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Research Paper

NUMERICAL ANALYSIS OF NON-NEWTONIAN FLUID FLOW OVER A CONTINUOUSLY STRETCHING SHEET INFLUENCED BY HALL CURRENT AND THERMAL RADIATION

Chandaka Umasankar
Lecture in Mathematics, Government polytechnic Parvathipuram, Parvathipuram manyam district, Andhra Pradesh, 535522, India.
Email: uma8941@gmail.com

Abstract:
This study presents a numerical investigation of non-Newtonian fluid flow over a continuously stretching sheet under the combined influence of Hall current, and thermal radiation. A transverse magnetic field is applied to the electrically conducting fluid, and the governing equations for momentum and energy transfer are formulated under the boundary-layer assumptions. Suitable similarity transformations are employed to reduce the coupled nonlinear partial differential equations to a system of ordinary differential equations, which is solved numerically using the MATLAB bvp4c solver. The effects of the Hall parameter, magnetic parameter, thermal-radiation parameter, and Prandtl number on the velocity, and temperature, distributions are systematically examined. The corresponding skin-friction coefficient, Nusselt number, and Sherwood number are also evaluated to characterize the momentum, heat transfer rates. The results demonstrate that Hall current significantly modifies the flow field, while thermal radiation strongly influence the coupled thermal distributions. The findings provide useful insights into the control of coupled momentum, heat transfer in non-Newtonian MHD systems relevant to thermal processing, chemical engineering, electromagnetic applications, and advanced energy systems.
Key words: Non-Newtonian fluid; thermal radiation; hall current; magnetohydrodynamics; Heat generation;

1. Introduction

Non-Newtonian fluids are complex fluids whose apparent viscosity varies with shear rate and applied stress, making them important in chemical processing, biomedical systems, energy conversion, thermal management, porous-media transport, and industrial applications. Among various non-Newtonian models, Casson fluids are particularly useful for describing yield-stress fluids. Kodi Raghunath [1] investigated radiation absorption, Hall and ion-slip effects on unsteady MHD Casson hybrid nanofluid flow through porous media, while V. Ramachandra Reddy et al. [2] examined thermo-physical and aligned magnetic-field effects on unsteady MHD Casson-fluid convection with Joule heating and viscous dissipation. S. Valiveti et al. [3] analyzed heat and mass transfer in unsteady MHD Casson flow considering thermal diffusion and heat-source effects. Dhananjay Yadav et al. [4] studied rotational effects on convection in a Casson-fluid-saturated porous layer with temperature-dependent thermal conductivity and viscosity. Dandu Sridevi et al. [5] investigated thermal radiation, chemical reactions, Brownian motion, and thermophoresis in Casson hybrid nanofluid flow, whereas Vaddemani Ramachandra Reddy et al. [6] examined Hall current, activation energy, diffusion-thermo, Brownian motion, and thermophoresis effects in MHD Darcy–Forchheimer Casson nanofluid flow. S. Li et al. [7] studied activation energy and chemical reaction effects in unsteady MHD dissipative Casson flow, while Y. Suresh Kumar et al. [8] analyzed activation energy, Hall current, and thermal radiation effects in MHD Casson nanofluids. V. Ramachandra Reddy et al. [9] investigated MHD Casson flow past an inclined vertical porous plate. K. Raghunath et al. [10] examined unsteady oscillatory Casson flow with chemical reaction, heat absorption, and Soret effects, while K. Raghunath et al. [11] studied thermal diffusion and chemical reaction effects on MHD Casson flow. Finally, C. Pavan Kumar et al. [12] analyzed thermal diffusion and inclined magnetic-field effects on MHD free-convection Casson flow.

