a significant gap in understanding the interplay between micro-structural effects (couple stress), shear-thinning behaviour (Williamson fluid), and non-Fourier heat transport mechanisms in wedge flows. The present study addresses this gap by providing a comprehensive numerical analysis of magnetohydrodynamic Williamson fluid flow over an angled wedge, incorporating the Cattaneo-Christov heat flux model along with heat source and entropy generation. The novelty lies in the simultaneous integration of these complex transport phenomena within a single framework, offering new insights into the thermal and hydrodynamic behaviour of shear-thinning fluids under realistic operating conditions. The findings hold significant practical relevance for applications such as advanced thermal management systems, polymer processing, enhanced oil recovery, and biomedical devices, where precise control of heat transfer and flow characteristics is essential for optimal performance and energy efficiency.

2. Formulation of the study

This study investigates the effect of several parameters, including couple stress and thermal radiation, on the steady-state movement of the Williamson fluid across an angled wedge with Cattaneo-Christov heat flux model. In this investigation, we presuppose the following:

- Thermal radiation follows the Rosseland approximation.
- The flow is influenced by an externally applied vertical magnetic field of strength B , as illustrated in Fig. 1.
- Induced magnetic field effects are disregarded since the magnetic Reynolds number is small.

The subsequent circumstances and equations are requisite for this study, predicated on the aforementioned assumptions:

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = v \left(\frac{\partial^2 u}{\partial y^2} + \sqrt{2} \gamma \frac{\partial u}{\partial y} \frac{\partial^2 u}{\partial y^2} \right) + g \beta_T (T - T_\infty) \sin \frac{\alpha}{2} - \frac{\sigma B^2}{\rho} u - \frac{\gamma_0}{\rho} \left(\frac{\partial^4 u}{\partial y^4} \right) \quad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + \delta \left(u^2 \frac{\partial^2 T}{\partial x^2} + 2uv \frac{\partial^2 T}{\partial x \partial y} + v^2 \frac{\partial^2 T}{\partial y^2} + \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) \frac{\partial T}{\partial x} + \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) \frac{\partial T}{\partial y} \right)$$

$$= \frac{k}{\rho C_p} \frac{\partial^2 T}{\partial y^2} + \frac{1}{\rho C_p} \frac{16}{3} \frac{\sigma^* T_\infty^3}{k^*} \frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p} (T - T_\infty) \quad (3)$$

$$\left. \begin{aligned} u = u_w = ax^n, v = 0, \frac{\partial^2 u}{\partial y^2} = 0, k \frac{\partial T}{\partial y} = h_f (T - T_w) \text{ at } y = 0, \\ u \rightarrow 0, \frac{\partial u}{\partial y} \rightarrow 0, T \rightarrow T_\infty \text{ as } y \rightarrow \infty. \end{aligned} \right\} \quad (4)$$

Bilal *et al.* [20] proposed the subsequent similarity transforms to translate governing equations:

$$\left. \begin{aligned} u = u_w f'(\eta), v = -\sqrt{\frac{n+1}{2}} \sqrt{\frac{v u_w}{x}} \left[f(\eta) + \frac{n-1}{n+1} \eta f'(\eta) \right], \\ T = T_\infty + (T_w - T_\infty) \theta(\eta), T_w - T_\infty = T_0 A x^m, \eta = y \sqrt{\frac{n+1}{2}} \sqrt{\frac{u_w}{v x}}. \end{aligned} \right\} \quad (5)$$

