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# VARIABLE THERMOPHYSICAL PROPERTY AND OHMIC HEATING IMPACT ON RADIATIVE CASSON FLUID FLOW PAST A STRETCHING CYLINDER

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**ABSTRACT**

This study investigates the effect of variable thermophysical properties on radiative Casson fluid flow around a stretching cylinder. The governing partial differential equations for momentum and energy are changed into ordinary differential equations with suitable similarity transformations. Our mathematical model analyses the impact of variable thermal conductivity, viscosity, and radiation parameters on the fluid flow system. The resulting coupled nonlinear equations are solved numerically using the Runge-Kutta fourth-order method with shooting technique. The effect of key parameters including Casson fluid parameter, thermal radiation parameter, magnetic parameter, Grashof number, Prandtl number, Eckert number, ohmic heating parameter and Biot number on velocity and temperature profiles is examined. Results indicate that increasing the Casson parameter reduces fluid velocity while increasing the temperature distribution. The thermal boundary layer thickness is seriously affected by the radiation parameter and variable thermal conductivity. In addition, the study reveals that heat transfer rates at the surface increase with higher values of the Biot number. These findings provide valuable insights into heat transfer optimization in industrial applications involving non-Newtonian fluids with radiative effects and variable properties.

**Keywords**: Variable thermophysical properties, Casson fluid, Thermal radiation, MHD fluid, Stretching cylinder, Radiative heat transfer

## INTRODUCTION

Thermal radiation plays a critical role in heat transfer processes, especially in high-temperature applications such as industrial equipment and space technologies. It changes how fluid move and has significant effect on the temperature profiles and flow characteristics under various conditions. (Dehghan, et al 2024) worked on the effects of thermal radiation, thermal conductivity, and variable viscosity on ferrofluid in porous medium under magnetic field. (Shah, et al 2023) studied the effect of thermal radiation on convective heat transfer in MHD boundary layer Carreau fluid with chemical reaction. (Aina, 2020) investigated thermal radiation effect on fully developed natural convection flow in a vertical micro-channel. (Samuel, 2022) carried out research on Numerical investigations of thermal radiation and activation energy imparts on chemically reactive Maxwell fluid flow over an exothermal stretching sheet in a porous medium. (Jamalabadi, & Park, 2014) analyzed thermal radiation, Joule heating, and viscous dissipation effects on MHD forced convection flow with uniform surface temperature. (Yusuf & Abdullahi, 2024) analysed the influence of temperature dependent viscosity, viscous dissipation and joule heating on MHD natural convection flow: a semi analytical approach. (Rao et al., 2015) examined Joule heating and thermal radiation effects on MHD boundary layer flow of a nanofluid over an exponentially stretching sheet in a porous medium. (Samuel & Olajuwon, 2022) provided insight into the effects of thermal radiation and Ohmic heating on chemically reactive Maxwell fluid subject to Lorentz force and buoyancy force. (Shateyi, & Motsa, 2009) explored thermal radiation effects on heat mass transfer over an unsteady stretching surface. (Cuevas, 2019) discussed thermal radiation from subwavelength objects and the violation of Planck's law. (Eldabe, et al. 2013) studied the effects of thermal radiation and magnetic field on heat transfer in a micropolar fluid along a vertical stretching surface with variable viscosity and internal heat generation. (Patel, 2021) analyzed thermal radiation effects on MHD flow with heat and mass transfer of micropolar fluid between two vertical walls. (Sobamowo, 2018) worked on combined effects of thermal radiation and nanoparticles on free convection flow and heat transfer of Casson fluid over a vertical plate. (Adegbie at al., 2019) presented radiative heat transfer fluid flow past a porous surface in the presence of viscous dissipation.

