Int. J. Adv. Res. Sci. Technol. Volume 15, Issue 8, 2026, pp. 2576-2582.

IJARST

International Journal of Advanced Research in Science and Technology

https://doi.org/10.62226/ijarst20262802

ISSN 2319 – 1783 (Print)

ISSN 2320 – 1126 (Online)

MHD Flow and Heat Transfer of a Tangent Hyperbolic Fluid over a Convectively Heated Sheet with Nonlinear Thermal Radiation

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ARTICLE INFO

Article history:

Received	23 Aug 2026
Accepted	28 Sep 2026
Available online	31 Sep 2026

Keywords:

Tangent hyperbolic fluid, nonlinear convection, nonlinear thermal radiation, heat source, numerical solution.

Indexed in:

Crossref

INDEX COPERNICUS INTERNATIONAL

Google scholar

and in major libraries

ABSTRACT

The nonlinear convection flow of tangent hyperbolic fluid through a convectively vertical surface has been investigated in present work. The effects of magnetic field, heat generation and nonlinear thermal radiation also enclosed. The converted set boundary layer equations are solved numerically by RKF method. Obtained numerical results for flow and heat transfer characteristics are discussed for various physical parameters. Additionally, the skin friction coefficient and Nusselt number are also presented, and the physical aspects of the problem are discussed via graphs and tables. It is found that, the skin friction factor and heat transfer rates are more in presence of nonlinear convection than its absence. Further, velocity profile decreases by increasing power law index but establishes opposite results for skin friction.

Introduction

A considerable body of research has been devoted to the study of non-Newtonian fluids because of their widespread relevance in industrial, engineering, and technological applications. In many practical systems, non-Newtonian fluids are more appropriate than Newtonian fluids because of their complex rheological behavior and the nonlinear relationship between shear stress and shear rate. Such fluids exhibit a wide range of flow characteristics depending on their composition and operating conditions. Consequently, several mathematical models have been developed to represent different rheological properties, including shear-thinning, shear-thickening, viscoelasticity, and yield-stress effects. These characteristics have motivated researchers to investigate various non-Newtonian fluid models under different physical configurations and boundary conditions. For example, Wang [1] examined non-Newtonian fluid flow and heat transfer associated with mixed convection over a vertical plate. Xu et al. [2] developed series solutions for the unsteady boundary-layer stagnation-point flow of non-Newtonian fluids. Rashidi et al. [3] obtained analytical approximate solutions for radiative heat transfer in a micropolar fluid flowing through a porous medium. Hayat et al. [4] investigated the coupled heat and mass transfer characteristics of a third-grade fluid between two heated porous sheets, employing a similarity transformation together with the homotopy analysis method to obtain analytical solutions. Hayat et al. [5] studied heat and mass transfer in the radiative flow of a Jeffrey fluid over a moving stretching surface while considering thermal and concentration stratification effects. Mushtaq et al. [6] analyzed the stagnation-point flow of an upper-convected Maxwell fluid over a stretching sheet in the presence of thermal radiation. Gireesha et al. [7] investigated the heat and mass transfer characteristics of a Casson fluid over a permeable stretching surface under the influence of a chemical reaction. More recently, several researchers [8-11] have examined non-Newtonian fluid flows by incorporating various physical effects, rheological models, and boundary conditions.

A one of the important non-Newtonian fluid models is tangent hyperbolic fluid model. This rheological model has certain advantages over the other non-Newtonian formulations. There is no single non-Newtonian model that exhibits all the properties of non-Newtonian fluids. Nadeem and Akram [12] have examined the peristaltic motion of a hyperbolic tangent liquid over an asymmetric channel. Akbar et al. [13] studied the steady MHD flow of tangent hyperbolic fluid in stretching sheet. They obtained the velocity profile decreases by increasing power law index and Weissenberg number. Peristaltic flow of hyperbolic tangent fluid in a diverging tube with heat and mass transfer is studied by Nadeem et al. [14]. Numerical solutions have been presented for the buoyancy driven flow and heat transfer of tangent hyperbolic flow external to a sphere was investigated by Abdul et al [15]. Abbas et al [16] have discussed the three-dimensional peristaltic flow of hyperbolic tangent fluid in a non-uniform channel has been investigated.