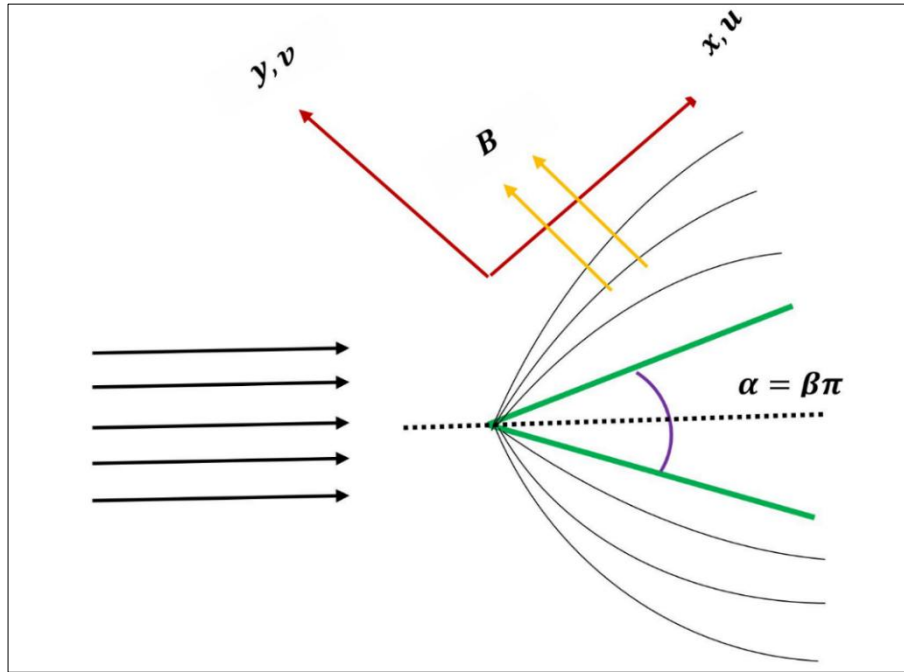


Fig 1: Graphical depiction of the current research

Terms in (5) transformed the equations (2-3) along with the conditions in (4) as follows:

$$\frac{n+1}{2} (f''' + W e f'' f''') - n f'^2 + \frac{n+1}{2} f f'' + \lambda \theta \sin \frac{\alpha}{2} - M g f' - \left(\frac{n+1}{2} \right)^2 C s f' v = 0 \quad (6)$$

$$\left(\left(\frac{n+1}{2} \right) \frac{1}{Pr \left(\frac{n+1}{2} \right) \frac{Ra}{Pr \left(\frac{n^2+1}{2} \eta^2 f'^2 - (n-1) \eta f'^2 + \left(\frac{n+1}{2} \right)^2 f^2 \right)}} \theta'' + \left(\frac{n+1}{2} \right) f \theta' - m f' \theta - \Gamma \left(\frac{2n^2-n-m(n-1)}{2} \eta f'^2 \theta' + (m^2 - m + mn) f'^2 \theta \right. \right. \\ \left. \left. + \frac{(n+1)(n+1-4m)}{4} f f' \theta' - \frac{n(n+1)}{2} f f'' \theta \right. \right. \\ \left. \left. + \frac{n(n-1)}{2} \eta^2 f' f'' \theta' - \frac{m(n+1)}{2} f f'' \theta \right) \right) = 0 \quad (7)$$

$$\left. \begin{aligned} \text{at } \eta = 0: f(\eta) = 0, f'(\eta) = 1, f'''(\eta) = 0, \theta'(\eta) = -Bi(1 - \theta(\eta)), \\ \text{as } \eta \rightarrow 0: f'(\eta) \rightarrow 0, f''(\eta) \rightarrow 0, \theta(\eta) \rightarrow 0. \end{aligned} \right\} \quad (8)$$

where

$$\left. \begin{aligned} C s = \frac{\gamma_0 a}{\rho v^2}, \gamma_0 = \gamma_1 x^{n-1}, M g = \frac{\sigma B_0^2}{\rho a}, B_0 = \frac{B}{x^{\frac{n-1}{2}}}, R e_x = \frac{x u_w}{\nu}, Q = \frac{Q_0}{(\rho C_p) a x^{n-1}}, \\ R = \frac{16 \sigma^* T_\infty^3}{3 k k^*}, Pr = \frac{\mu C_p}{k}, \lambda = \frac{Gr}{Re_x^2}, Gr = \frac{g \beta_T (T_w - T_\infty) x^3}{\nu^2}, We = \sqrt{\frac{\gamma^2 (n+1) U^3}{\nu x}}, \\ \Gamma = \delta a x^{n-1}. \end{aligned} \right\}$$

The friction factor can be expressed as follows:

$$Cf = \left. \frac{\tau_w}{\frac{1}{2}\rho u_w^2} \right|_{y=0}, \tau_w = \mu \left(\frac{\partial u}{\partial y} \right). \quad (9)$$

