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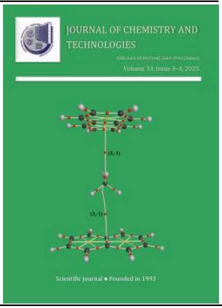

UDC 517.9 + 54.4

MODELING FLOW DYNAMICS OF CHEMICALLY REACTING MAXWELL FLUIDS OVER POROUS STRETCHING SHEETS

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Abstract

This study explores the flow dynamics of chemically reacting Maxwell fluids over porous stretching sheets, focusing on the interplay between fluid rheology, chemical kinetics, and porous media effects. It analyzes the influence of the viscoelastic properties of a fluid on momentum and concentration of boundary layers, considering chemical reactions and the permeability of the stretching sheet. The mathematical model accounts for the non-Newtonian nature of the Maxwell fluid, reaction kinetics, and porous medium resistance. Numerical solutions explore the effects of key parameters on velocity, concentration profiles, heat, and mass transfer rates. The findings offer insights into coupled transport phenomena in engineering processes involving non-Newtonian fluids, chemical reactions, and porous media. Dimensionless problems are numerically solved using the Runge-Kutta approach. The study focuses on important engineering parameters that affect velocity, concentration, and temperature profiles. Quantitative values of engineering factors such as skin-friction, Sherwood number, and Nusselt number coefficients are presented, and the results are analyzed using graphics and tabular representations. For program code validation, a numerical comparison with previously released data is provided.

Keywords: Maxwell fluid; Stretching sheet; Nanofluid; Chemical reaction; R-K technique; Porous medium**.**

МОДЕЛЮВАННЯ ДИНАМІКИ ПОТОКУ ХІМІЧНО РЕАГУЮЧИХ РІДИН МАКСВЕЛЛА НА ПОРИСТИХ РОЗТЯЖНИХ ЛИСТАХ

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Анотація

У цьому дослідженні вивчається динаміка потоку хімічно реактивних рідин Максвелла над пористими розтяжними листами, з акцентом на взаємодію між реологією рідини, хімічною кінетикою та ефектами пористого середовища. Аналізується вплив в'язкопружних властивостей рідини на імпульс і концентрацію примежових шарів з урахуванням хімічних реакцій і проникності розтяжного листа. Математична модель враховує неньютонівську природу рідини Максвелла, кінетику реакції та опір пористого середовища. Чисельні рішення досліджують вплив ключових параметрів на швидкість, профілі концентрації, тепло та швидкість масопереносу. Отримані результати дають уявлення про сполучені транспортні явища в інженерних процесах, що включають неньютонівські рідини, хімічні реакції та пористі середовища. Безрозмірні задачі чисельно вирішуються за допомогою методу Рунге-Кутта. Дослідження зосереджується на важливих інженерних параметрах, що впливають на профілі швидкості, концентрації та температури. Наводяться кількісні значення інженерних факторів, таких як коефіцієнти тертя об поверхню, число Шервуда та число Нуссельта, а результати аналізуються за допомогою графіків та таблиць. Для перевірки коду програми наводиться чисельне порівняння з раніше опублікованими даними.

Ключові слова: рідина Максвелла; розтяжний лист; нанорідина; хімічна реакція; метод Р-К; пористе середовище.

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Introduction

Advanced heat transfer fluids, or nanofluids, have been the focus of much study for almost 20 years. However, despite their complexity, there is disagreement about their potential benefits. The difficulties in formulating, implementing, and comprehending heat transfer processes restrict the practical use of nanofluids. One of the biggest technical challenges is optimizing the size and shape of nanoparticles. Future studies should examine the effects of viscosity and wettability, which are variables other than thermal conductivity, on fluid dynamics and thermal energy transfer. Nanofluids are synthesized using solid particles, which can be metallic (e.g., gold, silver, copper) or non-metallic (e.g., alumina, silica, titanium dioxide). Metallic liquids, such as sodium, can also be employed.

