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Research Article

Unsteady Magnetohydrodynamic Flow of a Nonlinear Third-grade Fluid with Variable Viscosity and Radiative Heat Transfer

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Abstract

This study investigates the unsteady Magnetohydrodynamic (MHD) flow and heat transfer characteristics of a nonlinear third-grade non-Newtonian fluid with temperature-dependent viscosity and nonlinear thermal radiation, which are commonly encountered in advanced engineering systems such as polymer processing, metallurgical operations, liquid-metal cooling technologies, and energy conversion devices. Owing to its viscoelastic nature, which deviates from classical Newtonian assumptions, the fluid behavior is described by coupled nonlinear momentum and energy equations incorporating magnetic field effects, viscous dissipation, nonlinear shear contributions, variable thermal conductivity, and wall suction. The governing equations are non-dimensionalised to identify the key controlling physical parameters and solved numerically using an explicit finite difference scheme, enabling a detailed parametric analysis of the effects of magnetic strength, nonlinear material parameters, radiation intensity, and viscosity variation on velocity and temperature distributions within the boundary layer. The results indicate that increasing magnetic field strength suppresses fluid motion through Lorentz force effects, thereby thinning the momentum boundary layer and providing an effective mechanism for electromagnetic flow control. Additionally, nonlinear rheological parameters significantly alter momentum transport, while radiative heat transfer and viscous dissipation elevate the thermal energy within the fluid, and variations in thermal conductivity strongly influence heat diffusion and temperature gradients. These findings offer valuable design insights for enhancing flow regulation and thermal performance in industrial systems involving electrically conducting non-Newtonian fluids operating under magnetic fields and high-temperature conditions.

Keywords

Non-linear Flow, Third-grade Fluids, Second-order Simulation, Viscous Dissipation, Variable Thermal Conductivity, Dynamic Viscosity, Viscoelastic

1. Introduction

Third-grade fluids are non-Newtonian fluids with viscoelastic characteristics. Intuitively, non-Newtonian fluids do not obey the Newtonian law of viscosity, which makes the Navier-Stokes equations inadequate for such flow due to the higher-

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order differential of the momentum equations, unlike the flow of viscous fluids. The industrial and technological applications of non-linear third-grade flow have been an important area of interest in every concerned field of engineering, science, and technology, such as ceramic processing, oil recovery, polymer synthesis, and food processing.

It is in the light of these efforts, Chinyoka and Makinde [1] investigated the unsteady flow of a non-Newtonian fluid with reacting species in a parallel plate channel filled with a homogeneous, isotropic, and saturated porous medium. A differential type third grade constitute equation is employed to model the non-Newtonian character of the fluid. The coupled nonlinear partial differential equations governing the problem are derived and solved numerically using a semi-implicit finite difference scheme. Makinde *et al*, [2] investigated the unsteady flow of reactive variable viscosity non-Newtonian fluid through a porous saturated medium by assuming the exothermic chemical reactions take place within the flow system. Akinbowale [3] steady flow and heat transfer analysis of third-grade fluid with porous medium, adopting a domain decomposition method with temperature-dependent base viscosity.

Hayat *et al*, [4] studied the flow of a third-grade fluid and heat transfer analysis between two stationary porous plates. The governing non-linear flow problem is solved analytically using the Homotropy Analysis Method (HAM). Ayub *et al*, [5] studied the exact flow of a third-grade fluid on a porous wall using the analytical group method. Aksoy and Mehmet [6] investigated the approximate analytical solutions for the flow of a third-grade fluid in a pipe with constant viscosity using the perturbation technique. Chauhan and Kumar [7] investigated the entropy analysis for third-grade fluid flow with temperature-dependent viscosity in an annulus partially filled with porous medium. Ali *et al* [8] studied the unsteady boundary layer flow and heat transfer analysis in a third-grade fluid over an oscillatory stretching sheet under the influences of thermal radiation and a heat source.