Hall current is an important electromagnetic phenomenon in electrically conducting fluids, arising when the applied magnetic field is sufficiently strong that the motion of charged particles produces a transverse electric current. Its inclusion modifies the Lorentz force and consequently influences velocity, temperature, and mass-transfer characteristics in magnetohydrodynamic (MHD) flows. Hall effects are particularly relevant to MHD generators and pumps, electromagnetic processing, cooling systems, plasma flows, metallurgical processes, rotating machinery, and advanced thermal-management applications. Ch. Bhargava et al. [13] investigated Hall current and thermal-radiation effects in unsteady MHD hybrid Cu–Al_2O_3/blood nanofluid flow with chemical reaction and internal heat generation, while Raghunath Kodi et al. [14] analyzed rotating Cu–Al_2O_3/water hybrid nanofluid flow with Hall current, Joule heating, and nonlinear thermal radiation using numerical and neural-network approaches. Katikala N. V. Ch. Bhargava et al. [15] examined Hall current, radiation absorption, and diffusion-thermo effects in unsteady MHD second-grade fluid flow through porous media with Joule heating and viscous dissipation, whereas V. R. Prasad et al. [16] investigated Hall current and thermal diffusion in rotating Cu–TiO_2/water nanofluid flow with thermal radiation and chemical reaction. Yedhiri Sunitha Rani et al. [17] studied Hall current together with Joule heating, thermal radiation, and radiation absorption in unsteady rotating MHD mixed-convective flow. Hari Babu Kommaddi et al. [18] analyzed Hall-current effects on heat and mass transfer in chemically reacting rotating Jeffrey-fluid flow with diffusion-thermo and radiation absorption. Raghunath Kodi et al. [19] investigated Hall current and thermal radiation in three-dimensional rotating reactive hybrid nanofluid flow with internal heat absorption, while Raghunath Kodi et al. [20] examined Hall current, thermal radiation, and Soret effects in unsteady MHD Jeffrey-fluid flow through porous media. Further, Raghunath Kodi et al. [21] studied Hall and ion-slip effects together with diffusion-thermo and radiation absorption in unsteady MHD second-grade fluid flow, and T. B. Omar et al. [22] investigated Hall and Soret effects in rotating second-grade MHD flow through porous media under thermal radiation and chemical reactions. V. V. L. Deepthi et al. [23] reviewed heat and mass transport involving Hall, ion-slip, and thermodiffusion effects in radiative second-grade materials, while G. Aruna et al. [24] examined Hall and ion-slip effects in unsteady MHD second-grade fluid flow through porous media with radiation absorption. Kodi Raghunath et al. [25] investigated the combined effects of Hall current, Soret diffusion, rotation, chemical reaction, and aligned magnetic fields in rotating second-grade MHD flow, whereas Raghunath Kodi et al. [26] analyzed Hall and ion-slip effects in radiative chemically reactive second-grade flow through porous media. Kodi Raghunath et al. [27] further examined Soret, rotation, Hall, and ion-slip effects on unsteady MHD Jeffrey-fluid flow through porous media with heat absorption and chemical reaction. Finally, K. Raghunath et al. [28] studied Hall effects on MHD convective rotating flow through porous media past an infinite vertical plate.

Magnetohydrodynamics (MHD) describes the interaction between electrically conducting fluids and magnetic fields and has important applications in energy conversion, nuclear cooling, electromagnetic processing, chemical engineering, plasma technology, and thermal management. K. Jyothi et al. [29] investigated MHD boundary-layer flow of SWCNT nanofluids using neural networks, while K. N. V. C. Bhargava et al. [30] studied 3D rotating hybrid nanofluid flow through porous media. D. Yadav et al. [31]

analyzed convection in rotating porous layers, whereas K. Raghunath et al. [32] examined Cu–TiO_2 nanoparticle flow over an inclined permeable surface. L. Zhang et al. [33] investigated 3D MHD mixed convection in Darcy–Forchheimer Maxwell fluid, and R. Kodi et al. [34] studied MHD Jeffrey nanofluid flow with diffusion-thermo and radiation-absorption effects. M. Ijaz Khan et al. [35] examined Prandtl-fluid flow with slip conditions, while K. V. Raju et al. [36] investigated MHD Jeffrey nanofluid flow with Soret and radiation effects. R. Kodi et al. [37] studied MHD mixed convection of Maxwell nanofluid through a porous cone, and K. Raghunath et al. [38–40] investigated MHD flows involving radiation absorption, chemical reactions, Soret and diffusion-thermo effects. Further studies by S. Maatoug et al. [41], M. Obulesu et al. [42,45], R. Kodi et al. [43], and K. Raghunath et al. [44,46] demonstrate the significance of MHD in complex non-Newtonian, porous-media, heat-transfer, and mass-transfer systems.