The use of (5) facilitates a more straightforward formulation of the equation presented in (9) as follows:

$$\sqrt{Re_x} Cf = \sqrt{2(n+1)} f''(0).$$

The subsequent formula can be used to determine the Nusselt number:

$$Nu = \frac{-x}{k_f(T_w - T_\infty)} \left(k + \frac{16\sigma T_\infty^3}{k^*} \right) \left. \frac{\partial T}{\partial y} \right|_{y=0}. \quad (10)$$

By employing (5), the formula utilized in (10) can be succinctly reformulated as:

$$(Re_x)^{\frac{-1}{2}} Nu = -\sqrt{\frac{n+1}{2}} (1+R) \theta'(0).$$

The formula that describes the dimensional computation of entropy production is mentioned as:

$$S_g = \left(\frac{k_f}{T_\infty^2} \right) \left(1 + 16 \frac{\sigma T_\infty^3}{3kk^*} \right) \left(\frac{\partial T}{\partial y} \right)^2 + \frac{\mu}{T_\infty} \left(\frac{\partial u}{\partial y} \right)^2 + \frac{\sigma}{T_\infty} u^2 B^2. \quad a(11)$$

By adopting (5), we may rewrite equation (11) as follows:

$$EG = \frac{n+1}{2} (1+Ra) \alpha_1 \theta'^2 + \frac{n+1}{2} Br f'^2 + Mg Br f'^2,$$

where

$$EG = \frac{vT_\infty x S_g}{ku_w(T_w - T_\infty)}, Br = \frac{\mu u_w^2}{k(T_w - T_\infty)}.$$

3. Results and discussion

The boundary value problem represented by equations (6) and (7), subject to the constraints in (8), is solved numerically using the `bvp4c` solver in MATLAB. A rise in the Weissenberg number indicates stronger elastic (or shear-thinning) effects, which increase the fluid's resistance to deformation. This enhanced elasticity dissipates more energy, thereby opposing the flow and reducing the fluid velocity (see Fig. 2). From Fig. 3, it is observed that the rise in the couple stress parameter causes a reduction in the velocity of the fluid. The couple stress parameter introduces a higher viscosity-like effect due to the fluid's micro-structure. This increases the internal resistance (or fluid friction) within the flow, which consequently suppresses the velocity field. Fig. 4 displayed that the rise in the magnetic field parameter decreases the fluid velocity. A rise in the magnetic field parameter strengthens the Lorentz force, which opposes the fluid motion. This resistive body force acts as a magnetic brake, decelerating the flow and thereby reducing the fluid velocity. The rise in the heat source parameter generates internal thermal energy within the fluid, which acts as a positive source of heat. This additional energy directly increases the fluid's enthalpy, leading to a consistent increment in its temperature profile (see Fig. 5). From Fig. 6, it is clear that the rise in the thermal relaxation parameter causes a reduction in the temperature profile. A rise in the thermal relaxation parameter (indicating a longer time for heat flux to respond to a temperature gradient) causes a decrement in fluid temperature because it introduces a lag in heat propagation, effectively reducing the effective thermal diffusivity. This delays the diffusion of heat from hotter regions, leading to slower thermal energy transfer and lower overall temperatures in the fluid. A rise in the thermal radiation parameter means the fluid emits and absorbs radiative energy more efficiently. This enhances heat transfer from the hotter boundary into the fluid interior, leading to greater internal energy absorption and a subsequent increase in the fluid temperature (see Fig. 7). Fig. 8 illustrates that the rise in the Brinkman number leads to the increment in the entropy generation. A rise in the Brinkman number signifies a dominance of viscous dissipation over conductive heat transfer. This intensifies irreversibilities from fluid friction, which directly increases the entropy generation within the system. An increase in the thermal radiation parameter intensifies the radiative heat flux, leading to steeper temperature gradients within the fluid. According to the entropy generation equation, which is proportional to the square of these temperature gradients, this directly results in higher thermodynamic irreversibility and increased entropy production (see Fig. 9). From Table 1, it is clear that the rise in the couple stress parameter and Weissenberg number enhance the skin friction coefficient. The rise in the couple stress parameter increases the fluid's resistance to rotational motion (sub-micron effects), which intensifies the velocity gradient at the wall. This higher shear rate directly results in a larger skin friction coefficient. Table 2 displayed that the rise in the thermal relaxation parameter causes an escalation in the Nusselt number and increase in the heat source parameter decreases the Nusselt number. A rise in the heat source parameter intensifies internal heat generation, which reduces the thermal gradient near the wall. This weaker gradient diminishes the rate of heat transfer from the surface, leading to a lower Nusselt number.

