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RESEARCH ARTICLE

The impact of velocity on Casson fluid passing through an infinite inclined accelerated plate

Nur Fatihah Mod Omar[1], Zulkhibri Ismail[1]*, Rahimah Jusoh[1], Husna Izzati Osman[1] and Ahmad Qushairi Mohamad[2]

[1]Centre for Mathematical Sciences, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia
[2]Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

Abstract - The current research examines the impact of velocity on a Casson fluid passing through an infinite inclined accelerated plate. The problem is the occurrence of radiation and magnetic parameters, and the governing equations are solved analytically using the Laplace transform method. The outcomes are illustrated through graphical representations, followed by a discussion on various physical aspects of the problem. The findings reveal that higher Casson parameter values reduce the velocity profile due to stronger yield-stress effects, while enhanced thermal radiation increases the fluid's kinetic energy, thereby accelerating motion. Over time, the velocity profiles extend deeper into the fluid domain. Conversely, stronger magnetic fields suppress the velocity, whereas greater porosity enhances it by reducing resistance within the porous medium and enabling smoother flow. Inclined plates are widely used to study heat and fluid transport in systems such as geothermal units, heat exchangers, and solar collectors. Their geometry introduces gravitational effects, making the analysis more realistic than for horizontal or vertical surfaces.

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1. Introduction

Research on fluid flow has expanded rapidly, largely stimulated by advancements in industrial applications. This growth reflects the rising demand for greater efficiency in processes where fluid motion plays a vital role in transport and mixing. Such applications are widely observed across multiple sectors, including petroleum and gas industries, food and beverage production, chemical manufacturing, plastics, and pharmaceuticals. In pursuit of more efficient methods for achieving high-quality end products, reliance on classical Newtonian fluids, such as water, has become inadequate due to their limitations in accurately representing fluid material properties, thereby constraining industrial applications [1]. A class of non-Newtonian fluids, named Casson fluid, exhibits a distinctive shear stress–strain relation that indicates elastic solid behaviour when subjected to low shear rates but approaches Newtonian behaviour under higher stress. Characterised as shear-thinning, it possesses infinite viscosity at zero shear rate. Practical examples include human blood, fruit juices (such as tomato and orange), and soup [2]. Recent studies have further highlighted its significance. Omar et al. [3] investigated unsteady Magnetohydrodynamics (MHD) Casson flow over an accelerated plate and demonstrated that both MHD and Casson parameters suppress the velocity field. Later, Abbas et al. [4] investigated double-diffusive convection of Casson fluid in a microchannel using the Caputo–Fabrizio fractional derivative and reported that higher Casson parameter values lead to a reduction in the velocity profile. Mahmood et al. [5] conducted a detailed evaluation of mixed convection in Casson fluid, examining the coupled effects of concentration and temperature on mass and heat transfer. Their findings similarly indicate that an increase in the Casson parameter suppresses the velocity field.

The investigation of thermal radiation and its influence on convective heat and mass transfer processes has attracted increasing attention in recent years due to its wide-ranging applications in steel rolling, fin design, nuclear power plants, space vehicles, gas turbines, satellites, aircraft, and missile propulsion systems [6]. Thermal radiation, a mode of heat transfer via electromagnetic waves, becomes significant when large temperature differences exist between two media. It holds considerable importance in high-temperature engineering applications, such as power generation, space technology, glass manufacturing, and furnace and nuclear reactor design, where it influences both fluid motion and thermal expansion [7]. Beyond these, thermal radiation is also exploited in astrophysical flows, solar energy systems, gas production, and spacecraft technologies [8]. In mathematical modelling, the heat flux due to radiation is commonly expressed by incorporating the Rosseland approximation into the energy equation [9]. Anantha Kumar et al. [10] examined the effects of thermal radiation on Magnetohydrodynamic Casson fluid flow across a curved surface with exponential stretching, reporting that the radiation elevated the temperature and introduced a temperature-dependent thermal conductivity, thereby causing irregularities in the heat parameters. Similarly, Shoaib et al. [11] analysed MHD Casson fluid flow over an inclined porous surface under radiative heat transfer, observing a reduction in temperature with increasing radiation and a decline in concentration due to chemical reactions. Chari et al. [12] investigated MHD Casson non-Newtonian flow in a channel with expanding porous walls, and their results indicated that the fluid temperature decreases with a higher Prandtl number but increases with greater radiation parameter values.