Thermal radiation is an important mode of heat transfer in which thermal energy is transported through electromagnetic waves, becoming particularly significant at high temperatures. Its incorporation into fluid-flow models is essential for accurately predicting temperature distributions and heat-transfer rates in thermal processing, energy systems, nuclear reactors, solar-energy devices, aerospace applications, chemical processing, and advanced cooling systems. K. N. V. Ch. Bhargava et al. [47] investigated thermal radiation and thermal diffusion in unsteady MHD Cu_3Zn_2–Co hybrid nanofluid flow using the Hamilton–Crosser model, while D. Chandar Rao et al. [48] analyzed radiative heat-transfer behavior in Jeffrey hybrid nanofluid flow over a rotating sphere. D. Rajani et al. [49] examined radiation effects together with Brownian motion, thermophoresis, and activation energy in MHD hybrid nanofluid flow, whereas K. Raghunath et al. [50] investigated MHD heat and mass transport in non-Newtonian nanofluids considering Joule heating and viscous dissipation. D. Yadav et al. [51] studied rotational and variable-viscosity effects on convective instability, while S. Ravikumar et al. [52] investigated radiative heat flux in peristaltic blood flow with chemical reaction mechanisms. S. Suneetha et al. [53] and G. Revathi et al. [54] examined non-Fourier heat-transfer effects in hybrid nanofluid flows and entropy generation. K. Viswanath et al. [55] investigated the thermo-physical effects of radiant heating on unsteady MHD hybrid nanofluid flow, while K. Jyothi et al. [56] analyzed MHD boundary-layer heat transfer in Sisko nanofluids. S. S. Bin Zafar et al. [57] studied Lorentz-force effects in Prandtl two-phase nanomaterials, and B. Lavanya et al. [58] investigated Carreau nanofluid flow with non-Fourier heat flux. Amjad Ali Pasha et al. [59] examined rotational and thermal-diffusion effects in unsteady MHD viscoelastic-fluid flow through porous media.

The novelty of this study lies in the combined numerical investigation of Hall current and diffusion-thermo effects on non-Newtonian MHD flow over a continuously stretching sheet under thermal radiation. The coupled effects on velocity, temperature, concentration, and engineering quantities such as skin friction, Nusselt number, and Sherwood number are systematically quantified using the MATLAB bvp4c method.

2. Formulation of the Problem

Consider a steady, two-dimensional, laminar, incompressible, electrically conducting Casson fluid flowing over a continuously stretching sheet. The sheet is stretched in the -direction with velocity, where is the stretching rate, and is the coordinate normal to the sheet. A transverse magnetic field is applied to the fluid, and the Hall current effect is incorporated into the momentum equations. The energy equation accounts for thermal radiation effect, representing the contribution of concentration gradients to heat transport. Appropriate boundary conditions are imposed at the stretching sheet and in the free-stream region. Suitable similarity transformations are introduced to transform the coupled nonlinear governing partial differential equations into a system of ordinary differential equations, which is solved numerically using the MATLAB bvp4c solver.

2.1. Flow Assumptions

- The fluid is a steady, two-dimensional, laminar, incompressible, electrically conducting Casson fluid.
- The Casson fluid flows over a continuously stretching sheet with stretching velocity.
- A transverse magnetic field is applied, and the Hall current effect is included in the momentum equations.
- Thermal radiation effects are incorporated into the energy equation.
- The induced magnetic field is neglected because of the small magnetic Reynolds-number assumption, and the fluid properties are assumed constant.

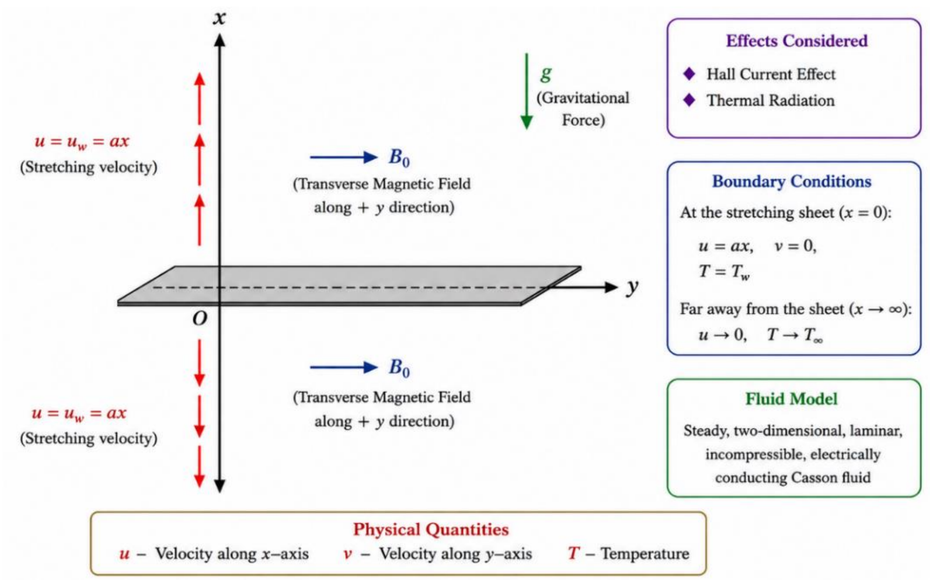

Figure: 1. Physical configuration of the Problem

Considering the premises discussed earlier and the Boussinesq approach, the following is the arithmetical representation of the problem [21]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

