

Effect of heat generation on MHD Maxwell fluid flow on a stretching cylinder embedded in a porous medium along with impact of radiation

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ABSTRACT

This study addresses the critical problem of understanding Maxwell fluids' thermal and flow behavior in the occurrence of magnetohydrodynamics (MHD), radiation, and heat generation over a stretching cylinder, which is of significant importance in various industrial applications such as polymer processing and heat exchangers. The novelty of this work lies in its detailed exploration of the curvature parameter (α_e) and its influence on the flow dynamics, extending beyond the scope of previous literature. The governing equations, incorporating the impacts of MHD, radiation, and heat generation, are derived and subsequently simplified using similarity transformations to convert them into ordinary differential equations. These equations are then solved numerically via the bvp4c solver in MATLAB. The results are presented through tables and graphical representations to deliver clear insights into the behavior of key non-dimensional parameters. Quantitative findings reveal that the temperature profile of the fluid increases with higher heat generation and radiation, with specific enhancements observed on both flat plates (curvature parameter $\alpha_e = 0$) and cylindrical surfaces ($\alpha_e = 1$). Our results are consistent with existing studies, validating the robustness of our numerical approach.

Key Words: MHD, Maxwell fluid, radiation, stretching cylinder, porous medium, heat generation

Nomenclature

Ambient fluid Concentration	C_∞
Ambient fluid temperature	T_∞
Concentration of the fluid	C
Concentration on the wall	C_w
Curvature parameter	a_e
Deborah number	β_p
Density of the fluid	ρ
Dimensional Porosity parameter	K
Dimensional heat generation	Q_b
Dimensionless concentration	ϕ
Dimensionless heat generation	Q_p
Dimensionless radiation	R_p
Dimensionless stream function	s
Directions	z, r
Electrical Conductivity	σ
Kinematic Viscosity	γ
Local Nusselt number	Nu_x
Local Reynolds number	Re_x
MHD parameter	M_p
Mass diffusion	D_B
Maxwell fluid parameter	λ_A
Mean absorption coefficient	k^*
non-dimensional temperature	θ
Prandtl number	Pr
Reference length	L
Schmidt number	Sc
Sherwood number	Sh_x
Similarity variable	η_I
Skin friction coefficient	C_f
Specific heat	C_p
Stefan blowing parameter	Sb_m

Stefan-Boltzmann constant	σ^*
Strength of magnetic field	B_0
Surface heat flux	q_w
Temperature of the fluid	T
Temperature on the wall	T_w
Thermal conductivity	k
Thermal diffusivity	α
Thermal viscosity	μ
Velocities of the fluid	u^*, v^*

1. INTRODUCTION

Studying fluid dynamics in the presence of complex physical phenomena is crucial for advancing various engineering applications. In this context, the flow of Maxwell fluid over a cylinder provides significant perceptions into the behavior of viscoelastic fluids under different conditions. This manuscript explores the intricate interplay of several factors, including radiation heat generation, magnetohydrodynamics (MHD), and porous media, in the flow dynamics of Maxwell fluids. Radiation heat generation contributes to the thermal field, influencing the fluid's temperature distribution and overall heat transfer characteristics. Concurrently, MHD effects, driven by the interaction of the fluid with an external magnetic field, introduce additional complexities in the fluid's behavior, impacting both the velocity and temperature fields. The inclusion of a porous medium further adds to the complexity by altering the flow resistance and heat transfer characteristics.

In the field of fluid dynamics and heat transfer, extensive research has been conducted to understand the behavior of Maxwell and hybrid nanofluids under various conditions. Maxwell's foundational work in (1881) introduced a rate-type model that effectively predicts viscoelastic and stress-relaxation behaviors in materials, laying the groundwork for subsequent studies. Crane's (1975) exploration of boundary layer flow near stretched cylinders and Grubka and Bobba's (1985) investigation into energy transfer on stretching surfaces with variable temperatures further contributed to the understanding of fluid-solid interactions and heat exchange dynamics. Building on this, Wang's (1988) study on viscous liquid flow around extended hollow cylinders and Reddy Gorla and Sidawi's (1994) research

on natural convection on vertical stretching surfaces expanded the knowledge of boundary layer flows and slip effects. Ishak's (2010) work on energy boundary layer flow in micropolar fluids and Mukhopadhyay's (2012) exploration of heat transfer in time-dependent Maxwell fluid flows introduced the significant effects of radiation and heat sources in fluid dynamics.

The early 2010s saw a surge in research focusing on more complex fluid systems. Yang et al. (2013) delved into the energy conductivity of Maxwell fluids in two-phase media, while Ramzan et al. (2016) and Markin et al. (2017) explored convective flows and stagnation point heat transfer, respectively. Irfan et al. (2018) advanced the field by employing the Homotopy Analysis Method to solve flow problems involving Maxwell fluids with heat sinks. In 2019, Ahmed et al. examined heterogeneous-homogeneous reactions and non-Fourier heat flux theory in Oldroyd-B fluids, highlighting the profound influence of chemical reactions on complex fluid systems.

