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Chemical Reaction and Thermal Radiation Effects on MHD Casson and Maxwell Nanofluid Flow over a Porous Stretching Surface

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ABSTRACT

The focus of this article is on two-dimensional magnetohydrodynamic Casson and Maxwell nanofluid flows on a porous stretched surface, considering the effects of chemical reactions and thermal radiation. For this problem, convective boundary conditions are assumed. By using similarity transformations, the governing partial differential equations of the issue were converted into ordinary differential equations with the help of the similarity transformation, which were then theoretically solved using the Runge-Kutta Fehlberg method and the shooting approach. Plots are used to show how relevant characteristics, such as heat radiation, porosity, and magnetic parameter, have an impact. It is seen that the velocity profiles decrease as the magnetic field increases. Furthermore, the local Sherwood number and the local Nusselt number decrease as the velocity slip parameter rises. The results of this study were compared with the previously published works under some restrictions, and they are found in excellent agreement.

1. Introduction

The heat and mass transfer in the laminar boundary layer flow on a stretching sheet are important from theoretical as well as practical point of view because of their wider applications to polymer technology and metallurgy. The thermal buoyancy force arising due to the heating of stretching surface, under some circumstances, may significantly alter the flow and thermal fields and thereby the heat transfer behaviour in the manufacturing processes. Venkateswarlu *et al.,* [1] have studied the radiation effects on MHD boundary layer flow of liquid metal over a porous stretching surface in porous medium with heat generation. Reddy *et al.,* [2] presented the thermal adiation and mass

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transfer effects on nonlinear MHD boundary layer flow of liquid metal over a porous stretching surface embedded in porous medium with heat generation. MHD mixed convection oscillatory flow over a vertical surface in a porous medium with chemical reaction and thermal radiation has been analyzed by Reddy *et al.,* [3]. Reddy and Krishna [4] considered the Soret and Dufour effects on MHD micropolar fluid flow over a linearly stretching sheet, through a non-Darcy porous medium. Kumaran *et al.,* [5] have studied the exponential heat source/sink, momentum, and thermal transport over the spinning paraboloid. Sobamowo *et al.,* [6] have looked at the effects of additional control features on the stream and heat transfer qualities to the nanofluids when the base fluid is implanted with the upper and silver nanoparticles.

Unsteady Carreau-Casson fluids in a solution of dust and graphene nanoparticles with non-Fourier heat flux across a radiating shrinking layer have been explored by Santhosh *et al.,* [7]. Santoshi *et al.,* [8] have studied the computational examination of 3D Casson-Carreau nanofluid flow. A colloidal postponement called nano fluid contains nanoparticles in a base fluid. Nano fluids have a wide range of uses in engineering, from the automotive industry to the medical sector. They are used in nuclear reactors, power plant cooling systems, geothermal energy extraction, automotive applications, electronic applications like cooling microchips, and biomedical applications like cancer therapeutics and nano cryosurgery, among other things. Due to these real characteristics, nano fluids are significant to investigate, as shown in previous studies in this debate [9-14]. The non-Newtonian fluid flow across a mixed stretchable surface has been studied with different variables by Sitamahalakshmi *et al.,* [15], Reddy *et al.,* [16], and Gladys and Reddy [17]. Nasir *et al.,* [18] looked at how thermal radiation affected MHD 3D flow across a stretched surface. A nano liquid film's Eyring-Powell slip flow has been studied by Khan *et al.,* [19].

In-depth previous studies on this topic examined non-Newtonian Maxwell fluids under a range of physical circumstances, including viscous dissipation, Newtonian heating, homogeneous–heterogeneous chemical interactions, and thermal stratification over a variety of stretching surfaces [20-23]. They found that when the Prandtl number climbed, both temperature and heat transfer rate dropped. The effect of radiation and convective boundary limitation on the oblique stagnation point of the non-Newtonian nano fluids past the stretching layer was studied by Ghaffari *et al.,* [24]. Abdela *et al.,* [25] numerical study of the stagnation point flow of nano fluid takes into account the sloped stretched sheet.