Thermal radiation has emerged as a significant mechanism in heat-transfer research owing to its importance in a wide range of engineering and industrial applications. Radiative heat transfer plays a vital role in systems such as nuclear reactors, thermal power plants, solar-energy technologies, high-temperature processing, electronic cooling, and aerospace systems. Owing to these practical applications, numerous studies have investigated fluid-flow and heat-transfer characteristics under the influence of thermal radiation for different physical configurations and flow conditions (Makinde [17], Mushtaq et al. [18], Sreedevi et al. [19], Gireesha et al. [20], Sampath Kumar et al. [21], Jyoti et al. [22]). Most of the earlier investigations have employed the linearized form of thermal radiation, which is generally appropriate when the temperature difference between the fluid and the surrounding medium is relatively small. However, substantial temperature variations can occur in many practical thermal systems, particularly in high-temperature environments. Under such conditions, the linear radiation approximation may not adequately describe the actual radiative heat-transfer mechanism. This limitation has motivated increasing attention toward nonlinear thermal radiation models, which provide a more realistic description of radiative heat transport over a wider temperature range. In this context, Pantokratoras et al. [23] examined Sakiadis flow incorporating nonlinear Rosseland thermal radiation and reported significant changes in the thermal boundary-layer characteristics compared with the corresponding linear radiation model. Cortell [24] investigated the flow and heat-transfer behavior over a stretching sheet by incorporating nonlinear thermal radiation effects. Hayat et al. [25] considered three-dimensional hydromagnetic viscoelastic fluid flow under nonlinear thermal radiation and demonstrated its influence on the associated transport characteristics. Mahanthesh et al. [26] numerically analyzed the nonlinear convective and radiative flow of a tangent hyperbolic fluid induced by a stretching surface subject to a convective boundary condition. Further investigations addressing nonlinear thermal radiation and its influence on fluid-flow and heat-transfer processes have been reported in the literature [27-30].

In this work, the nonlinear convection flow of non-Newtonian tangent hyperbolic fluid over stretching sheet has been examined. The effect of heat generation, nonlinear thermal radiation and convective conditions are considered for enhance of heat transformation. To best of our knowledge present work is new. The numerical solutions are computed for set of nonlinear ODE system by RKF method. The velocity, temperature, skin friction coefficient and heat transfer rate are analysed for different parameters through graphs and tables.

Mathematical formulation

Consider steady two-dimensional flow of an incompressible tangent hyperbolic fluid in the region $y > 0$ driven by a stretching surface located at $y = 0$. The stretching velocity is assumed $U_w(x) = cx$ where c is constant. Heat transfer analysis is carried out in the presence of nonlinear thermal radiation and heat source effects. The sheet is maintained at constant temperature T_f whereas T_∞ denotes the ambient fluid's temperature. We considered convective boundary condition at the boundary. The gravitational force g acts downwards and magnetic field B_0 applied perpendicular to the fluid motion. We also consider nonlinear convection; we assume that the Boussinesq approximation holds i.e. that density variation is only experienced in the buoyancy term in the momentum equation.

Governing boundary layer approximations can be defined as follows.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{2.1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu(1-n)\frac{\partial^2 u}{\partial y^2} + \sqrt{2}\nu n\Gamma\left(\frac{\partial u}{\partial y}\right)\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2}{\rho}u \tag{2.2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} + \frac{Q_0}{\rho c_p}(T - T_\infty) \tag{2.3}$$

Where u and v are the velocity components along the x- and y-axes, respectively. Further, $\alpha, \rho\ \nu, T,$ and T_∞ are, respectively, the thermal diffusivity, density of the fluid, kinematic viscosity of the fluid, fluid temperature, and ambient fluid temperature, Q_0 -dimensional heat generation/absorption coefficient, and c_p -specific heat at constant pressure.

