Hindawi
Journal of Mathematics
Volume 2024, Article ID 6947400, 13 pages
https://doi.org/10.1155/2024/6947400

Research Article

Exploring the Steady Flow of a Viscoelastic Fluid Passing over a Porous Perpendicular Plate Subjected to Heat Generation and Chemical Reactions

K. Sudarmozhi,[1] D. Iranian,[1] M. M. Alqarni,[2] Muhammad Sabeel Khan,[3] Emad E. Mahmoud,[4] R. Pradhan,[5] and M. M. Haque[6]

[1]*Department of Mathematics, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu, India*
[2]*Department of Mathematics, College of Sciences, King Khalid University, Abha 61413, Saudi Arabia*
[3]*Department of Mathematics, Capital University of Science and Technology, Islamabad 64000, Pakistan*
[4]*Department of Mathematics and Statistics, College of Science, Taif University, PO Box 11099, Taif 21944, Saudi Arabia*
[5]*Department of Computer Science, GLA University, Mathura, Uttar Pradesh, India*
[6]*Department of Mathematics, Jagannath University, Dhaka 1100, Bangladesh*

Correspondence should be addressed to M. M. Haque; mojammelmath@gmail.com

Received 25 October 2023; Revised 30 December 2023; Accepted 5 January 2024; Published 13 January 2024

Academic Editor: Qingkai Zhao

This study aims to bridge the gap by conducting a numerical analysis of Maxwell fluid behaviour on a perpendicular plate within a porous medium, considering both chemical reaction and heat generation. The investigation also encompasses the study of energy and mass transfer within magnetohydrodynamic (MHD) Maxwell fluids. We utilise a transformation technique employing similarity variables to address the challenge posed by the nonlinear partial differential equations (PDEs). These transformed equations are subsequently solved via the bvp4c solver in MATLAB. The obtained results exhibit a high degree of agreement with the previously published work. The study systematically explores the influence of chemical reaction, energy generation, and Deborah number parameters on temperature and velocity, as well as concentration, presenting the outcomes graphically. In addition, we calculate local Sherwood numbers, Nusselt numbers, and skin friction coefficients to assess the impact of chemical reactions. Our findings notably indicate that Sherwood numbers and skin friction coefficients increase with higher levels of chemical reaction, while local Nusselt numbers decrease as chemical reactions become more pronounced. By studying Maxwell fluid flow over a perpendicular plate with chemical reactions, this research contributes to optimizing processes, enhancing product quality, and providing deeper insights into the behaviour of complex fluids in real-world scenarios.

1. Introduction

Chemical reactions are fundamental processes in various natural and industrial systems, transforming substances into new products. These reactions often involve the issue or absorption of energy through heat. When these chemical reactions occur in fluid flow over a porous vertical plate, they give rise to a complex interplay between the fluid dynamics and the heat generation or absorption effects. In this context, the Maxwell fluid flow refers to the flow of a viscoelastic fluid that exhibits non-Newtonian behaviour. Maxwell fluids are characterized by a time-dependent stress response to deformation, making their flow behaviour distinct from Newtonian fluids such as water or air. When such a Maxwell fluid interacts with a porous vertical plate, it introduces unique challenges and opportunities for understanding the system's dynamics. The generation of heat due to chemical reactions adds complexity to the Maxwell fluid flow over the permeable vertical plate. This heat generation can have significant implications for the system's overall behaviour. Depending on the nature and rate of the chemical reactions, the generated heat can either enhance or hinder fluid flow and transfer. Understanding these effects is crucial in various engineering and industrial applications, including chemical reactors, heat exchangers, and environmental processes. This study aims to investigate the intricate relationship among chemical reactions, Maxwell fluid flow, and energy generation over a porous vertical plate. By analyzing the flow patterns, temperature distribution, and heat transfer characteristics, we can gain insights into how these factors interact and influence each other. This research contributes to our fundamental understanding of fluid dynamics and heat transfer and has practical implications for optimizing processes and systems where these phenomena are encountered.

Kashif et al. [1] undertook a comprehensive analysis focusing on the dynamic interactions of pressure gradients and heat transfer within the context of a Maxwell fluid. Their investigation centred on the boundary layer phenomena occurring over a stretched sheet. Liu et al. [2] delved into the intricacies of energy transfer in a Maxwell fluid flow situated on a moving plate. Their research featured applying a time-fractional constitutive model to unravel this context's complex heat transfer dynamics. Imran et al. [3] embarked on a study examining the magnetohydrodynamic (MHD) effects within a Maxwell fluid boundary layer flow across an exponentially infinite perpendicular surface. Their work introduced novel insights by incorporating slip conditions and Newtonian heating mechanisms at the boundary. Sudarmozhi et al. [4] directed their research efforts towards investigating radiation and heat transfer phenomena embedded within the dynamics of a Maxwell fluid flowing over an inclined permeable plate. This work shed light on the interplay of these complex physical processes. Na et al. [5] took a closer look at a Maxwell fluid flow confined between vertical plates, considering the influence of thermal flux and the presence of damped shear forces. Their study provided a comprehensive perspective on the behaviour of Maxwell fluids in this specific geometry. Riaz and Iftikha [6] thoroughly examined heat transfer flows involving magnetohydrodynamic (MHD) Maxwell fluids. They explored the comparative aspects of local and nonlocal differential operators, offering valuable insights into the heat transfer behaviour of these complex fluids. Rasa and Ullah [7] delved into the fascinating domain of MHD Maxwell fluid heat transfer. Their research featured a comparative analysis utilizing Caputo and Caputo–Fabrizio derivatives, contributing to a deeper understanding of the fluid's thermal dynamics. Riaz et al. [8] focused on the intriguing power-law kernel characteristics inherent in magnetohydrodynamic (MHD) Maxwell fluids. Their study included the investigation of transport phenomena while considering ramping boundary conditions and specific function-based solutions. Hanif et al. [9] employed computational methods to ascertain the fractional behaviour of Maxwell fluids within boundary layers, particularly by examining heat transfer flows. Their research introduced innovative techniques for characterizing these complex fluids at the boundary. Khan and Rasheed [10] explored fluid flow dynamics featuring fractional Maxwell fluids passing through a Forchheimer medium. Their study provided insights into this specific flow scenario's unique challenges and behaviour. Shah et al. [11] ventured into the realm of free convection flows, specifically considering Prabhakar-like fractional Maxwell fluids. Their research extended to encompass the influence of generalized heat transmission, enriching our understanding of these complex fluid dynamics. Zhang et al. [12] investigated the behaviour of Maxwell fluids within natural convection flows, focusing on generalized heat transfer and the application of Newtonian heating mechanisms. Their work contributed to comprehending heat transfer in these intricate fluid systems. Al Hajri et al. [13] researched into the Maxwell–Cattaneo properties within convective energy transfer flows inside a square enclosure filled with a permeable medium. Their research offered valuable insights into the thermal dynamics of such complex systems.

The complexities of magnetohydrodynamic-free convective flow in porous media (see for instance [14] and references therein) have piqued the interest of scientists across various domains, spanning from applications in flow meters, pumps, generators, and plasma jet engines to accelerators, metallurgical processes, chemical industry operations, material processing, industrial power engineering, and nuclear engineering. Mass transfer, which entails the movement of substances within a system due to differences in concentration, plays a pivotal role in many biological processes, such as respiration, blood oxygenation, renal function, osmosis, and absorption of nutrients and medications. Researchers have undertaken various investigations (see for instance [15, 16] and references therein) to unravel the intricacies of such dynamic systems. Reddy et al. [17] explored the behaviour of Casson fluid flowing across an oscillating permeable plate, systematically accounting for the influences of rotation and diffusion thermos on magnetohydrodynamic heat-generating mixed convection flow. Dadheech et al. [18] delved into the unique attributes of the Williamson fluid flow across a perpendicular plate, explicitly considering the impacts of Cattaneo–Christov heat flux.