The effects of slip on MHD flow have been studied by certain researchers using a variety of non-Newtonian nano fluid models, such as Casson fluid and Jeffery nano-fluid, across a flexible sheet with varied physical limits [26,27]. Ibrahim *et al.,*'s [28] investigation of the influence of chemical reaction on mass and heat transport characteristics. Nevertheless, the sources addressing chemical reactions and slip effects are addressed in previous studies [29-44]. The slip impact of MHD heat transmission of nano fluids over a stretched surface with chemical reaction has been studied by Ittedi *et al.,* [45]. The outcome of Newtonian heating on Couette flow of viscoelastic dusty fluid along with the heat transfer in a rotating frame: second law analysis is explored by Khan *et al.,* [46]. Khan *et al.,* [47] has analysed the relative magnetic field analysis on Casson dusty fluid of two-phase fluctuating flow over a parallel plate: second law analysis.

The analysis of the MHD stagnation point flow of Casson and Maxwell fluid with chemical reaction is not considered by any of the researchers due to the impacts of nanoparticles. Therefore, using the Runge-Kutta method along with the shooting technique, the current paper aims to investigate the impact of nanoparticle and chemical reaction on MHD Casson and Maxwell nanofluid boundary layer flow on heat and mass transfer.

2. Methodology

Consider the 2D motion of a non-Newtonian nanofluid with time dependence and incompressibility, as well as heat radiation and chemical reaction over a porous stretched surface under convective circumstances. The Free stream velocity $u_f(x)$ and the stretching velocity $u_w(x)$ are of the forms $u_f(x) = ax$ and $u_w(x) = bx$ where a and b are constants. The x-axis is along the sheet and normal to the sheet y-axis is chosen. The concentration is represented by C_w and the temperature is represented by T_w and the ambient concentration and ambient temperature are represented by C_∞ and T_∞.

The physical model of the flow and Cartesian coordinates are shown in Figure 1. The proposed Casson model for two-dimensional laminar steady flow has governing differential equations that are expressed in the following form:

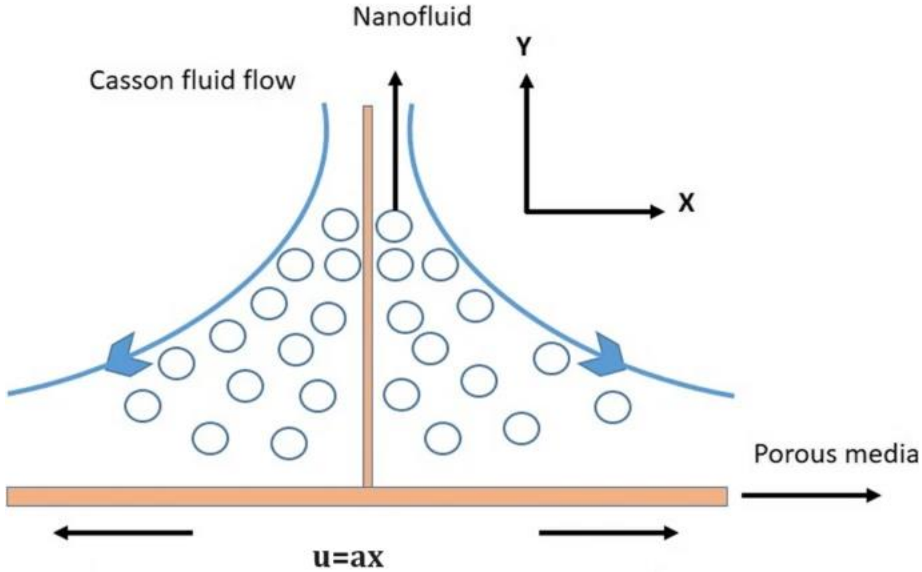

Fig. 1. Sketch of the physical model

The flow expressions are defined as

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \left[\left(1+\frac{1}{\gamma}\right)v\frac{\partial^2 u}{\partial y^2} - \varsigma\left(u^2\frac{\partial^2 u}{\partial x^2} + v^2\frac{\partial^2 u}{\partial y^2} + 2uv\frac{\partial^2 u}{\partial x \partial y}\right) - \left(\frac{\sigma B_0^2}{\rho_f} + \frac{\nu}{K_1}\right)\text{u}\right] \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \tau\left(D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y} + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right) - \frac{1}{\left(\rho c_p\right)_f}\frac{\partial q_r}{\partial y} + \frac{Q_0(T-T_\infty)}{\left(\rho c_p\right)_f} \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_B\frac{\partial^2 C}{\partial y^2} + \frac{D_r}{T_\infty}\frac{\partial^2 T}{\partial y^2} - K_r\left(C - C_\infty\right) \tag{4}$$