The associated boundary conditions for the present problem are;

$$u = U_w(x) = ax, \quad v = 0, \ -k\frac{\partial T}{\partial z} = h_f(T_f - T) \ \text{ at } \ y = 0,$$
$$u \to \infty, \quad T \to T_\infty \quad \text{as} \quad y \to \infty, \tag{2.4}$$

The radiative heat flux expression in Eq. (2.3) is given by the Rosseland approximation as given by;

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} = -\frac{16\sigma^*}{3k^*}T^3\frac{\partial T}{\partial y}, \tag{2.5}$$

Where σ^* and k^* are the Stefan-Boltzman constant and the mean absorption coefficient respectively, and in view to Eq. (2.5) in Eq. (2.3) reduces to

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial y^2}\right) + \frac{16\sigma^*}{3\rho_f c_p k^*}\left[T^3\frac{\partial T^2}{\partial y^2} + 3T^2\left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{Q_0}{\rho_f c_p}(T - T_\infty) \tag{2.6}$$

The similarity transformation;

$$u = axf'(\eta),\ \ v = -\sqrt{a\nu}f(\eta), \qquad \eta = \sqrt{\frac{a}{\nu}}y,\ \ ,\theta(\eta) = \frac{T-T_\infty}{T_f-T_\infty},$$

$$T = T_\infty(1+(\theta_w-1)\theta), \tag{2.7}$$

We obtain $T = T_\infty(1+(\theta_w-1)\theta)$ with $\theta_w = \frac{T_f}{T_\infty}$, $\theta_w(>1)$ being the temperature ratio parameter, where η is the independent dimensionless similarity variable, and primes denote the differentiation with respect to η, by similarity transformations, (2.1) is identically satisfied, while (2.2) and (2.6) give as;

$$(1-n)f''' - f'^2(\eta) + f(\eta)f''(\eta) + nWef'''(\eta)\big(f''(\eta)\big) - Mf'(\eta) \tag{2.8}$$

$$\theta''(\eta) + R\left[\big(1+(\theta_w-1)\theta(\eta)\big)^3\theta''(\eta) + 3(\theta_w-1)\theta'^2(\eta)\big(1+(\theta_w-1)\theta(\eta)\big)^2\right] + Prf(\eta)\theta'(\eta) + PrQ\theta(\eta) = 0, \tag{2.9}$$

The boundary conditions (2.4) become;

$$f'(0) = 1,\ \ f(0) = 0,\ \ \ \theta'(0) = Bi(\theta(0)-1), \quad \text{at} \quad \eta = 0,$$

$$f'(\infty) \to 0,\ \ \theta(\infty) \to 0, \quad \text{as} \quad \eta \longrightarrow \infty \tag{2.10}$$

The dimensionless parameters in (2.8), (2.9) are $W_e = \frac{\sqrt{2}a^{\frac{3}{2}}x\Gamma}{\sqrt{\nu}}$ Weissenberg number, n is power law index, $M = \frac{\sigma B^2}{\rho a}$ Magnetic parameter, $\lambda = \frac{Gr_x}{Re_x}$ buoyancy parameter $Gr_x = \frac{g\beta_0(T_w-T_\infty)x^3}{\nu^2}$ local Grashoff number, $Re_x = \frac{xU_w}{\nu}$ local Reynolds number, $\gamma = \frac{\beta_1}{\beta_0}(T_w-T_\infty)$ nonlinear convection parameter, $Pr = \frac{\nu}{\alpha}$ Prandtl number, $Q = \frac{Q_0}{a\rho c_p}$ heat generation or absorption parameter, $R = \frac{16\sigma^* T_\infty^3}{3k^*k}$ radiation parameter, Bi thermal Biot number, $\theta_w = \frac{T_f}{T_\infty}$ temperature parameter.