The 2020s introduced new dimensions to the investigation of Maxwell and hybrid nanofluids, particularly in the context of magnetohydrodynamics. Ahmed et al. (2020) investigated the MHD flow of Maxwell nanofluids, exploring radiation and convective energy transport, while Zhao (2020) focused on axisymmetric convection flow in geometrically complex scenarios. Loganathan et al. (2021) incorporated the Cattaneo-Christov model into the study of Maxwell fluids, furthering the understanding of multi-physical interactions in fluid systems. Khan et al. (2021) and Sajid et al. (2022) explored the Cattaneo-Christov theory's application to Maxwell fluid flow. Recent advances by Biswas et al. (2022, 2024) and Mandal et al. (2022, 2023) have highlighted the significant role of magnetic fields and enclosure geometries in influencing thermal performance and system irreversibility in hybrid nanofluidic systems. Manna et al. (2024) conducted a constraint-based investigation of energy transport and irreversibility in magnetic thermal systems.

1.1 Specific contributions and advancements and potential practical applications and industrial relevance

The practical implications of these findings are significant, particularly in industries where non-Newtonian fluids are used and precise thermal control is critical. For instance, in polymer processing, understanding the effects of radiation and heat generation on Maxwell

fluid behavior can enhance control over extrusion processes, improving product quality and reducing energy consumption. Moreover, the insights from this research can inform the design of more efficient heat exchangers and cooling systems that use non-Newtonian fluids, contributing to better performance and energy efficiency in various industrial applications. These contributions not only advance academic understanding but also have direct implications for improving industrial processes, demonstrating the practical significance of the study.

1.2 Novelty of this study

The extensive body of literature on Maxwell fluid dynamics has provided significant insights into boundary layer flows, energy transfer on stretching surfaces, and the effects of radiation and magnetohydrodynamics (MHD) across various geometries; however, a critical research gap remains unaddressed: none of the existing studies have investigated the collective effects of MHD, radiation, porosity, and heat generation on the flow of Maxwell fluids around cylindrical geometries. This research aims to fill that gap by thoroughly investigating these combined possessions on Maxwell fluid flow over a permeable stretching cylinder. A comprehensive comparison with existing literature validates the accuracy of our findings and highlights the consistency of our methodology. Furthermore, our study examines the effects of these parameters on both flat plates and cylindrical geometries, offering a holistic perspective on how they shape flow dynamics in different contexts.

2. MATHEMATICAL MODELLING

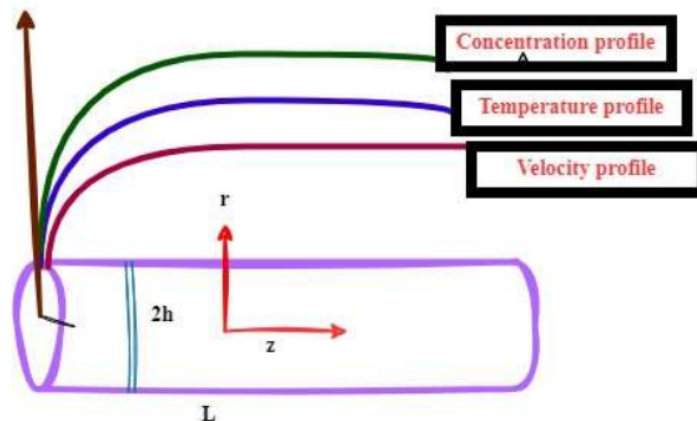


Figure 1 Schematic diagram for horizontal diagram

Consider a 2D steady flow of the MHD Maxwell fluid across a stretching cylinder of diameter '2h' implanted in a permeable medium. The MHD is useful perpendicular to the cylinder axis. The cylinder has the velocity $u_d z/L$ along the z direction; here, u_d means the velocity, and L means the specific length. Energy and concentration of the Maxwell fluid are constant at the cylinder's surface $T=T_\infty$ and $C=C_\infty$. Let (z, r) be cylindrical polar coordinates. So that the axis is parallel to the cylinder's axis and the r -axis is constrained along the radial direction. Viscous dissipation is neglected because, in typical engineering scenarios with moderate velocities and common fluids like air or water, the heat generated by viscous forces is minimal compared to conduction and convection. These assumptions simplify the governing equations while still accurately representing the essential physics of the system. From Irfan et al. [9],

