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Unveiling the Behavior of MHD Mixed Convective Nanofluid Slip Flow over a Moving Vertical Plate with Radiation, Chemical Reaction, and Viscous Dissipation

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ABSTRACT

The effects of chemical reactions on heat and mass transfer with radiation are extremely important in hydrometallurgical industries and chemical technology, such as polymer synthesis and food processing. A mathematical model for a viscous, incompressible, mixed convective, and MHD slip flow over a moving vertical plate is proposed in the present research. On account of physical relevance, the combined effect of radiation and chemical reaction on MHD nanofluid is studied. Using the similarity transformation method, the governing equations are converted into a system of ODEs. The transformed equations are then numerically solved by the Galerkin finite element method (GFEM). To analyse the characteristics of flow and heat transfer, a number of parameters are examined, including the slip, magnetic, radiation, and chemical reaction parameters, as well as the Schmidt, Grashof, Eckert, and Prandtl numbers. The coefficient of skin friction, Nusselt number, and Sherwood numbers for selected parameters are numerically presented. Graphs are used to determine and study the effects of magnetic fields, slip conditions, radiation, and chemical reactions on the temperature, concentration, and velocity profiles of nanofluids. This study shows that the presence of chemical reactions and radiation causes an increase in the velocity profile and temperature profile, respectively. Additionally, it is discovered that the temperature profile grows with increasing velocity slip, and concentration increases with increasing thermal slip. The current work has broad applications in various fields and can lead to the development of more efficient and effective systems in different industries, such as heat exchangers, energy production, environmental engineering, and biomedical engineering.

1. Introduction

Choi and Eastman [1] first described nanofluids as fluid suspensions of nanoparticles that exhibit notable property enhancements even at low nanoparticle concentrations. Analyse the behaviour of nanofluids is a major focus of many publications since it enables their use in many industrial applications, including nuclear reactors, transportation, electronics, biomedicine, and food, where

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effective heat transfer enhancement is crucial. Researchers have conducted a variety of experimental and theoretical investigations to determine the thermal properties of nanofluids [2-16].

Design of chemical processing equipment, fog creation and dispersion, food processing, and cooling towers are a few sample fields of interest where combined heat and mass transfer with chemical reactions play a significant role. A chemical reaction between a fluid and a foreign mass occurs in many chemical engineering procedures. These procedures are utilized in a variety of industrial applications, including polymer manufacture, ceramics or glassware making, oxidation, pollution studies, and so on. Because of this, flow studies on chemical reactions have recently received a lot of interest [5-7,9,12,15-20].

Recent advances in hypersonic flight, missile re-entry, rocket combustion chambers, interplanetary flight power plants, and gas-cooled nuclear reactors have focused attention on thermal radiation as a mode of energy transfer, emphasizing the need for a deeper understanding of radiative transfer in these processes. When the temperature difference between the surface and the ambient space is high, the radiation effect becomes significant. Natural convection flow from an inclined flat plate embedded in a porous medium due to solar radiation and in the presence of a magnetic field was studied by Chamkha and Khaled [21] and Chamkha *et al.,* [22]. Heat and mass transfer by natural convection hydromagnetic boundary layer flow around an isothermal permeable truncated cone were also examined by Chamkha and Khaled [23]. Later, Haile and Shankar [24] and Mustafa *et al.,* [25] studied the effects of thermal radiation on the natural convective boundary layer flow of nanofluid past a vertical plate. Further, a numerical investigation of mixed convection coupled with magnetic and radiation effects over a stretching sheet was conducted. The combined influence of thermal radiation, velocity slip, temperature jump, buoyancy force, viscous dissipation, Joule heating, and magnetic field was examined [26]. Recently, the radiative unsteady MHD flow of an incompressible viscous electrically conducting non-Newtonian Casson hybrid nanofluid over an exponentially accelerated vertically moving porous surface under the influence of slip velocity was examined by Krishna *et al.,* [27].