Sajid *et al*, [9] discussed the finite element solution for flow of a third-grade fluids past a horizontal porous plate with partial slip. Okoya [10] studied the steady incompressible flow of an exothermic reacting third-grade fluid with viscous heating in a circular cylindrical pipe, which is numerically studied for both cases of constant viscosity and Reynolds' viscosity model. Ogunsola and Peter [11] investigated the effect of variable viscosity on third-grade fluid over a radiative surface with Arrhenius reaction. Aziz *et al* [12] studied a non-linear time-dependent flow model of third-grade fluids in a porous half-space using a non-classical symmetry approach.

Ellahi *et al*, [13] investigated the effects of slip on the nonlinear flows of a third-grade fluid between concentric cylinders. Gaffer *et al*, [14] studied the radiative flow of third-grade non-Newtonian fluid from a horizontal circular cylinder. Carapau and Correia [15] investigated the numerical solution of third-grade fluid flow on a tube through a contraction using a director theory approach related to fluid dynamics. Adesanya *et al*, [16] discussed the inherent irreversibility in the flow of a reactive third-grade fluid through a channel with convective heating. The work of [4-8] adopted the concept of analytical method for their solution, while others were solved numerically with different approaches. [17] investigated the fluid flow and transport phenomena within a vertical channel featuring an exponentially decaying suction and a moving wall. The governing equations are formulated under the assumptions of incompressible flow influenced by buoyancy effects and viscous dissipation. A finite difference method is developed and applied to solve the system. Numerical results are displayed graphically, revealing that higher values of the Brinkman number, suction parameter, and Prandtl number enhance the temperature distribution, while increases in the thermal Grashof number, mass Grashof number, and suction parameter lead to a rise in flow velocity.

This work aims at investigating multi-dimensional extensions of a new unconditionally stable solver for the convection-diffusion-reaction equation of non-linear radiation and temperature-dependent viscosity with suction. It also extends the idea of [1, 2] in the study of non-Linear third grade fluids.

2. Method of Formulation

Consider the unsteady, incompressible magnetohydrodynamic flow and heat transfer of a nonlinear third-grade fluid along a vertical surface, considering temperature-dependent viscosity, nonlinear thermal radiation, viscous dissipation, and wall suction. Let $u^*(y^*, t^*)$ denote the fluid velocity in the streamwise direction and $\theta^*(y^*, t^*)$ the temperature field, where $y^*$is the normal coordinate and $t^*$is time.

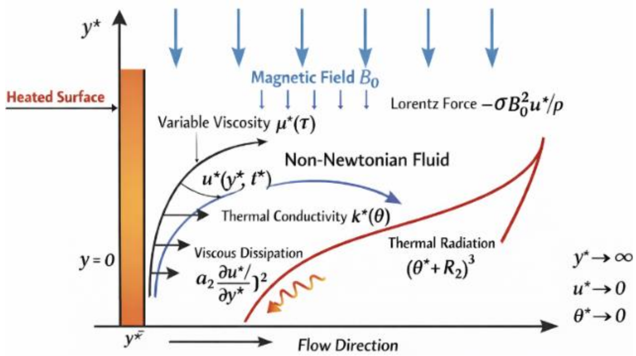

Figure 1. Schematic Diagram of the flow.

2.1. Mathematical Equations

The governing equations consist of the continuity, momentum, and energy equations expressed in dimensional form as follows.

The continuity equation for incompressible flow is

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

$$\frac{\partial u^*}{\partial t^*} + \gamma^* \frac{\partial u^*}{\partial y^*} = \frac{\partial}{\partial y^*}\left(\mu^*(\tau)\frac{\partial u^*}{\partial y^*}\right) + \beta_1^* \frac{\partial^3 u^*}{\partial y^{*2}\partial t^*} + \beta_2^* \frac{\partial^2 u^*}{\partial y^{*2}}\left(\frac{\partial u^*}{\partial y^*}\right)^2 - \frac{\sigma B_0^2 u^*}{\rho} \tag{2}$$

$$\frac{\partial \theta^*}{\partial t^*} + \gamma^* \frac{\partial \theta^*}{\partial y^*} = \alpha_0^* \frac{\partial}{\partial y^*}\left(k^*(\theta)\frac{\partial \theta^*}{\partial y^*}\right) + \alpha_1^* \frac{\partial}{\partial y^*}\left((\theta^* + R_2^*)^3 \frac{\partial \theta^*}{\partial y^*}\right) + \alpha_2^*\left(\frac{\partial u^*}{\partial y^*}\right)^2 \tag{3}$$