2.1 Continuity equation in dimensional form

$$(ru^*)_r + (rv^*)_z = 0 \quad (1)$$

2.2 Momentum equation in dimensional form

$$u^* v_r^* + v^* v_z^* + \lambda_4 [v^{*2} v_{zz}^* + u^{*2} v_{rr}^* + 2v^* u^* v_{zr}^*] = \nu \left[v_{rr}^* + \frac{v_r^*}{r} \right] - \frac{\sigma B_0^2}{\rho} [\lambda_4 u^* v_r^* + v^*] - \frac{\nu v^*}{K} \quad (2)$$

2.3 Energy equation in dimensional form

$$u^* T_r^* + v^* T_z^* = \alpha_e \left[T_{rr}^* + \frac{T_r^*}{r} \right] + \frac{16\sigma^* T_\infty^3 T_{rr}^*}{3(\rho c p) k^*} + Q_b (T - T_\infty) \quad (3)$$

2.4 Concentration equation in dimensional form

$$u^* C_r^* + v^* C_z^* = D_B \left[C_{rr}^* + \frac{C_r^*}{r} \right] \quad (4)$$

2.5 Boundary conditions with the effect of Stefan parameter

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$$u^* = u_w^*, v^* = \frac{-D_B C_r}{1 - C_w}, T = T_w, C = C_w \text{ at } r = h, \quad (5)$$

$$u^* \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty, \text{ at } r \rightarrow \infty \quad (6)$$

2.6 Similarity variables and non-dimensional quantities

$\phi(\eta_1) = \frac{C - C_\infty}{C_w - C_\infty}$ represents the dimensionless concentration, this parameter normalizes the concentration profile, making it independent of the specific concentrations involved.

$$v^* = \frac{zu_d^*}{L} s'(\eta_1), u^* = -\frac{h}{r} \sqrt{\frac{vu_d^*}{L}} s(\eta_1)$$

The specific forms of u^* and v^* in your equations are tied to the similarity solutions used to reduce the complexity of the problem.

$\theta(\eta_1) = \frac{T - T_\infty}{T_w - T_\infty}$ denotes the temperature, where is the temperature at a point, T_∞ means the ambient temperature, and T_w is the temperature at the boundary.

$\eta_1 = \sqrt{\frac{u_d^*}{Lv}} \left(\frac{r^2 - h^2}{2h} \right)$ is a similarity variable that combines spatial coordinates and flow properties, simplifying the governing equations by reducing the number of independent variables.

$\text{Pr} = \frac{\nu}{\alpha}$ indicates the relative thickness of the velocity boundary layer to the thermal boundary layer.

$\alpha = \left(\frac{Lv}{u_d h^2} \right)^{\frac{1}{2}}$ represent a ratio involving characteristic lengths, velocities, and fluid properties, typically seen in scaling analyses.

$M_p = \frac{\sigma B_0^2 L}{\rho u_d^*}$ signifies the ratio of magnetic force to inertial force in magnetohydrodynamic (MHD) flows.

$\phi_p = \frac{\nu L}{K u_d^*}$ represents the influence of a permeable medium on the flow, where K denotes the permeability of the medium.

$\beta_p = \frac{\lambda_4 u_d^*}{L}$ represents the Maxwell fluid, which personifies the viscoelastic behavior of the fluid.

$Sb_m = \frac{C_w - C_\infty}{1 - C_w}$ relates to phase change processes, such as melting or solidification, where the concentration gradient drives the phase change.

$Sc = \frac{\nu}{D_B}$ is the ratio of momentum diffusivity (kinematic viscosity ν) to mass diffusivity (D_B).

$R_p = \frac{16\sigma^* T_\infty^3}{3kk^*}$ is radiation parameter quantifies the relative contribution of radiation to the overall heat transfer process.

2.7 Dimensionless momentum equation

From (2) to (6), take the following form.

$$(1 + 2\eta_1\alpha)s''' + 2\alpha s'' - s'^2 + s s'' + 2\beta_p s s' s'' - \beta_p s^2 s''' - \frac{\alpha\beta_p}{(1 + 2\eta_1\alpha)} s^2 s'' - M_p [s' - \beta_p s s''] - \phi_p s' = 0 \quad (7)$$

2.8 Dimensionless energy equation

$$\left[(1 + R_p)(1 + 2\eta_1\alpha) \right] \theta'' + 2(1 + R_p)\alpha \theta' + Pr s \theta' + Pr Q_p \theta = 0 \quad (8)$$

2.9 Dimensionless concentration equation

$$(1 + 2\eta_1\alpha)\phi'' + 2\alpha\phi' + Sc s\phi' = 0 \quad (9)$$

2.10 Dimensionless boundary condition

$$s(0) = \frac{Sb_m}{Sc} (1 + 2\eta_1\alpha) \phi'(0), s'(0) = 1, \theta(0) = 1, \phi(0) = 1$$

$$s'(\infty) = 0, \theta(\infty) = 0, \phi(\infty) = 0 \quad (10)$$

2.11. Skin Friction Coefficient

$$C_f = \frac{\tau_w}{\rho u_d^2} = Re_x^{-\frac{1}{2}} s''(0) \quad (11)$$

2.12 Nusselt Number

$$Nu_x = \frac{zq_w}{k(T_w - T_\infty)}, q_w = -k \frac{\partial T}{\partial r} \Big|_{r=h}, \quad Nu_x Re_x^{-\frac{1}{2}} = -\theta'(0) \quad (12)$$

