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Spectral quasilinearization analysis of Casson fluid flow over a convectively heated inclined plate considering thermal dispersion and nonlinear thermal convection

Sathyendar Sreepada[1], Surender Ontela[2,1,†], and Padigepati Naveen[3]

[1] *Department of Mathematics, National Institute of Technology Mizoram, Aizawl, Mizoram* 796012, *India*
[2] *Department of Mathematics, National Institute of Technology Kurukshetra, Haryna* 136119, *India*
[3] *Department of Mathematics, School of Advanced Sciences, Vellore Institute of Technology, Vellore* 632014, *Tamil Nadu, India*

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The present study investigates the influence of thermal dispersion on the natural convective flow of a Casson fluid along an inclined plate embedded in a non-Darcy porous medium. The governing equations, representing momentum and energy conservations, are transformed into non-dimensional form using similarity transformations. To address the complexity of the resulting equations, a bivariate spectral quasilinearisation method is employed. The effects of relevant parameters — including thermal dispersion, Casson parameter, Biot number, Forchheimer number, inclination angle and nonlinear thermal convection parameter — are thoroughly examined. The results show that the drag coefficient and heat transfer rate increase with the nonlinear thermal convection parameter, Casson parameter and Biot number. In contrast, they decrease as the Forchheimer number and inclination angle increase. The velocity near the surface of the inclined plate increases with the Biot number, Casson parameter and nonlinear thermal convection parameter. However, it decreases farther from the plate. Additionally, the temperature of the Casson fluid increases with most parameters, except the Casson and nonlinear thermal convection parameters.

Keywords: Casson fluid, thermal dispersion effect, non-Darcy porous medium

PACS: 47.55.–t, 47.32.–y, 47.20.–k, 44.25.+f

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1. Introduction

The natural convective flow of non-Newtonian fluids over inclined surfaces embedded in porous media has garnered significant attention due to its broad range of industrial applications. Flows past inclined surfaces are prevalent in various engineering systems, including heat exchangers, geothermal energy extraction, solar collectors, chemical processing and enhanced oil recovery. In particular, inclined plates are preferred over other geometries such as V-shaped prisms, discs and bluff bodies due to their simplicity and practical relevance in industrial design.

In electrical systems, inclined plates are employed for efficient cooling of electronic components through enhanced convective heat transfer. In the chemical processing industry they are widely used in filtration systems, distillation columns and catalytic reactors, where efficient heat and mass transfer are critical for optimizing performance. Furthermore, inclined surfaces are essential in iron removal and brine clarification processes, where fluid flow behavior influences separation efficiency and thermal performance. Applications also extend to heat pipes, inclined solar collectors and thermal insulation systems, where natural convection plays a vital role in maintaining temperature regulation and improving energy efficiency. Kalendar and Oosthuizen[1] conducted theoretical and experimental studies to investigate natural convective flow over inclined flat plates. Recently, the significance of flow over an inclined plate in the presence of a heat source/sink was examined by Kodi and Mopuri.[2] Similarly, Ragul and Sambath[3] revealed that the inclination angle reduces the velocity profile near the boundary and increases it further away in the investigation of the free convective flow along a vertically inclined plate.

A Casson fluid is a type of non-Newtonian fluid characterized with yield stress behavior. It behaves like a solid until the applied stress exceeds a certain threshold, after which it flows like a viscous fluid. This rheological model is important in industries that use fluids such as paints, blood, cosmetics, drilling muds and food products. In these cases yield stress and shear-thinning properties significantly influence flow dynamics and heat transfer. In the context of natural convection over inclined surfaces, understanding the behavior of Casson fluids is crucial for optimizing heat transfer rates and predicting flow characteristics accurately. The problem becomes more complex when thermal dispersion effects and porous media are involved: the complexity of the problem increases, requiring advanced numerical techniques for precise analysis.

Initially, Casson[4] presented this model to forecast the

[†]Corresponding author. E-mail: reddysurender3@gmail.com

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flow characteristics of a pigment oil suspension. Shear-thinning behavior and yield stress characterize this family of non-Newtonian fluids.[5] The study of Casson fluid flow over inclined plates can be beneficial for the food, paint and biological fluid industries. Due to their unique flow characteristics, they are also suitable for use in applications involving the processing of chemical compounds where precise control over fluid behavior is essential. A recent study by Kumar *et al.*[6] indicates that higher inclination angles and the Casson fluid parameter reduce velocity. They also provided insights into the behavior of a Casson fluid under different scenarios. At the same time, Osman *et al.*[7] pointed out that the Casson fluid reduces yield stress and enhances the velocity in the study of time-dependent magnetized flow of Casson fluid flow past an inclined plate. With specific relevance to applications requiring the processing of chemical materials, Yedhiri *et al.*[8] examined the significance of thermal diffusion and chemical reactions on magnetized fluid flow.