Thermophysical parameters such as viscosity, conductivity, and density are paramount in determining fluid behavior under various temperature conditions, especially in nanofluids for enhanced heat transfer applications. The analysis of non-Newtonian fluid flows with variable thermophysical properties over stretching surfaces are important in many field due to its numerous industrial and engineering applications. Casson fluid, in particular, has become a focus of research because of its unique rheological properties that can model various complex fluids like blood, food products, and certain polymeric solutions (Samuel & Ajayi, 2018) studied the effects of thermo-physical parameters on free convective flow of chemically reactive power law fluid driven by exothermal plate. (Kalsi et al., 2023) highlighted thermophysical properties of nanofluids with potential applications in heat transfer enhancement. (Rudyak & Minakov, 2018) analyzed thermo-physical properties of nanofluid. (Latini, 2017) examined thermophysical properties of fluids: dynamic viscosity and thermal conductivity. (Durojaye et al., 2019) analyzed the effects of some thermo-physical properties of fluid on heat mass transfer flow past semi-infinite moving vertical plate with viscous dissipation. (Kanthimathi et al., 2024) explored thermophysical properties and heat transfer in mono and hybrid nanofluids with different base fluids. (Koriko, 2018) conducted analysis of variable thermophysical properties of thermophoretic viscoelastic fluid flow past a vertical surface with nth order chemical reaction. (Samuel and Fayemi, 2023) examined impact of temperature dependent viscosity on dissipating fluid flow in a porous medium. (Zainon & Azmi,

2021) reviewed recent progress on stability and thermo-physical properties of mono and hybrid green nanofluids.

Casson fluid models are mostly used to describe non-Newtonian fluids with yield stress characteristics, relevant in biomedical and industrial flows. Research has addressed Casson fluid flow under magnetic fields, chemical reactions, activation energy, and slip conditions over porous surfaces, stretching sheets, and microchannels. It has become a center of research because of its unique rheological properties that can model various complex fluids like blood, food products, and certain polymeric solutions. (Arthur et al., 2015) analyzed Casson fluid flow over a vertical porous surface with chemical reaction in the presence of magnetic field. (Alqarni et al., 2022) performed mathematical analysis of Casson fluid flow with energy and mass transfer under the influence of activation energy from a non-coaxially spinning disc. (Asogwa & Ibe, 2020) studied MHD Casson fluid flow over a permeable stretching sheet with heat and mass transfer. (Abbas et al., 2024) applied heat and mass transfer to convective flow of Casson fluids in a microchannel with Caputo–Fabrizio derivative approach. (Singh et al., 2022) worked on MHD Casson fluid flow with Navier's and second order slip due to a perforated stretching or shrinking sheet. (Ali et al., 2011) studied effect of Hall current on MHD mixed convection boundary layer flow over a stretched vertical flat plate. (Al-Hanaya, 2023) analyzed MHD effects on Casson fluid flow squeezing between parallel plates. (Ali et al, 2023) studied mixed convection in a Casson fluid flow towards a heated shrinking surface. (Elgendi, 2024) conducted computational analysis of the dissipative Casson fluid flow originating from a slippery sheet in porous media. (Samuel & Oladoja, 2023) examined natural convection flow of radiative Casson fluid past a stretching cylindrical surface in a porous medium with applied magnetic field and Joule heating.

Conclusively, while significant advancements have been made in understanding various aspects of Casson fluid flow with thermal radiation and variable properties, a unified approach that integrates all these phenomena in cylindrical geometry remains a valuable contribution to the field. The current study addresses this need by developing a mathematical model that provides a more comprehensive understanding of these complex interactions. The present investigation extends previous work on boundary layer flows in several significant ways that address important gaps in the existing literature. This study investigates flow past a stretching cylinder. The curvature effects introduce significant changes in the flow dynamics and heat transfer characteristics that cannot be captured by flat-plate models. The current model incorporates a more comprehensive treatment of thermal radiation effects in conjunction with variable thermal conductivity, providing deeper insights into radiative heat transfer mechanisms in non-Newtonian fluids. Few studies have simultaneously examined the combined effects of variable thermophysical properties, radiation, MHD effects, and non-Newtonian fluid behavior in cylindrical geometry. This study therefore bridges significant gaps in the current understanding of complex fluid flows with variable properties over curved surfaces, with direct implications for improving heat transfer efficiency in various engineering application

## MATERIALS AND METHODS

The problem of steady laminar two-dimensional natural convection flow of a Casson fluid past a cylindrical stretching surface is considered, with magnetic field effects included in the analysis. The governing equations are described by momentum and energy conservation principles, represented in partial differential form. The fundamental governing equations capture the fluid dynamics and heat transfer characteristics:

$$\frac{\partial(ru)}{\partial x} + \frac{\partial(rv)}{\partial r} = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r} = \upsilon\left(1+\frac{1}{\beta}\right)\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right) + g\beta_T(T-T_\infty) - \frac{\sigma}{\rho}B_0^2 u \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial r} = \frac{1}{r\rho C_p}\frac{\partial}{\partial r}\left(rK(T)\frac{\partial T}{\partial r}\right) + \frac{\sigma B_0^2}{\rho C_p}u^2 - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial r} \tag{3}$$