With the corresponding boundary Conditions,

$$u^* = 0,\ \theta^* = 1 \text{ at } y^* = 0$$

$$u^* = 0,\ \theta^* = 0 \text{ as } y^* \to \infty \tag{4}$$

Non-dimensional Variable

$$y = Ly^*,\ u = U_0 u^*,\ t = \frac{L^2}{U_0}t^*,\ \theta = \theta_w \theta^*,\ \gamma = \frac{U_0}{L}\gamma^*,$$

$$p = U_0^2 p^*,\ \mu = U_0 \mu^*,\ k = \frac{k^*}{k_0}$$

Non-dimensional Parameter

$$\beta_1^* = \frac{\beta_1 U_0}{L^2},\ \beta_2^* = \frac{\beta_2 U_0}{L^2},\ \alpha_0^* = \frac{\alpha_0}{k_0},\ \alpha_1^* = \frac{\alpha_1}{\theta_w^2},\ \alpha_2^* = \frac{\alpha_2^*}{\theta_w},$$

$$R_2^* = \frac{R_2}{\theta_w},\ M = \frac{\sigma B_0^2 u_0}{\rho L^2}$$

Applying the non-dimensional variables and parameters, we obtain the dimensionless equations for continuity, momentum, and energy equations.

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \tag{5}$$

$$\frac{\partial u}{\partial t} + \gamma \frac{\partial u}{\partial y} = \frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\left(\mu(\tau)\frac{\partial}{\partial y}\right) + \beta_1 \frac{\partial^2 u}{\partial y^2 \partial t} + \beta_2 \frac{\partial^2 u}{\partial y^2}\left(\frac{\partial u}{\partial y}\right)^2 - Mu \tag{6}$$

$$\frac{\partial \theta}{\partial t} + \gamma \frac{\partial \theta}{\partial y} = \alpha_0 \left(\kappa(\theta)\frac{\partial \theta}{\partial y}\right) + \alpha_1 \frac{\partial}{\partial y}\left((\theta + R_2)^3 \frac{\partial \theta}{\partial y}\right) + \alpha_2\left(\frac{\partial u}{\partial y}\right)^2 \tag{7}$$

$$u = 0,\ \theta = \theta_w \text{ at } y = 0$$

$$u = 0,\ \theta = 0 \text{ as } y \to \infty \tag{8}$$

2.2. Numerical Solution

We adopted a Finite Difference Method (FDM) explicit numerical scheme to obtain our solutions and results.

To obtain approximate solutions of the coupled nonlinear governing equations, an explicit finite difference method (FDM) was employed. The computational domain in the transverse direction was discretized into a uniform grid defined by

$$\Omega_h = \{z_i : z_i = ih, h = 1/Q, Q \in Z^+\},$$

where $h$represents the spatial step size and Q is the total number of subintervals. Time was discretized using a uniform time step Δt, and the solution variables were evaluated at discrete grid points (n), where $i$denotes the spatial index and $n$the time level.

2.3. Discretization of Derivatives

The spatial derivatives were approximated using finite difference operators. The forward difference operator in space is defined as

$$\delta_z^+ u_i = u_{i+1} - u_i,$$

while the forward difference operator in time is given by

$$\delta_t^+ v^n = v^{n+1} - v^n.$$

Second-order spatial derivatives were approximated using central difference schemes of the form

$$\frac{\partial^2 u}{\partial y^2} \approx \frac{u_{i+1}^n - 2u_i^n + u_{i-1}^n}{h^2},$$

which ensures improved spatial accuracy. Convective and nonlinear terms were discretized carefully to preserve stability and consistency of the explicit formulation.