The Navier slip conditions, convective conditions and Nield boundary conditions are assumed as follows:

$$u = ax, v = 0, T = T_w, C = C_w \text{ at } y = 0$$
$$u \to u_e(x) = bx, v \to 0, T \to T_\infty, C \to C_\infty \text{ as } y \to \infty \tag{5}$$

where u and v are the velocity components along the x and y directions, ρ_f is the density of the base fluid, $\alpha -$ is the thermal diffusivity, ς is the relaxation time parameter of the fluid, B_0 is the strength of the magnetic field, ν is the kinematic viscosity of the fluid, K_1 is the permeability parameter, γ is the Casson fluid parameter, D_B is the Brownian diffusion coefficient, D_r is the thermophoretic diffusion coefficient, τ is the ratio between the effective heat capacity of the nano particle material and heat capacity of the fluid, C is the volumetric volume expansion coefficient, and ρ is the density of the particle, K_r is the chemical reaction rate, m1, m2, and m3 are the velocity slip, thermal slip and concentration slip conditions respectively.

The radiation heat flux (q_r) is modeled by using Rosseland approximation given in:

$$q_r = -\left(\frac{4\sigma^*}{3k_1}\right)\frac{\partial T^4}{\partial y} \tag{6}$$

Here σ^* represents the constant of Stefan-Boltzmann, k_1 gives the coefficient of mean absorption. It is also assumed that if the difference in temperature within the flow is T^4, then T^4 can be expressed as a linear combination of the temperature by expanding the T^4 by Taylor's series about $T\infty$ to obtain (7):

$$T^4 = T_\infty^4 + 4T_\infty^3(T - T_\infty) + 6T_\infty^2(T - T_\infty)^2 + \cdots \tag{7}$$

If we neglect the higher order beyond the first degree in $(T - T_\infty)$ in this series and opening brackets on the right-hand sides of (7) we obtain (8):

$$T^4 \approx -3T_\infty^4 + 4T_\infty^3 T \tag{8}$$

Substituting the right-hand side of (8) into (6) for T^4 yield (9):

$$q_r = -\left(\frac{4\sigma^*}{3k_1}\right)\frac{\partial T^4}{\partial y} = -\left(\frac{4\sigma^*}{3k_1}\right)\frac{\partial}{\partial y}(-3T_\infty^4 + 4T_\infty^3 T) = -\left(\frac{16T_\infty^3\sigma^*}{3k_1}\right)\frac{\partial T}{\partial y} \tag{9}$$

The rate of change in radiative heat flux with respect y is given by (13)

$$\frac{\partial q_r}{\partial y} = -\left(\frac{16T_\infty^3\sigma^*}{3k_1}\right)\frac{\partial^2 T}{\partial y^2} \tag{10}$$

The partial differential equations (2), (3), (4) and (5) are transformed into ordinary differential equations by introducing the dimensionless variables are given by (11):

$$\psi=\sqrt{cv}\,f(\eta),\theta(\eta)=\frac{(T-T_\infty)}{(T_w-T_\infty)},\phi(\eta)=\frac{(C-C_\infty)}{(C_w-C_\infty)},\eta=\sqrt{\frac{c}{v}}y \tag{11}$$

The stream function velocity ψ can be defined as $u=\frac{\partial\psi}{\partial y},v=-\frac{\partial\psi}{\partial x}$ so that Eq. (1) satisfies the continuity equation. $f(\eta)$ denote the injection and suction, η is the dimensionless space variable, $\theta(\eta)$ and $\phi(\eta)$ are the dimensionless of temperature and concentration of the fluid respectively.

In view of the above-mentioned transformations Eq. (2), Eq. (3) and Eq. (8) are reduced to the following ODEs:

$$\left(1+\frac{1}{\gamma}\right)f'''+ff''-f'^2+(M+1/K)f'+\delta\left(2ff'f''-f'''\right)=0 \tag{12}$$

