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Coupled Magneto–Thermal–Diffusion Transport in an Unsteady Maxwell Polymer Fluid with Activation Energy over a Porous Stretching Surface

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Abstract

The present study investigates the combined effects of activation energy and diffusion-thermo (Dufour) processes on unsteady magnetohydrodynamic (MHD) flow, heat, and mass transfer of a Maxwell viscoelastic fluid past a porous exponentially stretching vertical sheet. The electrically conducting and incompressible polymeric fluid flows through a saturated porous medium under a transverse magnetic field. The governing momentum, energy, and concentration equations are transformed into nonlinear ordinary differential equations using similarity transformations and solved numerically using the fourth-order Runge–Kutta shooting method. The influence of key parameters such as magnetic field strength, porosity, relaxation time, activation energy, Dufour number, Prandtl number, and Schmidt number on the velocity, temperature, and concentration profiles is analyzed graphically. Additionally, the variations of the skin friction coefficient, Nusselt number, and Sherwood number are computed and presented to examine heat and mass transfer behavior. The results show that an increase in the magnetic parameter suppresses the velocity due to the Lorentz force, while higher relaxation time enhances elastic effects in the Maxwell fluid. Activation energy increases concentration distribution by reducing the chemical reaction rate, whereas the Dufour effect elevates temperature because of cross-diffusion between heat and mass transfer. These outcomes are relevant in polymer extrusion, chemical processing, geothermal systems, and thermal regulation of electrically conducting fluids in porous structures.

Keywords: Activation energy, dufour effect, magnetohydrodynamics, maxwell polymer fluid, porous medium

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INTRODUCTION

Viscoelastic non-Newtonian fluids exhibit both viscous and elastic characteristics, enabling them to store and dissipate mechanical energy during flow. These fluids play a crucial role in diverse industrial applications such as polymer processing, food manufacturing, cosmetics formulation, and pharmaceutical production, where their distinctive rheological behavior ensures improved control of mixing, coating, and extrusion processes. The combination of viscous and elastic effects allows viscoelastic fluids – such as Maxwell, Walters-B, and second-grade models – to accurately describe the mechanical response of polymeric materials and composite suspensions under varying thermal and mechanical conditions. Marinca et al. [1] examined the influence of a non-uniform heat source/sink on

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second-grade viscoelastic fluids, accounting for electromagnetic and thermal radiation effects over a stretching permeable surface, which provided a foundation for advanced modeling of coupled transport phenomena. Anupama et al. [2] analyzed the unsteady flow of non-Newtonian Walters-B and exponential fluids considering Brownian motion and thermal diffusion under a capacitive field, revealing the complexity of time-dependent polymeric behavior. Reddy et al. [3] employed machine learning-based predictive techniques to study viscoelastic non-Newtonian flow over a Riga plate with convective boundary conditions, incorporating the combined effects of electromagnetic forces and chemical convection. Sudarmozhi et al. [4] investigated Darcy–Forchheimer flow of non-Newtonian fluids through porous media under heat generation and mixed convection, emphasizing the role of permeability and heat source parameters on thermal boundary layer development.