Fluid flow through porous media is commonly encountered in various natural and industrial processes, such as groundwater hydrology, enhanced oil recovery, geothermal energy extraction, chemical filtration and packed-bed reactors. While Darcy's law effectively describes fluid motion through porous media at low velocities, it becomes inadequate when inertial effects become significant at higher velocities. In such cases, the flow regime deviates from the linear Darcy model, necessitating the use of non-Darcy models, such as the Forchheimer model, which introduces quadratic drag terms to account for inertial effects. Studying non-Darcy flow over inclined surfaces embedded in porous media is essential for accurately predicting fluid behavior, determining heat transfer rates, and optimizing processes involving non-Newtonian fluids such as Casson fluids.

Darcy flow,[9] which describes a linear relationship between pressure gradient and flow rate, has served as the foundation for much of the existing literature. Nevertheless, in many real-world scenarios, such as high flow rates (fluid viscosity), non-linear fluid properties, uneven porosity distribution and highly turbulent and porous media bounded by impermeable surfaces, Darcy's equation proves inadequate. In such cases, the Darcy–Forchheimer model[10] must be considered. Nakayama and Pop[11] developed a unified version of the similarity transformation for natural, mixed and forced convection, also highlighting the influence of slip effects on both Darcy and non-Darcy flow. Further explanations and applications of the Darcy–Forchheimer model can be found in Refs. [12–14].

The convective surface boundary condition is practical and thus valuable for heat transfer analysis in engineering and industrial applications such as nuclear power plants, gas turbines, heat exchangers, etc. The impact of non-linear convection on the non-Darcy flow of non-Newtonian fluid past an inclined plate was examined by Ramreddy *et al.*[15] Later, Madhavi*et al.*[16] highlighted the significance of convective surface boundary conditions in a study of Darcy fluid flow along an inclined sheet. The studies of Refs. [17–19] provide important insights into convective thermal conditions in investigations involving various non-Newtonian fluids.

Based on the existing literature, although numerous studies have explored the natural convective flow of non-Newtonian fluids over inclined plates and through porous media, limited attention has been given to the complex interplay between Casson fluid dynamics, thermal dispersion effects and nonlinear Boussinesq approximation under non-Darcy conditions. While previous research has primarily focused on Newtonian or simpler non-Newtonian fluids, the combined influence of these factors on heat transfer characteristics and fluid flow remains under explored. Furthermore, the effects of key parameters such as Forchheimer number, inclination angle, Biot number and nonlinear thermal convection parameter on the heat transfer rate and fluid dynamics have not been thoroughly investigated.

To address these gaps, the present study investigates the free convective flow of a Casson fluid along a vertically inclined plate saturated with a non-Darcy porous medium, considering the effects of the nonlinear Boussinesq approximation and convective heat transfer. The research is guided by the following questions. (i) How do the thermal dispersion effects and nonlinear Boussinesq approximation influence the flow and heat transfer characteristics of Casson fluid over an inclined plate? (ii) What is the combined impact of parameters such as the Casson parameter, Forchheimer number, Biot number and inclination angle on velocity, temperature distribution, skin friction and the Nusselt number? (iii) Can the heat transfer mechanism be optimized by adjusting relevant parameters to achieve the desired thermal performance?

2. Mathematical formulation

Consider the buoyancy-driven flow of an incompressible Casson fluid along a semi-infinite inclined plate embedded in a non-Darcy porous medium with an acute angle Ω to the vertical direction. To analyze this problem efficiently, the following assumptions are made. (i) As illustrated in Fig. 1, the flow is assumed to be steady state in the two-dimensional Cartesian coordinate system xy. (ii) With the exception of the buoyancy factor, constant physical parameters are assumed. (iii) Convective heating or cooling of the plate occurs from a fluid of temperature T_{f} on the left. A chilled surface corresponds to $T_{\mathrm{f}} < T_{\infty}$, while a heated surface corresponds to $T_{\mathrm{f}} > T_{\infty}$. (iv) In order for the nonlinear density–temperature (NDT) fluctuations in the buoyancy force to significantly affect the fluid flow,

the temperature difference between the ambient fluid and the plate surface is assumed to be sufficiently large.