The study of the inclined accelerated plate has been noticed in recent years. A paper presents an analysis of the influence of the Hall current and thermal radiation on MHD free convective heat and mass transfer in a radiating fluid past an accelerated inclined porous plate. The study also examines the effects of thermal diffusion and the presence of a heat source. Exact solutions for the velocity, temperature, and concentration distributions are obtained using the Laplace

***CORRESPONDING AUTHOR | Zulkhibri Ismail**| ✉ zulkhibri@umpsa.edu.my

transform technique. It can be concluded that the velocity profile is positively influenced by radiation and magnetic parameters but is negatively affected by inclination angle [13]. Furthermore, an investigation is carried out to examine the combined effects of thermal radiation and Hall current on MHD free convective heat and mass transfer flow of a radiating fluid along an accelerated inclined permeable surface. The analysis incorporates the influence of a heat source, thermal diffusion, and chemical reaction. Exact solutions for the velocity, temperature, and concentration fields are obtained using the Laplace transform method. It is observed that temperature declines as the Prandtl number and radiation increase. Additionally, the concentration profile declines with increasing Schmidt number [14]. Research has been conducted for an exact analysis of radiative magnetohydrodynamic flow over an accelerated inclined parabolic plate embedded in a permeable medium with variable fluid temperature and species concentration. The effects of an inclined magnetic field, chemical reaction, and internal heat generation are also taken into consideration. Closed-form analytical solutions to the governing flow equations are obtained using the Laplace transform method. The results indicate that increasing the magnetic field strength and its inclination angle decreases the fluid velocity, while the corresponding wall shear stress increases. The findings of this study provide valuable insights for enhancing rapid cooling processes and developing compact heat transfer systems with improved efficiency and cost-effectiveness [15]. In the same year, the influence of Soret and Dufour effects on unsteady magnetohydrodynamic fluid flow over an accelerated inclined vertical plate in the presence of thermal radiation and a heat source was studied. The nondimensional governing differential equations are solved using the Galerkin finite element method. The effects of various pertinent flow parameters on velocity, temperature, and concentration distributions are analysed and presented graphically. The results reveal that an increase in the Soret number enhances species concentration, whereas an increase in the Schmidt number produces the opposite effect. Furthermore, skin friction is found to decrease with increasing Soret and Dufour numbers. The findings of this study apply to the processing of magnetic materials in chemical and metallurgical industries [16]. The following year, the work examines the effects of heat and mass transfer on unsteady free convection flow past a linearly accelerated isothermal inclined plate with variable temperature and mass diffusion, in the presence of thermal radiation. For time t > 0, the plate is accelerated with velocity $u_0 t$ v, while both the plate temperature and mass diffusion increase linearly with time. The mathematical equations governing the flow problem are solved using the Laplace transform method. The results show that fluid velocity decreases with increasing radiation parameter, Prandtl number, and inclination angle parameter. It is also observed that the rate of heat transfer is higher for water compared to air [17]. However, all the above focus only on Newtonian fluids. Venkateswarlu et al. [18] explore the impulsive and accelerated motion of a Casson fluid past an inclined plate with MHD and heat generation effects. The momentum equation is formulated for two different cases: when the magnetic field is applied to the fluid region and when it is applied to the moving plate. Analytical solutions for the fluid velocity and temperature distributions are obtained using the Laplace transform technique. The effects of various physical parameters are examined for two types of motion: impulsive and accelerated. Both impulsive and accelerated fluid motion decrease with increasing values of the Casson fluid parameter, thermal radiation parameter, and angle of inclination. In addition, the thermal radiation parameter leads to a decrease in fluid temperature, whereas the heat generation parameter leads to an increase in temperature.

Analytical solutions provide numerous advantages. They are benchmarks to provide insights into underlying physical phenomena and to validate numerical methods [19]. In addition, they are valuable for addressing large-scale problems, for instance, modelling hydrocarbon reservoirs, by enabling dimensional analysis [20]. Analytical solutions are foundational or constructing solutions through superposition in heat conduction problems [21]. They also enable the efficient computation of exact results employing concise representations for short- and large-time behaviour [22]. Moreover, analytical solutions are important to verify numerical results generated by computational methods. Besides that, Computational Physicists play a crucial role in resolving inconsistencies between experimental data and numerical simulations, facilitating comparisons between simulations, theory, and experimental observations [23]. The analytical techniques include the Laplace transform [24-25], the Fourier series [26], the Homotopy analysis method [27], and the fractional derivative method [28-29].