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

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}=\nu\left(1+\frac{1}{\beta}\right)\frac{\partial^2 w}{\partial y^2}+\frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(mu-w\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{Q_0}{\rho C_p}(T-T_\infty)-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{4}$$

The associated boundary conditions for the PDEs that are in charge are as follows:

$$\begin{aligned} &u=ax,\quad v=0,\quad w=0,\quad T=T_w, && \text{at}\quad y=0\\ &u\to 0,\quad v\to 0,\quad w\to 0,\quad T\to T_\infty && \text{as}\quad y\to\infty \end{aligned} \tag{5}$$

The similarity conversion that was used so that the PDEs may be translated into dimensionless ODEs

$$\eta = \sqrt{\frac{a}{\nu}}y, \; \psi(x,y) = \sqrt{a\nu}\,x\,f(\eta), \quad w = ax\,g(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \tag{6}$$

Substitute Eq. (6) into Eq. (2), Eq. (3) and Eq. (4) generate to acquire the succeeding non-dimensional equations.

$$\left(1 + \frac{1}{\beta}\right) f''' + ff'' - f'^2 + Gr\theta - \frac{M}{1+m^2}\left(f' + mg\right) = 0 \tag{7}$$

$$\left(1 + \frac{1}{\beta}\right) g'' + fg' - f'g + \frac{M}{1+m^2}\left(mf' - g\right) = 0 \tag{8}$$

$$\theta''\left(1 + R\,\mathrm{Pr}\right) + \mathrm{Pr}\, f\theta' + \mathrm{Pr}\, Q\,\theta = 0$$

(9)

The dimensionless correlated boundary conditions (BCs) are as shadows:

$$\begin{aligned} &f(0) = 0, \quad f'(0) = 1, \quad g(0) = 0, \quad \theta(0) = 0 \qquad at \quad \eta = 0 \\ &f'(\eta) \to 0, \quad g(\eta) \to 0, \quad \theta(\eta) \to 0 \qquad as \quad \eta \to \infty \end{aligned} \tag{10}$$

The significant parameters are specified in the equations that do not include proportions.

$$M = \frac{\sigma B_0^2}{\rho a}, \; \mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\nu \rho C_p}{k}, \; Q = \frac{Q_0}{a\rho C_p}, \; Gr = \frac{g\beta_T\left(T_w - T_\infty\right)}{a^2 x}, R = \frac{16\sigma^* T_\infty^3}{3\rho C_p k^*}. \tag{11}$$

3. Physical quantities of Interests

The relevant physical parameters that have an impact on the flow are the local skin friction coefficient in the direction of x Cf_x and the direction of z Cf_z, and the local Nusselt number Nux, and. The following explanations apply to these numerical values:

$$C f_x = \frac{2\tau_{wx}}{\rho (ax)^2}, \; Cf_z = \frac{2\tau_{wz}}{\rho (ax)^2}, \; Nu_x = \frac{xq_w}{k\left(T_w - T_\infty\right)}, \; Sh_x = \frac{x\, j_w}{D_B\left(C_w - C_\infty\right)} \tag{12}$$

4. Results and Discussion

Plotting Figures 2-27 allows one to see the influence that several different physical factors have on the tangential velocity f'(η), the transverse velocity g(η), and the temperature θ(η) profiles. In each one of these calculations, unless it was specifically stated differently, we assumed that P r = 0.71, M = 0.5, m = 0.2, Gr = 0.5, Q_0 = 0.5, R = 1.

Figures 2–4 illustrate the influence of the magnetic parameter M on the primary velocity $f'(\eta)$, secondary velocity $g(\eta)$, and temperature $\theta(\eta)$, respectively. Figure 2 shows that increasing M from 0.5 to 2.0 decreases the primary velocity throughout the boundary layer due to the opposing Lorentz force generated by the applied magnetic field. Figure 3 indicates that the magnetic parameter significantly modifies the secondary velocity profile, with the stronger magnetic field altering the transverse momentum transport and producing a small negative region before the profile gradually approaches zero. In Figure 4, increasing M enhances the temperature profile, indicating an increase in thermal boundary-layer thickness as the stronger magnetic field suppresses fluid motion and promotes thermal energy accumulation.