Njane-Mutuku and Makinde [1] investigated nanofluid flow over a permeable surface with Newtonian heating under MHD boundary layer conditions. Sheikholeslami [2] presented a novel numerical methodology for analyzing MHD nanofluid flow in a porous enclosure. Further studies, such as those by Sheikholeslami et al. [3], Chamkha et al. [4; 5], Rashad et al. [6; 7], Sivasankaran et al. [8], Rokni and Sheikholeslami [9], Muhammad et al. [10], Sreenivasulu et al. [11], Zaidi et al. [12], and Ibrahim and Negera [13], have explored diverse aspects of nanofluid behavior under various conditions, including mixed convection, non-Newtonian fluids, thermal radiation, and magnetic fields. Behseresht [14] examined the influence of thermophoresis and Brownian motion on natural convection heat transfer of nanofluids near a vertical cone in a saturated porous medium, employing numerical methods such as the Runge-Kutta method. Several recent studies have further assessed the practicality and efficacy of nanofluids (references [15–23]), expanding on earlier studies (references [24–27]) and utilizing solutions for heat and mass transport concerns caused by MHD (references [28–30]).

This work investigates how MHD Maxwell nanofluid flow on a stretched surface is affected by velocity and concentration slip, incorporating chemical reactions and porous media effects. Expanding on prior research, the analysis emphasizes thermophoresis, Brownian motion, and chemical interactions under magnetic and porous conditions. The mathematical model was computationally solved through an optimized numerical approach combining fourth-order Runge-Kutta integration with an iterative shooting algorithm. This sophisticated dual-method technique enabled precise solution convergence while maintaining computational efficiency for the complex boundary value problem under investigation. The implementation incorporated adaptive step-size control to ensure solution accuracy across all parametric variations studied. Graphical results illustrate key trends, with atypical cases examined to confirm accuracy. The findings enhance understanding of nanofluid dynamics, offering valuable insights for hydrodynamic applications, including lubrication theory, thermo-bio convection, and oil reservoir modeling. This research provides a foundation for future studies on complex fluid behaviors in industrial and thermal systems.

Flow governing equations and their formulation

The present work investigates steady, two dimensional incompressible, viscous electrical conducting nanofluid flow, chemical reactions, velocity and concentration slip results, and surface stretching in the presence of a magnetic field.

The governing equations are given below:
Continuity Equation:

$$(u_x)+(u_y)=0 \tag{1}$$

Momentum equation

$$\begin{aligned} u(u_x)+v(u_y) &= -\frac{1}{\rho}(p_x)+v(u_{yy})-\left(\frac{\sigma B_0^2}{\rho}\right)u-v\left(\frac{u}{k_1}\right) \\ &\quad -\beta\left[u^2(u_{xx})+v^2(u_{yy})+2xy(u_{xy})\right] \end{aligned} \tag{2}$$

Equation of thermal energy:

$$u(T_x)+v(T_y)=(T_{yy})\alpha+\tau_B\left[(C_y)(T_y)D_B+\frac{D_T}{T_\infty}(T_y)^2\right] \tag{3}$$

equation for nanoparticle concentration distribution

$$u(C_x)+v(C_y)=(C_{yy})D_B+\left(\frac{D_T}{T_\infty}\right)(T_{yy})+Kr(C_\infty-C) \tag{4}$$

Maxwell-nanofluid flow's boundary conditions are

$$\left.\begin{array}{l} u \equiv u_w(x) = a * x + L_1(u_y), v \equiv 0, -\kappa(T_y) = (T_f - T)_f, C \equiv C_w + L_2(C_y) \quad at \quad y \equiv 0 \\ u \to 0, v \to 0, T \to T_\infty \quad as \quad y \to \infty \end{array}\right\} \quad (5)$$

Introducing the following similarity transformations

$$\left.\psi = \sqrt{a\nu}xf(\eta), \eta = y\sqrt{\frac{a}{\nu}}, \theta = \frac{T - T_\infty}{T_f - T_\infty}, \phi = \frac{C - C_\infty}{C_w - C_\infty}\right\} \quad (6)$$

Using standard boundary layer theory, a large-scale analysis of the transverse momentum equation was performed to determine the dominant terms by comparing characteristic values.