The Laplace transform belongs to a class of operations known as integral transforms. It converts a function $f(t)$ of a single variable t (interpreted as time) into a new function $F(s)$ defined in terms of another variable s, the complex frequency. The appeal of the Laplace transform lies in its ability to transform differential equations in the t, time domain into algebraic equations in the frequency domain. Hence, it simplifies the process of solving differential equations, reducing them to algebraic equations expressed in the form s domain. An additional significant advantage is that the Laplace transform inherently incorporates initial conditions into the solution, making it especially useful for solving initial-value problems commonly encountered in studies of mechanical vibrations and electrical circuits. The core idea involves transforming a differential equation with constant coefficients into an algebraic equation for its Laplace transform $F(s)$, solving that equation, and subsequently applying the inverse Laplace transform to return to the original time-domain solution, $f(t)$. The precise mathematical expression of the Laplace transform, and the specific properties it satisfies, make this process feasible [30].

In the previous study, no study has incorporated heat and mass transfer for a Casson fluid passing through an inclined accelerated plate. Hence, we propose to investigate the influence of velocity on the flow of Casson fluid and the impact of radiation and magnetic parameters. The governing equations are analytically solved using the Laplace transform method. The results are presented graphically, and the different physical aspects of the research are discussed.

2. Methodology

2.1 Mathematical Formulation

The mixed convection, time-dependent flow of a non-compressible, electrically conductive, and viscous fluid, imposing a magnetic field $B_\circ$, near an infinitely inclined accelerated plate is considered. At time $t=0$, the fluid and the plate are stationary and share a uniform temperature T_∞. For $t>0$, the plate starts to move within its own plane with a velocity At, where A represents the constant acceleration of the plate. Simultaneously, the plate temperature is increased to T_w and maintained at this constant value thereafter. In the governing unsteady boundary layer equations for Casson fluid, the heat transfer due to radiation and concentration fields are expressed in dimensional representation as follows [31]:

$$\rho\frac{\partial u'}{\partial t'}=\mu(1+\frac{1}{\gamma})\frac{\partial^2 u'}{\partial x'^2}+\rho g\beta_T\cos\phi(T'-T'_\infty)+\rho g\beta_C\cos\phi(C'-C'_\infty)-\sigma B_\circ u'-\frac{\mu\varphi}{K}u' \quad (1)$$

$$\rho c_p\frac{\partial T}{\partial t}=k\frac{\partial^2 T'}{\partial x'^2}-\frac{\partial q'_r}{\partial x'} \quad (2)$$

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C'}{\partial x'^2} \quad (3)$$

which C', T', u', denote concentration, temperature and velocity respectively, γ stands for the non-Newtonian Casson fluid parameter, μ reflects the dynamic viscosity, ρ delineates the fluid density, g depicts gravity acceleration, σ illustrates the electrical conductivity, K exhibits the permeability of the porous medium, whereas φ is the porosity of the medium, ϕ is the inclination angle, $B_\circ$ is known as an external magnetic field, β_C and β_T are the concentration and thermal expansion, c_p denotes the specific heat, k signifies the thermal conductivity, q_r reflects the radiative heat flux and D depicts the mass diffusion.

At time $t'\le 0$, both the fluid and the plate are stationary and have the same concentration C'_∞ and temperature T'_∞. At time $t'>0$, both concentration and temperature are raised to a constant temperature and concentration, T'_w and C'_w at other times $t'\ge 0$, concentration and temperature tend toward zero. The following condition explains the suitable boundary equations:

$$\begin{aligned} &u'\left(x',0\right)=0; && u'\left(0,t'\right)=At'; && u'\left(\infty,t'\right)=0;\\ &T'\left(x',0\right)=T'_\infty; && T'\left(0,t'\right)=T'_w; && T'\left(\infty,t'\right)=T'_\infty;\\ &C'\left(x',0\right)=C'_\infty; && C'\left(0,t'\right)=C'_w; && C'\left(\infty,t'\right)=C'_\infty; \end{aligned} \quad (4)$$

Based on the governing system of equations, the temperature of the plates, T'_∞ and T'_w, the generation of a radiative heat flux term is presumed. This term is simplified by employing the Rosseland approximation, and the expression is as follows:

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^{*4}}{\partial y^*} \quad (5)$$

Here, $\sigma*$ denotes the constant of Stefan-Boltzmann and $k*$ represents the mean absorption coefficient. It is presumed that temperature changes within the flow are minimal, so that varies linearly with temperature. By means of expanding T^{*4} in a Taylor series around $T_\infty^{\ *}$ and neglecting higher-order terms, the Rosseland approximation becomes,

$$T'^4\cong 4T'_\infty T-3T_\infty^4 \quad (6)$$

Rosseland approximation becomes,

$$q_r=-\frac{16\sigma^* T_\infty^{\ 3*}}{3k^*}\frac{\partial^2 T^{*4}}{\partial y^{*2}} \quad (7)$$