Figures 5–7 depict the effects of the Hall parameter m on the primary velocity $f'(\eta)$, secondary velocity $g(\eta)$, and temperature $\theta(\eta)$, respectively. Figure 5 shows that increasing m from 1 to 4 enhances the primary velocity profile, indicating that the Hall current modifies the magnetic resistance and weakens the direct influence of the Lorentz force on the primary flow. In Figure 6, the secondary velocity decreases noticeably with increasing m, demonstrating that the Hall effect redistributes the electromagnetic force between the primary and secondary momentum components. Figure 7 shows only a slight variation in the temperature profile with increasing m, with the profiles remaining closely grouped and gradually approaching the ambient temperature as η increases.

Figures 8–11 present the effects of the Casson parameter and thermal Grashof number on the velocity profiles. Figure 8 shows that increasing β from 0.2 to 0.8 generally decreases the primary velocity, indicating a reduction in the flow velocity as the Casson parameter increases. Figure 9 illustrates the effect of on the secondary velocity; increasing m slightly modifies the secondary-flow profile, with the curves remaining close to each other and gradually approaching zero. Figure 10 demonstrates that increasing the thermal Grashof number enhances the primary velocity, since stronger buoyancy forces assist the fluid motion. Similarly, Figure 11 shows that Grx modifies the secondary velocity, particularly within the near-wall region, while all profiles eventually approach the free-stream condition.

Figures 12 and 13 illustrate the effects of the thermal radiation parameter and heat-source parameter on the temperature profile, respectively. Figure 12 shows that increasing R from 0.3 to 1.2 generally decreases the temperature distribution, indicating that enhanced thermal radiation promotes energy transport away from the fluid and consequently reduces the thermal field. Figure 13 demonstrates that increasing the heat-source parameter Q from 0.2 to 0.8 increases the temperature profile throughout the boundary layer, as stronger internal heat generation adds thermal energy to the fluid.

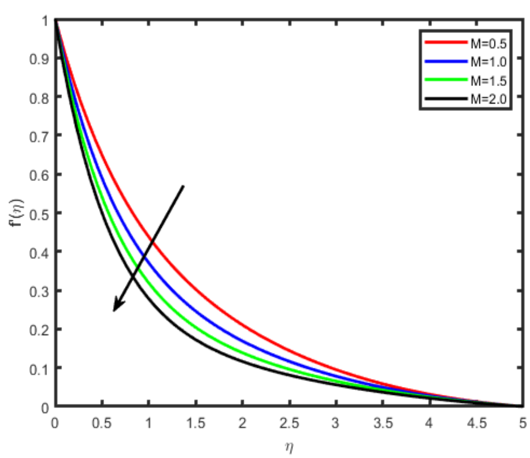

Figure: 2. Effect of M on f'(n)

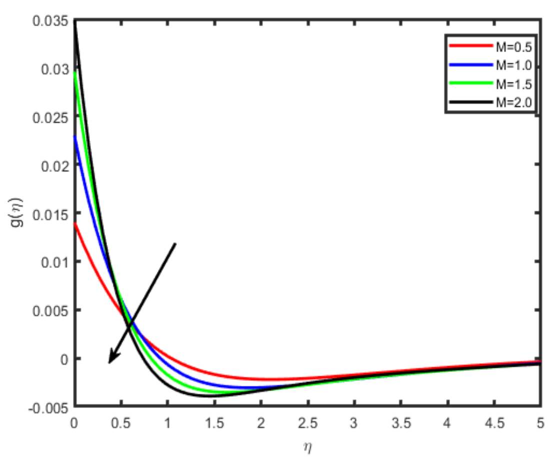

Figure: 3. Effect of M on g(n)

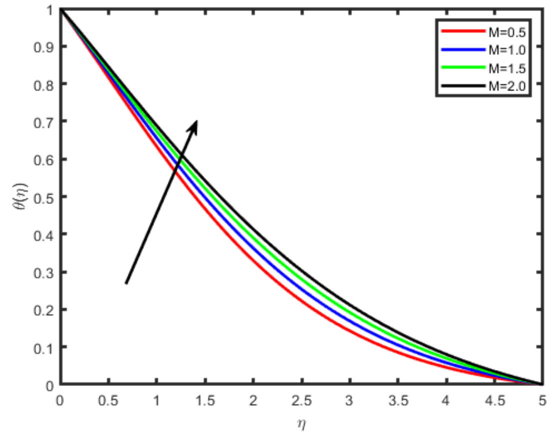

Figure: 4. Effect of M on θ(n)