2.13. Sherwood Number

$$Sh_x = \frac{zj_x}{D_B(C_w - C_\infty)}, j_x = -D_B \frac{\partial C}{\partial r} \Big|_{r=h}, \quad Sh_x Re_x^{-\frac{1}{2}} = -\phi'(0) \quad (13)$$

3. SOLUTION METHOD

The MATLAB function `bvp4c` is designed ³⁵ for solving boundary value problems for ODEs. It is particularly useful when the boundary conditions are specified at more than one point. `bvp4c` uses a collocation method to approximate the solution, making it suitable for both linear and nonlinear problems. Converting a nonlinear PDE into a linear form simplifies the problem, as linear equations are generally easier to solve analytically or numerically. Linearization often allows the use of established solution methods, ensures stability in numerical approaches, and makes the behavior of the system more predictable, hence the preference for linear forms in many practical scenarios.

$$s = O_1, s' = O_1' = O_2, s'' = O_2' = O_3, s''' = O_3',$$

$$\phi = O_6, \phi' = O_6' = O_7, \phi'' = O_7'$$

$$\theta = O_4, \theta' = O_4' = O_5, \theta'' = O_5',$$

The simplified governing equations can be expressed as

$$O_3' = \left[\frac{-2\alpha O_3 + O_2^2 - O_1 O_3 - 2\beta_p O_1 O_2 O_3 + \frac{\alpha\beta_p}{(1+2\eta_1\alpha)} O_1^2 O_3 + M_p [O_2 - \beta_p O_1 O_3] + \phi_p O_2}{(1+2\eta_1\alpha) - \beta_p O_1^2} \right] \quad (14)$$

$$O_5' = \frac{(-2(1+R_p)\alpha O_5 - Pr O_1 O_5 - Pr Q_p O_4)}{[(1+R_p)(1+2\eta_1\alpha)]} \quad (15)$$

$$O_7' = \frac{(-2\alpha O_7 - Sc O_1 O_7)}{(1+2\eta_1\alpha)} \quad (16)$$

3. VALIDATION

A significant correlation was identified when the data were verified by comparison with publicly accessible information, as demonstrated in Table. 1. Table 2 displays the numerical data for the Nu_x for distinct Pr values when chemical reaction and Brownian motions are zero in previous work of [24], our current work got good agreement. Table. 3 reveals that the skin friction profile increases with higher values of the MHD parameter, curvature parameter, and porosity parameter, while it shows a slight increase with the radiation parameter. The Nusselt number profile decreases with increasing values of the MHD parameter, curvature parameter, and porosity parameter, but increases with the radiation parameter. In contrast, the Sherwood number profile decreases as the MHD parameter and porosity parameter increase, while it increases with the curvature parameter and remains almost unchanged with variations in the radiation parameter.

M_p	Ahmed et al. [1]	Ahmed et al. [2]	Outcomes of this study
0.5	1.224745	1.224742	1.224745
1.0	1.414213	1.414213	1.414214
1.5	----	1.581136	1.581139
2.0	----	1.732045	1.732051
5.0	2.449474	2.446251	2.449490

Table. 1 Comparing the skin friction coefficient across various studies using different values for M_p while $\alpha_c = 0 = \beta_p$

Pr	RK45 Ref [24]	The outcome of this work
0.72	0.463145	0.463144
1	0.581978	0.581977
3	1.165253	1.165252
10	2.308025	2.308024
100	7.765899	7.765900

Table. 2 Comparison of Nusselt number for various Pr values

M_p	α_e	Sb_p	$\beta_p \phi_p$	R_p	$f''(0)$	$Nu_x Re_x^{-1}$	$Sh_x Re_x^{-1}$
0					1.70000	1.100396	1.002545
0.5					1.851437	1.048885	0.985034
2					2.242775	0.920616	0.945668
4					2.673555	0.793845	0.910683
	0				1.804788	0.943040	0.949326
	0.3				1.941746	0.599271	1.056166
	0.5				2.028778	0.468244	1.126356
	1				2.235357	0.365284	1.297585
		0			1.862967	0.977521	1.045743
		0.5			1.821397	0.337413	0.809416
		1			1.801882	0.206791	0.673391
		2			1.785161	0.764412	0.518718
			0		1.827097	0.842770	0.989704
			0.2		1.851434	0.821432	0.985035
			0.3		1.863505	0.810711	0.982755
			0.4		1.875506	0.799956	0.980512
				0	1.851434	0.352602	0.985035
				0.5	1.851434	0.618035	0.985035
				1	1.851434	0.821432	0.985035
				2	1.851435	1.069522	0.985035