Notably, the interplay between double-diffusive processes and chemical reactions adds complexity to these studies. The rates of double-diffusive phenomena can be substantially altered due to ongoing chemical reactions, which, in turn, depend on the reaction type—whether it is a mixed or identical reaction. The reaction order, characterized as first order when the reaction rate is directly proportional to the concentration, assumes paramount significance in understanding these dynamic systems. The natural environment rarely contains pure substances such as pristine water or unadulterated air. Consequently, comprehending the intricacies of chemical reactions is pivotal for improving numerous chemical technologies, including the synthesis of polymers, food processing, and fabricating ceramic or glass products. Technicians and scientists across various fields engage in processes where physical and chemical transformations convert raw materials into finished goods, underpinning key industries such as ammonia, sulfuric acid from sulphide ores, and a wide array of petrochemicals derived from petroleum feedstocks. The confluence of chemical reactions with heat and mass transfer has been the subject of rigorous investigation by researchers. Hussain et al. [19] explored natural convective heat transfer with the concurrent impact of hall current and chemical reactions, examining the impact of heat absorption past an accelerated moving plate in a rotating system. Saidulu and Reddy [20] delved into the intricacies of energy and mass transfer in hydromagnetic micropolar flow over a sheet, considering viscous dissipation along with chemical reactions. Sedia et al. [21] meticulously studied the convective heat-mass transport of a generalized Maxwell fluid under the impact of exponential heating and chemical reactions. Iftikhar et al. [22] investigated energy and mass transfer within magnetohydrodynamic Maxwell fluid dynamics across an infinite perpendicular plate.

Furthermore, Hanif [23] applied advanced numerical techniques such as the Cattaneo–Friedrich model and the crank-Nicolson method to analyze the behaviour of upper-convected Maxwell fluid [24], passing over a perpendicular plate. Abbas et al. [25] observed the computational implications of the Darcy–Forchheimer [26] relation, reduced gravity, and the influence of an externally applied magnetic field on the radiative fluid flow and heat transfer on a sphere. In a separate study, Abbas et al. [27] analyzed MHD Williamson nanofluid flow and heat transfer, investigating its interaction with a nonlinear stretching sheet implanted in a permeable medium. Munir et al. [28] focused on a numerical study involving entropy generation in the stagnation point flow of Oldroyd-B nanofluid. Cui et al. [29] also delved into a numerical investigation of the thermal transport properties of the three-dimensional bio-convective nanofluid flow.

1.1. Novelty of the Subject, Motivation, and Its Application. Maxwell fluids refer to a class of non-Newtonian fluids that exhibit viscoelastic behaviour. When studying the flow of Maxwell fluids on a perpendicular plate in the presence of a chemical reaction, several unique aspects and applications arise, contributing to the novelty of this subject. Maxwell fluids display viscoelastic properties, exhibiting viscous and elastic responses to applied stresses. This behaviour differs significantly from Newtonian fluids, which exhibit viscosity without elasticity. Understanding the flow characteristics of such fluids on a perpendicular plate provides insights into how these materials deform and flow under various conditions. The flow of fluids over a perpendicular plate is a classical problem in fluid mechanics. Investigating the Maxwell fluid flow over a vertical plate involves examining how the fluid's viscoelastic properties influence boundary layer formation, velocity profiles, and heat/mass transfer characteristics. The behaviour differs from Newtonian fluids due to the attendance of elastic effects. Introducing chemical reactions into the Maxwell fluid flow scenario adds another layer of complexity. The interaction between the fluid flow and chemical reactions can significantly alter flow properties, such as viscosity and density gradients. These alterations can, in turn, affect the overall flow pattern and boundary layer development. Studying the Maxwell fluid flow with a chemical reaction on a perpendicular plate is crucial in understanding heat and mass transfer processes. The chemical reaction can influence heat transfer and mass between the fluid and the plate, affecting the overall system's behaviour and efficiency. Understanding the Maxwell fluid flow on a perpendicular plate with chemical reactions finds applications in various fields. These include chemical engineering (for designing reactors or separation processes), material sciences (in understanding and processing viscoelastic materials), and environmental engineering (in modelling pollutant transport and reactions in fluids). Researchers use mathematical models and simulations to predict and analyze the behaviour of the Maxwell fluid flow with chemical reactions. These models involve complex equations representing fluid dynamics, heat transfer, mass transfer, and chemical kinetics, providing insights that help optimise processes and design efficient systems. The motivation behind studying the Maxwell fluid flow on a vertical plate with chemical reactions lies in its potential to advance multiple fields, improve industrial processes, deepen scientific understanding, and contribute to developing innovative materials and technologies.

1.2. Novelty of the Proposed Problem. These collective research endeavours significantly deepen our comprehension of the intricate interplay among fluid dynamics, energy transfer, and mass transfer, along with chemical reactions across diverse physical and technological environments. While prior studies have offered valuable insights into different facets of fluid dynamics, they have not thoroughly addressed the intricate interconnection of viscoelastic fluid flow, magnetohydrodynamics (MHD) over a perpendicular plate, combined radiation effects, heat generation, and chemical interactions influencing energy and mass transfer through a porous medium. No authors have explored the Maxwell fluid flow on a perpendicular plate while considering this combination of parameters. Recognizing this research gap, our study's primary aim is to fill this void in knowledge and conduct a comprehensive investigation into this multifaceted scenario. To confront this intricate problem, we transform the governing partial differential equations into more manageable ordinary differential equations (ODEs). These nonlinear ODEs are then solved via the robust MATLAB inbuilt software tool, the bvp4c solver. Our analysis thoroughly explores various critical parameters, encompassing temperature, velocity, and concentration contours and evaluating the local Sherwood number, skin friction coefficient, and Nusselt number. Our research seeks to illuminate the intricate dynamics in this complex fluid flow scenario through a systematic study and analysis of these governing parameters. This investigation not only enriches our fundamental understanding of fluid dynamics but also carries the potential to advance various practical applications in engineering, environmental science, and industrial processes. This research emphasizes and aims to address the following questions:

(i) What impact does fluid flow have on the behaviour of skin friction, Nusselt number, and Sherwood number concerning the chemical reaction parameter?

(ii) How does fluid flow influence the velocity profile, temperature profile, and concentration contour concerning the chemical reaction parameter?

(iii) How does fluid flow influence the velocity, temperature, and concentration outline concerning the heat generation parameter?

2. Mathematical Formulation

Consideration is given to a non-Newtonian viscoelastic fluid that is laminar, steady, and two-dimensional. Consideration is given to porous media exposed to magnetic fields. It is presumed that the y-axis is over the plate and the x-axis is perpendicular to it. Let u and v stand for the horizontal velocity in the x direction and the vertical velocity in the y direction, respectively. C represents the fluid concentration, and T represents the temperature. The convective boundary conditions obstruct the local temperature at the wall. A magnetic field with a constant strength of B_0 is provided perpendicular to the plate and along the y-axis of the vertical porous plate. The continuous concentration and temperature of the vertical plate are also supposed to be C_w and T_w, whereas those of the surrounding fluid are T_∞ and C_∞. The chemical reaction has been added to the flow, so the Boussinesq approximation says that all thermophysical properties are probably in the variable of the linear impetus expression. The physical mode of the problem is offered in Figure 1.

Upper-convected Maxwell fluid convinces are as follows:

$$\tau_{ij} + \lambda_1 \frac{\delta}{\delta t} \tau_{ij} = 2\mu d_{ij}, \tag{1}$$

where τ_{ij} is the stress tensor, μ is the zero shear rate viscosity, d_i represents the symmetric part of the velocity gradient tensor, and λ_1 is fluid's relaxation time.

$$d_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right). \tag{2}$$

Upper-convected time derivative is as follows:

$$\frac{\delta}{\delta t}\tau_{ij} = \frac{D}{Dt}\tau_{ij} - L_{ij}\tau_{ik} - \tau_{kj} L_{ik}, \tag{3}$$

where L_{ij} is the velocity tensor $(\partial u_i/\partial x_j)$ and (D/Dt) is the material time derivative

"The Cartesian form of the governing equations, along with the boundary layer calculations as mentioned by Reference [30], is presented as follows."