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

$$\phi''+Le\phi'+\frac{Nt}{Nb}\theta''-KrLe\phi=0 \tag{14}$$

The transformed boundary restrictions are:

$$\begin{aligned}&f(\eta)=S,\ f'(\eta)=1,\ \theta(\eta)=1,\ \phi(\eta)=1\ \text{ at }\ \eta=0\\&f'(\eta)\to\varepsilon,\theta(\eta)\to 0,\phi(\eta)\to 0\quad\text{as}\ \ \eta\to\infty\end{aligned} \tag{15}$$

where f' is dimensionless velocity, θ is dimensionless temperature, ϕ is dimensionless concentration, and η is the similarity variable. The prime denotes differentiation with respect to η. The skin friction C_f, local Nusselt number Nu_x and Sherwood number Sh_x are the important physical quantities they can be defined as follows

$$C_f=\frac{\tau_w}{\rho u_w^2},Nu_x=\frac{xq_w}{k\left(T_f-T_\infty\right)},Sh_x=\frac{xq_m}{D_B\left(C_w-C_\infty\right)}$$

Here $\tau_w=\mu\left(1+\frac{1}{\gamma}\right)\frac{\partial u}{\partial y}$ is the surface shear stress, $q_w=-k\left(\frac{\partial T}{\partial y}\right)_{y=0}+q_r$ is the surface heat flux and $q_m=-D_B\left(\frac{\partial C}{\partial y}\right)_{y=0}$.

Using the similarity transformation in (11) we have the following relations:

$$C_f\operatorname{Re}_x^{\frac{1}{2}}=f'(0),Nu_x\operatorname{Re}_x^{\frac{-1}{2}}=-\left(1+\frac{4}{3R}\right)\theta'(0),Sh_x\operatorname{Re}_x^{\frac{-1}{2}}=-\phi'(0)$$

where Re_x is the local Reynolds number.

2.1 Numerical Solution

The Runge-Kutta method based on the shooting scheme is used to solve numerically the converted ODE Eq. (12) through Eq. (14) subject to the boundary constraints (15). This study emphasizes the characteristics of motion, heat, and mass transmission. The field of velocity, energy, and concentration profile, as well as friction factor, Nusselt number, and Sherwood number, are all properly investigated.

3. Results and Discussion

In this connection the successive outcomes for physical variables are evaluated M=0.5 $\gamma = 0.2, \Pr = 0.71, Le = 1.0, Nb = 0.1, S = 0.5, Nt = 0.1, R = 0.2, Kr = 0.2, Q = 0.1.$ For this study, the successive outcomes for physical variables are evaluated.

Figure 2 depicts how the magnetic field's properties affect the flow velocity. It has been shown that the magnetic parameter generates the Lorentz force, which causes the fluid's velocity to slow down and the velocity profile to rise to higher magnetic parameter values. Figure 3 shows the variation of velocity profiles for various permeability parameter values (K). It is evident that the presence of a porous media increases the fluid flow's values, which accelerates the fluid. As a result, the influence of increasing permeability parameter values on fluid velocity results in a thickening of the thermal boundary layer.