Boundary conditions define the flow and thermal characteristics at the surface and far-field regions:

$$u(x,r) = v_w(x) = \frac{u_0 x}{l}, v(x,r) = 0, -k\frac{\partial T}{\partial r} = h_f\left(T_f - T\right) \text{ at } r = R \tag{4}$$

$$u \to 0, \quad T \to T_\infty \quad as \qquad r \to \infty, \tag{5}$$

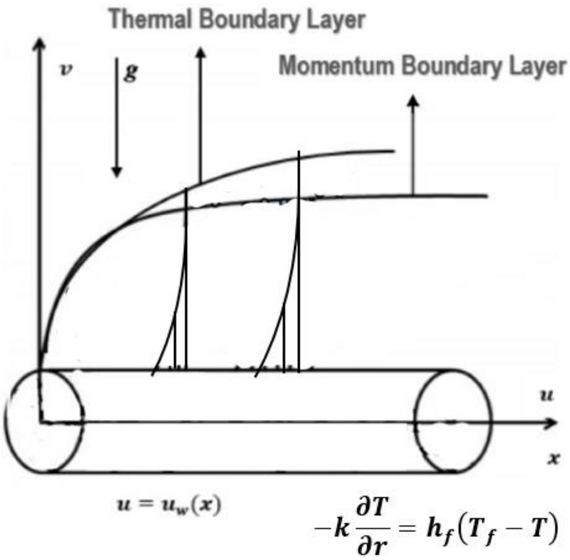


Figure 1: Flow Configuration

Thermal conductivity is modeled as a function of temperature characterized by:

$$K(T) = k\left[1 + \varepsilon\left(\frac{T - T_\infty}{T_f - T_0}\right)\right] \quad (6)$$

Where $\rho$ is the density of the fluid, $\beta$ is the variable viscosity parameter, $u$ is component in x direction, $v$ is component in r direction, $B_T$ is the volumetric thermal expansion coefficient, $g$ is the gravitational acceleration, $B_0$ is the magnetic field parameter, $C_p$ is specific heat capacity of the fluid, $T$ is the temperature of the fluid, $T_\infty$ is ambient temperature, $T_f$ is wall temperature, $k$ is free stream thermal conductivity, $l$ is the characteristics length, $u_w$ is the surface velocity, $h_f$ is the heat transfer coefficient and $\varepsilon$ is the activation energy. Radiation is approximated using the Rosseland model with a Taylor series expansion. In accordance to Rosseland approximation for optimally thick fluid, the radiative heat loss $q_r$ is given by (Samuel, 2022):

$$q_r = \frac{-4\sigma^1}{3k_0}\frac{\partial T^4}{\partial r} \quad (7)$$

Where $k_0$ is the absorption coefficient, $\sigma^1$is Stefan – Boltzman constant. $T^4$ is written as a linear function of the ambient temperature base on the assumption that difference in temperature within the flow in a minuscle. Expanding $T^4$ about an ambient temperature using Taylor's series expansion , ignoring the higher terms we arrives at Eq. 8:

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4 \quad (8)$$

So Eq. 7 and Eq. 8 result to

$$\frac{\partial q_r}{\partial y} = -\frac{4\sigma^1}{3k_0}\frac{\partial^2 T^4}{\partial y^2} \approx \frac{16\sigma^1 T_{\infty^3}}{3k_1}\frac{\partial^2 T}{\partial y^2} \quad (9)$$

A similarity transformation is applied to convert the partial differential equations into ordinary differential equations. The transformation introduces dimensionless variables:

$$\eta = \sqrt{\frac{U_0}{\nu l}}\left[\frac{r^2 - R^2}{2R}\right] \quad (10)$$

$$u = \frac{U_0 x}{l} f'(\eta), \quad v = -\frac{R}{r}\sqrt{\frac{U_0 \nu}{l}} f(\eta), \quad \theta = \frac{T - T_\infty}{T_f - T_\infty} \quad (11)$$

The transformed governing equations become:

$$\left(1 + \frac{1}{\beta}\right)[(1 + 2\tau\eta)f''' + 2\tau f''] + ff'' - (f')^2 + G_r\theta - Mf' = 0, \quad (12)$$

$$(1 + 2\tau\eta)\left[\left(1 + \varepsilon\theta + \frac{4}{3}R_a\right)\theta''\right] + (1 + 2\tau\eta)\varepsilon(\theta')^2 + \tau\left(2(1 + \varepsilon\theta) + \frac{4}{3}R_a\right)\theta' + PrH(f')^2 + P_r\theta' f = 0 \quad (13)$$