The physical quantities of interest are the skin friction coefficient C_f and the local Nusselt number Nu_x, which are defined as

$$C_f = \frac{\tau_w}{\rho U_w^2}, \qquad Nu_x = \frac{xq_w}{k(T-T_\infty)}, \tag{2.11}$$

Where τ_w is wall shear stress and q_w is the heat flux from the surface, which are given by

$$\tau_w = \mu\left((1-\mathrm{n})\frac{\partial \mathrm{u}}{\partial \mathrm{y}} + \frac{\mathrm{n}\Gamma}{\sqrt{2}}\left(\frac{\partial \mathrm{u}}{\partial \mathrm{y}}\right)^2\right), \quad q_w = -k\frac{\partial T}{\partial y} \tag{2.12}$$

With μ and k being the dynamic viscosity and the thermal conductivity. Using equation (2.12) and the similarity variables into (2.11) one can get;

$$C_f Re_x^{1/2} = \left[(1-n)f''(0) + \frac{n}{2}W_e f''(0)^2\right],$$

$$Nu_x Re_x^{-1/2} = -(1+R\theta_w^3)\theta'(0) \tag{2.13}$$

Where $Re_x = \frac{U_w x}{\nu}$ is the local Reynolds number.

Result and Discussion

The nonlinear ordinary differential equations (2.8)–(2.9), together with the associated boundary conditions (2.10), constitute a strongly coupled nonlinear boundary-value problem. The system is solved numerically using the fourth–fifth-order Runge–Kutta–Fehlberg (RKF45) method. Since the computational domain extends to infinity, the asymptotic boundary conditions are truncated at a sufficiently large finite value of the similarity variable, denoted by η_∞, following the standard procedure adopted in boundary-layer analysis. The value of η_∞ is selected such that further increases in the computational domain do not produce any significant variation in the numerical results. Figure 2 illustrates the influence of the magnetic parameter M on the velocity profiles. Physically, M characterizes the relative strength of the electromagnetic force to the viscous force. An increase in M enhances the Lorentz force, which opposes the fluid motion and consequently reduces the velocity profile. Figure 3 presents the effects of the power-law index n on the velocity distributions. It is observed that increasing n reduces the momentum boundary-layer thickness. This behavior is associated with the variation in the rheological properties of the non-Newtonian fluid as the power-law index changes.

Effect of the Biot number on the temperature profile

Figure 4 depicts the influence of the Biot number Bi on the temperature profile. It is observed that the temperature profile increases significantly with an increase in Bi. The Biot number represents the relative strength of convective heat transfer between the surface and the surrounding fluid. A larger Bi indicates stronger convective heating at the surface, which increases the amount of thermal energy transferred from the heated surface to the fluid. Consequently, the fluid temperature rises and the thermal boundary layer becomes thicker. Thus, an increase in the Biot number enhances the thermal field and significantly affects the heat-transfer characteristics of the flow.

Effect of the temperature-ratio parameter on the temperature profile

Figure 5 illustrates the influence of the temperature-ratio parameter θ_w on the temperature profile. It is observed that the temperature profile increases with increasing values of θ_w. Physically, θ_w represents the ratio of the surface temperature difference to the ambient temperature difference and characterizes the degree of temperature variation between the heated surface and the surrounding fluid. An increase in θ_w results in a higher surface temperature, thereby increasing the thermal energy transferred from the surface to the fluid. Consequently, the temperature within the boundary layer increases and the thermal boundary layer becomes thicker. This result indicates that the temperature-ratio parameter has a significant influence on the thermal characteristics of the flow.

Effect of the Prandtl number on the temperature profile

Figure 6 depicts the effect of the Prandtl number Pr on the temperature profile. It is observed that the temperature profile decreases with increasing values of Pr. Physically, the Prandtl number represents the ratio of momentum diffusivity to thermal diffusivity. An increase in Pr corresponds to a reduction in thermal diffusivity, which restricts the diffusion of heat away from the surface. Consequently, the temperature decreases more rapidly within the fluid, resulting in a thinner thermal boundary layer. Therefore, higher values of the Prandtl number lead to a reduction in the thermal boundary-layer thickness and significantly influence the heat-transfer characteristics of the flow.

Effect of the heat-generation parameter on the temperature profile

Figure 7 illustrates the effect of the heat-generation parameter Q on the temperature profile. It is observed that the temperature profile increases with increasing values of Q. Physically, a positive value of Q represents the generation of heat within the fluid, which provides an additional source of thermal energy to the flow. As Q increases, more heat is generated inside the boundary layer, resulting in an enhancement of the fluid temperature and an increase in the thermal boundary-layer thickness. Therefore, the heat-generation parameter plays an important role in controlling the thermal characteristics of the flow.