Table. 3 Results of C_f , Nu_x , Sh_x for various values of parameters

5. RESULTS AND DISCUSSIONS

Figure 2 demonstrates the influence of the (M_p) magnetohydrodynamic parameter on the velocity, temperature, and concentration outlines. As the M_p increases, the profile demonstrates a declining trend. This behavior can be attributed to the presence of a magnetic field, which exerts a Lorentz force that opposes the flow of the fluid, thereby reducing the fluid's velocity. The magnetic field effectively acts as a resistive force, slowing down the movement of charged particles in the fluid, leading to a reduction in the velocity outline. Conversely, the temperature outline exhibits an increasing trend with the rise in the M_p . The magnetic field's influence on the

charged particles within the fluid causes an increase in Joule heating, which is the dissipation of electrical energy into heat.

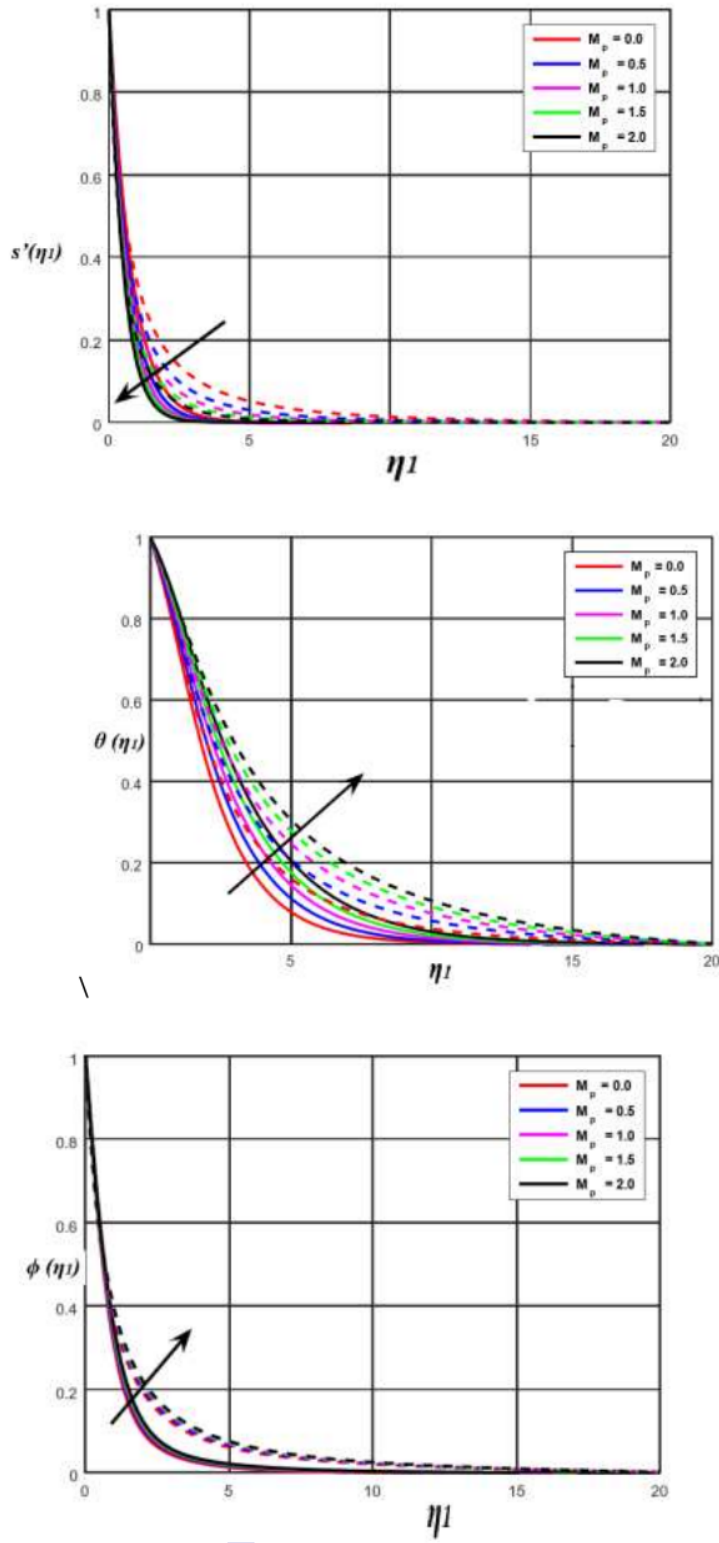


Figure 2. Impact of M_p on velocity, temperature and concentration profiles

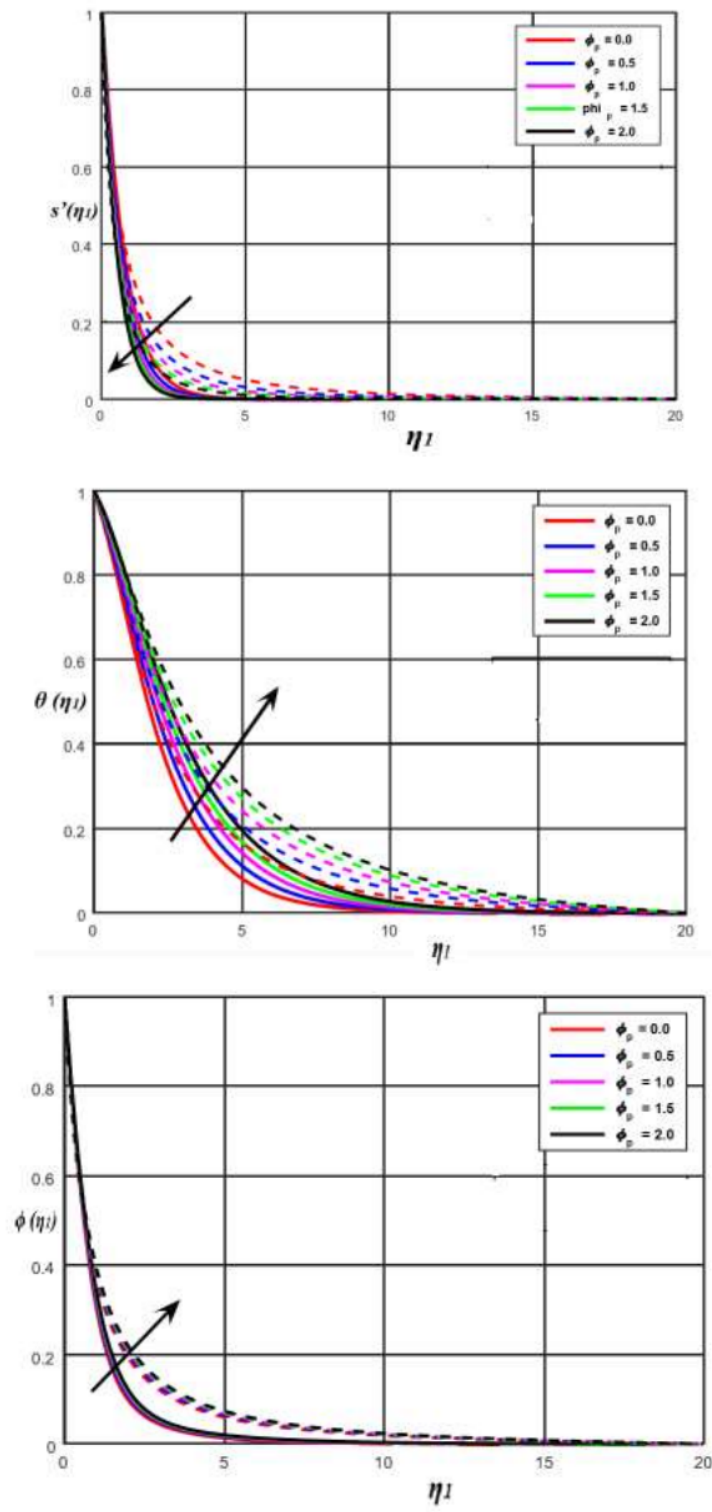


Figure 3. Impact of porosity parameter on velocity, temperature and concentration profile

Figure 3 depicts the impact of the porosity parameter (ϕ_p) on the velocity, temperature, and concentration outlines. As the ϕ_p increases, the profile shows a declining trend. This behavior is due to the increased resistance to fluid flow in a permeable medium. The porous structure hinders the movement of the fluid, creating more frictional resistance, which slows down the velocity of the flow through the medium. The higher the ϕ_p , the more pronounced this effect becomes, leading to a significant reduction in velocity. In contrast, the temperature outline rises with a surge in the ϕ_p . The reduced fluid velocity means that the fluid has more time to absorb and retain heat as it moves through the porous medium. Similarly, the concentration outline also increases with higher values of the porosity parameter. The slower fluid movement allows for more time for mass diffusion processes to occur within the medium. The porous structure can also facilitate greater mixing and diffusion of species, contributing to a surge in the concentration outline. As the fluid flow slows, the diffusion of particles becomes more effective, leading to a higher concentration of species within the fluid. This highlights the intricate relationship between fluid dynamics, heat transfer, and mass transfer in porous media systems.