The boundary conditions for the transformed equations are:

$$f'(0) = 1, \quad f(0) = 0, \quad \theta'(0) = -B_a(1 - \theta(0)) \quad (14)$$

$$f'(\infty) \to 0, \ \theta(\infty) \to 0 \quad (15)$$

Dimensionless parameters are defined as:

$$\tau = \frac{1}{R}\sqrt{\frac{\nu l}{U_0}}, \quad Pr = \frac{U_0 C_p}{K}, \quad M = \frac{\sigma B_0^2 l}{\rho U_0},$$

$$R_a = \frac{4\sigma T_\infty^3}{KK^*}, \quad H = \frac{\sigma B_0^2 l U_0^2 x^2}{\rho U_0 C_p (T_f - T_\infty)}, \quad G_r = \frac{g\beta_T l (T_f - T_\infty)}{U_0^2 x} \quad (16)$$

Where $Pr$ is the Prandtl number, $M$ is the magnetic parameter, $R_a$ is the radiation parameter, $H$ is the ohmic heating parameter, $G_r$ is the Grashof number, $\tau$ is the curvature parameter, $B_a$ is the Biot number.

The numerical solution is obtained using NDSolve with the Runge-Kutta-Fehlberg technique in Mathematica. The ordinary differential equations are converted to a system of first-order initial value problems:

$$y_1' = y_2, \quad (17)$$

$$y_2' = y_3, \quad (18)$$

$$y_3' = \frac{y_2^2 - G_r y_4 + My_2 - y_1 y_3 - (1 + \frac{1}{\beta})2\tau y_3}{\left(1 + \frac{1}{\beta}\right)(1 + 2\tau\eta)}, \quad (19)$$

$$y_4' = y_5, \quad (20)$$

$$y_5' = \frac{-(1 + 2\tau\eta)\varepsilon y_5^2 - \eta\left(2(1 + \varepsilon y_4) + \frac{4}{3}R_a\right)y_5 - Pry_4 y_1 - PrHy_2^2}{(1 + 2\tau\eta)(1 + \varepsilon y_4 + \frac{4}{3}R_a)}, \quad (21)$$

with combined boundary conditions:

$$y_2(0) = 1, \ \ y_1(0) = 0, \ \ y_5(0) = -B_a(1 - y_4(0)), \quad (22)$$

$$y_2(\infty) = 0, \quad y_4(\infty) = 0. \quad (23)$$

## RESULTS AND DISCUSSION

Equations (12) and (13), subject to the boundary conditions (14)-(15), are solved numerically using an NDSolve alongside the Runge-Kutta method in Mathematica. The values for the parameters used in this work are set as $G_r$= 0.5, $P_r$ = 0.71, $R_a$ = 1, $\beta$ = 0.5, $\tau$ = 0.1, $\varepsilon$ = 0.2, $H$ = 0.4, $B_a$ = 1.0, and $M$ = 0.5. A tabular comparison of the present study with existing literature is presented in Table 1.

**Table 1: Comparison of Skin Friction Coefficient $f''(0)$ for Various Values of $M$ when $G_r$= 1.0, $P_r$ = 1.0**

| $M$ | $Ali\ et\ al.\ (2011)$ $f''(0)$ | $Present\ Study$ $f''(0)$ |
|---|---|---|
| 1 | −1.0000 | −1.0004 |
| 4 | −1.8968 | −2.0000 |
| 25 | −4.9155 | −5.0000 |

Fig. 2 depicts Prandtl number ($P_r$) influence on velocity profile, showing that lower $P_r$ values indicate faster thermal diffusion relative to momentum diffusion, potentially affecting flow stability and velocity distributions. Fig. 3 represents $Pr$ effects on temperature profile, indicating that higher $Pr$ values reduce thermal diffusion efficiency, leading to more pronounced thermal gradients and higher temperatures near boundaries.