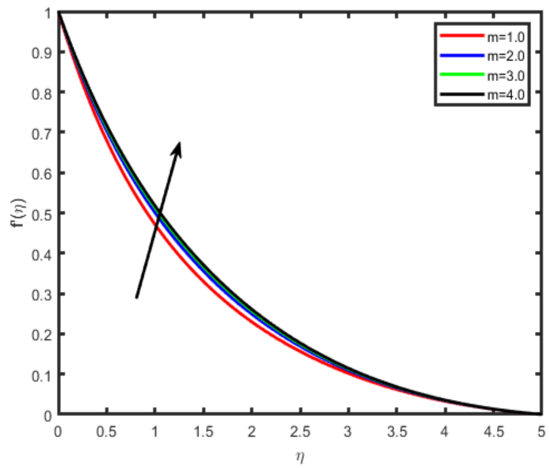

Figure: 5. Effect of m on f'(n)

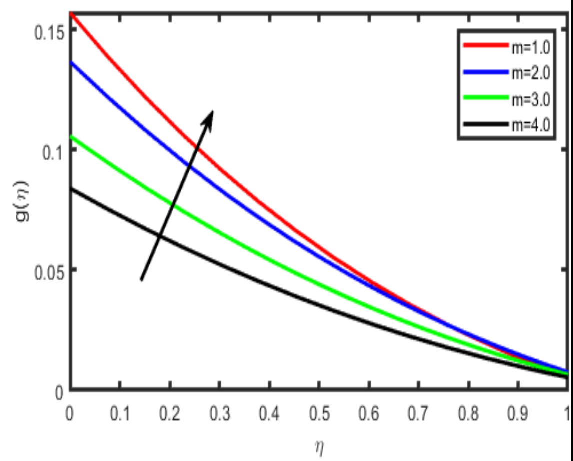

Figure: 6. Effect of m on g(n)

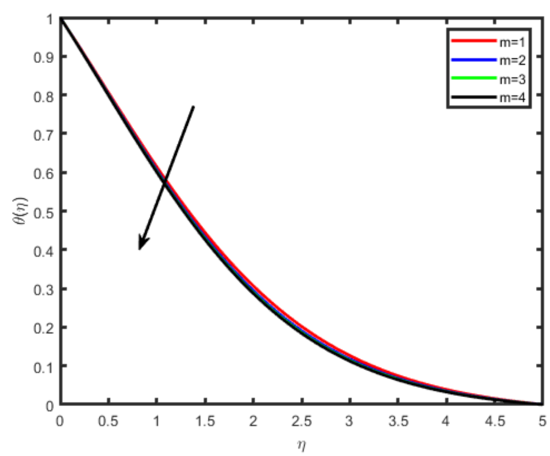

Figure: 7. Effect of m on θ(n)

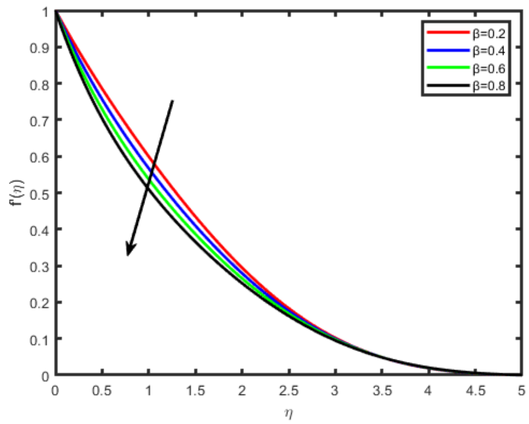

Figure: 8. Effect of β on f'(n)

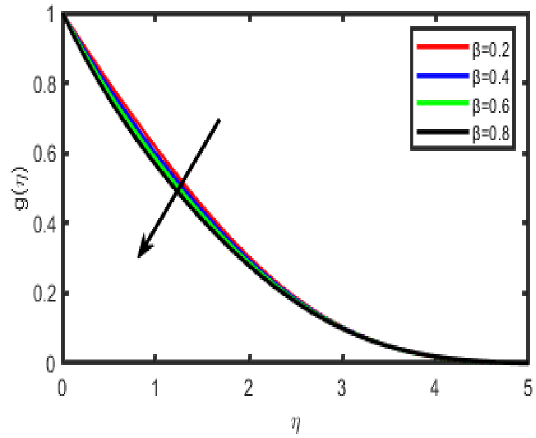

Figure: 9. Effect of β on g(n)