The dimensionless variables are introduced as follows [31]:

$$u=\frac{u'}{(vA)^{\frac{1}{3}}};\quad t=\frac{t'\ A^{\frac{2}{3}}}{v^{\frac{1}{3}}};\quad x=\frac{x'\ A^{\frac{1}{3}}}{v^{\frac{2}{3}}};\quad T=\frac{T'-T'_\infty}{T'_w-T'_\infty};\quad C=\frac{C'-C'_\infty}{C'_w-C'_\infty}. \quad (8)$$

Eqs. (1), (2), and (3) are utilised, and the transformation given in Equation (8) is applied; hence, the three-governing system of equations comprising momentum, energy, and concentration is simplified into the following nondimensional forms:

$$\frac{\partial u}{\partial t} = Z\frac{\partial^2 u}{\partial x^2} + GrT\cos\theta + GcC\cos\theta - Bu \quad (9)$$

$$\lambda\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} \quad (10)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 T}{\partial x^2} \quad (11)$$

in which;

$$Z = 1 + \frac{1}{\gamma}; \qquad B = M + \frac{1}{K}; \qquad \lambda = \frac{\Pr}{1+R};$$

where M depicts the magnetic parameter, K indicates the porosity parameter, Gr reflects the thermal Grashof number, Gc denotes the mass Grashof number, R delineates the radiation parameter, $\Pr$ represents the Prandtl number, and Sc signifies the Schmidt number. The initial and boundary conditions in dimensionless form become:

$$\begin{aligned} &u(x,0) = 0; && u(0,t) = t; && u(\infty,t) = 0; \\ &T(x,0) = 0; && T(0,t) = 1; && T(\infty,t) = 0; \\ &C(x,0) = 0; && C(0,t) = 1; && C(\infty,t) = 0; \end{aligned} \quad (12)$$

2.2 Mathematical Solution

The Laplace transform method is employed to analyse the equations. As a result, a solution $u(x,t)$ can be attained by solving the concentration $C(x,t)$ and the temperature $T(x,t)$ variables. Eqs. (2) and (3), which represent energy and concentration equations, are decoupled from the momentum Eq. (1). Eqs. (9-11) are resolved by employing the Laplace transform in the presence of Eq. (12), and by systematically solving the resulting expressions, we arrive at the following solutions:

Energy Equation:

$$\bar{T} = Ae^{-x\sqrt{\lambda s}} + Be^{x\sqrt{\lambda s}} \quad (13)$$

Concentration Equation:

$$\bar{C} = \frac{1}{s}e^{-x\sqrt{Scs}} \quad (14)$$

Momentum Equation:

$$\begin{aligned} \bar{u} = {} & [\frac{1}{s^2} - a_1(\frac{1}{a_2(s-a_2)} - \frac{1}{a_2 s}) - a_3(\frac{1}{a_4(s-a_4)} - \frac{1}{a_4 s})e^{-x\sqrt{\frac{1}{z}}\sqrt{s+B}} + a_1(\frac{1}{a_2(s-a_2)} - \frac{1}{a_2 s})e^{-x\sqrt{\lambda s}} \\ & + a_3(\frac{1}{a_4(s-a_4)} - \frac{1}{a_4 s})e^{-x\sqrt{Scs}} \end{aligned} \quad (15)$$

Thus, the analytical solutions for the temperature, subsequently the concentration, and then the velocity are obtained from Eqs. (13-15) through the application of the inversion of the Laplace transform. The resulting solutions are:

$$T = erfc(\frac{x}{2}\frac{\sqrt{\lambda}}{t}) \quad (16)$$

$$C = erfc(\frac{x}{2}\sqrt{\frac{Sc}{t}} \quad (17)$$

$$U_0(x,t) = \left((\frac{t}{2} + \frac{x}{4}\sqrt{\frac{1}{BZ}})e^{x\sqrt{\frac{B}{Z}}} erfc((\frac{x}{2\sqrt{Zt}}) + \sqrt{Bt}) + (\frac{t}{2} - \frac{x}{4}\sqrt{\frac{1}{BZ}})e^{-x\sqrt{\frac{B}{Z}}} erfc((\frac{x}{2\sqrt{Zt}}) - \sqrt{Bt}) \right)$$