The equation of continuity of the governing equation is as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \tag{4}$$

In manufacturing and technological applications, non-Newtonian fluids are preferable over Newtonian fluids. The governing equations are complicated, and getting solutions to the following equations is more challenging. Numerous non-Newtonian fluid models have been proposed and are currently being researched due to the complexity of fluids. So, with the occurrence of Maxwell fluid, the equation of conservation of linear momentum is as follows:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - \upsilon\left(\frac{\partial^2 u}{\partial y^2}\right) = g\left(\beta_T (T - T_\infty) + \beta_C (C - C_\infty)\right) - \frac{\sigma B_0^2}{\rho} u - \frac{\upsilon}{K} u - \lambda_1\left(u^2\frac{\partial^2 u}{\partial x^2} + v^2\frac{\partial^2 u}{\partial y^2} + 2uv\frac{\partial^2 u}{\partial x \partial y}\right). \tag{5}$$

The equation of conservation of energy in the occurrence of heat generation *(Q)* and thermal radiation is as follows:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{1}{\rho C_p}\frac{16\sigma^* T_\infty^3}{3k^*}\frac{\partial^2 T}{\partial y^2} + Q'\,(T - T_\infty). \tag{6}$$

Here, q_r characterizes the radiative heat flux and C_p characterizes the specific heat; if the thermal conductivity of the fluid k and temperature of the fluid have a linear relation, then according to Roseland [31], q_r is calculated as follows.

$q_r = (4\sigma^*/3k^*)(\partial T^4/\partial y)$; here, it can become close using series development about the ambient temperature of the fluid represented as T_∞ by $T^4 = T_\infty^4 + 4T_\infty^3\,(T - T_\infty) + 6T_\infty^2 (T - T_\infty) + \ldots$.

If we disregard higher-order terms, let us inscribe from the above equations $(\partial q_r/\partial y) = -(16T_\infty^3 \sigma^*/3k^*)\,(\partial^2 T/\partial y^2)$.

The equation of conservation of mass with chemical reaction occurrence is as follows:

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = -Kc'\,(C - C_\infty) + D_B\frac{\partial^2 C}{\partial y^2}. \tag{7}$$

The given problem's boundary conditions for the dimensional governing equations are as follows:

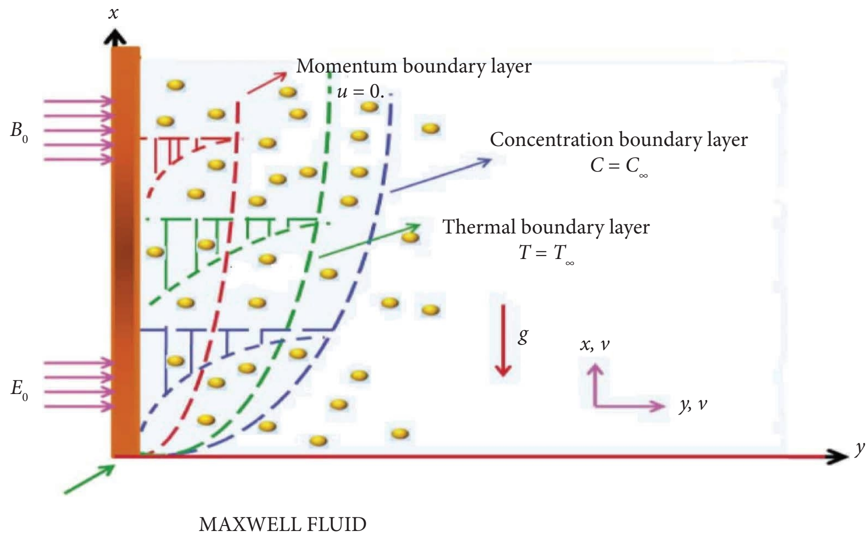

Figure 1: Schematic diagram.

$$\begin{aligned} &y = 0,\\ &T = T_w,\\ &v = 0,\\ &u = 0,\\ &C = C_w,\\ &y = \infty, T \longrightarrow T_\infty, C \longrightarrow C_\infty, u, v \longrightarrow 0. \end{aligned} \tag{8}$$

Using the similarity transformation, the nonlinear PDEs are changed into ODEs.

$$\eta = \frac{y}{x} Ra_x^{0.25}, \text{here } Ra_x = \frac{g\beta (T_w - T_\infty) x^3}{\alpha v}. \tag{9}$$

Dimensionless numbers lower the variables used to characterize them, minimizing the experimental data required to establish correlations between physical phenomena and scalable systems.

$$\begin{aligned} f(\eta) &= \frac{\psi}{\alpha Ra_x^{0.25}},\\ \theta(\eta) &= \frac{T - T_\infty}{T_w - T_\infty},\\ \phi(\eta) &= \frac{C - C_\infty}{C_w - C_\infty}. \end{aligned} \tag{10}$$

Flow characteristics typically expressed with the occurrence of stream function are given here.

$$u = \frac{\partial \psi}{\partial y} \text{and } v = -\frac{\partial \psi}{\partial x}. \tag{11}$$

PDEs are converted into ODEs using the above quantities.

The dimensionless momentum equation in the presence of dimensionless porous and MHD effect is as follows:

$$\begin{aligned} &f'''\left(4\,\mathrm{Pr} - \frac{9}{4}\beta\sqrt{Ra_x}\, f'^2\right) - \beta\sqrt{Ra_x}\left(\frac{7}{4}\eta f'^2 f'' - f'^3 - 1.5 f\, f' f''\right)\\ &- 4M\sqrt{\mathrm{Pr}} f' - 4\frac{\mathrm{Pr}}{\sqrt{Ra_x}}\lambda f' + 3 f f'' - 2 f'^2 + 4\,\mathrm{Pr}(\theta - Nr\phi) = 0. \end{aligned} \tag{12}$$

The dimensionless energy equation in the occurrence of radiation and heat generation is as follows:

$$\left(1 + \frac{4}{3}\mathrm{Rd}\right)\theta'' + \frac{3}{4} f\theta' + Q\theta = 0. \tag{13}$$

In the chemical and water industries, double diffusion with higher-order chemical processes utilizing a porous medium has several applications. In addition to chemical reactions, industrial processes such as filtration, cooling, distillation, and drying rely on transmitting heat and mass. The relationship between the concentration and the rate of a chemical reaction is explained by the order of the reaction.

$$\phi'' + \frac{3}{4} Le\left(f\phi'\right) - Kr\phi = 0. \tag{14}$$

Nondimensional numbers help determine the flow properties of a fluid.

$$M = \frac{\left(\sigma B_0^2 x^{1/2}\right)}{\left(\rho\sqrt{g\beta\left(T_w - T_\infty\right)}\right)} \text{ is the magnetic field parameter,}$$

$$\text{Lewis number Le} = \frac{\alpha}{D_B},$$

$$\text{Nr} = \left(\frac{D_B\left(C_w - C_\infty\right)}{\rho\beta\left(T_w - T_\infty\right)}\right) \text{ is the buoyancy ratio parameter,}$$

$$\text{Rd} = \left(\frac{4\sigma T_\infty^3}{k\delta}\right) \text{ represents thermal radiation,} \tag{15}$$

$$\text{Pr} = \frac{\nu}{\alpha} \text{ is the Prandtl number,}$$

$$\text{Thermal diffusivity } \alpha = \left(\frac{K}{\left(\rho c_p\right)}\right).$$