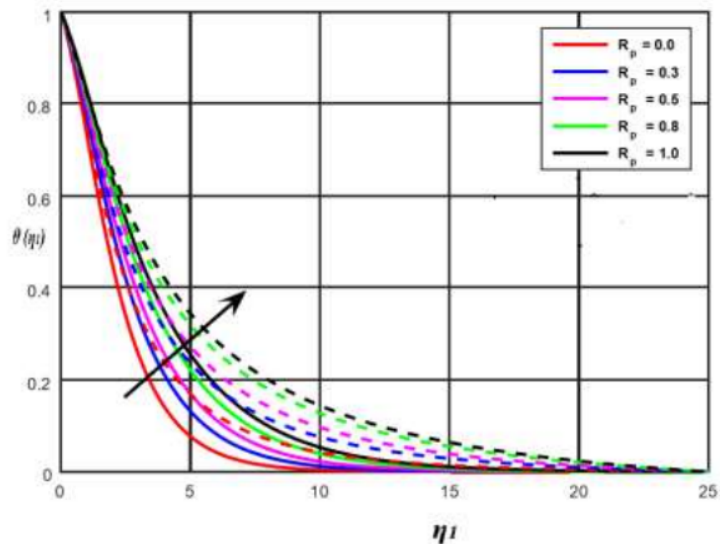


Figure. 4 Impact of radiation parameter on temperature profile, here solid line is for flat plates, curvature parameter $\alpha_e = 0$ and the dashed line is for cylindrical surfaces $\alpha_e = 1$

Figure 4 illustrates the effect of the radiation parameter (R_p) on the temperature outline, showing an upward trend as the radiation parameter increases. This behavior can be explained by the enhanced radiative heat transfer within the fluid. As the radiation parameter rises, the fluid absorbs more thermal energy from radiative sources, leading to an surge in the

overall temperature. The heightened radiation contributes to a thicker thermal boundary layer and greater heat retention, resulting in a more pronounced rise in the temperature profile.

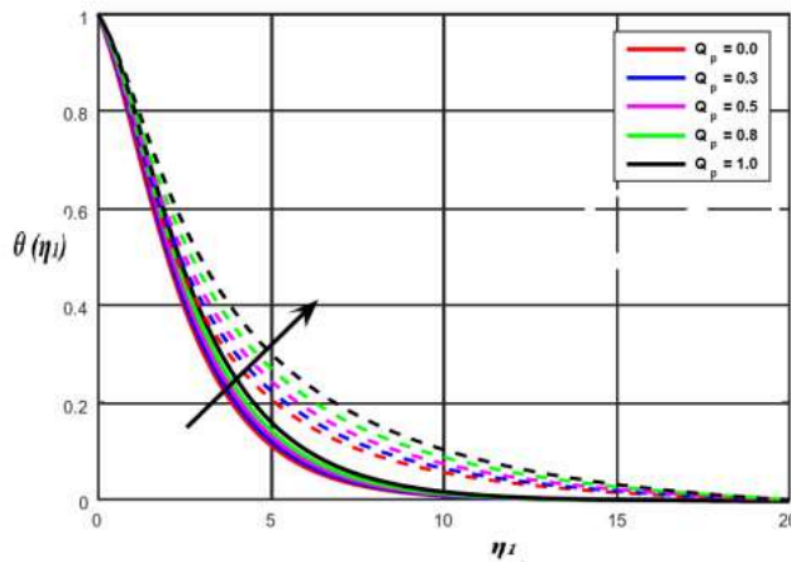


Figure 5 Impact of heat generation parameter on temperature profile, here solid line is for flat plates, curvature parameter $\alpha_e = 0$ and the dashed line is for cylindrical surfaces $\alpha_e = 1$

Figure 5 demonstrates the impact of the heat generation parameter Q_p on the temperature outline, which shows a swelling trend as the heat generation parameter rises. This effect occurs because the internal heat generation within the fluid adds thermal energy, thereby raising the overall temperature. As the Q_p increases, more heat is produced within the fluid, leading to a thicker thermal boundary layer and an elevated temperature profile. The additional heat generated enhances the fluid's capacity to retain thermal energy, resulting in the observed increase in temperature. This demonstrates the crucial role of internal heat generation in shaping the thermal behavior of the fluid.

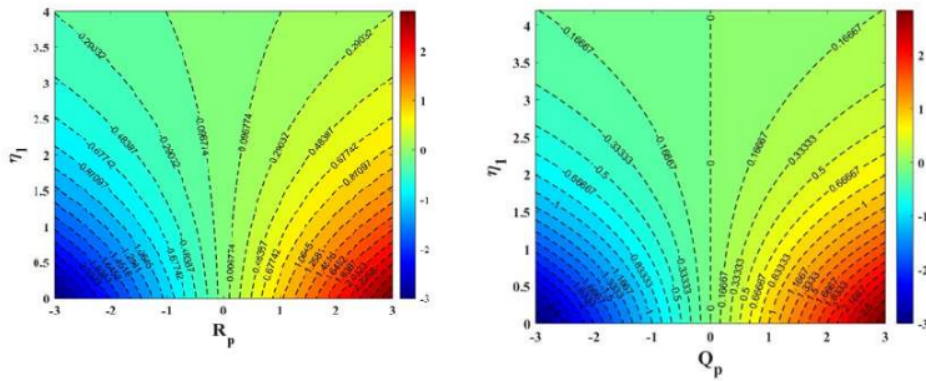


Figure. 6 Impact of radiation parameter $R_p=2$ and heat generation parameter $Q_p=0.5$ on Isotherm contour