$$\Omega_h = \left\{z_i : z_i = ih, h = \frac{1}{Q}, Q = Z^+\right\}.$$

Defined

$$\partial_z^{\pm} u_i = u_{i+1} - u_i$$

$$\forall u_i \in \ \{u_1 \dots, u_{Q-1}\},$$

$$\partial_t{}^{+v^n = v^{n+1} - v^n}$$

$$\frac{u_{i+1} - u_i}{h} + \frac{u_i^{n+1} - u_i^{n-1}}{2h} = 0$$

$$\frac{u_i^{n+1}-u_i^n}{\nabla t}+\gamma_i^n\frac{u_i^{n+1}-u_i^n}{h}=\frac{p_{i+1}^n-p_i^n}{h}+\frac{1}{h}\left(u_{i+\frac{1}{2}}^n\frac{u_{i+1}^n-u_i^n}{h}-u_{i-\frac{1}{2}}^n\frac{u_i^n-u_{i-1}^n}{h}\right)+\beta_1\frac{1}{\nabla t}\frac{u_{i+1}^n-2u_i^n+u_{i-1}^n}{h^2}+\beta_2\left(\frac{u_{i+1}^n-2u_i^n+u_{i-1}^n}{h^2}\left(\frac{u_{i+1}^n-u_i^n}{h}\right)^2\right)-Mu_i^n$$

$$\frac{\theta_i^{n+1}-\theta_i^n}{\nabla t}+\gamma_i^n\frac{\theta_i^{n+1}-\theta_i^n}{h}=\frac{1}{h}\left(\alpha_0k_{i+\frac{1}{2}}^n\frac{\theta_i^{n+1}-\theta_i^n}{h}-\alpha_0k_{i-\frac{1}{2}}^n\frac{\theta_i^n-\theta_{i-1}^n}{h}\right)+\frac{1}{h}\left(\alpha_1(\theta_{i+1}^n+R_2)^3\frac{\theta_i^n-\theta_{i-1}^n}{h}\right)+\alpha_2\left(\frac{u_{i+1}^n-u_i^n}{h}\right)^2$$

$$u_i^n=0,\ \theta_i^n=\theta_w \text{ at } y=0$$

$$u_i^n=0,\ \theta_i^n=0 \text{ as } y\to\infty$$

3. Results and Discussion

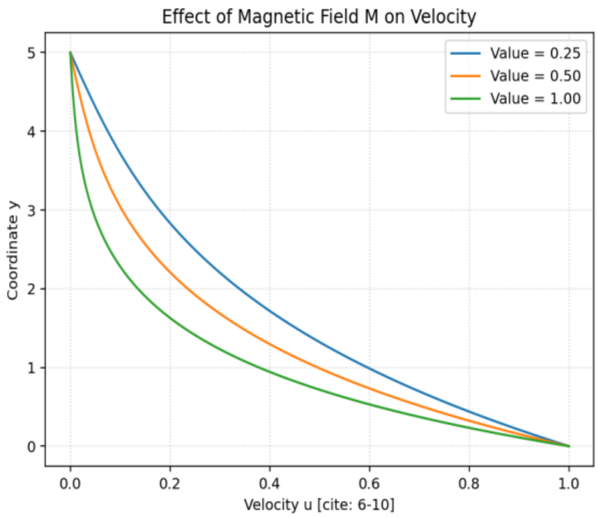

***Figure 2**. The effect of the variation of the magnetic field M on velocity with some parameter values $M=1.0,\ \mu=2.0,\ K=2.0,\ \alpha_1=1.0,\ \beta_2=0.1,\ \beta_1=0.2$.*

The results of this study highlight the intricate behavior of non-linear third-grade fluids, revealing how their unique properties influence both velocity and temperature distributions within fluid systems.

The results demonstrate that increasing the magnetic field parameter significantly suppresses fluid velocity due to the Lorentz force, leading to a thinner momentum boundary layer; this provides an effective mechanism for controlling flow behavior in electrically conducting non-Newtonian fluids used in advanced thermal and industrial systems.