The porosity is typically given by the ratio of void space volume to the total volume of the material.

$$\lambda = \frac{K}{ul}. \tag{16}$$

The Maxwell fluid model involves relaxation time (τ) and viscosity (μ). The nondimensional form of the Maxwell fluid parameter can be expressed as a ratio of relaxation time to characteristic time or any relevant length scale (u).

$$\beta = \frac{u\lambda_1}{l}. \tag{17}$$

In the context of heat generation in a system, the nondimensional representation depends on the specific design and the governing equations involved. However, we can typically define nondimensional heat generation as the ratio of heat generated to some characteristic value or scale in the system.

$$Q = \frac{Q'}{u\,\rho \text{cp}}. \tag{18}$$

The nondimensional representation of chemical reactions can vary based on the specific reaction rate and other factors.

$$Kr = \frac{l\,Kc'}{D}. \tag{19}$$

The appropriate corresponding dimensionless boundary conditions of the current problem are as follows:

$$\left.\begin{array}{l} f(0) = 0, f'(0) = 0, \theta(0) = 1, \phi(0) = 1, \\ f'(\infty) = 0, \theta(\infty) = 0, \phi(\infty) = 0. \end{array}\right\} \tag{20}$$

2.1. Essential Quantities of Engineering Interest

2.1.1. Coefficient of Skin Friction. Coefficient of skin friction is as follows:

$$Cf = \frac{\mu\left(\partial u/\partial y\right)_{y=o}}{\rho u^2}. \tag{21}$$

2.1.2. Local Nusselt Number. Local Nusselt number is as follows:

$$\text{Nu}_x = \frac{xq_w}{k\left(T_w - T_\infty\right)}, \qquad \text{where heat flux } q_w = -k\frac{\partial T}{\partial y} + q_r. \tag{22}$$

2.1.3. Local Sherwood Number. Local Sherwood number is as follows:

$$Sh_x = \frac{x\,j_w}{D\left(C_w - C_\infty\right)}. \tag{23}$$

Here, $j_w = -D\left(\partial C/\partial y_r\right)$ is the mass flux.

By using the dimensionless quantities listed above,

$$\begin{aligned} Cf_x \text{Re}_x^{(-1/2)} &= -f''(0), \\ \text{Nu}_x \text{Re}_x^{(-1/2)}\left(\frac{3}{3 + 4Rd}\right) &= -\theta', \\ \frac{\text{Sh}_x}{\sqrt{\text{Re}_x}} &= -\phi'(0). \end{aligned} \tag{24}$$

3. Methodology and Results of the Problem

To identify the answers to the dimensionless equations with boundary conditions, the shooting technique known as BVP4c in MATLAB software is utilized in order to obtain the numerical solution which is shown in Figures 2–10. Results can be summarized as graphs for the non-dimensional ordinary differential equations. Computational results are displayed for each parameter through temperature, velocity, and concentration contours. We investigate the skin friction coefficient, the Nusselt number, and the Sherwood number about fluid flow parameters (see Tables 1–3). This work aims to determine how a chemical reaction affects the steady state with energy and mass transport of an electrically conducting fluid that can either generate or absorb heat. "If not specified differently, the study assumes default or unchanged parameters." $M = 1.0$, $\mathrm{Pr} = 6.2$, $\mathrm{Rd} = 0.5$, $\mathrm{Nr} = 1.0$, $\mathrm{Ra} = 0.5$, $\lambda = 1.0$, $\beta = 0.2$, $\mathrm{Le} = 5$, $Q = 0.01$, and $\mathrm{Kr} = 0.5$ are taken by the standard literature. These parameter values are taken from the classic literature. Thus, unless otherwise noted on the relevant graph, all graphs correspond to these values.

3.1. Comparison of the Results to an Earlier Publication. To confirm the accuracy of our solution derived using the bvp4c MATLAB solver, we compared our recent results to those from a previous study conducted by Nield [32]. The significant alignment between our findings and those of the earlier research inspires us to examine the impacts of different controlling parameters on the behaviour of Maxwell fluid flowing over a porous perpendicular plate. The validation of our code against published research outcomes is presented in Table 4.

3.2. Velocity Profile. Figure 2 illustrates how the velocity profile is affected by the Maxwell fluid flow. As the value of the Maxwell fluid parameter (Deborah number) surges, so does the velocity profile. The increase in the Maxwell fluid parameter, also known as the Deborah number, leads to a corresponding increase in the velocity contour on a vertical plate in the Maxwell fluid flow. This is due to the physical mechanism of the fluid's viscoelastic properties. Maxwell fluids exhibit both viscous and elastic behaviour. As the Deborah number increases, it signifies a higher dominance of flexible effects over viscous effects in the fluid flow. This higher elasticity allows the fluid to deform and respond more readily to applied forces, resulting in increased velocity profiles on the vertical plate. A higher Deborah number indicates that the liquid can more effectively transmit applied forces, causing more significant deformation and, consequently, higher velocity profiles along the vertical plate in the Maxwell fluid flow.

Figure 3 demonstrates the effect on the velocity outline when augmenting the chemical reaction (Kr) on a vertical plate in Maxwell fluid flow, resulting in an increased velocity outline. Elevating the Kr on the sheer scale during Maxwell fluid flow leads to an observed enhancement in the velocity profile. The physical mechanism behind the increase in the velocity profile due to an elevated chemical reaction parameter in Maxwell fluid flow on a vertical plate involves several factors related to the chemical reactions occurring within the fluid. Chemical reactions often involve the release or absorption of energy. This change in power can affect the temperature and, consequently, the fluid's viscosity. In some cases, an increase in Kr can result in a decrease in density, facilitating faster flow and, hence, an increased velocity profile. Chemical reactions may involve species transport or generation, altering the mass transport properties of the fluid. This could lead to changes in density or composition, impacting the fluid's flow behaviour and influencing the velocity profile. Chemical reactions can modify the rheological properties of the liquid, such as viscosity and elasticity. Alterations in these properties affect how the fluid responds to applied forces, potentially leading to changes in velocity profiles. Reactions that generate or consume heat

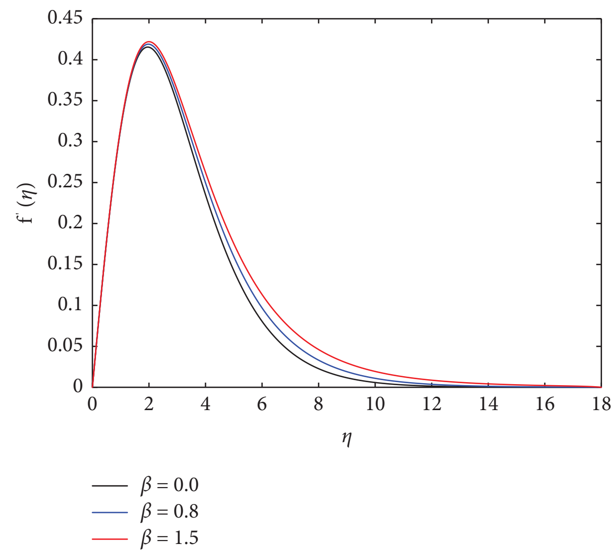

Figure 2: Result of β over the velocity outline.

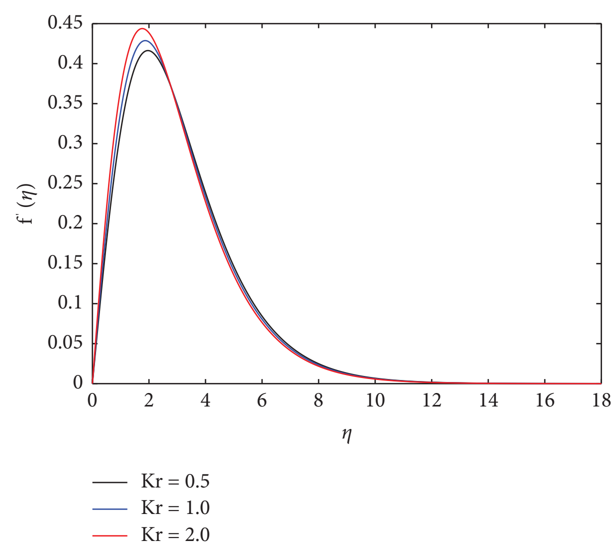

Figure 3: Outcome of Kr on velocity outline.