The presence of internal heat generation plays a significant role in modifying the thermal and flow behavior of non-Newtonian fluids, particularly under magnetic and diffusive influences. Iqbal et al. [5] explored the combined impact of variable thermal conductivity and magnetic fields on the motion of non-Newtonian nanofluids, highlighting the enhancement of thermal radiation and magnetic control for potential biomedical and energy transport applications. Maxwell fluids, characterized by their microstructural viscoelasticity, incorporate internal interactions and micro-rotational dynamics, making them relevant for biomedical engineering processes such as drug delivery systems, microvascular flow modeling, and tissue engineering simulations. Alao et al. [6] examined the motion of micropolar fluids under a magnetic field across a porous plate, emphasizing the effects of viscous dissipation and nonlinear thermal radiation on heat transfer. Mishra et al. [7] analytically studied the Hall current influence on magnetohydrodynamic (MHD) flow in polar fluids, particularly focusing on natural convection phenomena induced around circular cylinders. Ahmed et al. [8] provided a comprehensive review of micropolar fluid models, incorporating magnetic flux strips to establish new perspectives in magneto-fluid dynamics. Furthermore, Al Khayer et al. [9] demonstrated that dust particulates on permeable membranes significantly affect molecular diffusivity and double stratification in viscoelastic micropolar surfaces, where Joule heating acts as a key thermal source along inclined channels. In related work, Sudarmozhi et al. [10] investigated chemical diffusion and thermal emission effects on the motion of viscoelastic fluids through absorbing media, offering insights into coupled heat and mass transfer dynamics. Tangent hyperbolic fluids – exhibiting shear-thinning behavior governed by the hyperbolic tangent constitutive model – are also vital for modeling complex polymeric and bio-viscoelastic materials, with applications in microfluidic devices, blood circulation, and drug delivery systems. Oyelami et al. [11] reported that Soret–Dufour effects and heat radiation significantly influence hyperbolic tangent fluids subjected to Joule heating over porous plates. Similarly, Kamran et al. [12] and Prajapati et al. [13] analyzed ferromagnetic hyperbolic fluid flows induced by rotating disks, demonstrating the dominance of magnetic field variations on energy and mass transport processes.

Magnetohydrodynamics (MHD) concerns the study of electrically conducting fluids influenced by magnetic fields, integrating the principles of fluid mechanics and electromagnetism. The interaction between the induced magnetic field and the motion of a conducting fluid generates a Lorentz force, which significantly alters both momentum and thermal transport characteristics. The associated Joule heating effect further modifies the temperature distribution by converting electrical energy into internal heat, thereby influencing the viscosity, conductivity, and flow structure of the medium. MHD plays a pivotal role in a wide range of scientific, industrial, and biomedical applications, including blood flow regulation, polymer extrusion, glass fiber drawing, and papermaking processes, where magnetic control can optimize product uniformity and heat dissipation. Although an applied magnetic field generally suppresses fluid motion by introducing an opposing resistive force, it also enhances energy transfer and stability across stream layers as the temperature field varies [14]. This resistive interaction – arising from the Lorentz force – is fundamental in controlling electrically conducting flows and is particularly useful for precision flow modulation in polymer processing and composite material fabrication.

The implications of MHD-based flow control extend beyond engineering to medical and energy applications, such as magnetofluid-based blood pumps, hyperthermia-assisted cancer treatment,

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electromagnetic material separation, and targeted drug delivery. Moreover, MHD principles are integral to the design of bio-microfluidic devices, MHD energy generators, and electroconductive polymer systems that require precise manipulation of heat and mass transfer processes [15]. Several researchers [16–26] have explored MHD flow phenomena under diverse physical conditions ranging from mixed convection and heat generation to reactive diffusion and porous media effects providing a robust foundation for advanced theoretical and computational analysis in polymeric and composite fluid dynamics.

The primary objective of this study is to investigate the effects of activation energy and diffusive heating on the unsteady flow of a viscoelastic fluid through a vertically stretched porous sheet. By applying similarity transformations, the governing partial differential equations (PDEs) are transformed into a system of ordinary differential equations (ODEs) while preserving the integrity of the mathematical framework. The fourth-order Runge-Kutta method combined with the shooting technique is employed to obtain numerical solutions. The influence of key flow parameters on velocity, temperature, and concentration profiles is analyzed through graphical representations, providing insights into the fluid behavior under various physical conditions.

PROBLEM FORMULATION

This study considers the bi-dimensional viscoelastic incompressible laminar flow and heat transfer of an electrically conductive viscoelastic fluid through a porous medium. The analysis incorporates the combined effects of convective boundary conditions and simultaneous convection within the system. A capacitive field is applied in the opposite direction of the fluid flow to investigate its influence on the velocity and temperature distributions. The stretched sheet velocity is represented by u and v, where c and χ are positive constants. To ensure consistency, all physical properties and governing equations are carefully evaluated.

