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Modeling and Analysis of Magnetic Field Effects on Magnetohydrodynamic Two-dimensional Steady Carreau-nanofluid Flow with Suction or Injection

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Abstract

This research investigates the influence of magnetic fields on the two-dimensional flow of a Carreau nanofluid past a permeable stretching sheet using numerical analysis. The study employs computational methods to analyze the complex interplay between the magnetic field, the non-newtonian fluid behavior characterized by the Carreau model, and the nanofluid's properties within the context of a permeable stretching sheet. This approach allows for a detailed examination of the velocity and temperature profiles, as well as other relevant flow characteristics, under the influence of varying magnetic field strengths and other pertinent parameters. The numerical results provide valuable insights into the dynamics of this specific fluid flow scenario, contributing to a deeper understanding of Magneto Hydrodynamic (MHD) effects in non-newtonian nanofluids. The findings are expected to have implications for various engineering applications involving such complex fluid systems. To facilitate numerical solution, local similarity transformations were employed to reduce the governing partial differential equations to a system of ordinary differential equations, subsequently solved using a robust numerical scheme combining the Runge-Kutta method with a shooting technique. The findings demonstrate consistency with established research, thereby validating the methodology's accuracy and effectiveness in characterizing the complex flow dynamics under consideration.

Major Findings: *The study examines MHD effects on Carreau nanofluid flow over a permeable stretching sheet. Numerical analysis reveals how magnetic fields and fluid properties alter velocity/temperature profiles, aiding engineering applications like thermal systems and fluid dynamics.*

Keywords: *Carreau Nanofluid, Magnetic Field, Runge kutta Method, Thermal Radiation, Two Dimensional*

1.0 Introduction

The non-newtonian rheology of Carreau fluids, especially when enhanced by the incorporation of nanofluid particles, constitutes a significant area of ongoing research in fluid dynamics. Nanofluids, engineered by dispersing nanoparticles within a base fluid, demonstrate superior properties compared to their base fluids alone. These

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improvements are particularly evident in enhanced heat transfer capabilities, modified rheological characteristics, and overall increased efficiency, making them highly valuable across a broad spectrum of technological applications. This study undertakes a comprehensive investigation into the intricate dynamics governing the behavior of Carreau nanofluids, exploring their multifaceted performance across diverse industrial and biological systems. The complex interplay between the non-newtonian fluid behavior and the nanoparticle properties will be meticulously examined to elucidate the underlying mechanisms and to further optimize the design and application of these advanced fluids. A detailed analysis of the rheological models and their predictive capabilities will be presented, along with a discussion of the potential for future advancements in this rapidly evolving field.

The rheological intricacies of Carreau-yasuda fluids under diverse conditions have been extensively investigated. Previous studies, such as the numerical study of double diffusion effects on Carreau-yasuda fluid flow by Khan *et al*., and the examination of bioconvection's influence on magnetized Carreau-yasuda nanofluid flow with chemical reactivity and thermal radiation by Waqas *et al*., have significantly advanced our understanding[1,2]. Further contributions include Riaz *et al*.'s, exploration of nanoparticle-mediated thermal management in wavy Carreau fluid flow through a three-dimensional channel, Irfan *et al*.'s, numerical analyses of unsteady Carreau nanofluid flow with variable conductivity and the shear-thinning or thickening behavior in radiative magnetite Carreau nanofluids, considering Brownian motion, thermophoretic diffusion, and nanoparticle mass flux effects on nonlinear mixed convection, and Rehman *et al*.'s, application of group theoretic analysis to MHD thermally-slipping Carreau fluid heat transfer under various flow regimes[3-7]. Numerical analysis with different fluids was also conducted by Salahuddin *et al*[8]. Studies analyze MHD flows in porous/non-Newtonian fluids, examining heat transfer with radiation, Hall currents, and Soret/Dufour effects[9-12]. Numerical methods model flows past plates/bidirectional surfaces, relevant to pharmaceutical and engineering applications. These studies, along with the substantial body of work detailed in the given references provide a robust foundation for the present research[13-47].

The model incorporates several key physical phenomena, including thermal radiation, Brownian motion, magnetic field effects, and thermophoresis, alongside the inherent properties of the nanofluid particles. Numerical solutions to the governing equations are obtained using the Runge-kutta method in conjunction with the shooting technique. The primary objective is to elucidate the influence of these physical parameters on the resulting velocity, temperature, and concentration profiles, providing a detailed analysis of their interplay and impact on the overall fluid behavior.