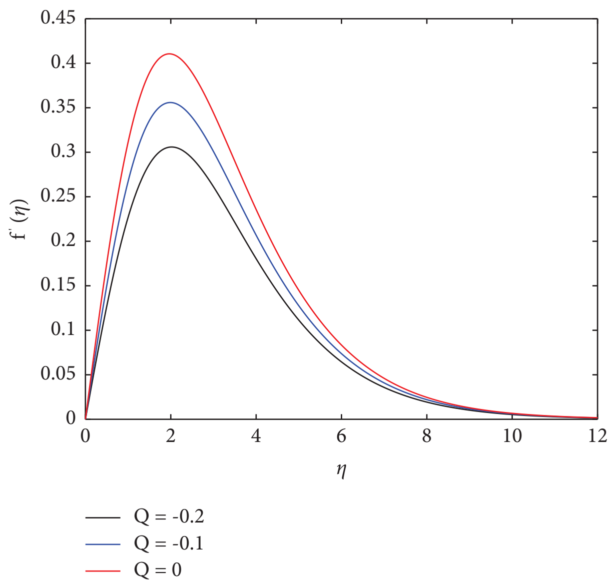

Figure 4: Result of Q on velocity outline.

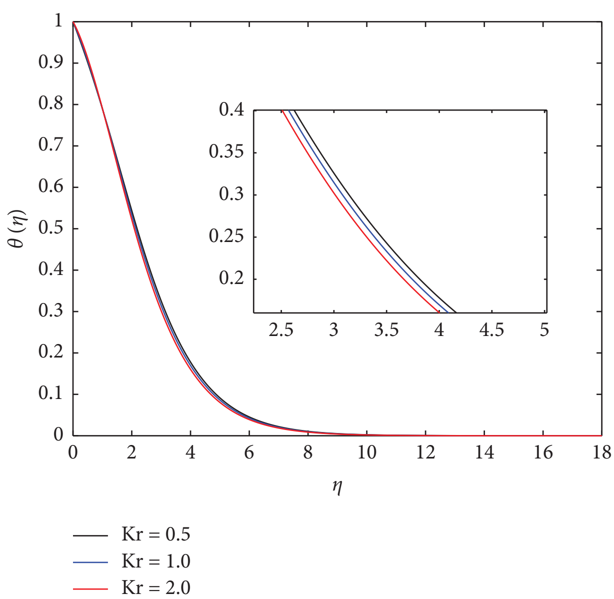

Figure 5: Result of Kr on temperature outline.

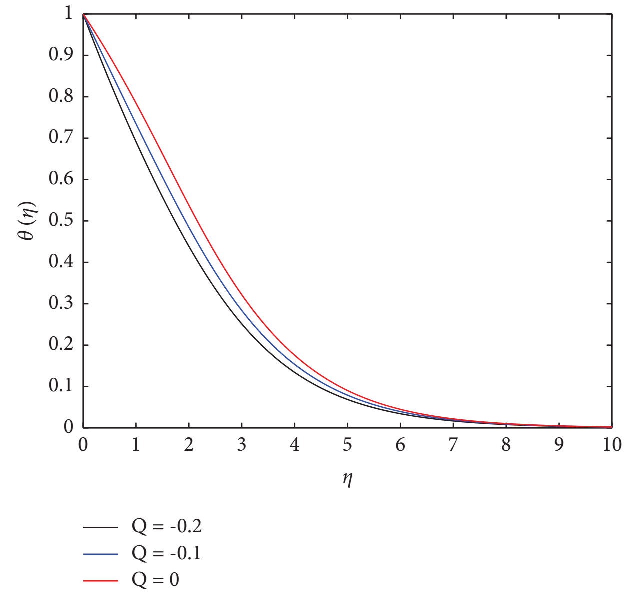

Figure 6: Result of Q on temperature outline.

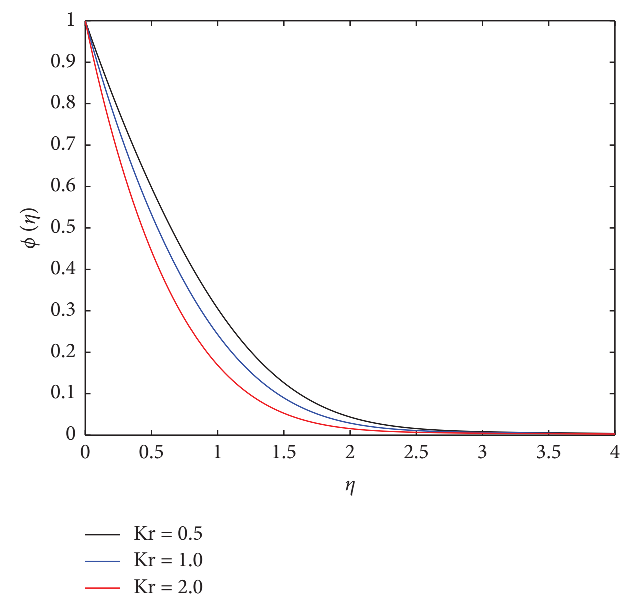

Figure 7: Result of Kr on the concentration outline.

can influence the temperature distribution within the fluid. Temperature changes can, in turn, affect the fluid's viscosity and flow characteristics, controlling the velocity outline. Overall, the interaction between chemical reactions and fluid properties such as viscosity, density, temperature, and rheology directly impacts the flow behaviour and subsequently influences the velocity profile on the vertical plate in Maxwell fluid flow.

Figure 4 provides insight into how heat generation impacts the velocity profile, showcasing a direct correlation between increased heat generation and an augmented velocity profile. The physical mechanism underlying this phenomenon involves several interconnected processes within the fluid. As heat is generated, the fluid's temperature rises, leading to thermal expansion. This expansion decreases the fluid density near the heated surface, creating a less dense layer that tends to increase due to buoyancy. The warmed fluid, being less viscous, ascends upward due to buoyancy forces. This upward movement of the heated fluid establishes a vertical flow component, contributing to an overall increase in the velocity profile. Heat generation induces a heightened temperature gradient in the liquid. This amplified gradient encourages convection, characterized by the bulk movement of the fluid. As the buoyant-heated fluid rises, it draws in denser fluid from below, fostering a convective flow that supplements the overall fluid velocity. Higher temperatures often lead to a reduction in fluid

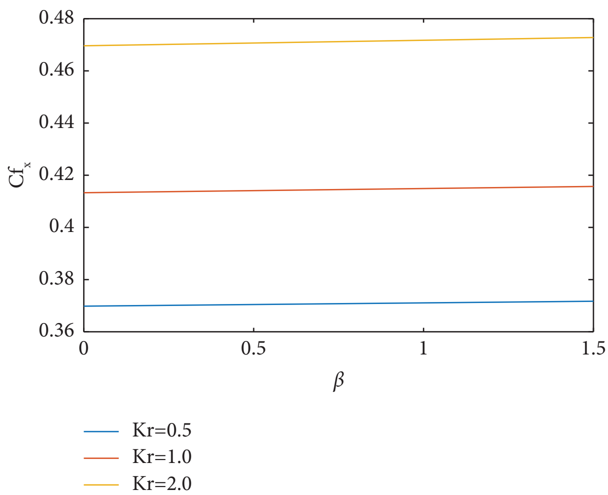

Figure 8: Effect of Kr on the skin friction profile.