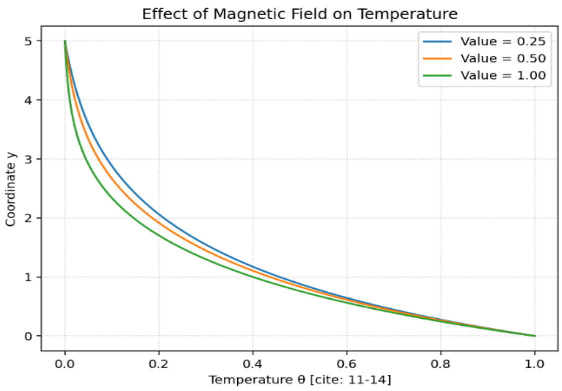

***Figure 3**. The effect of magnetic fluid on the temperature of some parameter values $M=1.0,\ \mu=2.0,\ K=2.0,\ \alpha_1=1.0,\ \beta_2=0.1,\ \beta_1=0.2$.*

Increasing magnetic field strength suppresses fluid motion via Lorentz forces, thereby reducing temperature distribution and thinning the thermal boundary layer, which provides an effective mechanism for controlling heat transfer in electrically conducting non-Newtonian fluids.

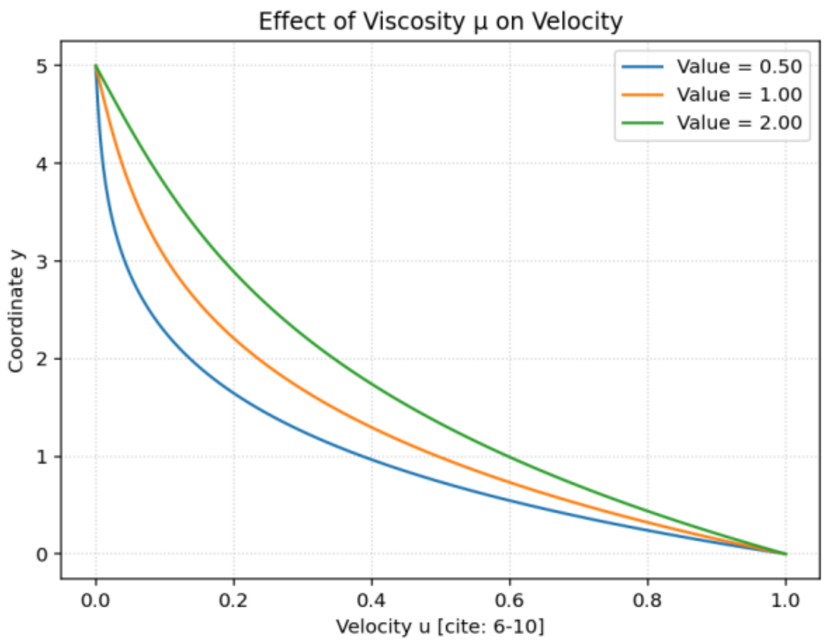

Figure 4. *The effect of viscosity* μ *on velocity with some parameter values* $M = 1.0,\ \mu = 2.0,\ K = 2.0,\ \alpha_1 = 1.0,\ \beta_2 = 0.1,\ \beta_1 = 0.2$.

The results indicate that increasing viscosity enhances momentum diffusion within the nonlinear third-grade fluid, resulting in higher velocities and a thicker hydrodynamic boundary layer. This behavior highlights the critical role of viscosity in controlling flow uniformity and stability in industrial processes involving highly viscous non-Newtonian fluids.