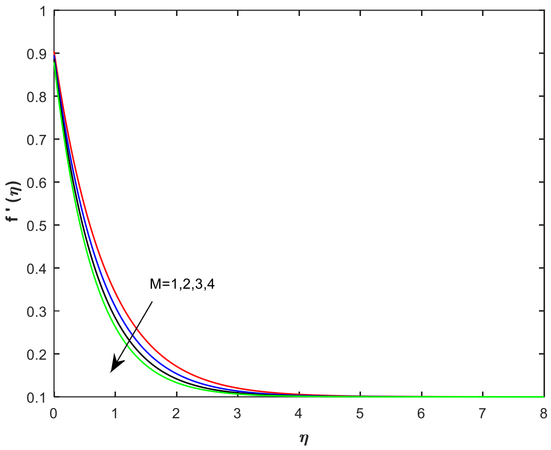

Fig. 2. Velocity Profile for various values of M

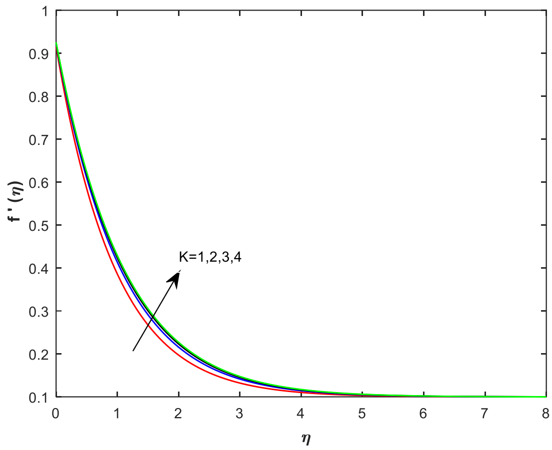

Fig. 3. Velocity Profiles for various values of K

The Casson effect in Figure 4 reduces the fluid's velocity. It is essential because the Casson fluid's yield stress is decreasing. Physically, an increase in the Casson parameter appears to minimise the yield strain, which results in an increase in the liquid's plastic dynamic viscosity and a thickening of the momentum boundary layer. Figure 5 shows the temperature curves for several estimations of the thermal radiation parameter. The temperature profile and the thickness of the temperature boundary layer are found to increase when thermal radiation calculations are upgraded. Figure 6 demonstrates how the temperature and thermal boundary layer thickness reduced when the estimations of Pr were improved and thermal diffusivity decreased, resulting in a decrease in temperature profile. When Pr is greater, heat diffuses more slowly and more quickly than when Pr is lower, controlling the relative thickness of momentum and thermal boundary layers. Figure 7 demonstrates how the thermal boundary layers are enhanced by temperature profiles with rising Q values. The energy is released to the flow when a heat source is present. The thermal boundary layers are improved by the energy. By increasing the thermophoresis parameter values, the concentration shown in this figure decreases. The influence of the thermophoresis parameter on the temperature profiles is seen in Figure 8 The thermal and concentration boundary layer thickness increases as Nt increases. As the Nb concentration and temperature curves in Figure 9 and Figure 10 increase the thickness of the thermal boundary layer is seen growing at the surface. The concentration profile for various Kr levels is shown in Figure 11.