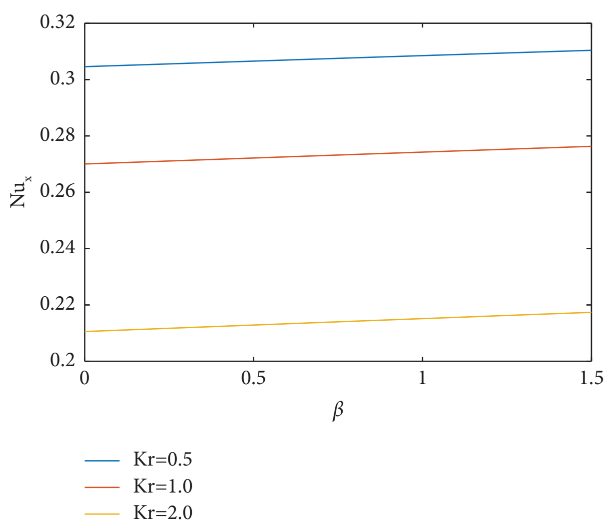

Figure 9: Outcome of Kr on the local Nusselt number profile.

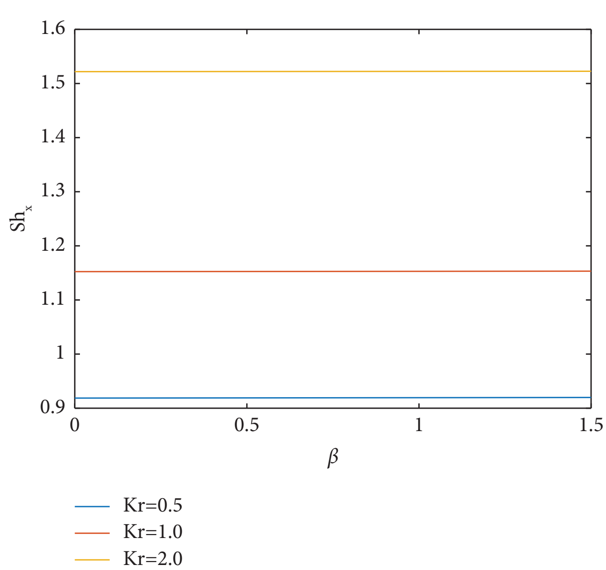

Figure 10: Effect of Kr on the Sh_x profile.

Table 1: Calculated values of skin friction coefficient for $M = 1.0$, $Rd = 0.5$, $Nr = 1.0$, $Ra = 0.5$, $\lambda = 1.0$, $\beta = 0.2$, $Le = 5$, $Q = 0.01$, $Pr = 6.2$, and $Kr = 0.5$.

M	Rd	Ra	λ	β	Cf_x
0					0.494348
1					0.372553
3					0.250333
5					0.188691
	0				0.338084
	1				0.397158
	2				0.431039
	3				0.454065
		1			0.397765
		2			0.418015
		3			0.427835
		4			0.434018
			0		0.475490
			1		0.372554
			3		0.260559
			5		0.200464
				0	0.372379
				0.5	0.372815
				1	0.373242
				1.5	0.373670

Table 2: Computed values of Nu_x for $M = 1.0$, $Rd = 0.5$, $Nr = 1.0$, $Ra = 0.5$, $\lambda = 1.0$, $\beta = 0.2$, $Le = 5$, $Q = 0.01$, $Pr = 6.2$, and $Kr = 0.5$.

M	Rd	Nr	Λ	Q	Le	Kr	Nu_x
0							0.366624
1							0.302810
3							0.225291
5							0.177124
	0						0.180984
	1						0.409204
	2						0.593760
	3						0.754189
		0.4					0.331711
		0.8					0.313264
		1.2					0.291213
		1.6					0.262537
			0				0.357357
			1				0.302811
			3				0.232535
			5				0.187012
				−0.2			0.564737
				−0.1			0.447196
				0.0			0.316662
				0.02			0.288791
					5		0.302805
					10		0.291537
					15		0.275401
					20		0.259210
						0.5	0.302804
						1	0.268460
						2	0.209214
						3	0.158102

viscosity. With lower density, the fluid encounters less resistance to flow, enabling it to move more swiftly. This diminished resistance further bolsters the increase in fluid velocity.

Table 3: Computed values of the local Sherwood number for $M = 1.0$, $\mathrm{Rd} = 0.5$, $\mathrm{Nr} = 1.0$, $\mathrm{Ra} = 0.5$, $\lambda = 1.0$, $\beta = 0.2$, $\mathrm{Le} = 5$, $Q = 0.01$, $\mathrm{Pr} = 6.2$, and $\mathrm{Kr} = 0.5$.

M	Rd	Nr	λ	Q	Le	Kr	Sh_x
0							0.968033
1							0.919959
3							0.864939
5							0.833611
	0						0.906049
	1						0.930242
	2						0.944369
	3						0.953832
		0.4					0.978019
		0.8					0.940949
		1.2					0.896741
		1.6					0.840139
			0				0.960939
			1				0.919959
			3				0.869872
			5				0.839819
				−0.2			0.852798
				−0.1			0.884148
				0.0			0.916638
				0.02			0.923294
					5		0.919959
					10		1.091947
					15		1.229265
					20		1.344668
						0.5	0.919959
						1	1.153152
						2	1.522417
						3	1.821786

Table 4: Computed values of the Nusselt number $\mathrm{Nur}=\mathrm{Nu}/\mathrm{Ra}_x^{1/4}$ for limiting case of the regular fluid with $\mathrm{Nr} = \mathrm{Nb} = 10^{-5}$ and $\mathrm{Le} = 10$.

Pr	Nur (present)	Nur (Nield) [32]
100	0.481	0.481
1	0.402	0.401
10	0.462	0.463

3.3. Temperature Outline. Figure 5 visually elucidates the relationship between heightened chemical reaction values and their influence on the temperature profile in our study, incorporating the underlying physical mechanisms at play within the fluid. Chemical reactions typically produce heat as a byproduct. Increasing the chemical reaction values results in more significant heat generation within the system. The additional heat energy generated raises the overall temperature of the fluid. This thermal energy transfer heats the surrounding liquid near the reaction site. The heated fluid conducts heat to adjacent areas, fostering a widespread increase in temperature across the fluid. This conduction mechanism influences the entire temperature profile. Higher chemical reaction values intensify fluid motion and mixing. This increased agitation aids in spreading elevated temperatures throughout a broader region within the fluid. Chemical reactions create temperature gradients in the liquid. These gradients induce fluid motion through natural convection, where warmer fluid ascends while more excellent fluid descends. This circulation alters the temperature contour within the system.

Figure 6 depicts an escalation in the heat generation parameter directly correlating with a heightened temperature profile. This relationship is primarily governed by principles rooted in heat transfer and thermodynamics. The heat generation parameter signifies a heat source within the system, typically represented by various physical processes such as chemical reactions, electrical resistance, or mechanical work. Its increase results in a proportionate rise in the rate of energy generation within the system. The temperature profile denotes a material or design's spatial and temporal temperature variation. It represents temperature distributions across different points within the system. Augmenting the heat generation parameter amplifies the rate at which heat is generated within the system. This increase causes a localized temperature rise near the heat source as more heat accumulates.

Consequently, the temperature gradient steepens within the system, indicating a more significant temperature disparity between regions close to the heat source and those farther away. Continued heat generation perpetuates its impact across the entire system, leading to an overall elevation in the temperature profile. Consequently, both the local temperature near the heat source and the temperature in the whole system increase due to the escalated heat generation.