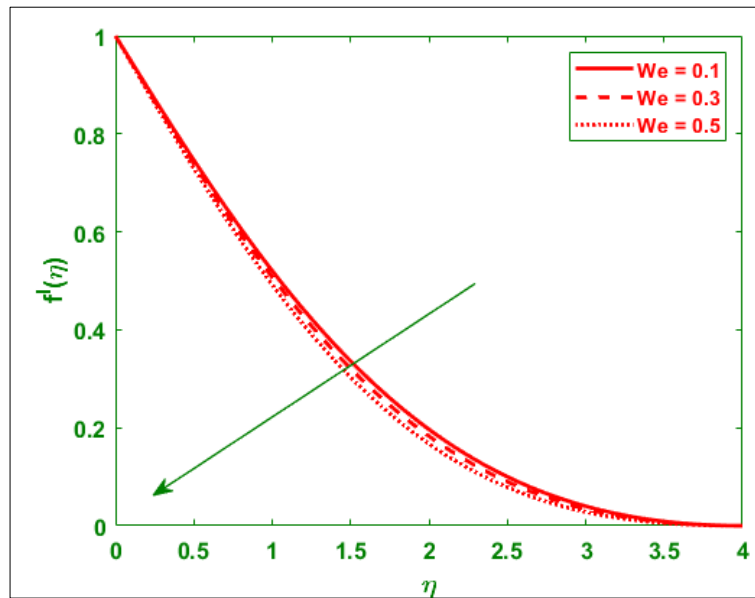


Fig 2: Influence of Weissenberg number on velocity profile

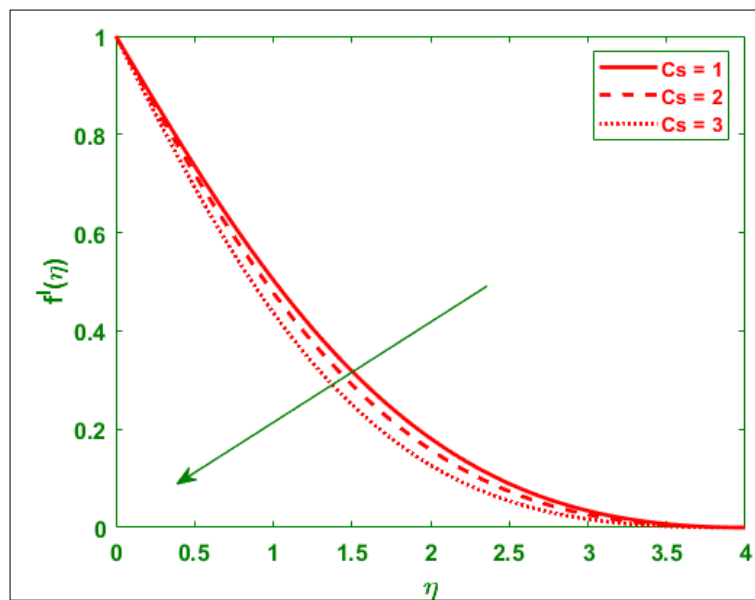


Fig 3: Influence of couple stress parameter on velocity profile

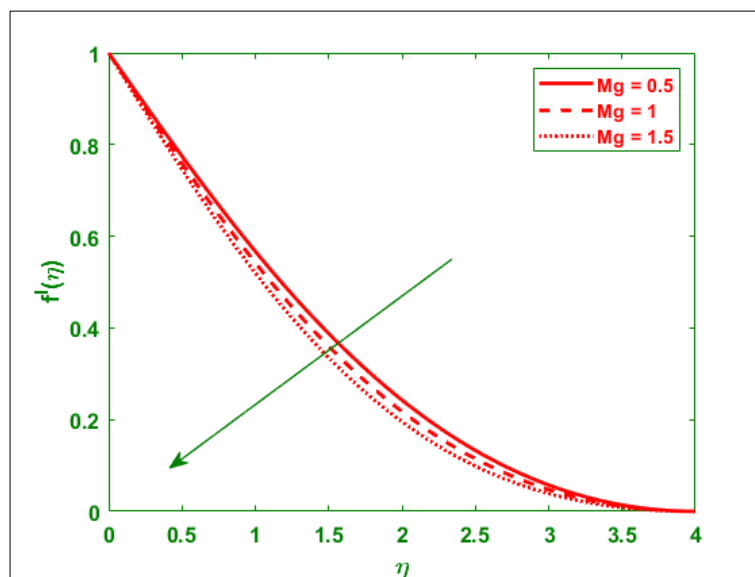