Effect of the nonlinear thermal radiation parameter on the temperature profile

Figure 8 illustrates the influence of the nonlinear thermal radiation parameter R on the temperature profile. It is observed that the temperature profile increases with increasing values of R. An increase in R enhances the contribution of thermal radiation to the energy transport within the fluid, thereby increasing the thermal energy available in the boundary layer. Consequently, the fluid temperature increases and the thermal boundary layer becomes thicker. This result demonstrates that nonlinear thermal radiation has a significant influence on the thermal characteristics of the flow, particularly in situations involving large temperature differences between the surface and the ambient fluid.

3. Conclusions

The present study examines the steady two-dimensional boundary-layer flow and heat-transfer characteristics of a tangent hyperbolic fluid over a convectively heated vertical sheet in the presence of nonlinear thermal radiation. The governing equations are transformed into a system of nonlinear ordinary differential equations using suitable similarity transformations and solved numerically by employing the fourth–fifth-order Runge–Kutta–Fehlberg method. The effects of the governing physical parameters on the velocity and temperature fields are analyzed in detail.

The principal findings of the study can be summarized as follows:

- An increase in the magnetic parameter M suppresses the fluid velocity owing to the enhanced Lorentz force, while the thermal boundary layer becomes thicker.
- The velocity profile decreases with increasing power-law index n, whereas the temperature field exhibits an opposite trend.
- Increasing the Biot number Bi enhances the temperature profile because stronger convective heating transfers more thermal energy from the surface to the fluid.
- An increase in the temperature-ratio parameter θw increases the temperature distribution and thickens the thermal boundary layer.
- The temperature profile decreases with increasing Prandtl number Pr, owing to the reduction in thermal diffusivity and the consequent confinement of heat near the surface.
- Increasing the heat-generation parameter Q enhances the temperature profile and increases the thermal boundary-layer thickness due to the additional energy released within the fluid.
- The nonlinear thermal radiation parameter R enhances the temperature distribution, demonstrating the important contribution of radiative heat transfer to

Overall, the results demonstrate that nonlinear thermal radiation and convective heating substantially modify the thermal characteristics of tangent hyperbolic fluid flow. The incorporation of nonlinear radiation provides a more realistic representation of heat transfer when appreciable temperature differences exist between the surface and the surrounding fluid. The present findings may therefore be useful in the design and optimization of thermal systems involving non-Newtonian fluids, convective surfaces, and high-temperature radiative environments.

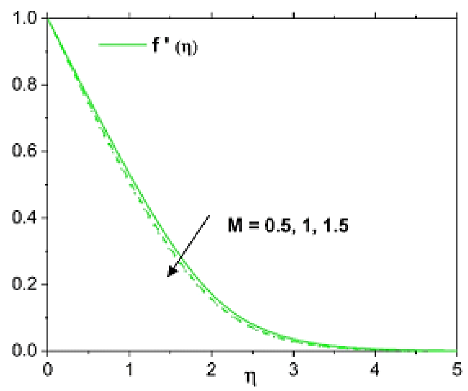

Fig. 2: Influence of M on $f'(\eta)$ and $\theta(\eta)$.

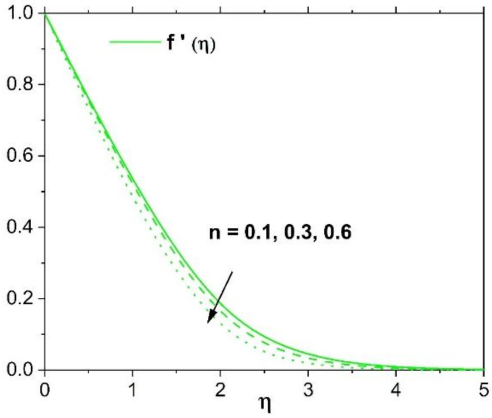

Fig. 3: Influence of n on $f'(\eta)$ and $\theta(\eta)$.