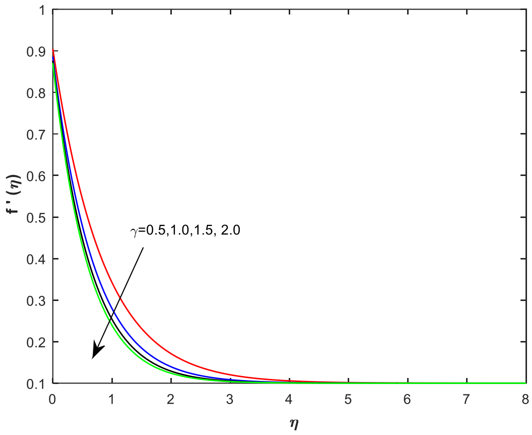

Fig. 4. Velocity Profile for various values of γ

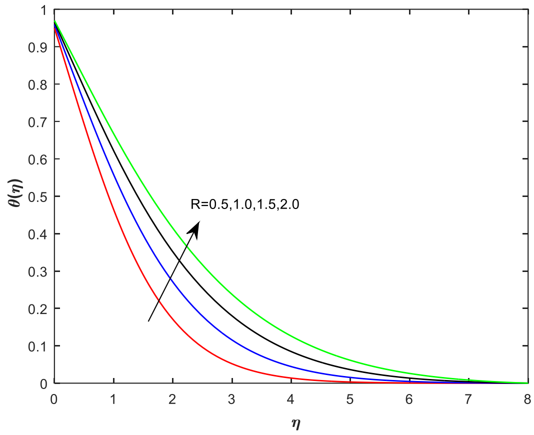

Fig. 5. Temperature Profile for various values of R

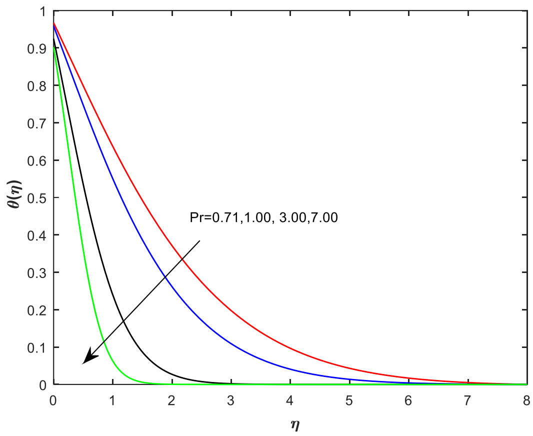

Fig. 6. Temperature Profile for various values of Pr

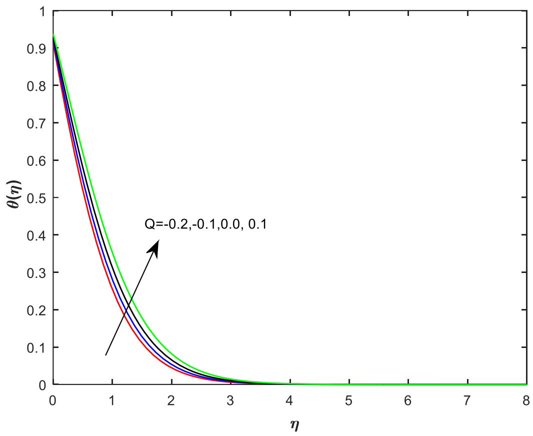

Fig. 7. Temperature Profile for various values of Q

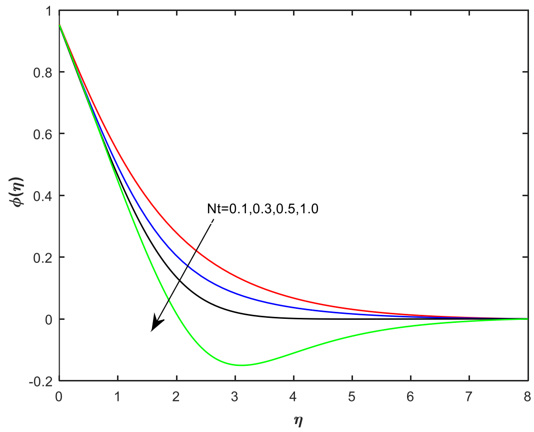

Fig. 8. Concentration Profile for various values of Nt

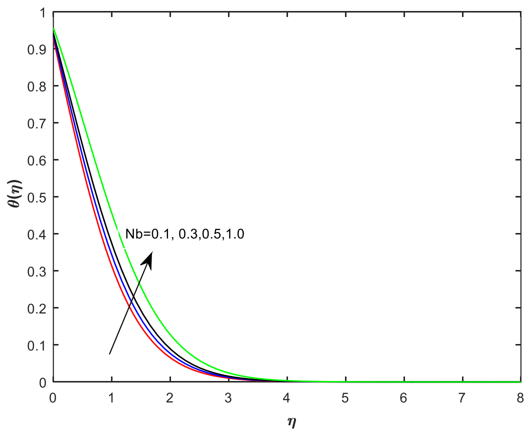

Fig. 9. Temperature Profile for various values of Nb

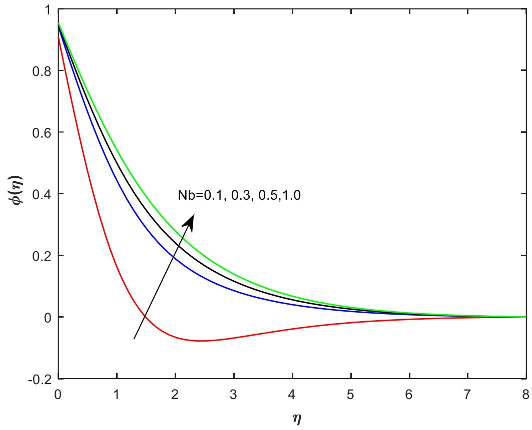

Fig. 10. Concentration Profile for various values of Nb

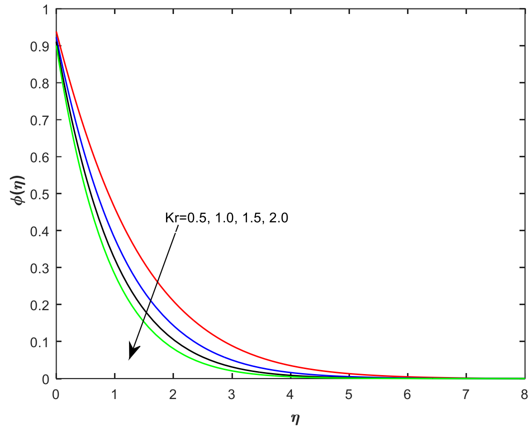

Fig. 11. Concentration Profile for various values of Kr

It was observed that the concentration profile decreased with an update to the Kr. This demonstrates how thickening the concentration boundary layer results in a drop in the concentration profile due to an increase in the chemical reaction parameter. The effect of the Lewis number on concentration profiles is seen in Figure 12. The graphic shows that the thickness of the concentration graph and the concentration border layer decreases with increasing Lewis number values.