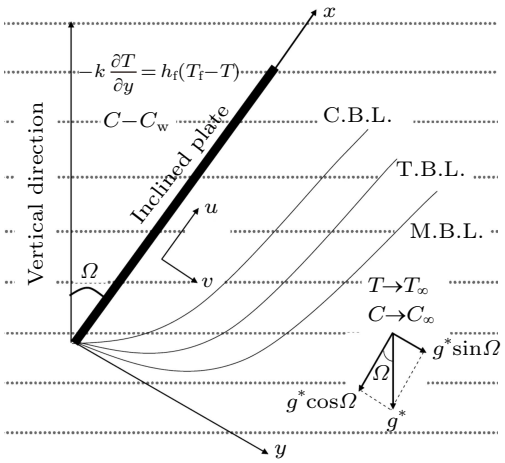


Fig. 1. Physical model.

Making use of the above-mentioned assumptions and the standard boundary layer assumptions, the Casson fluid flow equations for Darcy–Forchhiemer model are given by

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

$$\begin{aligned}&\frac{\rho}{\varepsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)\\ &=\frac{\mu}{\varepsilon}\left(1+\frac{1}{C_F}\right)\frac{\partial^2 u}{\partial y^2}-\frac{\mu}{K_p}u-\frac{\rho\, b}{K_p}u^2\\ &\quad+\rho g^*\left[\beta_0(T-T_\infty)+\beta_1(T-T_\infty)^2\right]\cos\Omega,\end{aligned} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial}{\partial y}\left[\alpha_e\frac{\partial T}{\partial y}\right]. \tag{3}$$

Based on the above assumptions, the boundary conditions are expressed as follows:

$$\begin{aligned}&u=0,\quad v=0,\quad -k\frac{\partial T}{\partial y}=h_f(T_f-T),\quad \text{on}\quad y=0,\\ &u=0,\quad T=T_\infty,\quad \text{as}\quad y\to\infty,\end{aligned} \tag{4}$$

where (u,v) are the Darcian velocities in the (x,y) directions. Here, ε, b, g^*, K_p, T, ρ, μ, Ω, k and h_f denote the porosity, empirical constant, acceleration due to gravity, permeability, temperature, density, dynamic viscosity, inclination of angle, thermal conductivity of the fluid and convective heat transfer coefficient, respectively. The Casson fluid parameter is denoted by $C_F\,(0<C_F<\infty)$. Here β_0 and β_1 are the first- and second-order expansions of thermal coefficients, respectively. Further, the effective thermal diffusivity and effective solutal diffusivity are defined as $\alpha_e=\alpha+\chi\, d\, u$, respectively, and α, χ and d represent the molecular thermal diffusivity, thermal dispersion coefficient and pore diameter, respectively.

We introduce the stream function ψ with the assumptions $u=\partial\psi/\partial y$, $v=-\partial\psi/\partial x$ in Eq. (1) and apply the following non-similarity transformations:

$$\begin{aligned}&\xi=\frac{x}{L},\quad \eta=\frac{y}{L}\left(\frac{Gr}{\xi}\right)^{\frac{1}{4}},\\ &\psi(\xi,\eta)=\frac{\mu\, Gr^{\frac{1}{4}}\,\xi^{\frac{3}{4}}}{\rho}f(\xi,\eta),\\ &\theta(\xi,\eta)=\frac{T-T_\infty}{T_f-T_\infty}.\end{aligned} \tag{5}$$