The geometry of the problem is illustrated in Figure 1, showing the momentum, thermal, and concentration boundary layers in the porous medium. The Boussinesq approximation is applied for energy (temperature) and concentration profiles, while the governing continuity, momentum, energy, and concentration equations are formulated under the influence of chemical reactions.

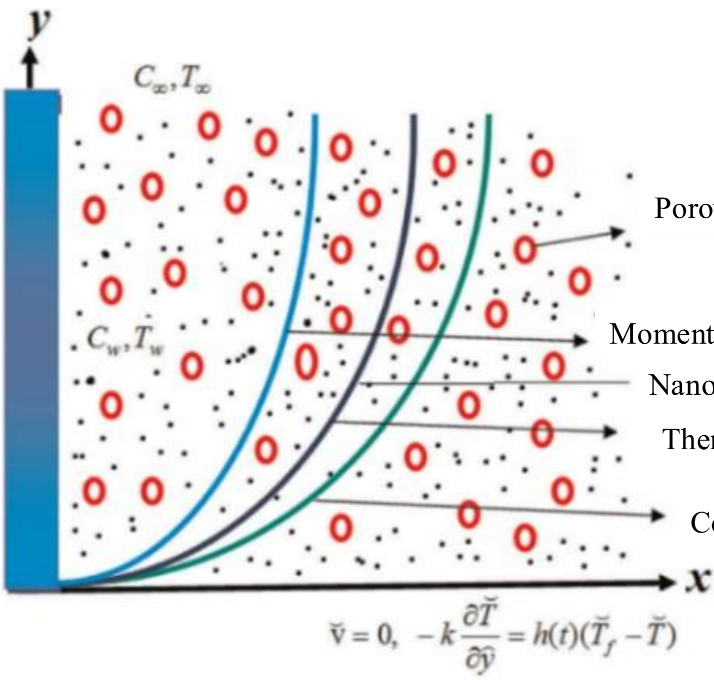

Figure 1. The problem's physical structure

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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=v\frac{\partial^2 u}{\partial y^2}-\lambda_1\left(u^2\frac{\partial^2 u}{\partial x^2}+v^2\frac{\partial^2 u}{\partial y^2}+2uv\frac{\partial^2 u}{\partial x\partial y}\right)+g\beta_T(T-T_\infty)+g\beta_C(C-C_\infty)-\sigma\frac{B_0(t)}{\alpha}-\frac{\vartheta}{k}u \tag{2}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_m\left(\frac{\partial^2 T}{\partial y^2}\right)+\frac{D_m k_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2} \tag{3}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\left(\frac{\partial^2 C}{\partial y^2}\right)--k_r^2(C-C_\infty)\left(\frac{T}{T_\infty}\right)^m exp\left(\frac{-E_a}{K^*T}\right) \tag{4}$$

The boundary conditions that are associated with the present problem are

$$u=U_w(x,t), v=0, -k\frac{\partial T}{\partial y}=h(t)\left(T_f-T_\infty\right), C=C_w \text{at} y=0 u\to 0, v\to 0, T\to T_\infty C\to C_\infty \text{as} y\to\infty \tag{5}$$

The following similarity transformations are implemented:

$$\boldsymbol{u=\frac{ax}{1-\chi t}f'(\eta), \eta=\sqrt{\frac{va}{1-\chi t}}y, \varphi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}, \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, h(t)=\frac{d}{\sqrt{1-\chi t}} v=-\sqrt{\frac{a}{(1-\chi t)}}f(\eta)} \tag{6}$$