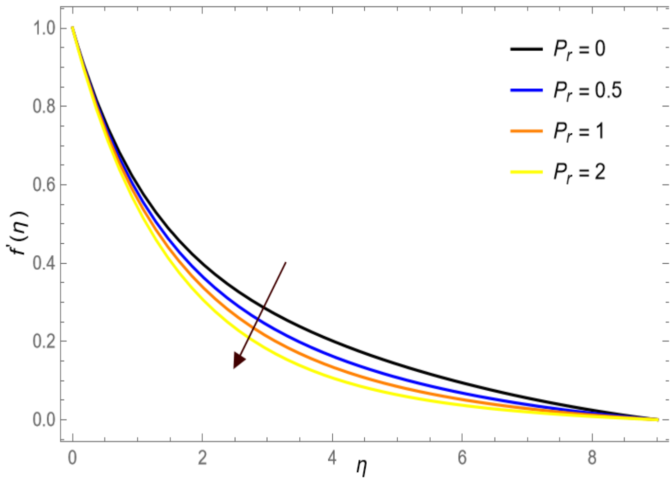


Figure 2: Effect of $P_r$ on $f'(\eta)$

As demonstrated in figure 4, temperature distribution is a decreasing function of larger values of $P_r$. Fig. 4 illustrates the impact of magnetic parameter ($M$) on velocity profile, revealing that increasing $M$ decreases velocity magnitude due to stronger Lorentz force opposing fluid motion. This electromagnetic drag effect creates thinner boundary layers and reduces overall flow momentum throughout the domain. Fig. 5 demonstrates how magnetic parameter ($M$) influences temperature profile, indicating that higher $M$ values generate additional thermal energy through Joule heating from magnetic field interactions. This results in elevated fluid temperatures, particularly near boundaries where velocity gradients are steepest, with thermal effects gradually diminishing farther from surfaces.

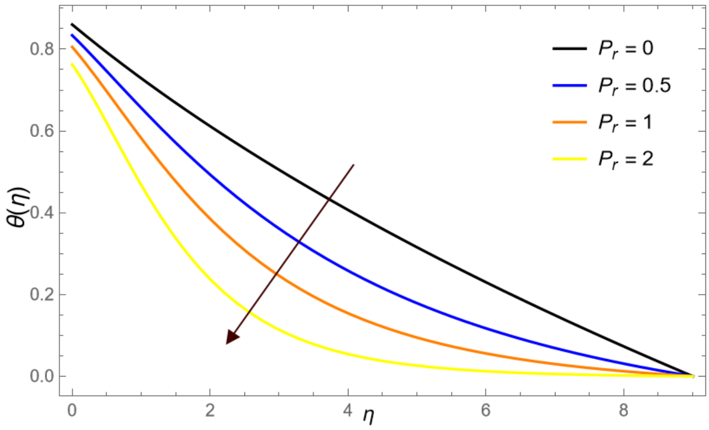


Figure 3: Effect of $P_r$ on $\theta(\eta)$

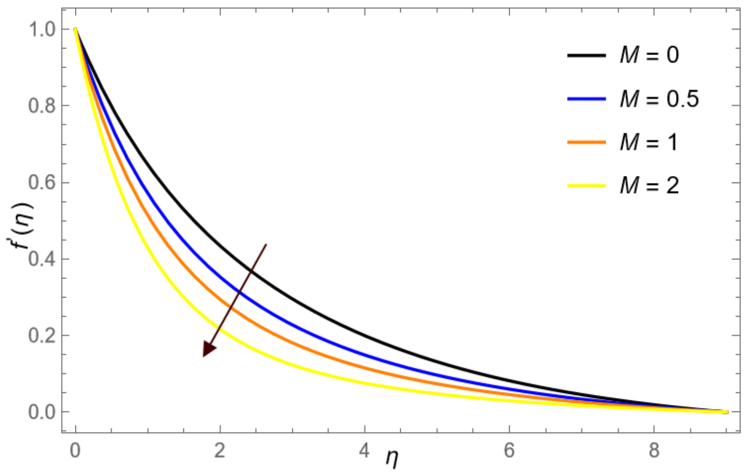


Figure 4: Effect of $M$ on $f'(\eta)$

Fig. 6 portrays the relationship between radiation parameter ($R_a$) and velocity profile, confirming that increased $R_a$ enhances thermal radiation effects that indirectly affect momentum transfer. Greater radiation alters temperature distributions, which modifies buoyancy-driven flows, resulting in modified velocity patterns and boundary behaviors. Fig. 7 shows radiation parameter ($R_a$) effects on temperature profile, indicating that higher $R_a$ values facilitate enhanced radiative heat transfer mechanisms. This promotes more efficient temperature distribution with reduced gradients and lower overall temperatures in the thermal boundary layer as radiation becomes more dominant.