The combined effects of chemical reactions on heat and mass transfer with radiation are extremely important in hydrometallurgical industries and chemical technology, such as polymer synthesis and food processing. Heat and mass transfer analysis of hybrid nanofuid flow over stretching surface with chemical reactions, suction, slip effects, and thermal radiation was analyzed by Dandu *et al.,* [29]. Various scientists have studied the impact of radiation on chemical reactions, and references are available in Srinivasacharya and Reddy [7], Konda *et al.,* [9], Khan *et al.,* [14], Rahman and Uddin [15], Arulmozhi *et al.,* [16], Daba and Devaraj [18], Haile and Shankar [24], Omar *et al.,* [28], and Dandu *et al.,* [29].

The process of dissipation involves transforming the mechanical energy of water flowing downstream into thermal and acoustic energy. The kinetic energy of flowing rivers is reduced by a variety of devices built into streambeds, lowering the risk of erosion on banks and river bottoms. Ganga *et al.,* [4] examined the boundary layer flow of nanofluid past a vertical plate with thermal radiation effects in the presence of internal heat generation/absorption, viscous, and ohmic dissipations. Konda *et al.,* [9] explored the flow of a Casson nanofluid stretching sheet in the presence of thermal radiation, chemical reactions, viscous dissipation, a heat source, and magnetohydrodynamics. Later, the impact of MHD mixed convection stagnation-point flow towards a stretching vertical sheet in the presence of thermal radiation and viscous dissipation is numerically investigated by Shateyi and Mabood [30]. Recently, some studies on the MHD mixed convection flow along with heat transfer in the presence of viscous dissipation over an inclined stretching cylinder, stretching sheet, and moving plate were conducted by Daniel *et al.,* [8], Konda *et al.,* [9], Mondal *et al.,* [12], Upreti and Kumar [13], Shateyi and Mabood [30], Takhar *et al.,* [31], and Wakif *et al.,* [32].

The conjugate effects of heat and mass transfer are useful for improving a wide range of technologies, including underground energy transport, polymer and ceramic production, enhanced oil recovery, food processing, fog formation and dispersion, temperature and moisture distribution over agricultural fields, and environmental pollution [6]**.** The study of mixed convection boundary layer flow along a vertical surface embedded in a porous medium has piqued the theoretical and practical interests of many researchers. A number of studies focusing on the problem of mixed convection about various surface geometries have been reported in the literature by Mahanthesh *et al.,* [6], Daniel *et al.,* [8], Konda *et al.,* [9], Mondal *et al.,* [12], Upreti and Kumar [13], Daba and Devaraj [18], Suneetha *et al.,* [19], Muhammad and Makinde [26], Shateyi and Mabood [30], Abbas *et al.,* [33], Hussain *et al.,* [34], and Chamkha and Ben-Nakhi [35]. The problem of conjugate effects over a moving vertical plate under the influence of thermal radiation, internal heat generation/absorption, and chemical reactions has been studied by Mahanthesh *et al.,* [6]. Daba and Devaraj [18] extended the study of Mahanthesh *et al.,* [6] and investigated the flow of viscous fluid past a vertically moving stretching sheet with slip effects. Further, the combined effects of different parameters with unsteady mixed convection in the presence of stratifications over stretching sheets were explored by Daniel *et al.,* [8]. Suneetha *et al.,* [19] discussed the influence of ohmic heating, viscous dissipation, and chemical reactions on MHD mixed convection flow. Hydromagnetic natural convection from an isothermal inclined surface adjacent to a thermally stratified porous medium was investigated by Chamkha [36]. Solar radiation assisted natural convection in uniform porous medium supported by a vertical flat plate was also studied by Chamkha [37]. Later, the effect of heat generation or absorption on the thermophoretic free convection boundary layer from a vertical flat plate was also evaluated [38]. Kuznetsov and Nield [39] examined the effects of nanoparticles on natural convection boundary-layer flow past a vertical plate.