Fig 4: Influence of magnetic field parameter on velocity profile

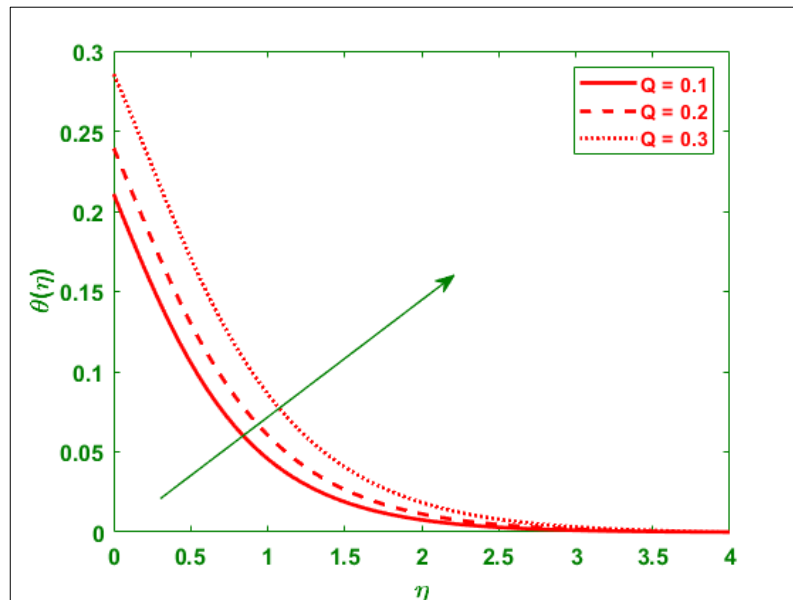


Fig 5: Influence of heat source parameter on temperature profile

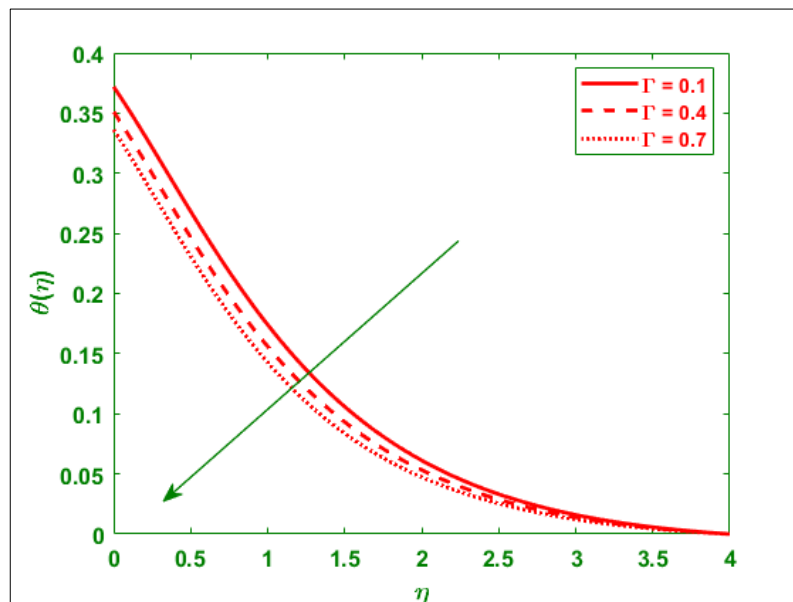
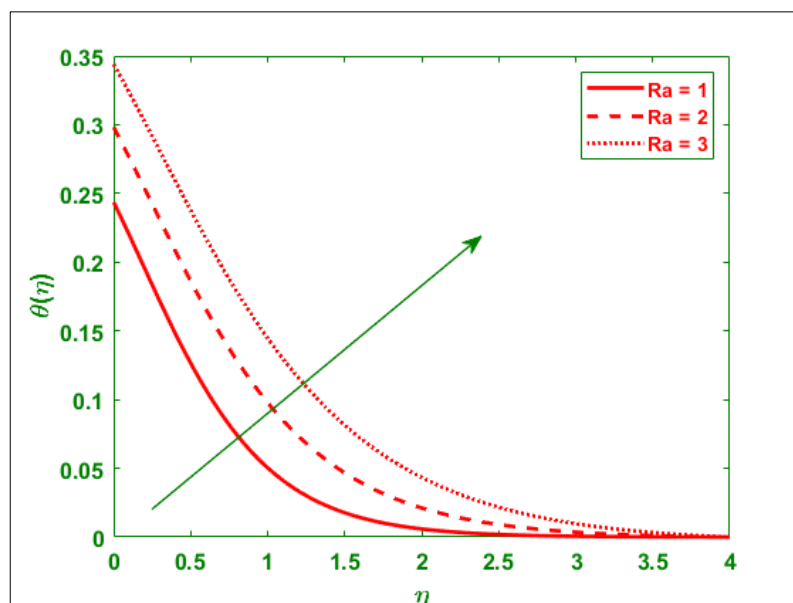