The governing equations (2) and (3) along with surface condition Eq. (4) are reduced into

$$\begin{aligned}&\frac{1}{\varepsilon}\left(1+\frac{1}{C_F}\right)f'''+\frac{3}{4\varepsilon^2}ff''-\frac{1}{2\varepsilon^2}f'^2-\frac{1}{Da}\left(\frac{\xi}{Gr}\right)^{\frac{1}{2}}f'\\ &-\frac{Fs}{Da}\xi\, f'^2+[\theta(1+\alpha_1\theta)]\cos\Omega\\ &=\frac{\xi}{\varepsilon^2}\left(f'\frac{\partial f'}{\partial\xi}-f''\frac{\partial f}{\partial\xi}\right),\end{aligned} \tag{6}$$

$$\frac{1}{Pr}\theta''+\frac{3}{4}f\theta'+Ds\,\xi^{\frac{1}{2}}\left(f'\,\theta'\right)'=\xi\left(f'\frac{\partial\theta}{\partial\xi}-\frac{\partial f}{\partial\xi}\theta'\right), \tag{7}$$

along with

$$\begin{aligned}&f'(\xi,0)=0,\quad f(\xi,0)=-\frac{4}{3}\xi\left(\frac{\partial f}{\partial\xi}\right)_{\eta=0},\\ &\theta'(\xi,0)=-Bi\,\xi^{\frac{1}{4}}\left[1-\theta(\xi,0)\right],\\ &f'(\xi,\infty)=0,\quad \theta(\xi,\infty)=0,\end{aligned} \tag{8}$$

where the primes represent partial derivatives with respect to η alone. Furthermore, $Gr=(g^*\beta_0(T_f-T_\infty)L^3)/\nu^2$, $Da=K_p/L^2$, $Fs=b/L$, $Pr=\nu/\alpha$, $Ds=[\chi\, d\, Gr^{\frac{1}{2}}]/L$, $\alpha_1=\beta_1(T_f-T_\infty)/\beta_0$ represent the global thermal Grashof number, Darcy number, Forchheimer number, Prandtl number, thermal dispersion parameter and nonlinear temperature parameter, respectively. Here, ξ, η, L, f, θ, T_f, T_∞, ν and Bi denote the dimensionless streamwise coordinate, similarity variable, characteristic length, dimensionless stream function, dimensionless temperature, convective wall temperature, ambient temperature, kinematic viscosity and Biot number, respectively.

The physical parameters of interest, the frictional coefficient $C_f=\frac{2}{\rho U_*^2}\left[\mu\frac{\partial u}{\partial y}\right]_{y=0}$ and the Nusselt number $Nu_x=-\frac{x}{k(T_f-T_\infty)}\left[k_e\frac{\partial T}{\partial y}\right]_{y=0}$ in non-dimensional form are given by

$$\begin{aligned}&C_f Gr_x^{1/4}=2\left(1+\frac{1}{C_F}\right)f''(\xi,0),\\ &\frac{Nu_x}{Gr_x^{1/4}}=-\left[1+Ds\,Pr\,\xi^{\frac{1}{2}}f'(\xi,0)\right]\theta'(\xi,0),\end{aligned} \tag{9}$$

where U_* and $Gr_x=[g^*\beta_0(T_f-T_\infty)x^3]/\nu^2$ are the characteristic velocity and the local thermal Grashof number, respectively.

2.1. Numerical method and validation

A new and rapidly converging technique for solving the system of equations (6) and (7) with boundary conditions (8) is the spectral quasi-linearization method, which is a generalized version of the Newton–Raphson scheme.[20,21]

To evaluate the validity and accuracy of the current study, the results of Eqs. (6)–(8) have been compared with those for a regular fluid.[22] Table 1 demonstrates the comparison and agrees well with the current findings. Numerical computations are carried out with the following default values of the parameters: $Da = 0.1$, $Pr = 1.0$, $\xi = 0.5$, $Gr = 10$ and $\varepsilon = 0.5$.

Table 1. Comparison of $-\theta'(\xi, 0)$ for natural convection along a vertical flat plate in a regular fluid when $\alpha_1 = 0$, $\varepsilon = 1$, $Da \to \infty$, $\xi = 1$, $Bi \to \infty$, $\Omega = 0$, and $Pr = 1$.

Bejan[23]	Present
0.401	0.40103

3. Results and discussion

This section provides a comprehensive analysis of the results obtained from the numerical simulations of the free convective flow of a Casson fluid over an inclined plate embedded in a non-Darcy porous medium. The governing equations, transformed into dimensionless form, are solved using the bivariate spectral quasilinearization method. The effects of various physical parameters — including the Casson parameter, Forchheimer number, inclination angle, Biot number and nonlinear thermal convection parameter — are thoroughly examined. The results are presented graphically to highlight the influence of these parameters on the velocity and temperature profiles, skin friction and Nusselt number. A detailed discussion is provided to interpret the physical implications of the findings and their relevance to practical applications involving non-Newtonian fluid flow and heat transfer.