Using similarity transformation equations (6), Equations (2) − (5) takes the form:

$$f'''-f'^2+ff''-(M+\beta)f'+\lambda(\theta+N\varphi)-\delta\left(f'+\frac{1}{2}\eta f''\right)+\Lambda\left(2ff'f''-f^2f'''\right)=0 \tag{7}$$

$$\theta''-\delta\, Pr\frac{1}{2}\eta\theta'-Pr\, f\,\theta'+Pr\, D_u\,\varphi'=0 \tag{8}$$

$$\varphi''-\delta\, Pr\frac{1}{2}\eta\varphi'-Scf\varphi'-K_E(1+\theta)^m exp\left(\frac{-E}{1+\theta}\right)\varphi=0 \tag{9}$$

These boundary conditions (5) are the ones that relate to them.

$$f(\eta)=S,\ \theta'(\eta)=-\gamma\left(1-\theta(\eta)\right), at\eta=0\ \varphi(\eta)=1, at\eta=0$$
$$f(\eta)\to 0, \varphi(\eta)\to 0\ \theta(\eta)\to 0, as\eta\to\infty \tag{10}$$

In order to circumvent the difficulty of the described issue, we take into consideration the non-dimensional similarity transformations that are listed below:

$$\delta=\frac{c}{\chi}, Q=\frac{Q_0}{\alpha\rho C_p}, \Lambda=c\lambda_1, \lambda=\left(\frac{g\beta_T(T_w-T_\infty)x}{U_w^2}\right), N=\frac{\beta_c(C_w-C_\infty)}{\beta_T(T_w-T_\infty)}, \beta=c\lambda_1, M=\frac{\sigma B_0^2}{\rho Cp},$$

$$Pr=\frac{v\rho C_p}{k}, Sc=\frac{v}{D_B}, \gamma=\left(\frac{h_f}{k}\sqrt{\frac{v}{\alpha}}\right), Du=\frac{D_M k_T(C_w-C_\infty)}{C_S C_p v a^2(T_w-T_\infty)}, \delta_1=\frac{T-T_\infty}{T_\infty}, K_E=\frac{k_r^2}{c}, E=\frac{E_a}{K^*T_\infty}.$$

PHYSICAL QUANTITIES

The skin friction coefficients, the reduced Nusselt numeral and the Sherwood numbers which are characterized, respectively, as follows:

$$Cf=\frac{\tau_w}{\rho U_w^2}, Nu_x=\frac{xq_w}{k(T_w-T_\infty)}, Sh_x=\frac{xq_m}{D_B(C_w-C_\infty)} \tag{11}$$

CODE VALIDATION

The accuracy of the present numerical results was validated by comparing the Sherwood number values with those reported by Indira and Srinivas Raju [16]. The comparison, shown in the Table 1, demonstrates excellent agreement, confirming the reliability of the computational approach.

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RESULT AND DISCUSSION

Examination of the MHD flow of viscoelastic liquid with convective perimeter layer is the focus of the study that is currently being done. Additionally taken into consideration are heat transport and viscous dissipation. Calculating the outcome that was produced allows one to demonstrate the impact of a number of relevant physical elements. As a result of these physical parameters, the conclusion is expanded by graphs 2–9, and the value of for entrenched flow variables is calculated and shown in Table 2. Figure 2 and Figure 3 both show the speed and temperature outlines for a variety numerous of the Lorentz force M. These profiles are presented in relative order. Figure 2 makes it abundantly evident that a decrease in velocity is the result of a rise in the Lorentz force M. Figure 3 illustrates the impacts of the Lorentz force, which are observed to be responsible for the elevation of the temperature profiles. As a consequence of the presence of the Lorentz force, the force that is applied to the velocity field is slowed down. As a consequence of this, the velocity profiles, which are influenced by the magnetic parameter, are decreased.

Figures 4–5 illustrate the influence of the viscoelastic liquid factor ($\wedge$) on $f'(\eta)$ and $\theta(\eta)$. The results clearly indicate a decreasing trend in $f'(\eta)$ with increasing $\wedge$, highlighting the declining behavior of the velocity field. This reduction is associated with a decrease in boundary layer thickness, as higher viscoelastic effects reduce fluid consistency and resist flow acceleration.