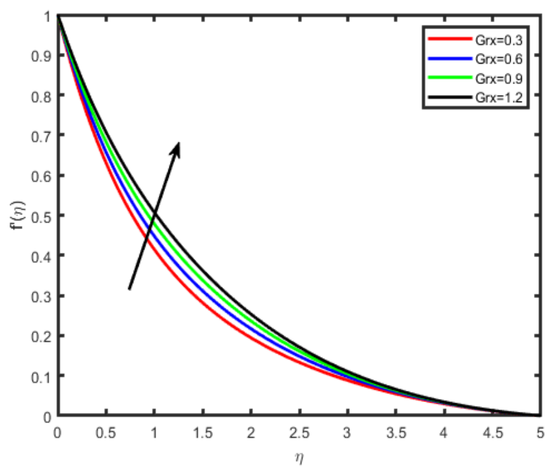

Figure: 10. Effect of Gr on f'(n)

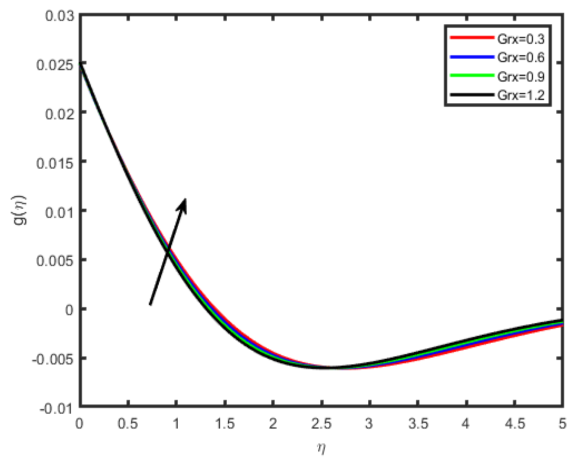

Figure: 11. Effect of Gr on g(n)

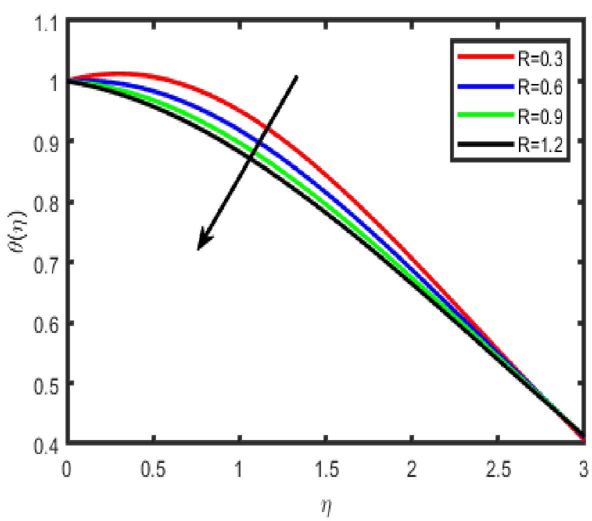

Figure: 12. Effect of R on θ(n)

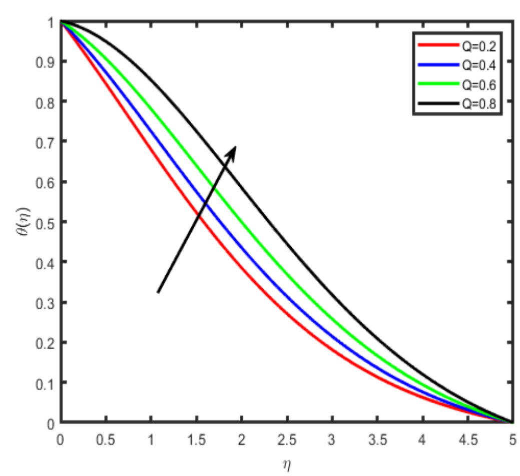

Figure: 13. Effect of Q on θ(n)