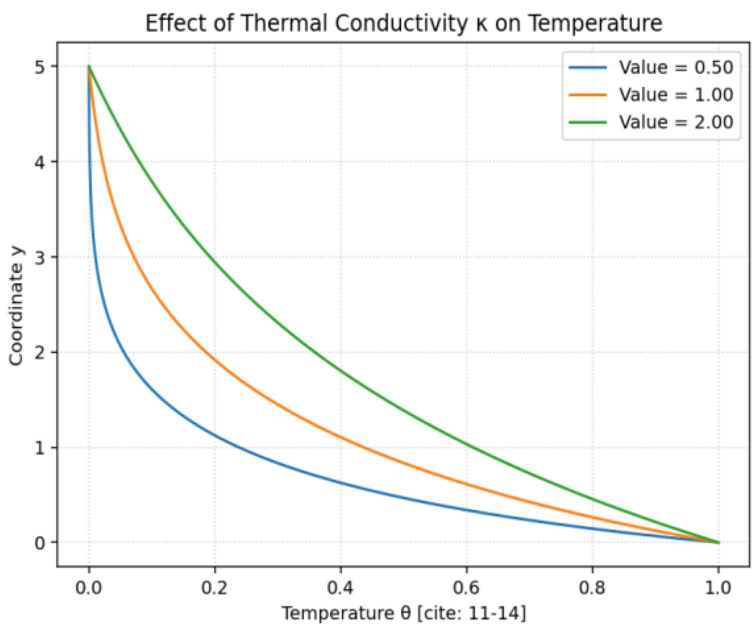

Figure 5. *The effect of thermal conductivity* K *on the temperature of some parameter values* $M = 1.0,\ \mu = 2.0,\ K = 2.0,\ \alpha_1 = 1.0,\ \beta_2 = 0.1,\ \beta_1 = 0.2$.

Figure 5. shows that increasing thermal conductivity smooths temperature fields, thickens thermal boundary layers, reduces peak thermal gradients that drive buoyant forcing, and thereby alters convection strength, plume characteristics, and conjugate heat-transfer behavior; conversely, low κ concentrates heat, sharpens gradients, and promotes stronger local buoyancy-driven flows and instabilities.

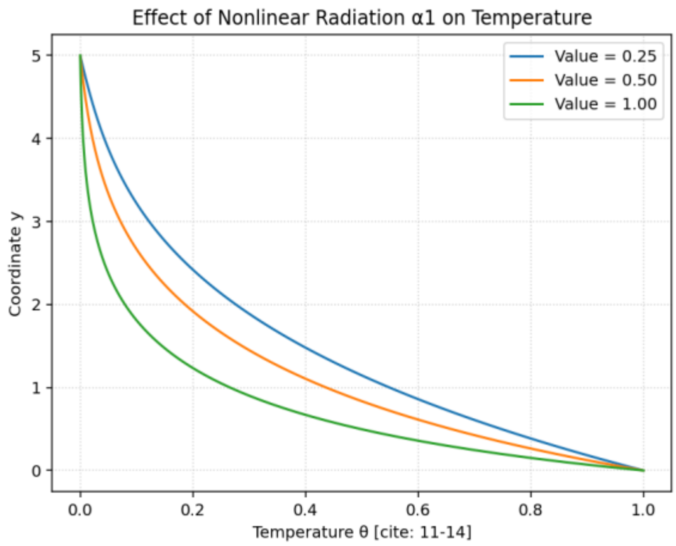

Figure 6. *The effect of Nonlinear Radiation* α_1 *on temperature with some parameter values* $M = 1.0,\ \mu = 2.0,\ K = 2.0,\ \alpha_1 = 1.0,\ \beta_2 = 0.1,\ \beta_1 = 0.2$.

This plot effectively illustrates the effect of the variation of nonlinear radiation α_1 on temperature distribution in a fluid system. The stronger nonlinear radiation (larger α_1) steepens temperature gradients and thins thermal boundary layers, confining buoyant forcing nearer the source and producing narrower, more intense near-source plumes while reducing far-field thermal penetration.