Figure 6 shows the impact of $R_p=2$ and the heat generation parameter $Q_p=0.5$ on the isotherm contours. The isotherm contours exhibit a significant rise in temperature due to the combined effects of R_p and internal Q_p . The radiation parameter enhances radiative heat transfer within the fluid, increasing the thermal energy absorbed and retained by the fluid. Simultaneously, the heat generation parameter contributes additional thermal energy from within the fluid, further elevating the temperature.

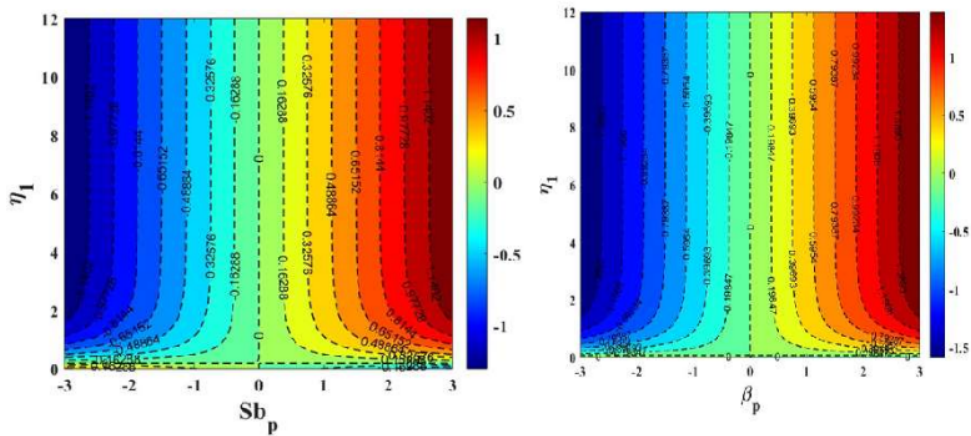


Figure. 7 Impact of Stefan parameter $Sb_p=0.4$ and Maxwell fluid parameter $\beta_p=0.4$ on streamline contour

Figure 7 illustrates the impact of the Stefan parameter $Sb_p=0.4$ and the Maxwell fluid parameter $\beta_p=0.4$ on the streamline contours. The streamline patterns show noticeable changes due to the combined influence of these parameters. The Stefan parameter, associated with phase change phenomena, affects the fluid's flow characteristics by altering the energy transfer and energy distribution within the system. Concurrently, the β_p , which characterizes the viscoelastic nature of the fluid, influences the fluid's deformation and flow behavior. Together, these parameters create a more complex flow pattern, reflected in the streamlined contours. The viscoelastic nature of the Maxwell fluid, combined with the heat transfer effects driven by the Stefan parameter, leads to a more intricate and modified flow structure within the fluid.

6. CONCLUSIONS

The primary aim of this manuscript was to examine the thermal and flow behavior of Maxwell fluids under the impact of magnetohydrodynamics, R_p , and Q_p over a stretching cylinder. The study specifically focused on understanding how the curvature parameter impacts these dynamics, with the results providing significant insights relevant to industrial applications such as polymer processing and heat exchangers. The governing equations were derived, shortened using similarity transformations, and solved numerically using bvp4c solver. The key findings are summarized here.

- Increasing the magnetic parameter reduces velocity due to the Lorentz force, while temperature and concentration profiles rise from enhanced Joule heating and diffusion.
- Higher porosity decreases velocity due to added resistance, but temperature and concentration increase, indicating extended heat retention and diffusion.
- Radiation parameter increases the temperature profile, enhancing heat transfer and thickening the thermal boundary layer.
- Similarly, higher heat generation elevates temperature due to internal heat production, thickening the boundary layer.
- Combined effects of radiation and heat generation significantly raise temperature contours.
- Stefan and Maxwell parameters create a complex flow pattern, influenced by phase change and viscoelastic effects.
- This study provides insights into the combined impact of these parameters on Maxwell fluid flow, aiding in process optimization.

Future work

Future work could include studying non-Newtonian fluids with variable properties under MHD, radiation, and heat generation. Exploring time-dependent boundary conditions, transient heat transfer, and multi-phase flow dynamics would offer deeper insights. Three-dimensional analysis and experimental validation would further improve the accuracy and applicability of the findings for industrial processes.

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Conflicts of Interest: The authors declare no conflict of interest.

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