3.1. Effect of non-linear convection parameters

The impact of varying the nonlinear convection parameter (α_1) on the fluid flow characteristics is demonstrated in Figs. 2(a) and 2(b). In Fig. 2(a), an increase in α_1 results in an enhancement of the velocity if the Casson fluid and a corresponding reduction in temperature. This phenomenon can be attributed to the fact that higher values of α_1 amplify the buoyancy force, thereby promoting fluid motion within the boundary layer and accelerating the flow of the Casson fluid. The enhanced buoyancy effect facilitates the upward movement of the fluid along the inclined plate, which explains the increased velocity profiles. Moreover, the condition $\alpha_1 > 0$ implies that the ambient fluid temperature T_f is greater than the ambient temperature T_∞. As a result, the fluid absorbs thermal energy from the surface, thereby increasing the thermal transmission rate as depicted in Fig. 2. The enhanced heat transfer is indicated by the increased Nusselt number with higher α_1 values, which implies improved heat dissipation from the plate to the fluid.

Furthermore, the rise in α_1 intensifies the velocity gradient near the surface, thereby increasing the shear stress. Consequently, this leads to a higher skin friction coefficient, as observed in Fig. 2(b). Overall, the nonlinear convection parameter α_1 significantly enhances fluid velocity and heat transfer. It also increases shear stress at the boundary.

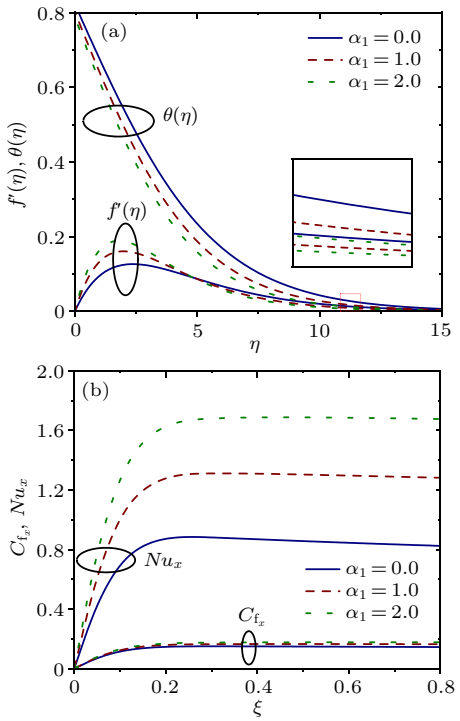


Fig. 2. Effect of the nonlinear density–temperature (NDT) parameter (α_1) on (a) velocity (f'), temperature (θ), and (b) skin friction (C_f), heat transfer rate (Nu).

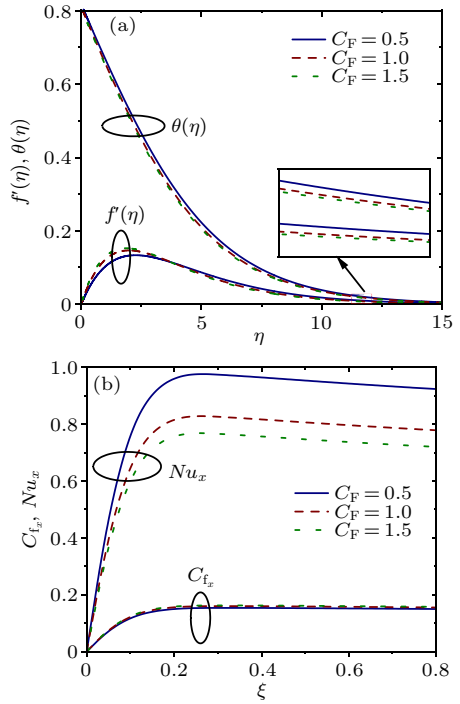


Fig. 3. Effect of the Casson parameter (C_F) on (a) velocity (f'), temperature (θ) and (b) skin friction (C_f), heat transfer rate (Nu).

3.2. Effect of the Casson parameter

Positive variations in the Casson parameter (C_F) intensify the fluid's non-Newtonian behavior by increasing its viscosity, which leads to greater frictional resistance near the plate. Consequently, the skin friction coefficient rises, as illustrated in Fig. 3(b). Due to elevated viscosity, the fluid velocity increases near the plate. However, farther from the surface, the flow decelerates, as illustrated in Fig. 3(a). Higher viscosity and frictional resistance increase energy dissipation. This dissipated energy is converted into thermal energy and released into the surroundings. This process results in a temperature reduction, as observed in Fig. 3(b), and a corresponding decrease in the Nusselt number depicted in Fig. 3(a).