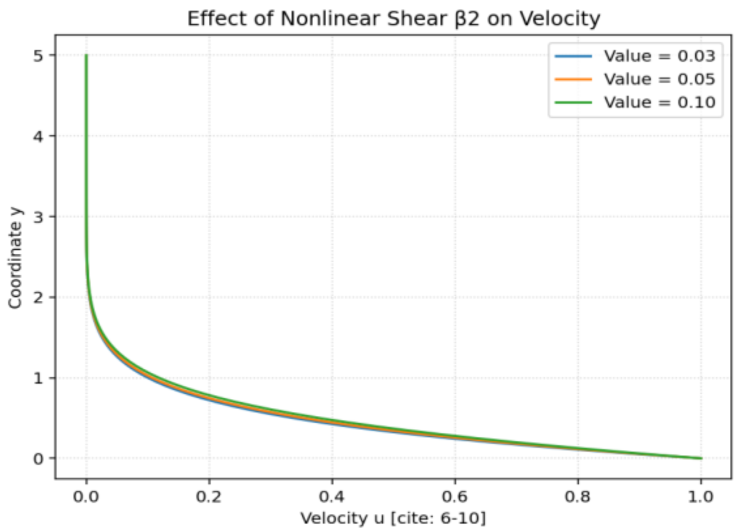

Figure 7. *The effect of Nonlinear Shear* β_2 *on the velocity of some parameter values* $M = 1.0,\ \mu = 2.0,\ K = 2.0,\ \alpha_1 = 1.0,\ \beta_2 = 0.1,\ \beta_1 = 0.2$.

This figure illustrates that increasing the nonlinear shear parameter β_2 slightly enhances the velocity gradient near the wall, reducing the momentum boundary layer thickness and increasing the local wall shear while exerting minimal influence on the outer flow. Thus, β_2 primarily affects localized shear stresses and near-wall transport, leaving the overall bulk velocity distribution largely unchanged at the values considered.

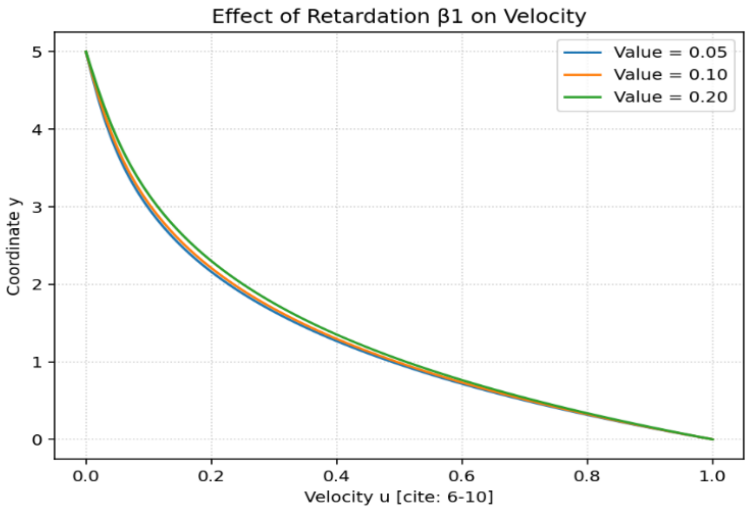

Figure 8. *The effect of Retardation* β_1 *on velocity with some parameter values* $M = 1.0,\ \mu = 2.0,\ K = 2.0,\ \alpha_1 = 1.0,\ \beta_2 = 0.1,\ \beta_1 = 0.2.$

The figure shows that the increase in the retardation parameter β_1 strengthens the near-wall momentum resistance, which thickens the momentum boundary layer, slightly increases pressure drop, and wall shear. It reduces near-wall convective heat and mass.

4. Conclusions

In this study, we investigated the second-order simulation of non-linear third-grade flow characterized by the governing equations that describe the dynamics of velocity u and temperature θ The findings from our simulations reveal that the non-linear characteristics of third-grade fluids significantly influence both the velocity and temperature distributions. The presence of parameters such as β_1 and β_2 demonstrates their critical role in enhancing flow dynamics and thermal behavior, providing insights that are essential for applications in industrial processes involving complex fluids.

Significant Findings

1) The non-linear characteristics of third-grade fluids significantly affect both velocity and temperature distributions.
2) The use of time-dependent and spatial derivatives in the governing equations allows for a detailed understanding of flow and thermal behavior.
3) The finite difference method (FDM) proves effective in accurately simulating complex interactions in non-linear fluid systems.

Abbreviations

MHD	Magnetohydordynamics
FDM	Forward Differences Method
HAM	Homotopy Analysis Method

Acknowledgments

This goes to Rivers State University.

Author Contributions

Chukwuemeka Paul Amadi: Visualization, Writing – original draft, Validation, Methodology

Iyowuna Winston Gobo: Writing – review & editing, supervision

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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