Fig 6: Influence of thermal relaxation parameter on temperature profile



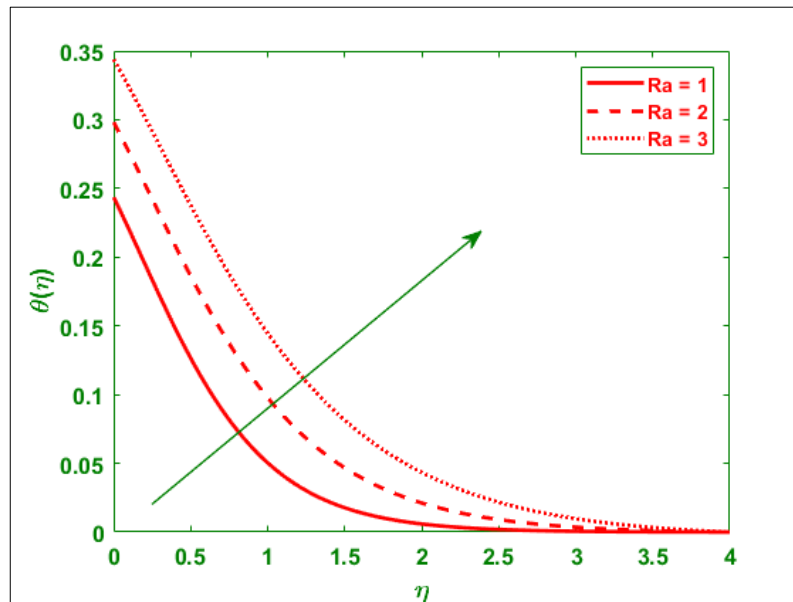


Fig 7: Influence of thermal radiation parameter on temperature profile

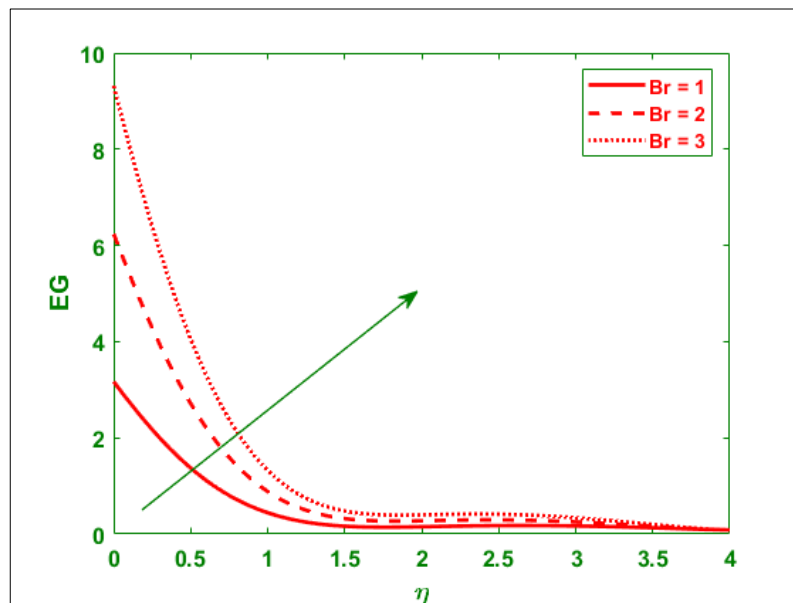


Fig 8: Influence of Brinkman number on entropy generation profile

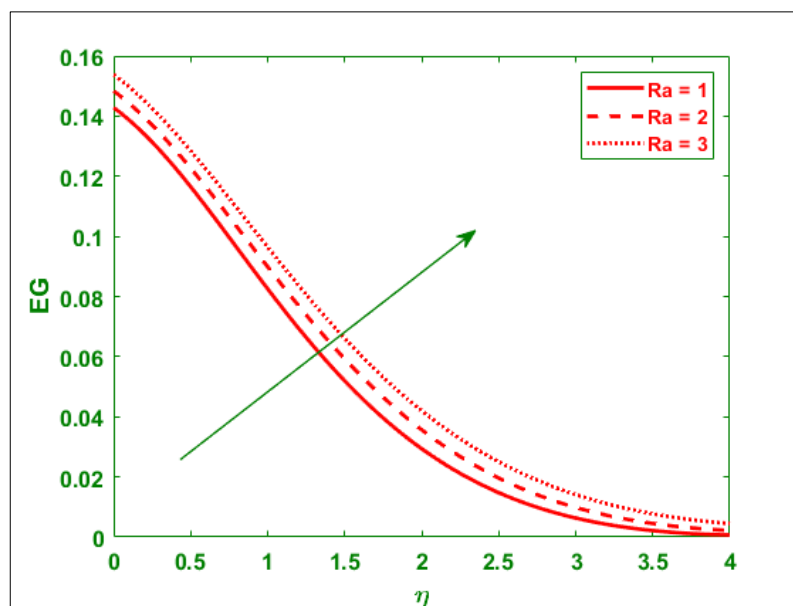


Fig 9: Influence of thermal radiation parameter on temperature profile

Table 1: Influence of couple stress parameter and Weissenberg number on Cf

Cs	We	Cf
0.5		-0.95657
1		-0.83884
1.5		-0.7719
2		-0.72556
2.5		-0.69054
	0	-0.71004
	0.3	-0.70327
	0.6	-0.69678
	0.9	-0.69054
	1.2	-0.68454

Table 2: Influence of thermal relaxation and heat source parameters on Nu

Γ	Q	Nu
0		0.180004
0.1		0.185442
0.2		0.190122
0.3		0.194192
0.4		0.19776
	0	0.240277
	0.1	0.229574
	0.2	0.213505
	0.3	0.185442
	0.4	0.122049

4. Conclusion

The present study numerically investigates the steady-state magnetohydrodynamic (MHD) flow of a Williamson non-Newtonian fluid over an angled wedge, incorporating the Cattaneo-Christov heat flux model, couple stress, thermal radiation, and heat source effects. The transformed governing equations are solved using the bvp4c solver in MATLAB. Based on the numerical results, the following important conclusions are drawn:

- Velocity field decreases with increasing Weissenberg number, couple stress parameter, and magnetic field parameter due to enhanced elastic effects, internal micro-structural resistance, and Lorentz force, respectively.
- Temperature profile rises with increasing heat source parameter and thermal radiation parameter, as internal heat generation and enhanced radiative absorption increase the fluid enthalpy.
- Temperature profile diminishes with increasing thermal relaxation parameter, as a longer relaxation time reduces effective thermal diffusivity and delays heat propagation.
- Entropy generation intensifies with higher Brinkman number and thermal radiation parameter, owing to the dominance of viscous dissipation and steeper temperature gradients, respectively.
- Skin friction coefficient is enhanced by both the couple stress parameter and the Weissenberg number, indicating greater resistance at the wall due to micro-structural effects and shear-thinning behaviour.
- Nusselt number increases with the thermal relaxation parameter but decreases with the heat source parameter, as internal heat generation reduces the thermal gradient near the wall, thereby weakening convective heat transfer.

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