3.4. Concentration Profile. Figure 7 illustrates the concentration outline as the value of the chemical reaction increases, revealing a declining concentration trend. The decrease in the concentration observed in the concentration outline with an increase in the value of the Kr, as depicted in Figure 7, can be attributed to several physical mechanisms associated with chemical reactions within the system. Elevating the chemical reaction parameter typically implies a higher rate of chemical reactions within the system. As reactions progress more rapidly, reactants are consumed faster, reducing their concentration over time. Chemical reactions often involve the consumption of reactants to produce products. As the reaction rate increases due to higher parameter values, more reactants get converted into products, consequently depleting the concentration of reactants in the system. Specific reactions might be reversible and tend towards reaching an equilibrium state. Increasing the chemical reaction parameter could shift the equilibrium towards products, thereby reducing the concentration of reactants and favouring product formation. Higher chemical reaction rates may intensify fluid motion and mixing within the system. This increased mixing can disperse the reactants more uniformly, potentially leading to lower localized concentrations as the reactants become more distributed. Accelerated chemical reactions induce faster diffusion rates of reactants, causing them to spread more rapidly within the system. This enhanced diffusion could contribute to a decrease in the concentration profile depicted in Figure 7.

3.5. Engineering Quantities. Figures 8–10 portray the profiles of skin friction, Nusselt number, and Sherwood number, respectively, concerning the escalating value of the chemical reaction parameter. Notably, when the chemical reaction parameter rises, the skin friction and Sherwood number profiles demonstrate an upward trend, whereas the Nusselt number profile exhibits a declining trend in isolation. The varying behaviour observed in the skin friction, Nusselt number, and Sherwood number profiles concerning the rise in the chemical reaction parameter can be attributed to distinct physical mechanisms associated with heat and mass transfer, as well as fluid dynamics.

3.5.1. Skin Friction. Physical mechanism: increasing the chemical reaction parameter often leads to elevated fluid motion and mixing due to higher reaction rates. This augmented fluid movement tends to increase the frictional forces exerted on the surface, increasing the skin friction profile. The heightened chemical reactions can intensify the momentum transfer between the fluid and the surface, leading to an enhanced skin friction profile.

3.5.2. Nusselt Number. Physical mechanism: the decrease in the Nusselt number profile can be attributed to the complex interplay between heat transfer mechanisms. Increasing chemical reactions might alter the flow patterns and energy transfer characteristics to suppress the convective heat transfer rate while potentially enhancing the conductive energy transfer. As a result, the convective heat transfer rate decreases despite the increased fluid motion, leading to a decline in the Nusselt number profile.

3.5.3. Sherwood Number. Physical mechanism: the surge in the Sherwood number profile is typically associated with mass transfer enhancement due to intensified fluid motion caused by higher chemical reaction rates. This increased fluid movement and mixing facilitate more excellent mass transport or diffusion of substances from the surface into the fluid, leading to an elevated Sherwood number profile.

4. Conclusion

This study fills a gap by numerically analyzing Maxwell fluid behaviour on a porous perpendicular plate, considering chemical reactions, heat generation, and magnetohydrodynamic effects. Using MATLAB's bvp4c solver and transformation techniques, we tackle the challenges posed by nonlinear equations, exploring their impact on temperature, velocity, and concentration. In addition, we evaluate Sherwood numbers, Nusselt numbers, and skin friction coefficients to assess chemical reaction effects. Our detailed investigation sheds light on the intricate relationship among Maxwell fluid flow, chemical reactions, and heat generation on a vertical plate. These insights are crucial for applications in chemical processes, heat exchangers, and environmental engineering, offering opportunities for process optimization and further research in similar fluid flow scenarios. Key findings from our study are outlined as follows:

(1) We observed that changes in the chemical reaction parameters and heat generation significantly affect the velocity profile. Higher chemical reaction rates and heat generation led to a surge in fluid velocity near the plate.

(2) The temperature profile exhibited variations corresponding to the levels of chemical reactions and heat generation. Elevated chemical reaction rates and increased heat generation caused higher temperatures in the fluid near the plate.

(3) Our study also considered the concentration profile, which reflects how chemical reactions influence fluid substance distribution. The concentration profiles demonstrated changes in response to varying chemical reaction rates and heat generation levels.

(4) We analyzed the skin friction outline, indicating the fluid flow resistance along the plate. Chemical reactions and heat generation influenced skin friction, with higher values of these parameters leading to altered frictional forces.

(5) The Nusselt number profile, a dimensionless energy transfer coefficient, showed significant variations with changes in chemical reactions and heat generation. This parameter is crucial for understanding heat transfer rates.

(6) We also considered the Sherwood number profile related to mass transfer rates. Chemical reactions and heat generation were observed to impact the mass transfer rate, resulting in variations in the Sherwood number profile.

4.1. Future Work. There is a potential to expand the scope of this paper by introducing additional parameters or altering the geometry, alongside incorporating a more extensive range of fluid variables.

Nomenclature

C: Concentration of the fluid
T_w: Temperature on the wall (K)
C_∞: Concentration on the free stream
M: Magnetic field
β: Deborah number
T: Temperature of the fluid (K)
Pr: Prandtl number
u, v: Velocity of the fluid (ms^{-1})
B_0: Magnetic component
Kc': Dimensional chemical reaction
C_f: Skin friction
θ: Dimensionless temperature
D_B: Mass diffusion
f: Dimensionless stream function
D: Diffusion term
K: Permeability of a porous medium

T_∞: Temperature on the free stream
Kr: Dimensionless chemical reaction parameter
λ_1: Maxwell fluid parameter (s)
Rd: Dimensionless radiation
C_p: Specific heat at constant pressure ($JK^{-1}\cdot kg^{-1}$)
v: Kinematic viscosity (m^2s^{-1})
β_c: Coefficient of mass expansion (K^{-1})
$Q^{'}$: Dimensional heat generation
ρ: Density of the fluid (kg^{-3})
Q: Dimensionless heat generation
Re_x: Local Reynolds number
Ra: Rayleigh number
σ^*: Stefan–Boltzmann constant
λ: Porosity dimensionless parameter
β_T: Coefficient of thermal expansion (K^{-1})
ϕ: Dimensionless concentration
η, ψ: Similarity variables (m^2s^{-1})
μ: Dynamic viscosities ($kg\cdot m^{-1}\cdot s^{-1}$)
k: Thermal conductivity ($Wm^{-1}k^{-1}$)
g: Gravitation (ms^{-2})
ρc_p: Heat capacity ($Jkg^{-1}\cdot K^{-1}$).

Data Availability

No data were required to perform this research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through large group Research Project under grant no. RGP2/340/44.

References

[1] A. N. Kashif, F. Salah, D. S. Sankar, M. D. Izyan, and K. K. Viswanathan, "Effects of pressure gradient on convective heat transfer in a boundary layer flow of a Maxwell fluid past a stretching sheet," *International Journal of Applied Mechanics and Engineering*, vol. 26, no. 3, pp. 104–118, 2021.

[2] L. Liu, L. Feng, Q. Xu, L. Zheng, and F. Liu, "Flow and heat transfer of generalized Maxwell fluid over a moving plate with distributed order time fractional constitutive models," *International Communications in Heat and Mass Transfer*, vol. 116, Article ID 104679, 2020.

[3] M. A. Imran, M. B. Riaz, N. A. Shah, and A. A. Zafar, "Boundary layer flow of MHD generalized Maxwell fluid over an exponentially accelerated infinite vertical surface with slip and Newtonian heating at the boundary," *Results in Physics*, vol. 8, pp. 1061–1067, 2018.

[4] K. Sudarmozhi, D. Iranian, I. Khan, J. Alzahrani, A. S. Al-johani, and S. M. Eldin, "Double diffusion in a porous medium of MHD Maxwell fluid with thermal radiation, heat generation and chemical reaction," *Case Studies in Thermal Engineering*, vol. 43, Article ID 102700, 2023.