Velocity slip, also known as fluid non-adherence to solid boundaries, is a phenomenon that has been seen in specific situations. The no-slip requirement is insufficient when there is particulate matter present, such as in emulsions, suspensions, foams, and polymer solutions. Slip also occurs when fluoroplastic coatings, like Teflon resists adhesion. There are several uses for fluids that exhibit the slip effect, including polishing interior cavities and artificial heart valves. Martin and Boyd [40] studied the boundary layer flow model using a slip boundary condition. Mixed convection flow of nanofluid on a stretching sheet in the presence of electric and magnetic fields, thermal radiation, viscous dissipation, and chemical reaction with slip conditions was scrutinized by Daniel *et al.,* [10]. The study of the MHD buoyancy effect over a vertical plate with thermal and velocity slip was done by Ali *et al.,* [11]. Cao and Baker [41] explored the flow problem of velocity slip and temperature jump boundary conditions. An analysis of MHD boundary layer flow over a flat plate with slip conditions was presented by Bhattacharyya *et al.,* [42]. Later, Mukhopadhyay and Mandal [43] investigated MHD mixed convection boundary layer slip flow over a porous plate. Recently, MHD nanofluid flow with thermal, velocity, and concentration slip over a moving plate was explored by Rai and Mishra [44].

For solving ordinary or partial differential equations, the finite element method is an effective technique. The basic idea behind the finite element method (FEM) is that the entire domain is divided into smaller, finite-dimensional elements called finite elements. The method essentially consists of assuming a piecewise continuous function for the solution and obtaining the parameters of the functions in such a way that the error in the solution is minimized. This method is the most general-purpose numerical technique in engineering analysis, and it has been used to investigate a wide range of problems in heat transfer, fluid mechanics, rigid body dynamics, solid mechanics, chemical processing, electrical systems, acoustics, and many other areas [45]. In order to solve the problem of unsteady mixed convection flow and heat transmission along a vertical stretching sheet, Sharma and

Singh [46] investigated the element free Galerkin technique (EFGM). Using a finite element method based on a Galerkin weighted residual approach, we were able to find both analytical and numerical solutions for the unsteady natural convection flow of a fluid past a vertical plate with variable temperature and mass diffusion under the influence of chemical reaction, radiation, and viscous dissipation [5]. A variational finite element technique (FEM) was used by Uddin *et al.,* [47] to handle the boundary value issue of a nonlinear mathematical model. Using the finite element approach, Jyothi *et al.,* [48] investigated the effects of slip on chemically reacting Carreau nanofluid flow over a wedge. To explore the impact of a heat source on an unsteady MHD free convection flow of Casson fluid via a vertical oscillating plate, Goud *et al.,* [49] imposed a Galerkin finite element approach. By using the finite element method, Ibrahim and Gadisa [45] examined the properties of the nonlinear convective flow of an Oldroyd-B fluid with a Cattaneo-Christov heat flux model.

Therefore, the objective of the present study is to extend the work of researchers on MHD slip flow of nanofluid over a moving vertical plate in the presence of viscous dissipation, radiation, and chemical reactions with slip conditions. Convergent solutions for the governing equations are obtained by using the Galerkin finite element method (GFEM) technique. Variations of several pertinent emerging parameters are analyzed in detail. We expect that the study of the effects of slip conditions and viscous dissipation on magnetohydrodynamic boundary layer flow over a moving plate in a nanofluid is not yet available. Also, unlike the present investigation, the power full technique GFEM does not yet apply to solve highly nonlinear coupled differential equations governing boundary layer flow problems. So, we hope that the present study has an important contribution to make to future study.

2. Formulation of Problem

We consider a steady two dimensional MHD boundary layer flow of a nanofluid past a moving semi- infinite vertical plate in a uniform free stream in the presence of thermal radiation, chemical reactions and viscous dissipation. It is assumed that the velocity of the uniform free stream is $\boldsymbol{U}$ and that of the plate is $U_w = \epsilon U$, where ϵ is the velocity parameter. The flow is assumed to occur at $y \geq 0$, with y being the coordinate measured normal to the moving surface. A magnetic field of strength B is assumed to be applied in the direction normal to the surface shown in Figure 1. The induced magnetic field and Hall current impacts are ignored due to a small magnetic Reynolds number [29]. The temperature and the amount of nanoparticles have constant values at the moving plate, Tw and Cw, respectively.