2.0 Modeling of the Flow

The study investigates the impact of a magnetic field and heat radiation on the flow of a Carreau nanofluid, a non-newtonian fluid, next to a permeable, non-linearly isothermal sheet. It considers transpiration and the sheet's nonlinear elasticity, driven by transpiration, and the fluctuating magnetic field on its surface.

Continuity Equation:

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

Momentum Equation:

$$u\left(\frac{\partial u}{\partial x}\right)+v\left(\frac{\partial u}{\partial y}\right)=\nu\left\{1+\left[\frac{3(n-1)}{2}\right]\lambda^2\left(\frac{\partial u}{\partial y}\right)^2\right\}\left(\frac{\partial^2 u}{\partial y^2}\right)-\left(\frac{\sigma B_o^2}{\rho}\right)u-\left(\frac{\nu}{K_o}\right)u \tag{2}$$

Equation of thermal energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_m\nabla^2 T+\tau\left\{D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\}-\frac{1}{\rho C_p}\left(\frac{\partial q_r}{\partial y}\right) \tag{3}$$

The heat flux q_r is defined as

$$q_r=-\frac{4\sigma^*}{3K^*}\left(\frac{\partial T^4}{\partial y}\right) \tag{4}$$

Using Taylor series T^4 is as follows

$$T^4=T_\infty^4+4T_\infty^3(T-T_\infty)+6T_\infty^2(T-T_\infty)^2+\ldots\ldots\ldots \tag{5}$$

$$T^4\cong 4T_\infty^3T-3T_\infty^4 \tag{6}$$

$$q_r = -\frac{16T_\infty^3\sigma^*}{3K^*}\left(\frac{\partial T}{\partial y}\right) \tag{7}$$

Using by using (9), (5) will get the following form

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_m\nabla^2 T+\tau\left\{D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\}$$

$$+\frac{1}{\rho C_p}\left(\frac{16T_\infty^3\sigma^*}{3K^*}\right)\left(\frac{\partial^2 T}{\partial y^2}\right) \tag{8}$$

Equation of species concentration:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \tag{9}$$

$$\left.\begin{aligned} &u=u_w(x)=ax^n,\ v=v_w(x),\ T=T_w,\ C=C_w\ \ at\ \ y=0\\ &u\to 0,\ v\to 0,\ T\to T_\infty,\ C\to C_\infty\ \ as\ \ y\to\infty \end{aligned}\right\} \tag{10}$$

The following are the applied similarity variables

$$\eta=y\sqrt{\frac{a(n+1)}{2\nu}}x^{\frac{n-1}{2}},\ v=-\sqrt{\frac{a\nu(n+1)}{2}}x^{\frac{n-1}{2}}\left[f(\eta)+\left(\frac{n-1}{n+1}\right)\eta f'(\eta)\right],$$
$$\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\ \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty},\ u=ax^n f'(\eta) \tag{11}$$

By (11), Equations (2), (3)-(8) will take the following form

$$f'''+ff''-\left(\frac{2n}{n+1}\right)f'^2-Mf'+\frac{3(n-1)}{2}Wef''^2ff'''-Kf'=0 \tag{12}$$

$$\left(1+\frac{4R}{3}\right)\theta''+\Pr f\theta'+\Pr Nb\theta'\phi'+\Pr Nt\theta'^2=0 \tag{13}$$

$$2Nb\phi''+NbLef\phi'+2Nt\theta''=0 \tag{14}$$

Conditions (10) will take the following form

$$\left.\begin{aligned} &f=f_w,\ f'=1,\ \theta=1,\ \phi=1\ \ \ at\ \ \ \eta=0\\ &f'\to 0,\ \theta\to 0,\ \phi\to 0\ \ \ as\ \ \ \eta\to\infty \end{aligned}\right\} \tag{15}$$

Defined and associated parameters

$$\left.\begin{aligned} &\Pr=\frac{\nu}{\alpha},\ M=\frac{\sigma B_o^2 x}{\rho a},\ Nb=\frac{(\rho C)_p D_B(C_w-C_\infty)}{(\rho C)_f\nu},\ R=\frac{4\sigma^* T_\infty^3}{\kappa K^*},\ Le=\frac{\nu}{D_B},\\ &Nt=\frac{(\rho C)_p D_T(T_w-T_\infty)}{(\rho C)_f\nu T_\infty},\ f_w=-\frac{v_w(x)}{\sqrt{\frac{a\nu(n+1)}{2}}x^{\frac{n-1}{2}}},\ We=\frac{a^2x^2\lambda^2}{\nu},\ K=\frac{\nu}{aK_o}, \end{aligned}\right\} \tag{16}$$