$$U_1(x,t) = \left((\frac{a_1}{2a_2}e^{a2t}[e^{x\sqrt{\frac{B+a2}{Z}}} erfc(\frac{x\sqrt{1}}{2\sqrt{Zt}} + \sqrt{(B+a_2)t} + (e^{-x\sqrt{\frac{B+a2}{Z}}} eerfc(\frac{x\sqrt{1}}{2\sqrt{Zt}} - \sqrt{(B+a_2)t}) \right)$$

$$U_2(x,t) = \left(\frac{a_1}{2a_2}(e^{x\sqrt{\frac{B}{Z}}} erfc(\frac{x\sqrt{Sc}}{2\sqrt{t}}) + \sqrt{Bt} + \frac{a_1}{2a_2}(e^{x\sqrt{\frac{B}{Z}}} erfc(\frac{x\sqrt{Sc}}{2\sqrt{t}}) + \sqrt{Bt} \right)$$

$$U_3(x,t)=\left(\frac{a_3}{2a_4}e^{a_4 t}[e^{x\sqrt{\frac{B+a_2}{Z}}}erfc(\frac{x}{2})\sqrt{\frac{1}{Z}}+\sqrt{(B+a_4)t}+e^{-x\sqrt{\frac{B+a_2}{Z}}}erfc(\frac{x}{2})\sqrt{\frac{1}{Z}}-\sqrt{(B+a_4)t}]\right)$$

$$U_4(x,t)=\left(\frac{a_3}{2a_4}[e^{x\sqrt{\frac{B}{Z}}}erfc(\frac{x}{2})\sqrt{\frac{1}{Zt}}+\sqrt{Bt}+e^{-x\sqrt{\frac{B}{Z}}}erfc(\frac{x}{2})\sqrt{\frac{1}{Zt}}-\sqrt{Bt}]\right)$$

$$U_5(x,t)=\left(\frac{a_1}{2a_2}e^{a2t}[e^{x\sqrt{a_2\lambda}}erfc(\frac{x}{2})\sqrt{\frac{\lambda}{t}}+\sqrt{a_2 t}+e-^{x\sqrt{a_2\lambda}}erfc(\frac{x}{2})\sqrt{\frac{\lambda}{t}}-\sqrt{a_2 t}]\right)$$

$$U_6(x,t)=\left(\frac{1}{a_2}erfc(\frac{x}{2})\sqrt{\frac{\lambda}{t}}\right)$$

$$U_7(x,t)=\left(\frac{a_3}{2a_4}e^{a_4 t}[e^{x\sqrt{a_4 Sc}}erfc(\frac{x}{2})\sqrt{\frac{Sc}{t}}+\sqrt{a_4 t}+e^{-x\sqrt{a_4 Sc}}erfc(\frac{x}{2})\sqrt{\frac{Sc}{t}}-\sqrt{a_4 t}]\right)$$

$$U_8(x,t)=\left(\frac{1}{2a_4}erfc(\frac{x}{2})\sqrt{\frac{Sc}{t}}\right)$$

$$U(x,t) = U_0(x,t) - U_1(x,t) + U_2(x,t) - U_3(x,t) + U_4(x,t) + U_5(x,t) +- U_6(x,t) + U_7(x,t) - U_8(x,t) \quad (18)$$

3. Results and Discussion

The plots of velocity profiles demonstrate that the curves satisfy both the initial and boundary conditions, thereby validating the accuracy of our solution. Velocity graphs analyse the influences of several physical parameters, specifically the Casson parameter, radiation, time, magnetic, and porosity, on the flow.