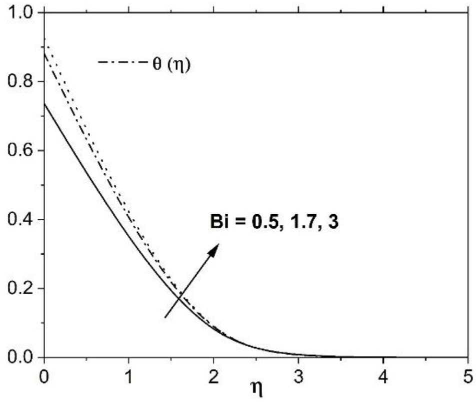

Fig. 4: Influence of Bi on $f'(\eta)$ and $\theta(\eta)$.

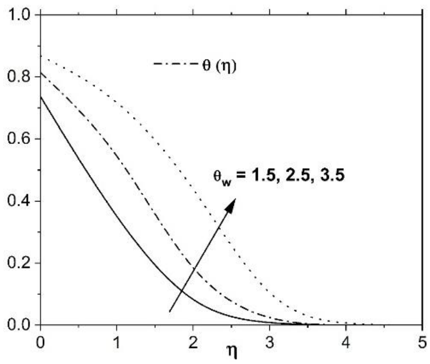

Fig. 5: Influence of θ_w on $f'(\eta)$ and $\theta(\eta)$.

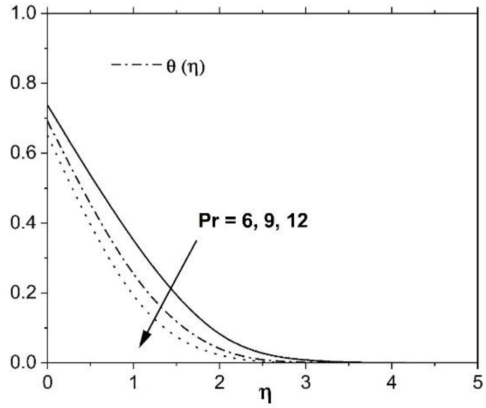

Fig. 6: Influence of Pr on $f'(\eta)$ and $\theta(\eta)$.

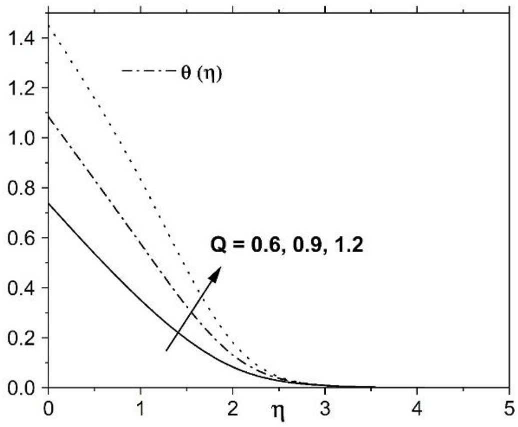

Fig. 7: Influence of Q on $f'(\eta)$ and $\theta(\eta)$.

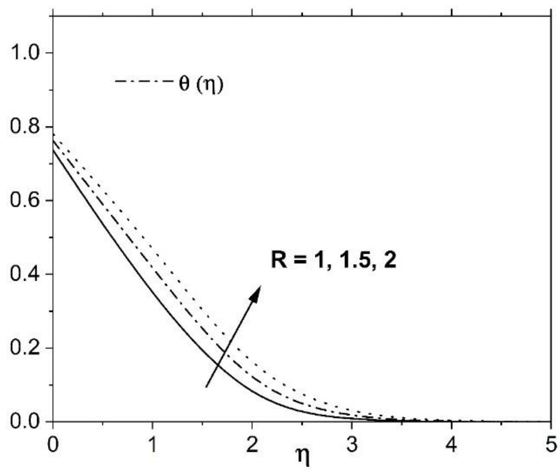

Fig. 8: Influence of R on $f'(\eta)$ and $\theta(\eta)$.

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