Figures 6–7 illustrate the impact of diffusive heating on the temperature ($\theta(\eta)$) and concentration ($\phi(\eta)$) profiles. The results indicate that as diffusive heating increases, both temperature and concentration profiles rise. This correlation highlights that a higher rate of heat transfer via diffusion leads to an overall increase in fluid temperature and species concentration, enhancing thermal energy distribution within the system.

Figure 8 illustrates the significant influence of activation energy (E) on the concentration field. The results indicate that as E increases, the concentration profile also rises. This occurs because higher activation energy weakens the Arrhenius function, slowing the reaction rate and reducing the consumption of reactive species, leading to an overall increase in concentration. Conversely, Figure 9 shows that as the chemical reaction rate (δ_1) increases, the concentration profile decreases. A higher reaction rate accelerates species depletion, resulting in a denser solute boundary layer and a sharper decline in concentration.

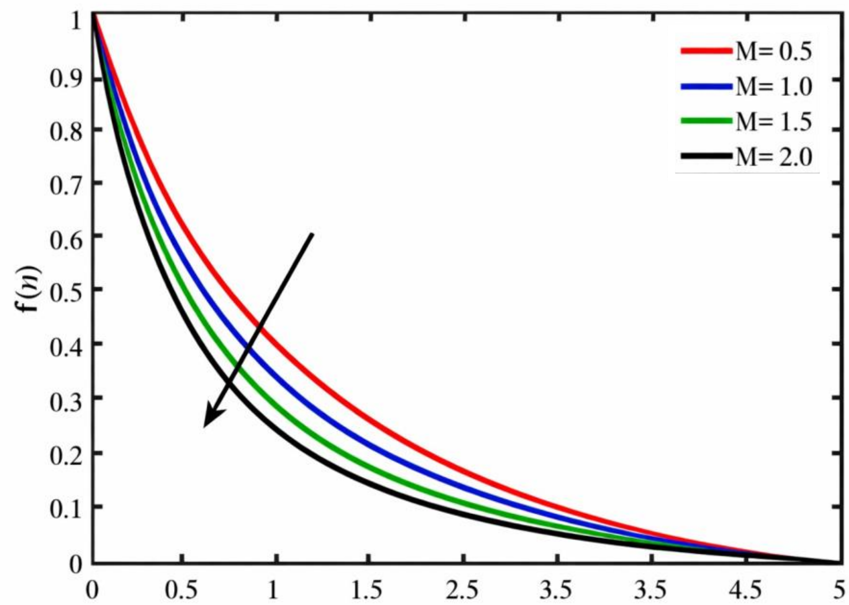

Figure 2. Effect of M on $f'(n)$

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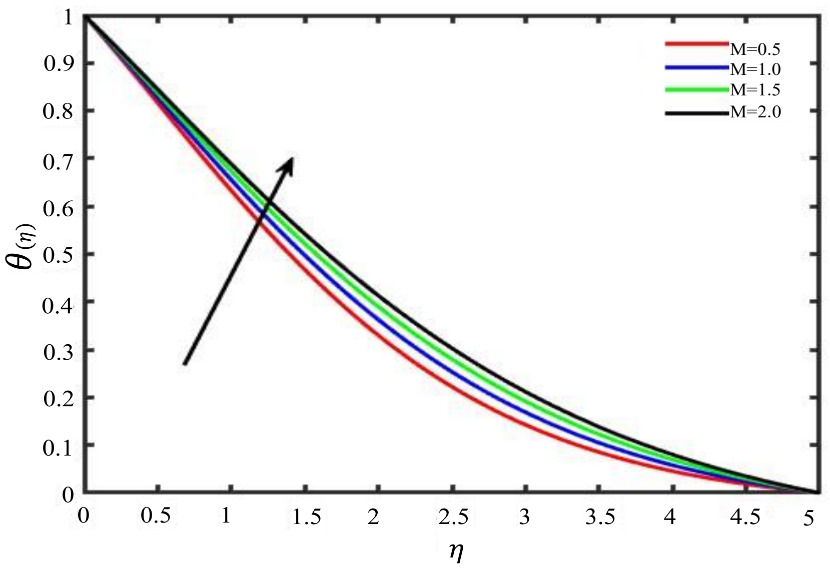

Figure 3. Effect of M on θ(n).