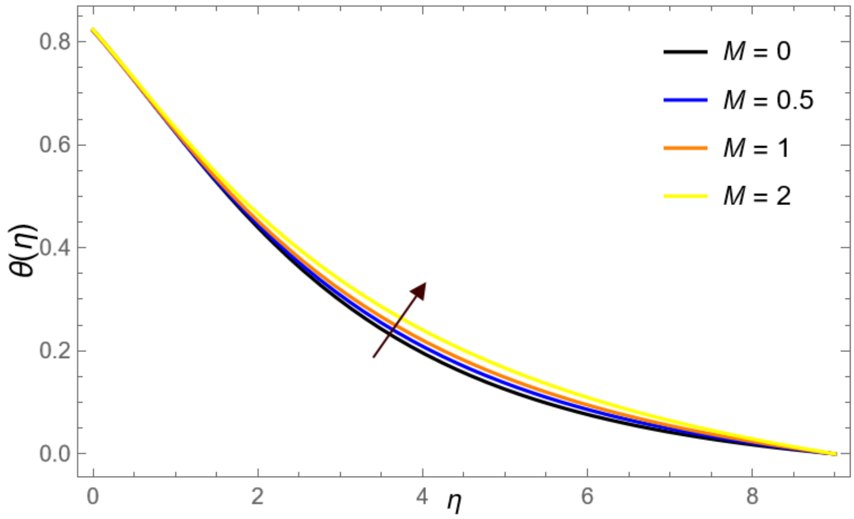

Figure 5: Effect of *M* on *θ(η)*

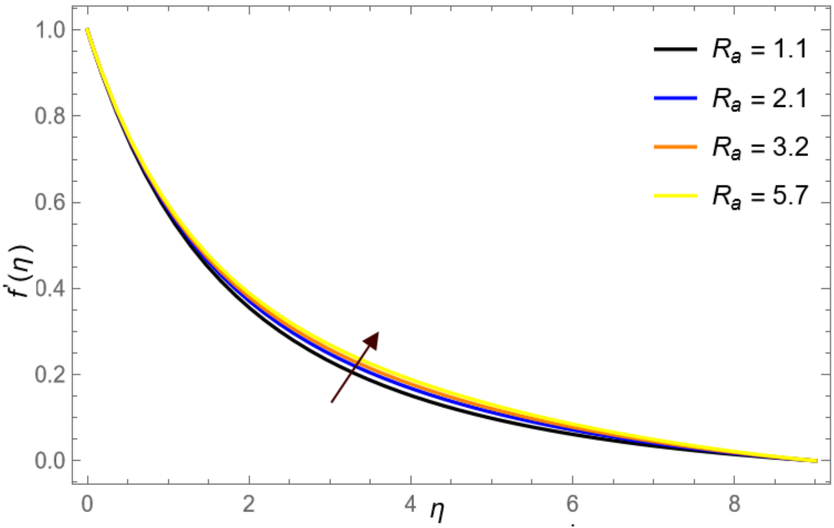

Figure 6: Effect of $R_a$ on *f'(η)*

Fig. 8 illustrates Grashof number ($G_r$) effects on velocity profile, indicating that increased $G_r$ enhances buoyancy-driven flows, leading to increased velocity magnitudes and more pronounced velocity gradients due to stronger natural convection. Fig. 9 illustrates the impact of the parameter $\beta$ on velocity profile, revealing that increased $\beta$ significantly decelerate fluid flow. Fig. 10 represents Ohmic heating parameter (*H*) effects on temperature profile, revealing that higher *H* values contribute additional thermal energy directly to the fluid. This result is expected since the Ohmic heating parameter is directly proportional to magnetic field strength and inversely proportional to the temperature difference between the surface and fluid. Consequently, increasing the Ohmic heating parameter leads to elevated fluid temperatures and reduced heat transfer rates.