3.3. Effect of the Biot number

Figures 4(a) and 4(b) depict the influence of convective boundary conditions on the flow field. As the Biot number (Bi) increases, the thermal resistance of the inclined plate decreases. As a result, the maximum flow field velocity shifts closer to the boundary layer, as shown in Fig. 4(a). The reduced thermal resistance allows more thermal energy to be generated within the fluid, and this heat generation enhances the temperature of the Casson fluid in Fig. 4(a). Consequently, both the heat transfer rate and skin friction coefficient increase, as depicted in Fig. 4(b).

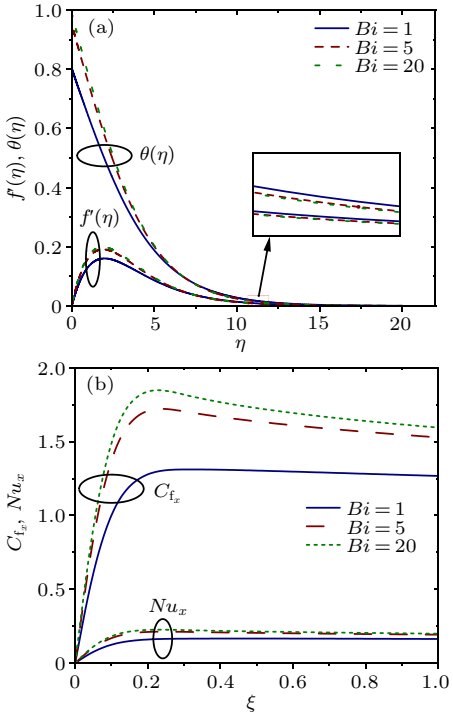


Fig. 4. Effect of the Biot number (Bi) on (a) velocity (f'), temperature (θ) and (b) skin friction (C_f), heat transfer rate (Nu).

3.4. Effect of the non-Darcy parameter

The behavioral change in the fluid flow region resulting from variations in the Forchheimer parameter (Fs) is illustrated in Figs. 5(a) and 5(b). Increasing Fs values dominate the inertial force, which resists the Casson fluid from moving freely near the inclined plate. As a result, the velocity profile becomes shorter, as seen in Fig. 5(a). Additionally, higher Fs values enhance the capacity of the porous medium to store thermal energy, leading to the decreased rate of heat transfer in Fig. 5(b) and increased Casson fluid temperature in Fig. 5(a). The Darcy–Forchheimer model improves the prediction of thermal transmission rates compared with the Darcy model.

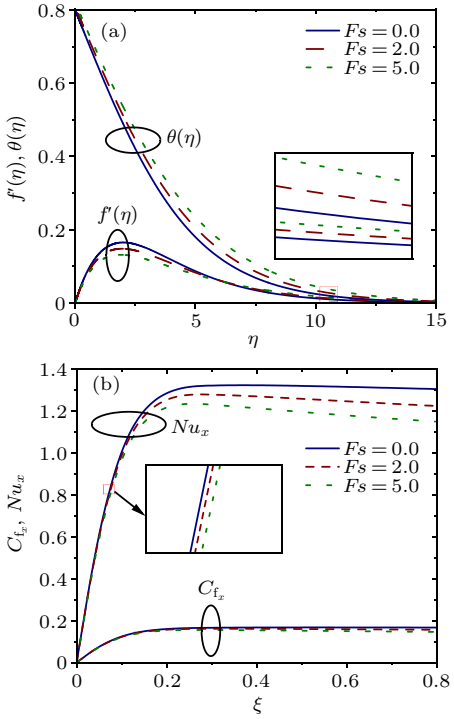


Fig. 5. Effect of the Forchheimer number (Fs) on (a) velocity (f'), temperature (θ) and (b) skin friction (C_f), heat transfer rate (Nu).