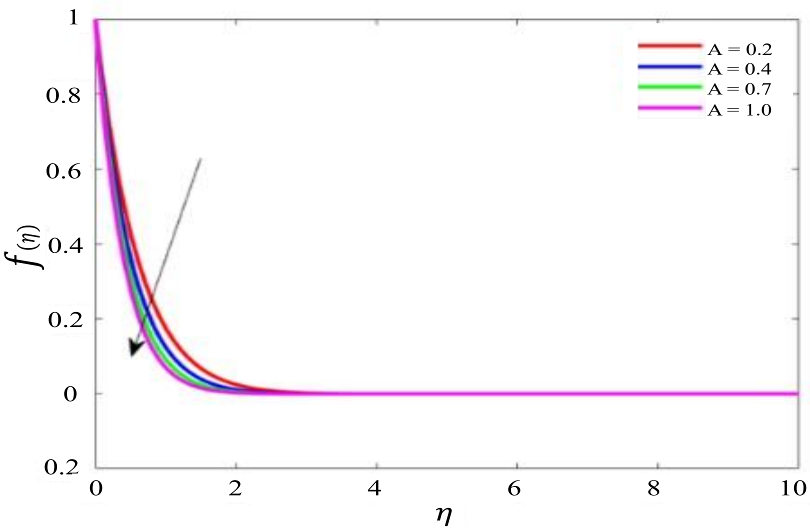

Figure 4. Effect of ʌ on f'(n).

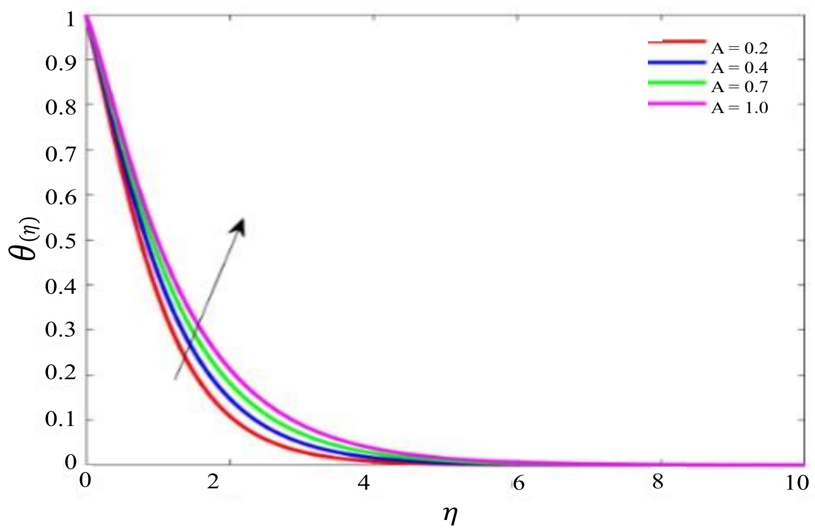

Figure 5. Effect of ʌ on θ(n).

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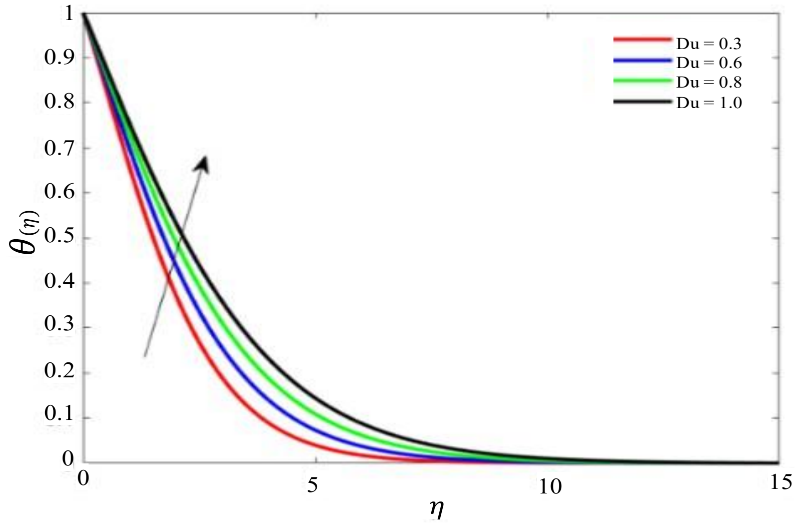