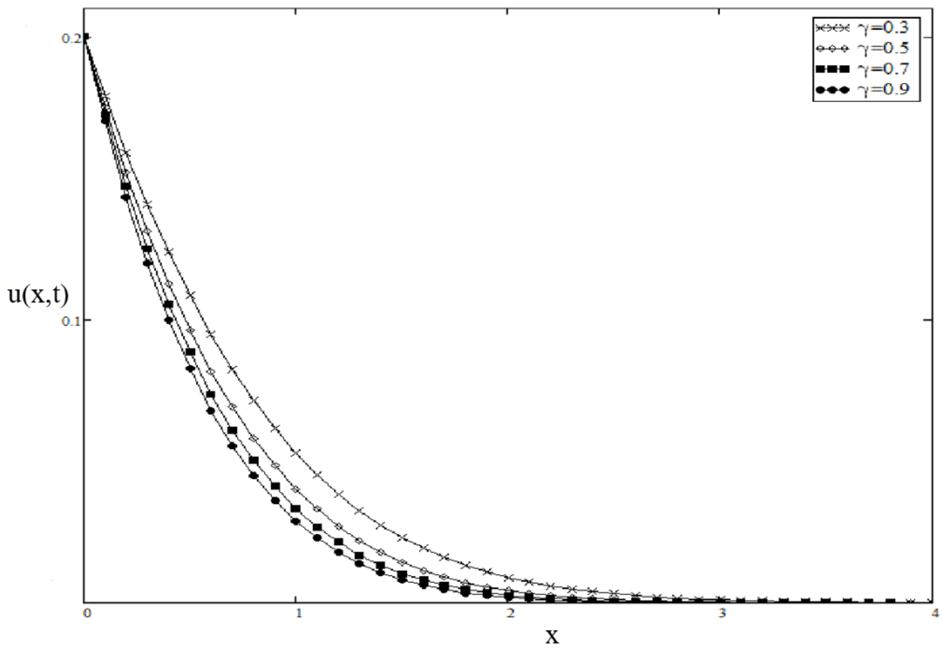

Figure 1. Velocity profiles for different Casson parameter values, γ

A discussion of these graphs is provided. Figure 1 depicts the influence of the Casson parameter on the velocity distribution. It is concluded that a rise in the Casson parameter corresponds to a reduction in velocity. This behaviour arises from diminished resistance to yield stress, which weakens the flow field and consequently lowers the velocity profile. Figure 2 demonstrates the fluid's behaviour under an increase in the radiation parameter. The elevated thermal radiation enhances the fluid's kinetic energy, which, in turn, improves its motion and increases its velocity. In addition, Figure 3 illustrates that the velocity profile increases when the t increase. As time progresses, the fluid gradually overcomes the initial resistance, leading to an increase in velocity and smoother flow. After a sufficient duration, the velocity approaches a steady state, remaining nearly constant as long as external forces remain unchanged. Consequently, the velocity of a Casson fluid generally increases with time before stabilizing at a steady value.