$u >> v \Rightarrow u_x, v_x, v_y$ Shows that $p_x = 0$ (7)

Under the above conditions, the governing equations will take the following forms:

$$f''' + ff'' - Mf' - (f'^2) - Kf' - \lambda(f^2 f'' - 2ff'f'') = 0 \quad (8)$$

$$\theta'' + Pr\, f\, \theta' + Pr\, N\, b\theta'\phi' + Pr\, N\, t(\theta')^2 = 0 \quad (9)$$

$$Nb\phi'' + LeNb\, Pr\, f\, \phi' + Nt\theta'' - Nb\gamma\phi = 0 \quad (10)$$

The governing boundary conditions for equation (6) are formulated as follows:

$$\left.\begin{array}{l} f(0) = 0, f'(0) = 1 + \chi f''(0), \theta'(0) = -Bi(1 - \theta(0)), \phi(0) = 1 + \delta\phi'(0) \\ f'(\infty) \to 0, \theta(\infty) \to 0, \phi(\infty) \to 0 \end{array}\right\} \quad (11)$$

Engineering parameters concerned are

$$\left.\begin{array}{l} Pr = \frac{\nu}{\alpha}, Le = \frac{\nu}{D_B}, Nb = \frac{(\rho c)_p D_B (C_w - C_\infty)}{(\rho c)_f \nu}, Nt = \frac{(\rho c)_p D_T (T_f - T_\infty)}{(\rho c)_f \nu T_\infty}, Bi = \frac{hx}{\kappa}\sqrt{\frac{\nu}{a}}, \\ M = \frac{\sigma B_o^2}{a\rho}, K = \frac{ak_1}{\mu}, \chi = L_1\sqrt{\frac{a}{\nu}}, \delta = L_2\sqrt{\frac{a}{\nu}}, \lambda = k_o a, \gamma = \frac{Kr}{a} \end{array}\right\} \quad (12)$$

Quantities of physical interest

$$C_f = (\lambda + 1)\frac{\tau_w}{\rho U_w} \Rightarrow Re_x^{\frac{1}{2}} C_f = f''(0)(\lambda + 1)$$

$$Nu_x = \frac{xq_w}{\kappa(T_w - T_\infty)} \text{ where } q_w = -\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0} \Rightarrow Re_x^{-\frac{1}{2}} N u_x = -\theta'(0) \quad (13)$$

$$Sh_x = \frac{xq_m}{D_B(T_w - T_\infty)} \text{ where } q_m = -D_B\left(\frac{\partial C}{\partial y}\right)_{y=0} \Rightarrow Re_x^{-\frac{1}{2}} S h_x = -\phi'(0)$$

Methods

The study employs an advanced computational scheme to solve the governing equations (8)-(10) with boundary conditions (11). The infinite physical domain $[0, \infty)$ is truncated to a finite computational domain while maintaining solution accuracy. The higher-order differential equations are systematically reduced to a system of seven first-order equations through strategic variable transformations:

$$f = y_1;\, f' = y_2;\, f'' = y_3; \theta = y_4; \phi = y_5; \phi' = y_7.\} \quad (14)$$

A sophisticated numerical framework combining fourth-order Runge-Kutta integration with an adaptive shooting algorithm is implemented. This approach converts the boundary value problem to an initial value formulation, utilizes the MAPLE's computational environment for efficient solution, and incorporates an iterative procedure to satisfy all boundary constraints. The solution protocol features: a) precision step size control (Δη = 0.001); b) strict convergence criteria (10^{-6} tolerance; c) careful specification of initial values $f(0), f'(0), \theta(0)\, \phi(0)$,

Results and discussion

This study analyzes the behavior of a non-Newtonian Maxwell nanofluid under the influence of magnetic fields, slip effects, and porous media, employing the R-K method with a shooting technique for numerical solutions. Key observations include:

Magnetic field (M) reduces fluid velocity (Fig. 1), while *permeability (K)* opposes boundary layer thickness and flow speed (Fig. 2). Higher porosity weakens momentum distribution. The *Deborah number (λ)*, linked to relaxation time, decreases velocity as it increases (Fig. 3), particularly in highly viscous fluids.