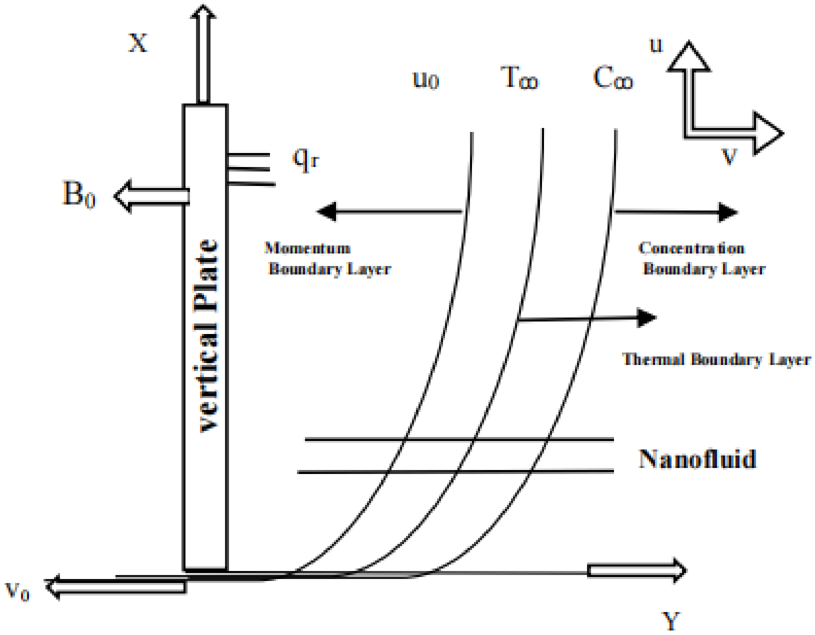

Fig. 1. Physical Model of Mathematical problem

Under such conditions, the governing boundary layer equations of continuity, momentum, energy, and diffusion with thermal radiation, viscous dissipation, chemical reaction, and slip effects of the nanofluids can be written in cartesian coordinates of x and y in dimensional form as [4,11,24,50]:

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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2}{\rho}u+g\beta_t(T-T_\infty)+g\beta_c(C-C_\infty) \tag{2}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+Q_0(T-T_\infty)+\frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{3}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}-\gamma_1(C-C_\infty) \tag{4}$$

Subjected to the boundary conditions

$$\begin{cases} u=\epsilon\, u_0, u=U_w+S_u\frac{\partial u}{\partial y}, T=T_w+S_t\frac{\partial T}{\partial y}, C=C_w+S_c\frac{\partial C}{\partial y}, & at\ y=0 \\ u\to U_\infty, T\to T_\infty, C\to C_\infty, & at\ y\to\infty \end{cases} \tag{5}$$

Where (u,v) are the x and y velocity components, T is temperature, T∞ and C∞ are temperature and nanoparticle concentration far from the sheet, respectively, k is the thermal conductivity of fluid,ρ is the density of the fluid, σ is the electrical conductivity of the fluid. $C_p$is the heat capacity of the fluid. S_u, S_t and $S_c$are velocity, thermal and concentration slip.