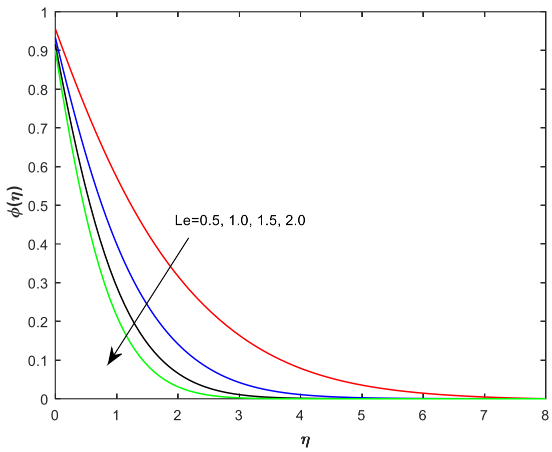

Fig. 12. Concentration Profile for various values of Le

In regard to another investigation, Table 1 compares the variation of the skin coefficient for various values of the magnetic field parameter M. The results appear to be admirably consistent with the findings of researchers Ittedi *et al.,* [45] on a restricted scale, according to the values. So, we may be sure that the numerical technique is appropriate for studying our topic.

Table 1
Comparison of skin friction coefficient $-f''(0)$ for different values of magnetic field parameter M when E = 0, β = 0, Le = 2.0, Pr = 2.0, and Kr = 0.1

M	Ittedi *et al.,* [45]	Present Study
0.0	1.2104	1.2105021
0.3	1.3578	1.3577802
0.5	1.1175	1.4475690
1.0	1.6500	1.6503921

For different values of S, and δ , the variation of $-f''(0), -\theta'(0)$ and $-\phi'(0)$ is given in Table 2. The table shows that when the suction-injection parameter S, the skin friction coefficient rises but falls the velocity parameter. The table also demonstrates how the local Nusselt number, and the local Sherwood number of the flow region change when the values of S.

Table 2
The estimates of skin friction factor, Nusselt number, Sherwood number for different values of γ, Q Nt, Nb, Kr, Le and S

γ	Q	Nt	Nb	Kr	Le	S	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.953373	0.544371	0.755949
1							1.141696	0.557614	0.770806
1.5							1.236429	0.579709	0.795489
0.1	-0.2	0.1	0.1	0.1	0.1	0.1	0.957216	0.623708	0.844095
	0						0.957216	0.799163	1.002185
	0.1						0.957216	0.871248	1.067662
0.1	0	0.1	1	0.1	0.1	0.1	0.957216	0.190038	0.462225
		0.3					0.957216	0.287873	0.479390
		0.5					0.957216	0.352388	0.488595
0.1	0	0.1	0.1	0.1	0.1	0.1	0.957216	0.439896	0.462225
			0.3				0.957216	0.585888	0.512357
			0.5				0.957216	0.650337	0.581223
0.1	0	0.1	11	0.5	0.1	0.1	0.957216	0.000001	0.614295
				1			0.957216	0.000001	0.769625
				1.5			0.957216	0.000001	0.891445
0.1	0	0.1	11	0.1	0.5	0.1	0.957216	0.000000	0.437074
					1		0.957216	0.000000	0.663644
					1.5		0.957216	0.000001	0.842443
0.1	0	0.1	11	0.1	0.5	0	0.942680	0.000003	0.407666
						0.5	1.020500	0.000012	0.561738
						1	1.113429	0.000033	0.728104

4. Conclusions

This study illustrates the MHD slip effect and Casson upper convected Maxwell fluid stagnation point flow with chemical reaction on a stretchy sheet. A similarity solution is obtained depending on the governing variables, including the velocity ratio, suction-injection parameter, Lewis numbers, Deborah number, magnetic field, Brownian motion parameter, thermophoresis parameter, chemical reactions parameter, thermal radiation parameter, velocity slip parameter, thermal slip parameter, singular slip parameter, Casson fluid parameter, and heat source parameter. The following details of the current work are displayed:

i. The effect of the magnetic field parameter's increase on the velocity field is lessened.
ii. Concentration profiles are lowered by raising the values of Brownian motion, chemical reaction, Lewis number, thermal slip parameter, and singular slip parameter.
iii. Thermal radiation increased the thermal boundary layer's thickness.
iv. The characteristics of velocity profiles about changes in the suction parameter leads to a weakening of the velocity field.

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