Engineering Quantities

$$Cf=\frac{\tau_w}{\rho a^2}\ \text{where}\ \tau_w=\frac{\partial u}{\partial x}+\frac{(n-1)}{2}\lambda^2\left(\frac{\partial u}{\partial y}\right)^3\Rightarrow Cf=\frac{1}{\sqrt{\mathrm{Re}_x}}\left\{f''(0)+\frac{(n-1)}{2}We\left[f''(0)\right]^3\right\}$$
$$Nu_x=\frac{xq_w}{\kappa(T_w-T_\infty)}\ \text{Where}\ q_w=-\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0}+(q_r)_w\Rightarrow Nu=\frac{Nu_x}{\sqrt{\mathrm{Re}_x}}=-\left(1+\frac{4R}{3}\right)\theta'(0)$$
$$Sh_x=\left[-\left(\frac{x}{C_w-C_\infty}\right)\left(\frac{\partial C}{\partial y}\right)\right]_{y=0}\Rightarrow Sh=\frac{Sh}{\sqrt{\mathrm{Re}_x}}=-\left(\sqrt{\mathrm{Re}_x}\right)\phi'(0),$$

3.0 Numerical Solutions

Since Equations (12)-(14) are nonlinear, accurate solutions are not feasible and appropriate boundary conditions and numerical methods are required. Through similarity transformations, the equations are converted into non-linear ordinary differential equations that may be quantitatively solved. Numerical solutions are found for the governing partial differential equations. To solve the boundary value problem numerically, a Runge-kutta approach must be used in conjunction with the shooting process.

$$\left.\begin{aligned} &f'=p\Rightarrow f''=p'=q\Rightarrow f'''=p''=q'\\ &\Rightarrow q'=-fq+\left(\frac{2n}{n+1}\right)p^2+Mp-\left(\frac{3(n-1)}{2}\right)We^2q^2fq'p^2+Kp\\ &\theta'=r\Rightarrow\theta''=r'\ \text{then}\ r'=\frac{-(\Pr)fr-(\Pr)Nbrz-(\Pr)(Nt)r^2}{\left(1+\frac{4R}{3}\right)}\\ &\&\ \ \phi'=z\Rightarrow\phi''=z'\ \text{then}\ z'=\frac{-(Le)(Nb)fz-2(Nt)r'}{2Nb} \end{aligned}\right\} \tag{17}$$

Cconditions will be of the following form

$$f(0)=f_w,\ p(0)=1,\ \theta(0)=1,\ \phi(0)=1,\ p(\infty)\to 0,$$
$$\theta(\infty)\to 0,\ \phi(\infty)\to 0 \tag{18}$$

The shooting technique is used to solve the boundary value issue once it has been converted into an Initial Value Problem (IVP). A 10^{-6} error tolerance and a step size of h = 0.1 are employed.

4.0 Results and Discussion

The following non-dimensional parameters regulate the flow. This section illustrates how these parameters influenced the velocity profiles, temperature profiles, and concentration profiles, as depicted in the subsequent figures. The magnetic parameter and velocity profiles exhibit an inverse relationship, as illustrated in Figure 1. With an increase in the magnetic parameter, a Lorentz force is generated, resulting in a resistive force that opposes the motion of fluid particles and reduces velocity profiles.

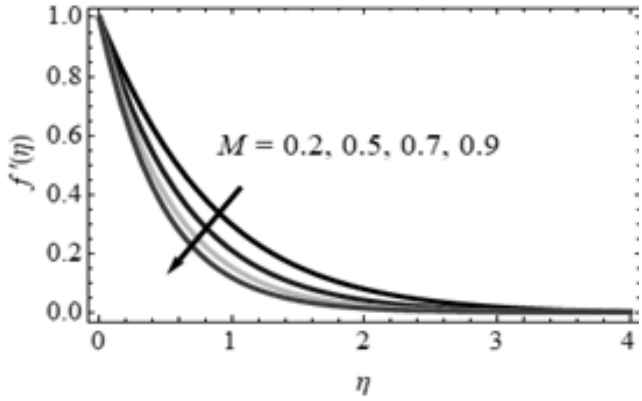


Figure 1. *M* effect on velocity profiles.