According to the Rosseland diffusion approximation, the radiative heat flux is given by q_r

$$q_r=\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{6}$$

Where σ^* and k^* are the Stefan-Boltzmann constant and the Rosseland mean absorption Coefficient, respectively. We assume that the temperature differences within the flow are sufficiently small so that T^4 may be expressed as a linear function of temperature

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4 \tag{7}$$

Using (6) and (7) in Eq. (3), we obtain

$$\frac{\partial q_r}{\partial y} = -\frac{16\,\sigma^* T_\infty^3}{3k^*}\frac{\partial T^4}{\partial y} \tag{8}$$

Eq. (1) to Eq. (4) subjected to boundary conditions (5) are defining similarity transformation as follow

$$\begin{aligned} &\eta = \left(\frac{U_\infty}{2\nu x}\right)^{1/2} y, \psi = (2U_\infty \nu x)^{1/2} f(\eta) \\ &T = T_\infty + (T_w - T_\infty)\theta(\eta) \\ &C = C_\infty + (C_w - C_\infty)\phi(\eta) \\ &\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \end{aligned} \tag{9}$$

Where θ and ϕ denote dimensionless temperature and resealed nanoparticle volume fraction respectively. Stream function ψ is assumed as $u = \frac{\partial \psi}{\partial y}$ and $= -\frac{\partial \psi}{\partial x}$, as a result of

$$u = U_\infty f'(\eta) \tag{10}$$

$$v = -\left(\frac{U_\infty \nu}{2x}\right)^{\frac{1}{2}} f(\eta) + \frac{U_\infty y}{2x} f'(\eta) \tag{11}$$

By applying the similarity transformation to Eq. (2) to Eq. (5) the resulting equations are as follows:

$$f''' + ff'' - Mf' + G_r\theta + G_c\phi = 0 \tag{12}$$

$$P_r(f\theta' + Q\theta + Ec\,(f'')^2 + \left(1 + \frac{4}{3}Rd\right)\theta'' = 0 \tag{13}$$

$$\phi'' + S_c f\phi' - \gamma\phi = 0 \tag{14}$$

Corresponding boundary conditions

$$\begin{cases} f(\eta) = \epsilon V_0, f'(\eta) = 1 + \lambda_u f''(\eta), \theta(\eta) = 1 + \lambda_t \theta'(\eta), \phi(\eta) = 1 + \lambda_c \phi'(\eta), & at\ \eta = 0 \\ f'(\infty) \to 1, \theta(\infty) \to 0, \phi(\infty) \to 0, & at\ \eta \to \infty \end{cases} \tag{15}$$

Where $\mathrm{Pr} = \frac{\nu\rho C_p}{k}$ represents the Prandtl number, $G_r = \frac{g\beta(T_w - T_\infty)x^3}{\nu^2}$, $G_c = \frac{g\beta(C_w - C_\infty)}{\nu^2}$, $Q = \frac{Q_0}{\rho C_p}$, $Ec = \frac{(U_\infty)^2}{C_p(T_w - T_\infty)}$ indicates Eckert number and $Sc = \frac{\nu}{D_B}$ is given by the Schmidt number, $\gamma = \frac{2\nu\gamma_1}{U_\infty}$ represents chemical reaction parameter, $M = \frac{2x\sigma B_0^2}{\rho U_\infty}$ is defined as the magnetic parameter.

Note that $\lambda_u = N_1 \left(\frac{U_\infty}{2\nu x}\right)^{\frac{1}{2}}$ is the velocity slip, $\lambda_t = N_2 \left(\frac{U_\infty}{2\nu x}\right)^{\frac{1}{2}}$ thermal slip and $\lambda_c = N_3 \left(\frac{U_\infty}{2\nu x}\right)^{\frac{1}{2}}$ is the concentration slip parameter. The Physical quantities, C_f, Nu_x and Sh_x are given by

$$C_f = \frac{\tau_w}{\rho u_e^2}, Nu_x = \frac{x q_w}{k(T_w - T_\infty)}, Sh_x = \frac{x j_w}{D_B(C_w - C_\infty)}. \quad (16)$$

The shear stress, heat flux and mass flux on surface are denoted by τ_w , q_w , j_w respectively and also shown as

$$\tau_w = \mu \left(\frac{\partial u}{\partial y}\right)_{y=0}, q_w = -\left(k + \frac{16\,\sigma^* T_\infty^3}{3k^*}\right)\left(\frac{\partial T}{\partial y}\right)_{y=0}, j_w = -D_B \left(\frac{\partial C}{\partial y}\right)_{y=0} \quad (17)$$

Where μ = ρν is the dynamic viscosity.