Figure 6. Effect of Du on θ(n).

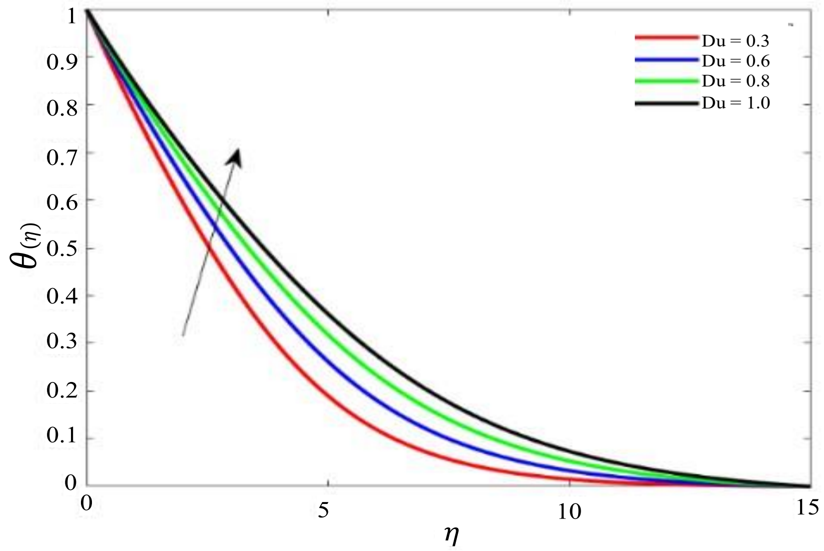

Figure 7. Effect of Du on φ(n).

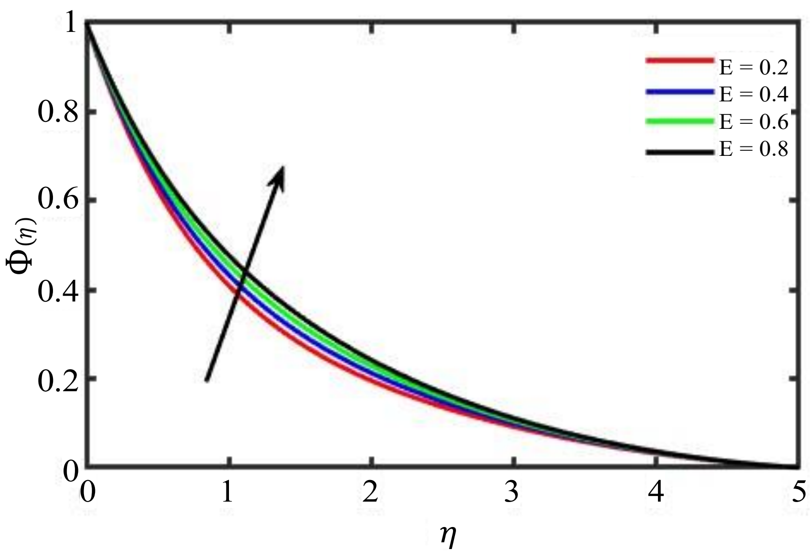

Figure 8. Effect of E on φ(n).