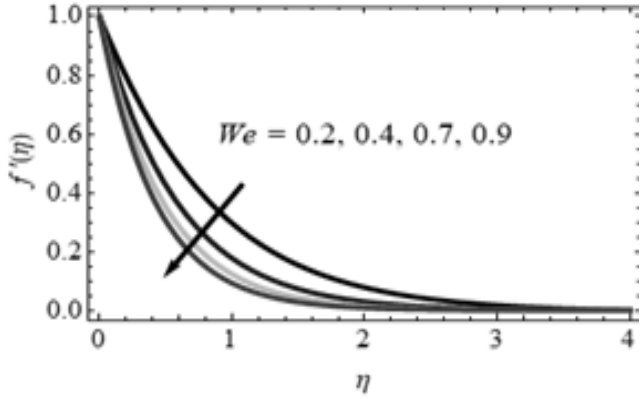


Figure 2. *We* effect on velocity profiles.

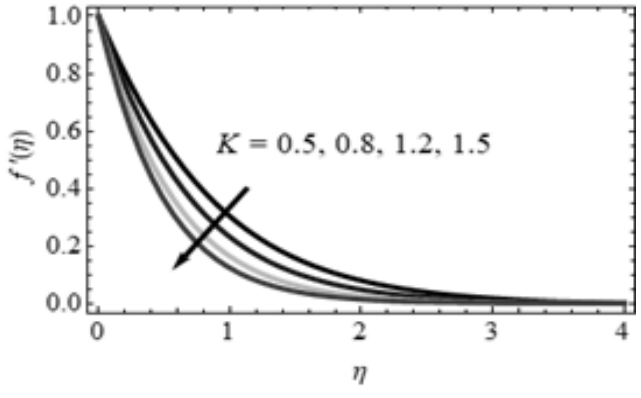


Figure 3. *K* effect on velocity profiles.

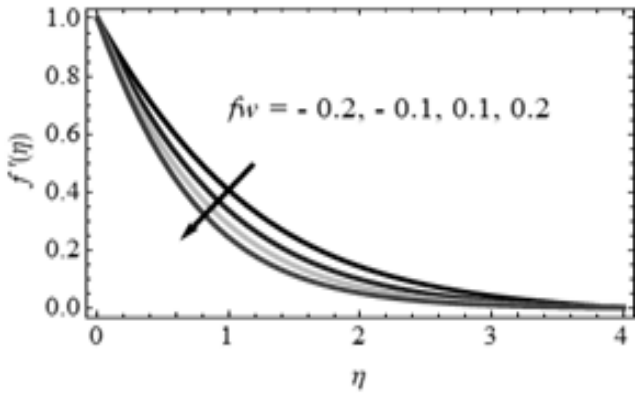


Figure 4. *fw* effect on velocity profiles.

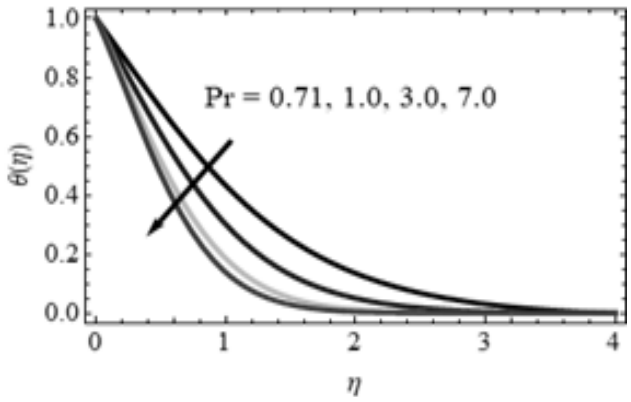


Figure 5. Pr effect on temperature profiles.

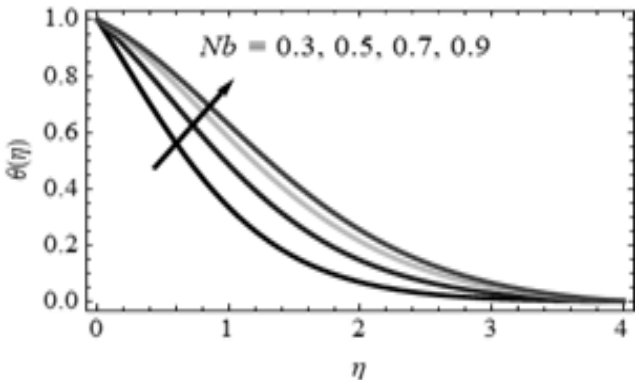


Figure 6. *Nb* effect on temperature profiles.