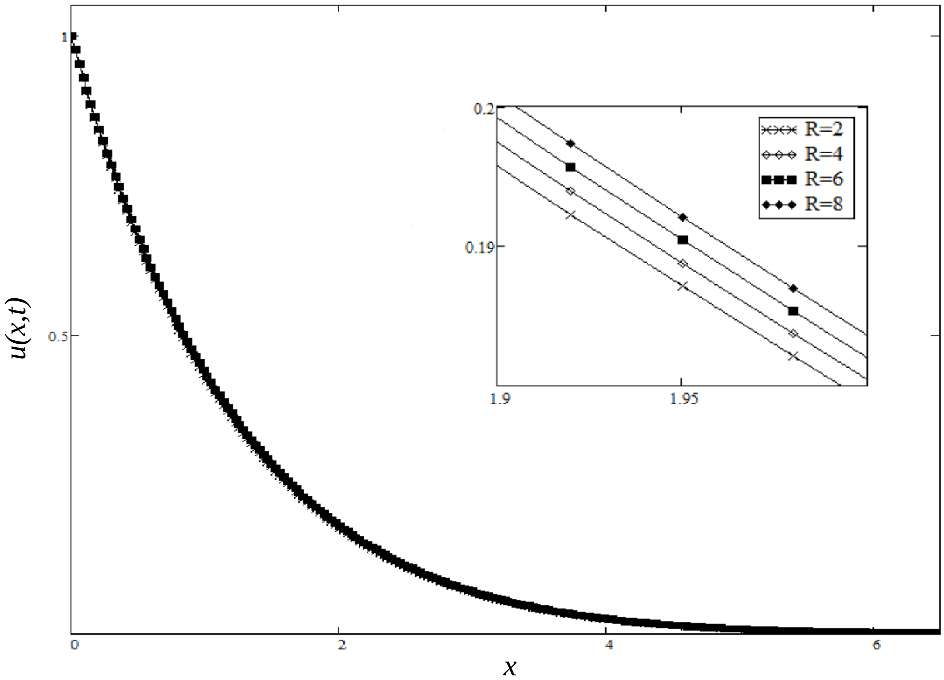

Figure 2. Velocity profiles for different radiation parameter values, R

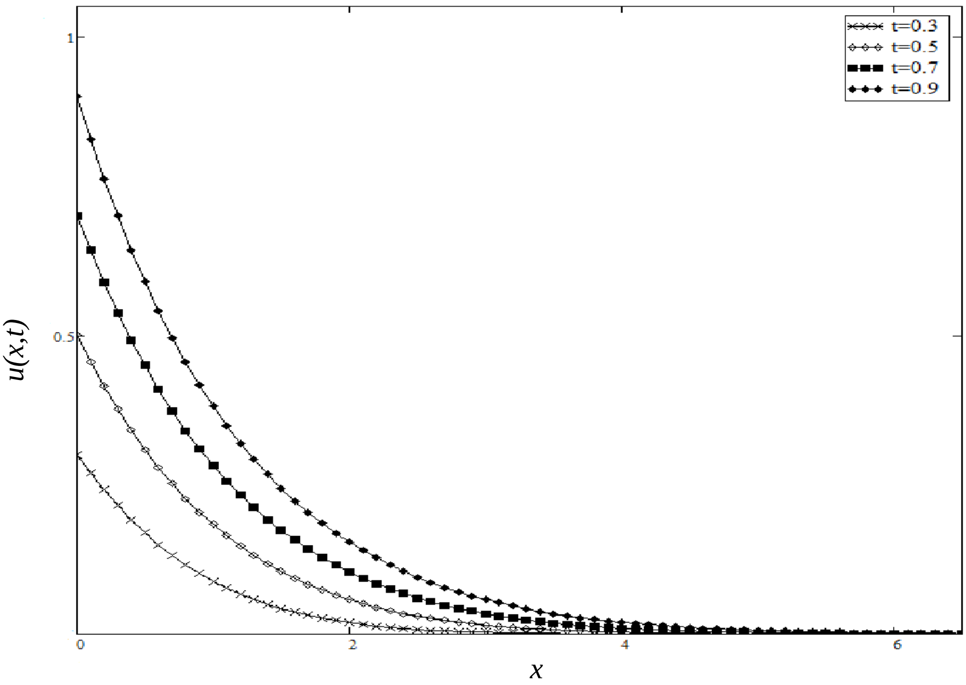

Figure 3. Velocity profiles for different time parameter values, t

On top of that, it is apparent that the velocity decreases with increasing magnetic field strength, as illustrated in Figure 4. The application of a transverse magnetic field introduces a resistive force, known as the Lorentz force, which in turn increases the thickness of both the momentum and thermal boundary layers, as shown in Figure 4.

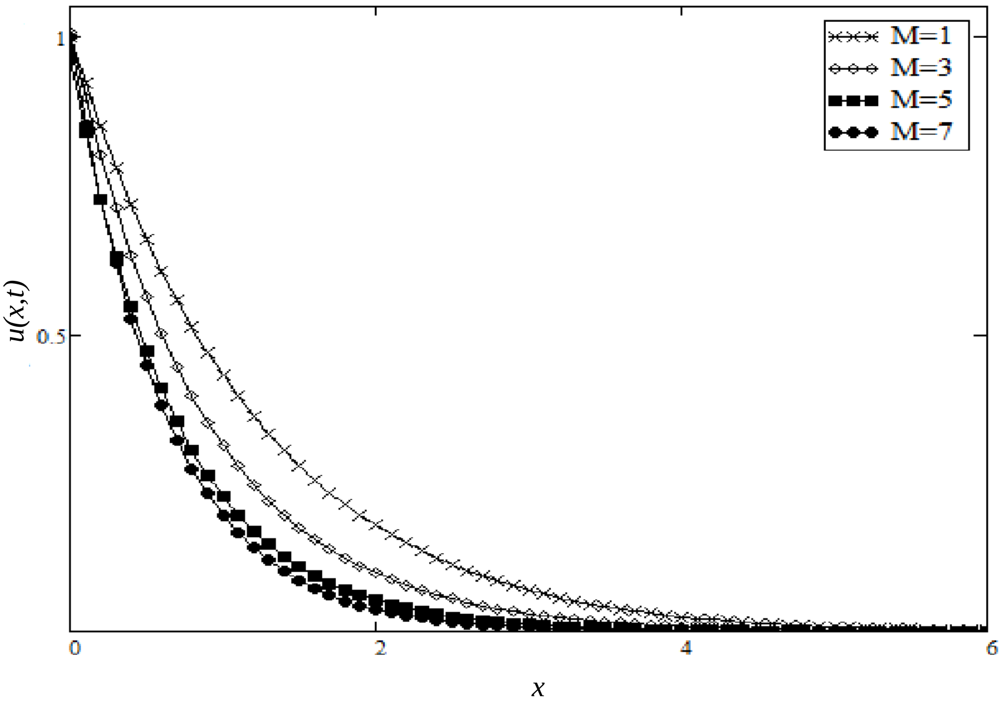

Figure 4. Velocity profiles for different magnetic parameter values, M

Finally, the effect of the porosity parameter K is illustrated in Figure 5. It is observed that the fluid velocity increases as the values of K rise. A higher permeability indicates that the medium provides less resistance to the flow. Consequently, as resistance in the porous medium decreases, the fluid moves more freely, leading to an increase in velocity.