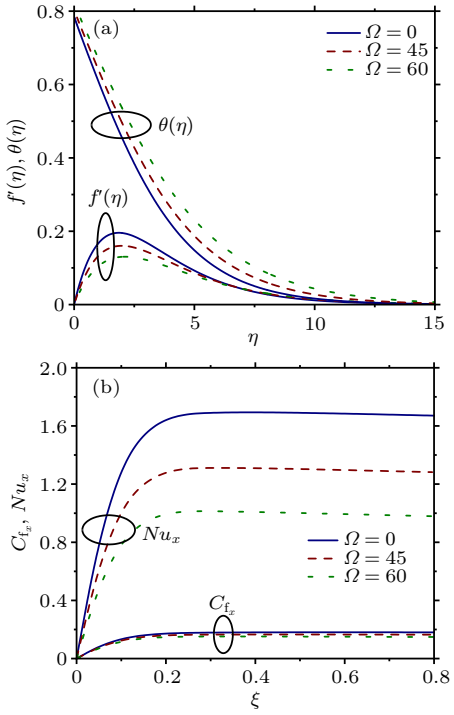


Fig. 6. Effect of the inclination angle (Ω) on (a) velocity (f'), temperature (θ) and (b) skin friction (C_f), heat transfer rate (Nu).

3.5. Effect of the angle of inclination

A higher inclination angle of the plate (Ω) results in a stronger gravitational pull, which increases fluid resistance and reduces the velocity of the Casson fluid, as shown in Fig. 6(a). Shear stress and convective heat transfer are minimized due to the decreased velocity profile and velocity gradient. Consequently, the lower shear stress leads to a reduced skin friction coefficient, and diminished thermal transmission results in a lower Nusselt number, as illustrated in Fig. 6(b). Additionally, the temperature profile rises in Fig. 6(a) due to the reduced heat transmission from the plate to the fluid.

4. Conclusions

In this study, the buoyancy-driven flow and heat transfer characteristics of a Casson fluid over a convectively heated inclined plate embedded in a non-Darcy porous medium were investigated, incorporating the effects of thermal dispersion and non-linear thermal convection. The governing equations were solved using the spectral quasilinearization method, a robust and fast-converging numerical approach. A comprehensive analysis has been conducted to examine the influence of various parameters (α_1, C_F, Bi, Fs and Ω) on the velocity ($f'(\eta)$) and temperature ($\theta(\eta)$) profiles, as well as on the heat transfer and drag coefficients.

The key findings of this study can be summarized as follows.

Nonlinear thermal convection parameter (α_1) An increase in α_1 significantly boosts the buoyancy forces, which accelerates the Casson fluid near the surface and enhances heat transfer. This results in a higher velocity and increased Nusselt number, along with greater skin friction due to steeper velocity gradients at the wall.

Casson parameter (C_F) As C_F increases, the non-Newtonian nature of the fluid becomes more pronounced, increasing its apparent viscosity. This leads to greater frictional resistance, raising the skin friction coefficient near the surface. However, the velocity reduces away from the plate due to viscous damping, resulting in a decreased Nusselt number and lower heat transfer efficiency.

Biot number (Bi) A higher Bi indicates stronger convective heating at the wall, which reduces thermal resistance. This enhances fluid temperature and boosts heat transfer rates, evident from the increased Nusselt number and skin friction coefficient.

Forchheimer number (Fs) Increasing Fs introduces more inertial resistance in the porous medium, which impedes fluid motion. This reduces the velocity near the surface, diminishes heat transfer (lower Nusselt number) and elevates the fluid temperature due to energy storage within the porous matrix. Compared with the Darcy model, the Darcy–Forchheimer model captures this resistance more effectively.

Inclination angle (Ω) A steeper plate (higher Ω) increases the gravitational opposition to flow, resulting in reduced velocity profiles and weakened buoyancy-induced convection. This causes decreases in skin friction and Nusselt number and increases in temperature due to diminished convective cooling.

Except for the Casson and nonlinear thermal convection parameters, most parameters (Bi, Fs, Ω) lead to increased fluid temperature, suggesting lower heat dissipation. The velocity near the wall increases with α_1, Bi and C_F, but decays farther from the plate, indicating a boundary layer-thickening effect due to higher viscosity or enhanced surface convection.

Engineering implications These results provide valuable insights for engineering systems that require precise thermal control, such as heat exchangers, chemical processing units and biomedical fluid systems involving non-Newtonian fluids. Optimizing parameters such as α_1, Bi and C_f can significantly improve heat transfer efficiency, while understanding the resistance introduced by Fs and Ω helps in the prediction of performance limits in porous media configurations.

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