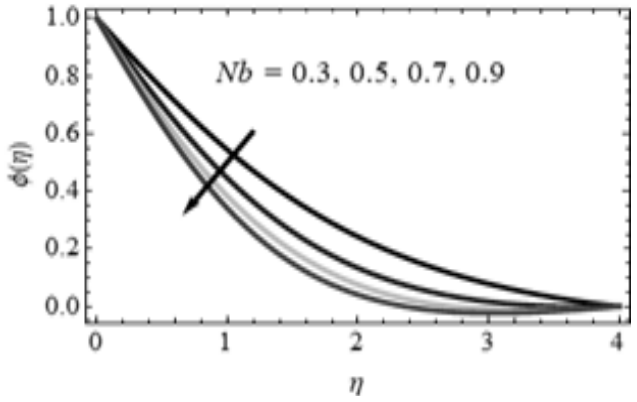


Figure 7. *Nb* effect on concentration profiles.

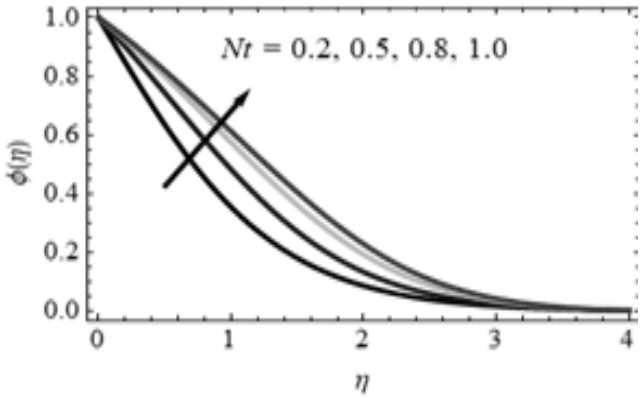


Figure 8. *Nt* effect on temperature profiles.

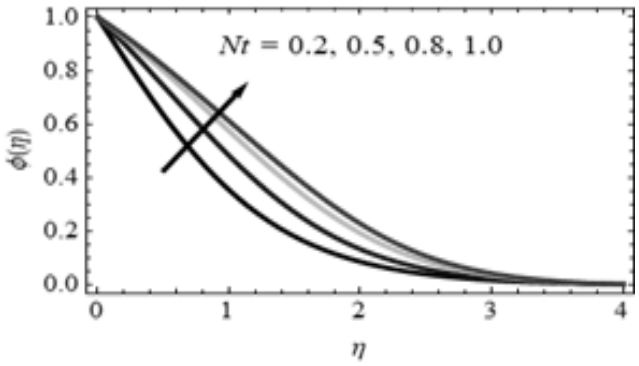


Figure 9. *Nt* effect on concentration profiles.

The Carreau fluid parameter exhibits a decreasing influence on velocity profiles, as illustrated in Figure 2. Figure 3 demonstrates the influence of the wall transpiration parameter fw, on the velocity profiles within the boundary layer of a stretching sheet.

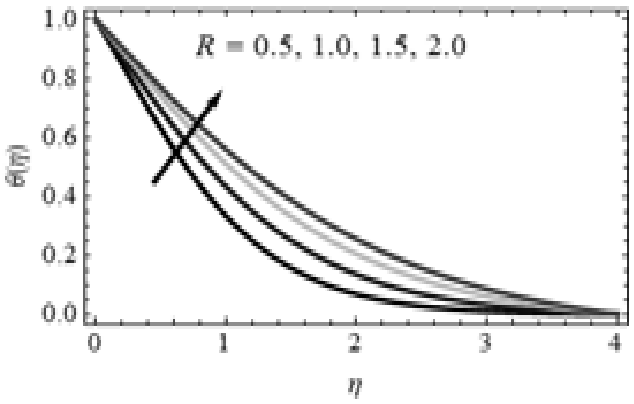


Figure 10. *R* effect on temperature profiles.

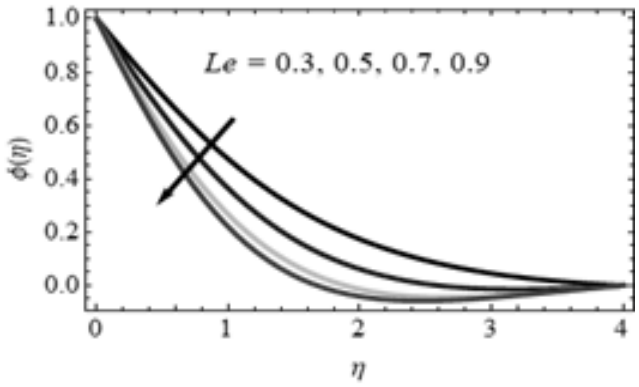


Figure 11. *Le* effect on concentration profiles.