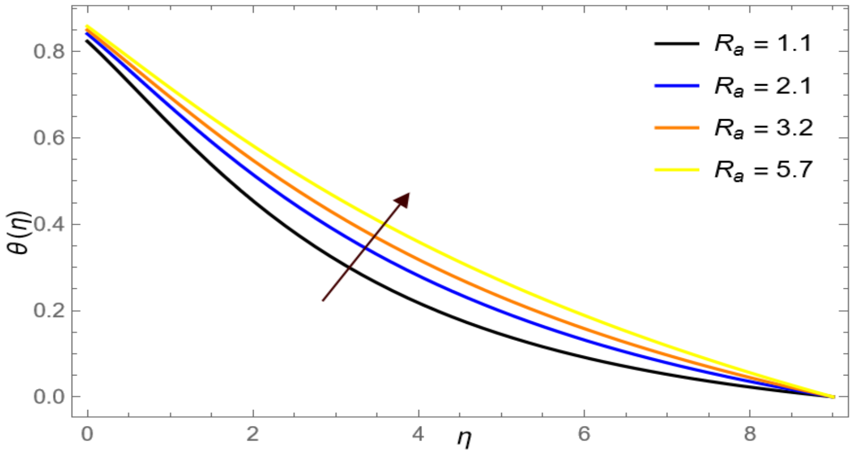

Figure 7: Effect of $R_a$ on $\theta(\eta)$

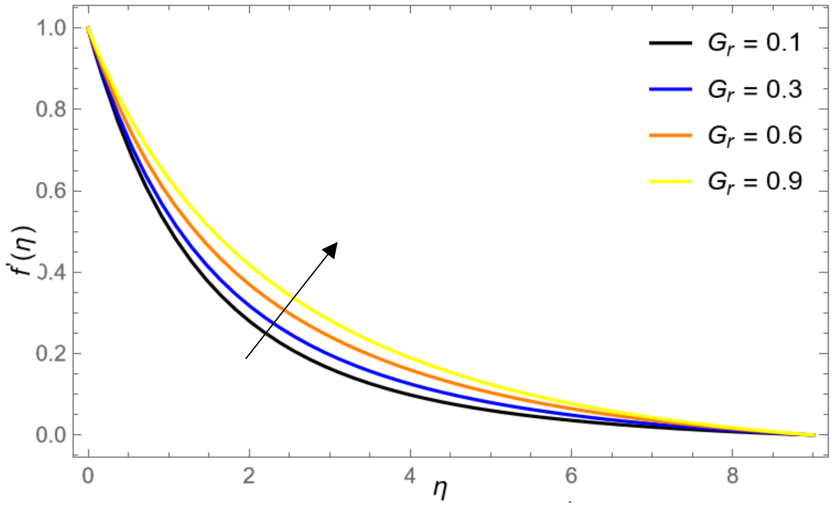

Figure 8: Effect of $G_r$ on $f'(\eta)$

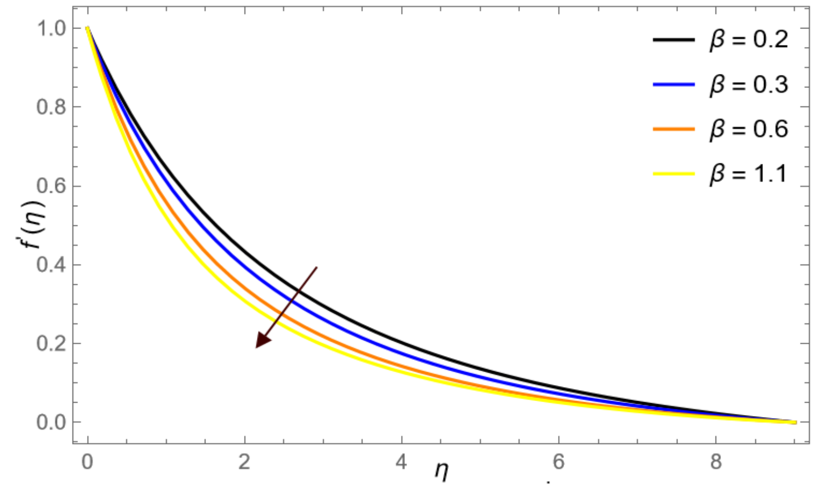

Figure 9: Effect of $\beta$ on $f'(\eta)$

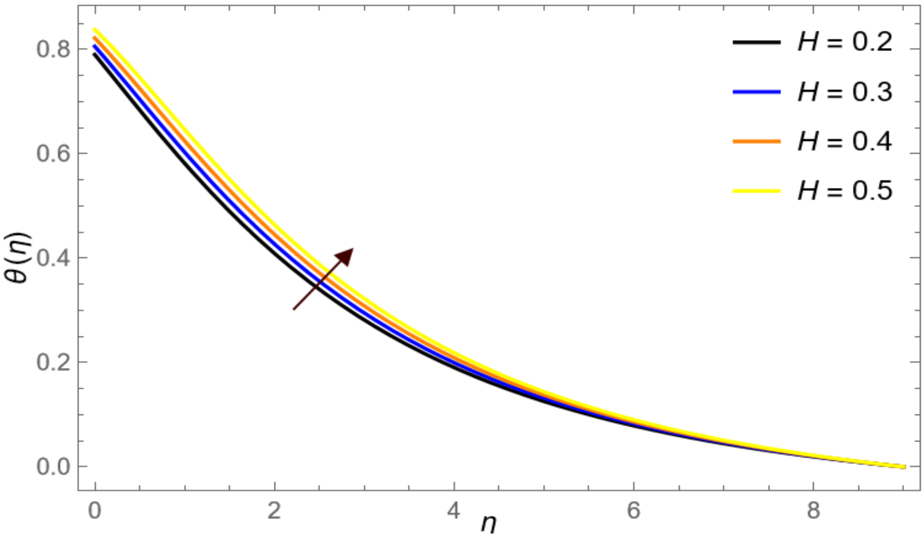


Figure 10: Effect of $H$ on $\theta(\eta)$

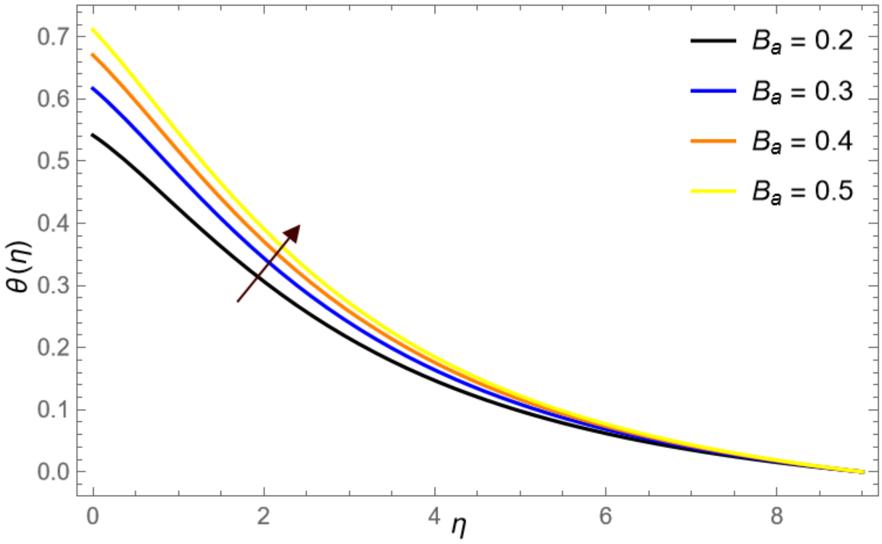


Figure 11: Effect of $B_a$ on $\theta(\eta)$

Fig. 11 outlines Biot number ($B_a$) influence on temperature profile, showing that higher $B_a$ values strengthen convective boundary heat transfer. This substantially alters temperature profiles near walls, creating steeper temperature gradients at the boundary while affecting overall thermal distribution patterns as heat transfer efficiency at the boundary increases.

## CONCLUSION

This study investigated the influence of variable thermophysical properties and Ohmic heating on radiative Casson fluid flow past a stretching cylinder, addressing a gap in the literature by integrating these phenomena in a comprehensive model. Numerical solutions, obtained using the Runge-Kutta-Fehlberg method with a shooting technique, revealed significant insights into the interplay of key parameters:

Specifically, increasing the Casson parameter $\beta$ reduces fluid velocity.

The thermal boundary layer thickness is significantly affected by the radiation parameter ($R_a$), highlighting the importance of considering these factors in heat transfer analyses.

Moreover, higher Biot number ($B_a$) values increase heat transfer rates at the surface, indicating enhanced convective cooling.

The magnetic parameter ($M$) demonstrates a significant influence by reducing velocity magnitude due to the stronger Lorentz force, while simultaneously generating additional thermal energy, which affects the temperature profile.

These findings offer valuable insights for optimizing heat transfer in industrial applications involving non-Newtonian fluids with radiative effects and variable properties, particularly in scenarios involving cylindrical geometries. The results contribute to a deeper understanding of complex fluid flows and provide a basis for improved thermal management strategies in engineering systems.

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