Table 1 presents the numerical values of the skin-friction coefficients in the primary and secondary flow directions, $-2f''(0)$ and $-2g'(0)$, respectively, together with the local heat-transfer rate, $-\theta'(0)$, for different governing parameters. For increasing magnetic parameter M, $-2f''(0)$ increases from 0.9452 to 1.4035, whereas $-2g'(0)$ and $-\theta'(0)$ decrease, indicating that the magnetic field strongly modifies the momentum and heat-transfer characteristics. As the Hall parameter m increases from 1 to 3, $-2f''(0)$ decreases from 1.5214 to 0.8125, while $-2g'(0)$ increases from 0.8521 to 0.9985; meanwhile, $-\theta'(0)$ decreases from 0.3145 to 0.2312, showing the significant influence of Hall current on the primary and secondary flow fields. Increasing the Casson parameter β from 0.5 to 1.5 increases $-2f''(0)$ from 0.8752 to 0.9125, while both $-2g'(0)$ and $-\theta'(0)$ decrease, reflecting the effect of fluid rheology on momentum and heat transfer. For increasing thermal Grashof number Gr, $-2f''(0)$ decreases from 1.2547 to 0.7354, whereas $-2g'(0)$ and $-\theta'(0)$ increase, demonstrating the role of thermal buoyancy in modifying the transport rates. The thermal radiation parameter R causes a decrease in $-2f''(0)$ and $-2g'(0)$, while $-\theta'(0)$ increases from 0.1254 to 0.1987, indicating enhanced radiative heat transfer. Finally, increasing the heat-source/sink parameter Q from 0.2 to 0.6 increases $-2f''(0)$, while $-2g'(0)$ and $-\theta'(0)$ decrease.

Table 1. Numerical values of skin-friction coefficients and heat-transfer rate for different governing parameters

Parameter	Value	$-2f''(0)$	$-2g'(0)$	$-\theta'(0)$
Magnetic parameter, M	0.5	0.9452	1.0254	0.9875
	1.0	1.2454	0.9852	0.9125
	1.5	1.4035	0.8512	0.8952
Hall parameter, m	1	1.5214	0.8521	0.3145
	2	1.0214	0.9547	0.2978
	3	0.8125	0.9985	0.2312
Casson parameter, β	0.5	0.8752	1.0875	0.7452
	1.0	0.8952	0.9442	0.7365
	1.5	0.9125	0.9114	0.7154
Thermal Grashof number, Gr	0.5	1.2547	0.8521	0.5212
	1.0	0.9978	0.9125	0.5323
	1.5	0.7354	0.9542	0.5457
Thermal radiation parameter, R	0.68	0.9785	1.0214	0.1254
	0.71	0.9120	0.9852	0.1578
	0.76	0.8452	0.9032	0.1987
Heat source/sink parameter, Q	0.2	0.7124	0.9875	0.9542
	0.4	0.7852	0.9452	0.9125
	0.6	0.8125	0.9132	0.8657

5. Conclusion

This study numerically investigated the effects of magnetic field, Hall current, Casson rheology, thermal buoyancy, thermal radiation, and heat generation/absorption on the flow and heat-transfer characteristics of an electrically conducting Casson fluid over a continuously stretching sheet. The governing equations were transformed into a system of nonlinear ordinary differential equations using suitable similarity transformations and solved using the MATLAB bvp4c technique. The major conclusions obtained from the present analysis are:

- Increasing the magnetic parameter suppresses the primary velocity because of the opposing Lorentz force, while the temperature profile is enhanced, indicating an increase in the thermal boundary-layer thickness.
- The Hall parameter significantly modifies both primary and secondary velocity fields. Increasing enhances the primary velocity while reducing the magnitude of the secondary-flow response and produces a comparatively weaker influence on the temperature distribution.
- Increasing the Casson parameter modifies the rheological behavior of the fluid and generally reduces the primary velocity, demonstrating the important role of non-Newtonian characteristics in controlling momentum transport.
- An increase in the thermal Grashof number strengthens the buoyancy-driven flow and consequently enhances the primary velocity, while also modifying the secondary velocity and heat-transfer characteristics.
- Increasing the thermal radiation parameter reduces the temperature field and enhances radiative energy transport away from the fluid, thereby affecting the thermal boundary layer and local heat-transfer rate.
- Increasing the heat-source/sink parameter significantly influences the thermal field. For the positive values considered in the present study, the heat-source effect increases the thermal energy within the boundary layer and consequently alters the associated heat-transfer characteristics.
- The numerical values in Table 1 confirm that the governing parameters substantially affect the primary and secondary skin-friction coefficients and the local Nusselt number, demonstrating strong coupling between electromagnetic forces, Casson rheology, buoyancy, and thermal transport.

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