Injection accelerates flow, while suction decelerates it.

Figure 4 demonstrates the impact of the permeability parameter (K) on the velocity distribution, indicating a decrease in the velocity profile with an increase in K.

The reduction in the thickness of the momentum barrier layer and the enhancement of the porous layer are the underlying reasons for this phenomenon. Figure 5 illustrates the effect of Pr , indicating that a higher momentum diffusivity overshadows thermal diffusivity, leading to a reduction in the temperature gradient as Pr increases. Increasing the Brownian motion parameter (Nb) results in an elevation of the temperature profile, while concurrently causing a decrease in the nanoparticle volume concentration profile, as illustrated in Figures 6 to 7.

The temperature gradient induces a thermophoretic force, resulting in a rapid flow away from the stretched sheet. Consequently, as Nt increases, both the

Table 1. Numerical values of skin-friction coefficient

M	f_w	*We*	*n*	*K*	Pr	*R*	*Nb*	*Nt*	*Le*	*Cf*
0.2	- 0.2	0.2	0.1	0.5	0.71	0.5	0.3	0.2	0.3	1.4575256027239
0.5										1.4187687812872
0.7										1.3976582182468
	- 0.1									1.4265876192856
	0.1									1.3958768765891
	0.2									1.3766087609876
		0.4								1.4356868165898
		0.7								1.4065659641291
			0.3							1.4189682425452
			0.5							1.3856896987634
				0.8						1.4156587672342
				1.2						1.3790668678688
					1.00					1.4065876876134
					3.00					1.3687687656181
						1.0				1.4965876180568
						1.5				1.5214255982897
							0.5			1.4858598289154
							0.7			1.5051859825982
								0.5		1.5076475217346
								0.8		1.5258769876125
									0.5	1.4159956345859
									0.7	1.3908676062361

dimensionless temperature and nanoparticle volume fraction rise.

Figure 10 demonstrates the influence of R on temperature distribution, indicating that heat dispersion increases as the parameter exceeds its default value. The thermal boundary layer thickness decreases while the thermal buoyancy force increases with rising R. Figure 11 illustrates the effect of the Le on concentration profiles, revealing a significant reduction for lower values of Le.

4.1 Engineering Parameters Affect Heat and Mass Transfer

Table 1 shows that the skin-friction coefficient decreases with higher We, M, fw, n, K, Pr, and Le, but increases with Nb, R, and Nt. Table 2 indicates that the heat transfer coefficient rises with R, Nb, and Nt, but falls with increasing Pr. Table 3 reveals that the mass transfer coefficient decreases with Nt and increases with Nb and Le. These findings highlight the varying impacts of different parameters on friction, heat, and mass transfer in engineering contexts.

Table 2. Nusselt number values

Pr	*Nb*	*Nt*	*R*	Nu_x
0.71	0.5	0.5	0.5	0.561548548259828
1.00				0.514589258925367
3.00				0.497856523547625
	0.8			0.597634652745922
	1.0			0.613576185782436
		0.8		0.584664554726872
		1.0		0.601582589256822
			0.8	0.539876876452568
			1.0	0.516787987325676

Table 3. Sherwood number values

Nb	*Nt*	*Le*	Sh_x
0.5	0.5	0.5	0.664572345722962
0.8			0.630988979898238
1.0			0.615485982586145
	0.8		0.685656868612585
	1.0		0.704765471256971
		1.0	0.645659659123415
		1.2	0.617687653134576

5.0 Conclusions

This research examines the numerical solutions to a set of nonlinear equations and presents the findings as graphs. This highlights unique aspects of the solutions. The paper offers ideas for designing effective fluid systems at the nanoscale and validates convergence using the Runge-kutta technique, shooting methods, and visual aids. The following are the major findings.

1. Fluid viscosity and internal velocity profiles are impacted by non-newtonian effects, which are amplified by the Carreau fluid parameter.
2. Designing non-newtonian fluid systems for improved performance and efficiency is made easier with this knowledge.
3. Velocity profiles are greatly affected by the magnetic field's intensity, which causes resistive forces to change flow patterns.
4. The magnetic field parameter M causes the Lorentz force to decrease fluid velocity.

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