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Velocity slip further diminishes flow speed (Fig. 4), whereas the *Prandtl number* thins the thermal boundary layer, lowering temperatures (Fig. 5). *Brownian motion* enhances thermal boundary layer thickness but reduces nanoparticle concentration (Figs. 6 & 7). *Thermophoresis* boosts both temperature and concentration profiles (Figs. 8 & 9).

The *Biot number* elevates temperature (Fig. 10), while the *Lewis number* suppresses nanoparticle concentration (Fig. 11). *Chemical reaction rates (γ)* delay concentration buildup due to rapid molecular interactions (Fig. 12). Lastly, *concentration slip (δ)* decreases nanoparticle distribution as it rises (Fig. 13). These insights advance the understanding of nanofluid dynamics, with potential applications in heat transfer and industrial fluid systems. Future studies could explore additional non-Newtonian models under varying conditions.

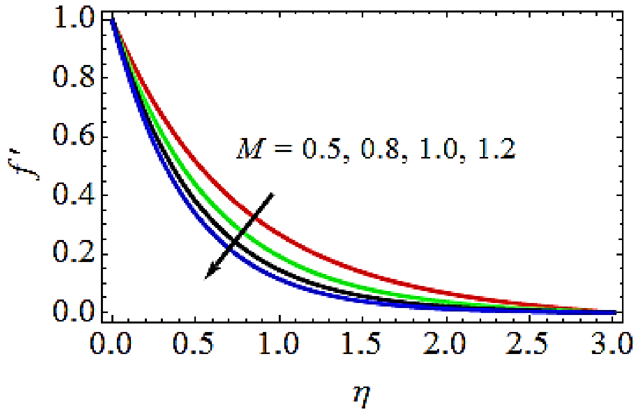

Fig. 1. Velocity patterns for Magnetic parameter

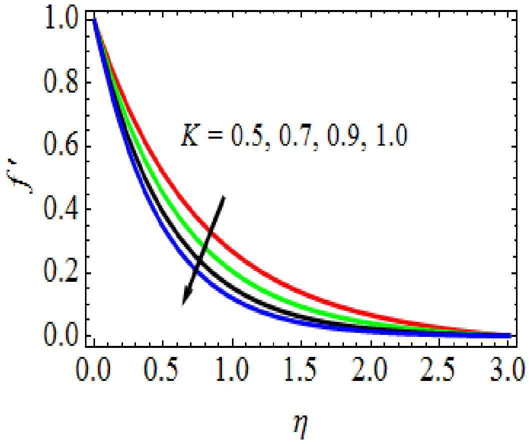

Fig. 2. Velocity patterns for *K*

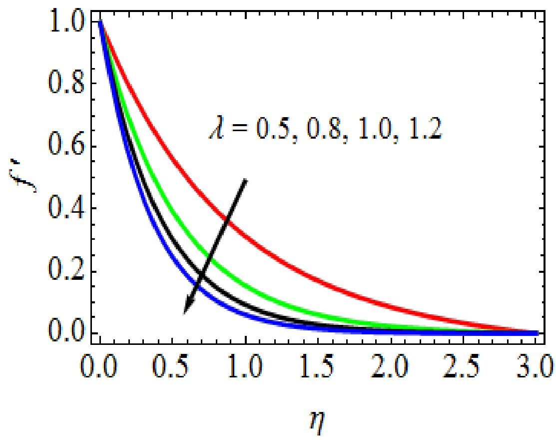

Fig. 3. Velocity patterns for *λ*

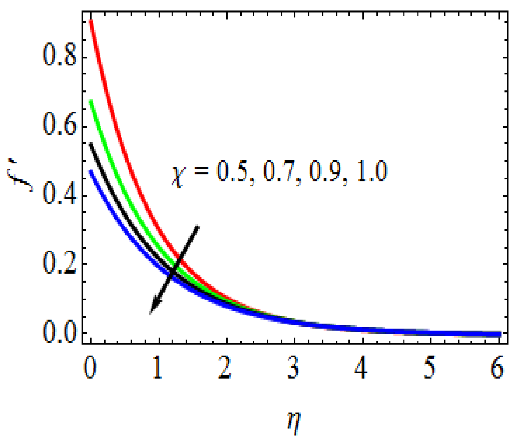

Fig. 4. Velocity patterns for *χ*

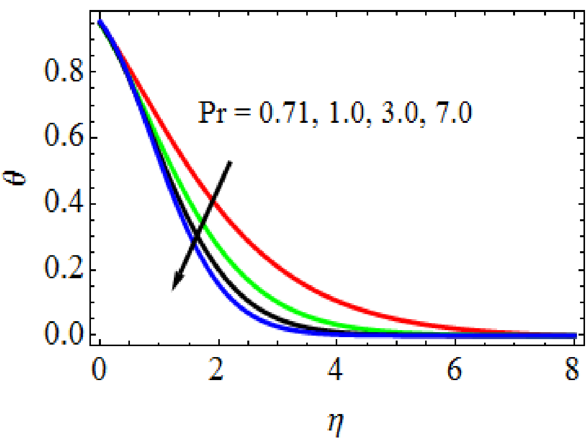

Fig. 5. Temperature patterns for Pr

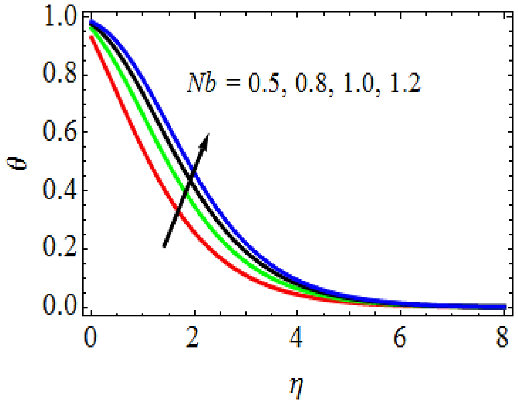

Fig. 6. Temperature patterns for *Nb*