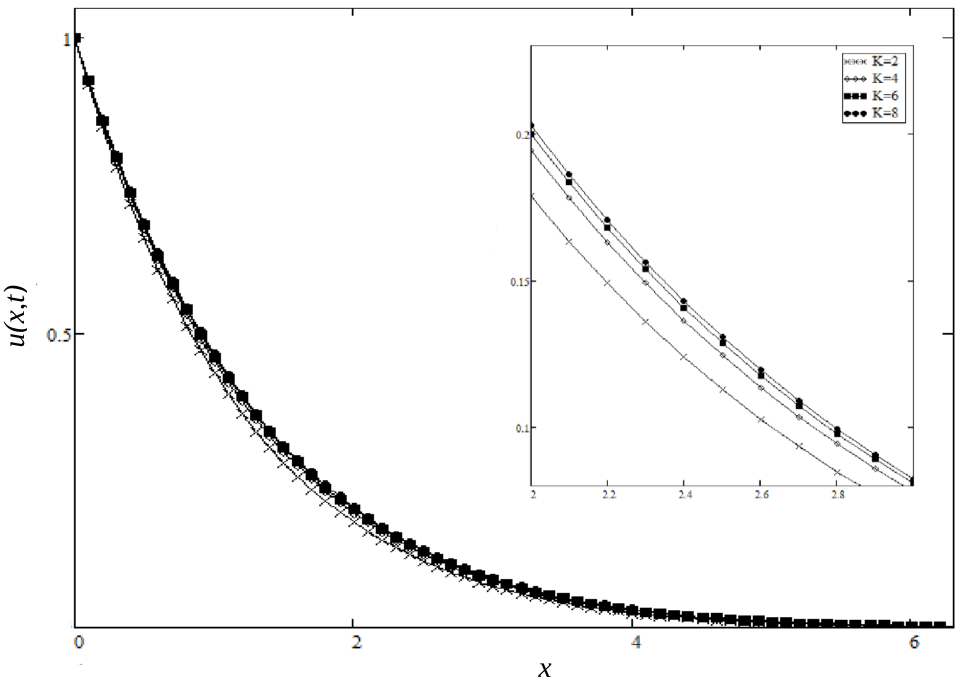

Figure 5. Velocity profiles for different porosity parameter values, K

4. Conclusions

This study examines the mixed convection flow of a Casson fluid past an infinitely inclined accelerated plate. Using the Laplace transform method, the effects of velocity on the Casson parameter, radiation, time, magnetic field, and porosity are analysed. These analytical solutions can help scientists and engineers validate the accuracy of complex models obtained through numerical methods. Moreover, the proposed mathematical model is expected to serve as a valuable reference for researchers in academia, engineering, and industry, enabling deeper analysis of the flow behaviour and heat and mass transfer characteristics of such fluids. The key findings can be summarised as follows:

i. Larger Casson parameter values suppress the velocity profile, reflecting stronger yield-stress effects.
ii. An increase in thermal radiation elevates the fluid's stored kinetic energy, thereby intensifying its motion and accelerating the velocity field.
iii. Velocity profiles extend farther into the fluid domain over time.
iv. The velocity decreases as the magnetic field strength increases.
v. Increasing the porosity parameter enhances fluid velocity, as higher permeability reduces resistance within the porous medium, allowing smoother flow.

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Declaration of Competing Interest
The authors declare no conflict of interest.

CRediT Authorship Contribution Statement
Nur Fatihah Mod Omar (Conceptualisation; Methodology; Writing - original draft; Formal analysis)
Zulkhibri Ismail (Validation; Supervision)
Rahimah Jusoh (Writing - review & editing)
Husna Izzati Osman (Conceptualisation; Methodology)
Ahmad Qushairi Mohamad (Formal analysis)

Availability of the Data and Materials
The data used to support the findings of this study are included within the article.

Ethical Declarations
No artificial intelligence tools were used in the preparation of this manuscript. All content was developed manually by the authors. This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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