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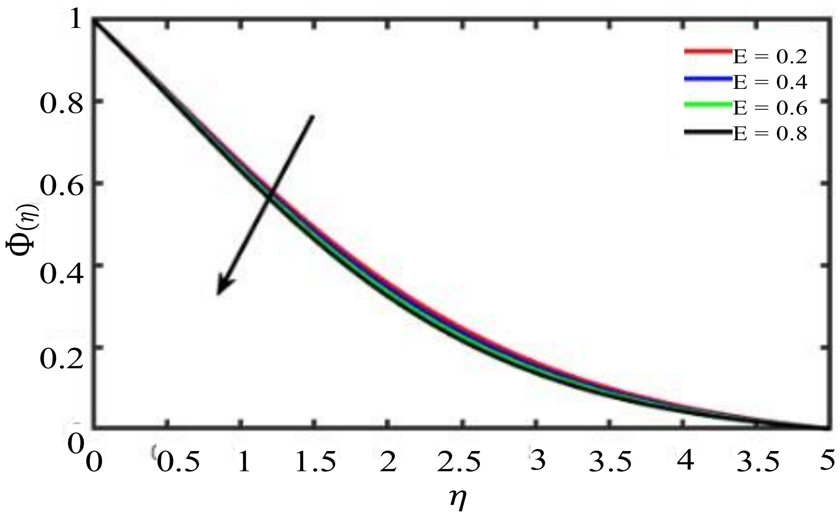

Figure 9. Effect of δ on φ(n).

Table 1. Comparison of the Present Sherwood Number with Published Sherwood Number Results for the Case E = δ_1 = 0

Sh	**Indira and Srinivasa Raju [16]**	**Present Study**
0.20	0.47563	0.47873
0.40	0.44584	0.44884
0.60	0.48473	0.48873

Table 2. Computation of $Re_x^{1/2}\, C\, f_x, Re_x^{-1/2}\, N\, u_x and\, Re_x^{-1/2}\, S\, h_x$ for different parameters.

δ	**B**	**Sc**	**E**	**Du**	**M**	**Λ**	$Re_x^{1/2}\, C f_x$	$Re_x^{-1/2}\, N u_x$	$Re_x^{-1/2}\, S h_x$
					1		1.1195	0.8972	0.2531
					2		1.4445	0.7636	0.6544
					3		1.8705	0.5434	0.9837
0.5							1.6505	0.8272	0.7384
1.0							1.1893	0.7268	0.9878
1.5							0.9905	0.5634	1.3534
	0.2						1.2343	0.9847	0.3647
	0.4						1.4282	0.7633	0.1095
	0.7						1.6298	0.5396	0.0944
		0.5					1.1085	0.1133	0.1248
		1.0					1.3595	0.1097	0.1184
		1.5					1.7154	0.0893	0.2128
			0.2				1.2503	0.1126	0.2174
			0.4				1.4929	0.1085	0.2178
			0.6				1.82387	0.0774	0.3081
				0.3			1.0086	0.7106	0.3756
				0.6			1.0475	0.6823	0.2985
				0.8			1.0985	0.6555	0.2763
						0.2	1.5134	0.1093	0.3782
						0.4	1.5993	0.0992	0.1094
						0.7	1.9183	0.0463	0.2146

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CONCLUSION

This study investigates the MHD flow of a viscoelastic fluid with a convective boundary layer, considering the effects of heat transfer, viscous dissipation, Lorentz force, diffusive heating, activation energy, and chemical reaction rate.

The results provide the following key insights:

- An increase in the magnetic parameter reduces velocity due to the resistive nature of the Lorentz force, while enhancing temperature profiles as a result of increased heat generation.
- Higher viscoelasticity leads to a decrease in velocity gradients, reducing the thickness of the boundary layer and increasing resistance to flow acceleration.
- Increased diffusive heating raises both temperature and concentration profiles, enhancing thermal energy distribution and species diffusion within the system.
- A higher activation energy weakens the reaction rate, reducing species depletion and leading to an increase in concentration levels.
- An increase in the chemical reaction rate accelerates species consumption, resulting in a denser solute boundary layer and a decline in concentration.

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