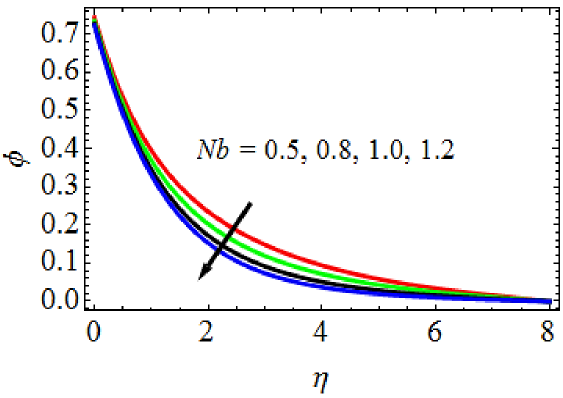

Fig. 7. Concentration patterns for *Nb*

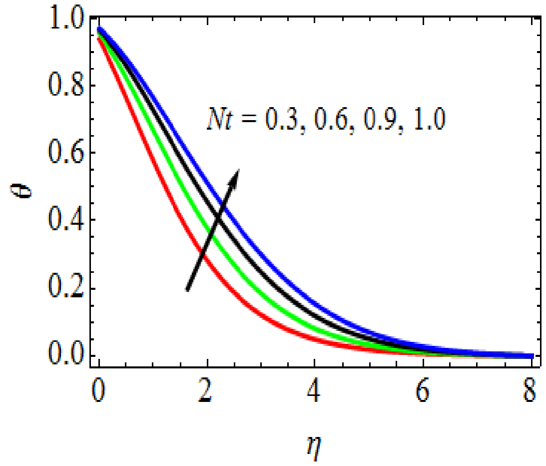

Fig. 8. Sequel of *Nt*: temperature patterns

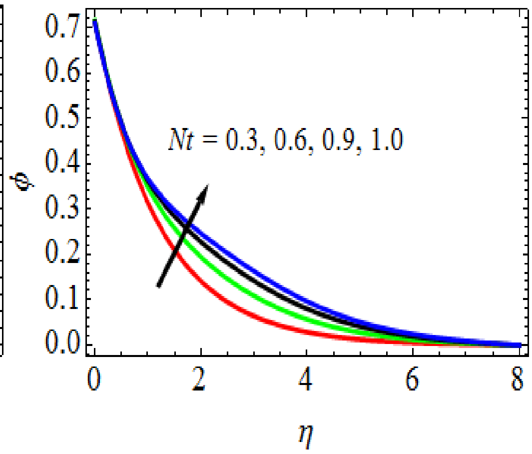

Fig.9. Sequel of *Nt* : concentration fields

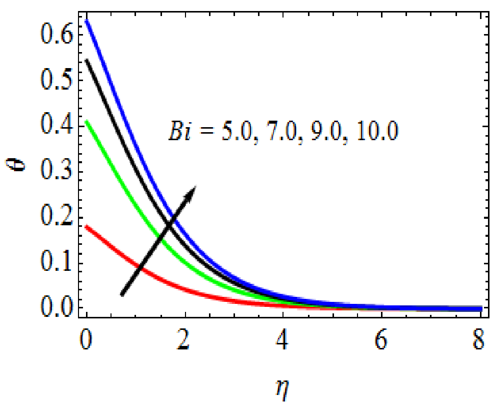

Fig. 10. Temperature patterns for *Bi*

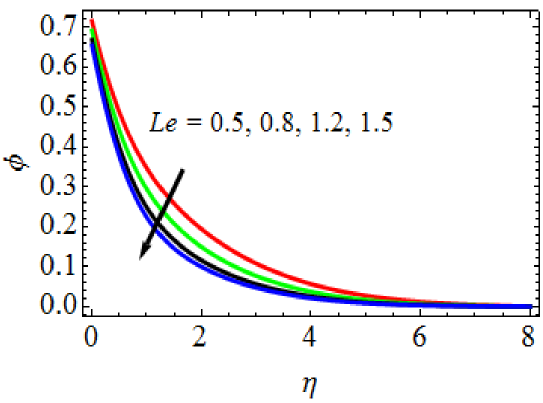

Fig. 11. Concentration patterns for *Le*

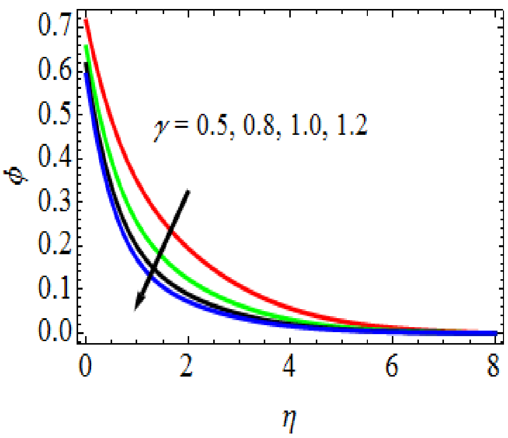

Fig. 12. Concentration patterns for γ

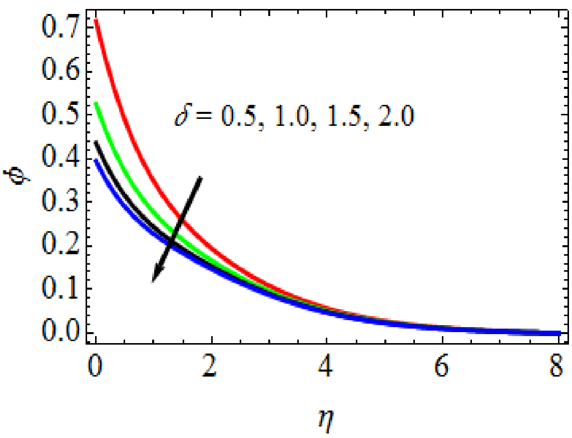

Fig. 13. Concentration patterns for δ

Numerical values of the Skin-friction coefficient resulting from velocity profiles are displayed in Table 1. The values of the Skin-friction coefficient increase in tandem with the values of these factors. The Nusselt number or rate of heat transfer coefficient values for different parameters are shown in Table 2. While Prandtl number values are inverted, Nusselt number values rise as these parameters' values do. The Sherwood number, also known as the rate of mass transfer coefficient, is shown in Table 3 as a function of concentration profiles for a variety of factors. It decreases as Le-, Nb-, δ-, γ-, and Nt-values increase, and increases as Nt-values increase.

Table 1

Skin-friction coefficient results

M	K	λ	Pr	Nb	Nt	Le	Γ	χ	Bi	δ	Cf
0.5	0.5	0.5	0.71	0.3	0.5	0.5	0.5	0.5	5.0	0.5	2.1874530124536
0.8											2.1546343436869