[5] W. Na, N. A. Shah, I. Tlili, and I. Siddique, "Maxwell fluid flow between vertical plates with damped shear and thermal flux: free convection," *Chinese Journal of Physics*, vol. 65, pp. 367–376, 2020.

[6] M. B. Riaz and N. Iftikhar, "A comparative study of heat transfer analysis of MHD Maxwell fluid in view of local and nonlocal differential operators," *Chaos, Solitons & Fractals*, vol. 132, Article ID 109556, 2020.

[7] N. Raza and M. A. Ullah, "A comparative study of heat transfer analysis of fractional Maxwell fluid by using Caputo and Caputo–Fabrizio derivatives," *Canadian Journal of Physics*, vol. 98, no. 1, pp. 89–101, 2020.

[8] M. B. Riaz, A. U. Rehman, J. Awrejcewicz, and A. Akgül, "Power law kernel analysis of MHD Maxwell fluid with ramped boundary conditions: transport phenomena solutions based on special functions," *Fractal and Fractional*, vol. 5, no. 4, p. 248, 2021.

[9] H. Hanif, "A computational approach for boundary layer flow and heat transfer of fractional Maxwell fluid," *Mathematics and Computers in Simulation*, vol. 191, pp. 1–13, 2022.

[10] A. Q. Khan and A. Rasheed, "Numerical simulation of fractional Maxwell fluid flow through Forchheimer medium," *International Communications in Heat and Mass Transfer*, vol. 119, Article ID 104872, 2020.

[11] N. A. Shah, C. Fetecau, and D. Vieru, "Natural convection flows of Prabhakar-like fractional Maxwell fluids with generalized thermal transport," *Journal of Thermal Analysis and Calorimetry*, vol. 143, pp. 2245–2258, 2021.

[12] X. H. Zhang, R. Shah, S. Saleem, N. A. Shah, Z. A. Khan, and J. D. Chung, "Natural convection flow Maxwell fluids with generalized thermal transport and Newtonian heating," *Case Studies in Thermal Engineering*, vol. 27, Article ID 101226, 2021.

[13] A. R. Al Hajri, M. M. Rahman, and I. A. Eltayeb, "Impacts of Maxwell-Cattaneo effects on the convective heat transfer flow inside a square enclosure filled with a porous medium," *International Journal of Thermofluids*, vol. 17, Article ID 100254, 2023.

[14] M. A. Memon, M. S. Khan, S. Saleem, S. M. Eldin, and K. Jacob, "Heat transfer through a higher grade Forchheimer porous CuO–H2O-nano-medium confined between non-isothermal moving plates," *Case Studies in Thermal Engineering*, vol. 47, Article ID 103035, 2023.

[15] K. Sudarmozhi, D. Iranian, M. A. Memon, P. D. Selvi, M. S. Khan, and A. Fenta, "Viscoelastic fluid flow over a horizontal flat plate with various boundary slip conditions and suction effects," *Nanoscale Advances*, vol. 5, no. 22, pp. 6102–6114, 2023.

[16] M. S. Khan, M. A. Memon, I. Khan, and S. M. Eldin, "Finite element based direct and iterative approach to investigate a magneto-micropolar flow through a rectangular channel," *Alexandria Engineering Journal*, vol. 75, pp. 55–66, 2023.

[17] B. P. Reddy, O. D. Makinde, and A. Hugo, "A computational study on diffusion-thermo and rotation effects on heat generated mixed convection flow of MHD Casson fluid past an oscillating porous plate," *International Communications in Heat and Mass Transfer*, vol. 138, Article ID 106389, 2022.

[18] A. Dadheech, A. Parmar, K. Agrawal, Q. Al-Mdallal, and S. Sharma, "Second law analysis for MHD slip flow for Williamson fluid over a vertical plate with Cattaneo-Christov heat flux," *Case Studies in Thermal Engineering*, vol. 33, Article ID 101931, 2022.

[19] S. M. Hussain, J. Jain, G. S. Seth, and M. M. Rashidi, "Free convective heat transfer with hall effects, heat absorption and chemical reaction over an accelerated moving plate in

a rotating system," *Journal of Magnetism and Magnetic Materials*, vol. 422, pp. 112–123, 2017.
[20] B. Saidulu and K. S. Reddy, "Evaluation of combined heat and mass transfer in hydromagnetic micropolar flow along a stretching sheet when viscous dissipation and chemical reaction is present," *Partial Differential Equations in Applied Mathematics*, vol. 7, Article ID 100467, 2023.
[21] H. Sadia, H. Sadia, N. Gul, A. Zeb, and Z. A. Khan, "Convection heat–mass transfer of generalized Maxwell fluid with radiation effect, exponential heating, and chemical reaction using fractional Caputo–Fabrizio derivatives," *Open Physics*, vol. 20, no. 1, pp. 1250–1266, 2022.
[22] N. A. Iftikhar, S. M. Husnine, and M. B. Riaz, "Heat and mass transfer in MHD Maxwell fluid over an infinite vertical plate," *Journal of Prime Research in Mathematics*, vol. 15, pp. 63–80, 2019.
[23] H. Hanif, "Cattaneo–Friedrich and Crank–Nicolson analysis of upper-convected Maxwell fluid along a vertical plate," *Chaos, Solitons & Fractals*, vol. 153, Article ID 111463, 2021.
[24] S. M. Khan, M. Hammad, S. Batool, and H. Kaneez, "Investigation of MHD effects and heat transfer for the upper-convected Maxwell (UCM-M) micropolar fluid with Joule heating and thermal radiation using a hyperbolic heat flux equation," *The European Physical Journal Plus*, vol. 132, no. 4, p. 158, 2017.
[25] A. Abbas, M. Ashraf, H. Ahmad et al., "Computational analysis of Darcy-Forchheimer relation, reduced gravity, and external applied magnetic field influence on radiative fluid flow and heat transfer past a sphere: finite difference method," *Heliyon*, vol. 9, no. 5, Article ID e15696, 2023.
[26] M. A. Memon, D. E. S. Sagheer, M. A. Al-Malki et al., "Squeezed Darcy–Forchheimer Casson nanofluid flow between horizontal plates under the effect of inclined magnetic field," *Nanoscale Advances*, vol. 5, no. 24, pp. 6925–6934, 2023.
[27] A. Abbas, M. B. Jeelani, A. S. Alnahdi, and A. Ilyas, "MHD Williamson nanofluid fluid flow and heat transfer past a nonlinear stretching sheet implanted in a porous medium: effects of heat generation and viscous dissipation," *Processes*, vol. 10, no. 6, p. 1221, 2022.
[28] S. Munir, A. Maqsood, U. Farooq, M. Hussain, M. I. Siddiqui, and T. Muhammad, "Numerical analysis of entropy generation in the stagnation point flow of oldroyd-B nanofluid," *Waves in Random and Complex Media*, vol. 12, pp. 1–7, 2022.
[29] J. Cui, S. Munir, U. Farooq, M. E. Rabie, T. Muhammad, and R. Razzaq, "On numerical thermal transport analysis of three-dimensional bioconvective nanofluid flow," *Journal of Mathematics*, vol. 2021, Article ID 5931989, 11 pages, 2021.
[30] K. Venkatadri, S. A. Gaffar, C. S. Babu, and S. Fazuruddin, "MHD radiative heat transfer analysis of Carreau nanofluid flow past over a vertical plate: a numerical study," *Nanoscience and Technology: International Journal*, vol. 12, no. 4, pp. 81–103, 2021.
[31] S. Rosseland, *Astrophysik und atom-theoretische Grundlagen*, Springer, Berlin, China, 1931.
[32] A. V. Kuznetsov and D. A. Nield, "Natural convective boundary-layer flow of a nanofluid past a vertical plate," *International Journal of Thermal Sciences*, vol. 49, no. 2, pp. 243–247, 2010.