1.0											2.1277582493938
	0.7										2.1686633476349
	0.9										2.1486347438077
		0.8									2.1556378373460
		1.0									2.1316642708401
			1.00								2.1434451878437
			3.00								2.1296744874380
				0.6							2.2026473834392
				0.9							2.2267474170307
					0.8						2.2186787394933
					1.0						2.2394634608742
						0.8					2.1567898196836
						1.2					2.1315674028702
							0.8				2.1676743139033
							1.0				2.1377813986234
								0.7			2.1576634780467
								0.9			2.1315674082402
									7.0		2.2164637383460
									9.0		2.2346763643086
										1.0	2.1567673763430
										1.5	2.1216768739363

Table 2

Nusselt Number results

Pr	Nb	Nt	Bi	Nu_x
0.71	0.3	0.5	5.0	1.7561396938639
1.00				1.7275317403640
3.00				1.7078768183967
	0.6			1.7875738734783
	0.9			1.8078789481892
		0.8		1.7998719786897
		1.0		1.8116547387845
			7.0	1.7965763783641
			9.0	1.8206398463961

Table 3

Skin-friction coefficient results

Nb	Nt	Le	γ	Δ	Sh_x
0.3	0.5	0.5	0.5	0.5	1.9678719386983
0.6					1.9488168979181
0.9					1.9215673468659
	0.8				1.9878498187367
	1.0				2.0867847597199
		0.8			1.9277548185971
		1.2			1.8977888738768
			0.8		1.9377489304730
			1.0		1.9115643762304
				1.0	1.9463738368063
				1.5	1.9215674362076

Conclusions

This research examines the steady, two-dimensional flow of an incompressible Maxwell nanofluid over a porous stretching sheet under electromagnetic effects. The analysis demonstrates that:

- Magnetic fields inhibit velocity profiles, while permeability and slip parameters show diminishing effects
- The Maxwell parameter contributes to additional velocity reduction
- Thermal profiles intensify with Brownian motion and thermophoresis but weaken with Prandtl number elevation
- Biot number augmentation improves heat transfer characteristics
- Concentration fields are suppressed by Lewis number, Brownian effects, chemical reactions, and slip parameters, but enhanced by thermophoresis
- The study provides significant insights into the coupled thermo-fluid phenomena in complex media, highlighting:
- The intricate balance between electromagnetic and rheological factors
- The competing influences of various transport mechanisms
- Practical implications for thermal management systems

Future research directions

Future research directions should investigate alternative non-Newtonian fluid models, examine more complex geometrical configurations such as wavy or inclined surfaces, and explore multi-physical interaction scenarios combining thermal, chemical, and electromagnetic effects to further advance the understanding of nanofluid dynamics in porous media.

These findings advance the fundamental understanding of nanofluid dynamics in porous environments, offering valuable perspectives for energy systems and industrial applications

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