By applying the similarity variables in Eq. (6), following relation are obtained

$$C_f (2Re_x)^{1/2} = f''(0), Nu_x \left(\frac{Re_x}{2}\right)^{-1/2} = -\left(\frac{3+4\mathrm{R}}{3}\right)\theta'(0), Sh_x \left(\frac{Re_x}{2}\right)^{-1/2} = -\emptyset'(0) \quad (18)$$

Where $\mathrm{Re}_x = \frac{U_\infty x}{\nu}$ is local Reynolds number and $(2Re_x)^{1/2}, Nu_x \left(\frac{Re_x}{2}\right)^{-1/2}$ and $Sh_x \left(\frac{Re_x}{2}\right)^{-1/2}$ are defined by reduced C_{fr}, Nur and Shr and also given as $f''(0), -\theta'(0)$ and $-\emptyset'(0)$, respectively.

3. Result and Discussion

The values of $-\theta'(0)/\sqrt{2)}$ for with varied values of Pr (Prandtl Number) were determined to ensure the accuracy and validity of the results. The values obtained are compared with those reported by Bejan [51] and Pop *et al.,* [52] as shown in Table 1. The numerical values obtained using the finite element method show great agreement with the earlier investigations.

Table 1
Comparing the Numerical values of $\mathrm{Nu_x}\sqrt{\mathrm{Re_x}}$ or $(-\theta'(0)/\sqrt{2)}$ (With regard to different values of Pr for $\epsilon = \gamma = \mathrm{Rd} = \mathrm{M} = \mathrm{Ec} = 0$

Pr	Bejan [51]	Pop *et al.,* [52]	Present Results
0.7	0.292	0.29268	0.293460081
0.8	0.307	0.30691	0.306911034
1	0.332	0.33205	0.332901232
5	0.585	0.57668	0.574532044
10	0.730	0.72814	0.729897789

The effects of non-dimensional governing parameters on the friction factor, local Nusselt, and Sherwood numbers are shown in Table 2 and Table 3. According to the table, increasing the Pradtl number, thermal, velocity, and concentration slip parameters resulted in a decrease in friction factor and sherwood numbers but an increase in heat and mass transfer rate. The friction factor and Sherwood numbers improve as the magnetic field, Eckart number, thermal and concentration Grashof numbers, and radiation parameters increase. However, increasing the chemical reaction parameter resulted in an increase in the Nusselt and Sherwood numbers but a decrease in the coefficient of skin friction.

Table 2
Numerical values of local skin friction coefficient, reduced Nusselt number and reduced Sherwood number for different parameters with $\epsilon = 0.1, \mathrm{Pr} = 7, \lambda_u, \lambda_t, \lambda_p = 1$

M	Gr	Gc	Q	Rd	Sc	γ	C_{fr}	Nur	Shr
0.1							-0.079416000	0.350641798	0.404712466
0.2							-0.125841027	0.332529090	0.406985010
0.3							-0.168513161	0.441405642	0.409089343
	0.1						-0.079416000	0.350641798	0.404712466
	0.5						-0.121012483	0.336807310	0.406370751
	1						-0.187704934	0.437324107	0.409103579
		0.1					-0.079416000	0.350641798	0.404712466
		0.3					-0.119373515	0.336082202	0.406520520
		0.5					-0.159718297	0.450795073	0.408354503
			0				-0.075578185	0.453767738	0.404555648
			0.2				-0.076639423	0.424406013	0.404598778
			0.4				-0.078248130	0.539184740	0.404664531
				0			-0.078047955	0.371857823	0.404651922
				0.5			-0.081201098	0.326166479	0.404793691
				1			-0.083613700	0.420705182	0.404906873
					0.1		-0.077089739	0.351472303	0.435625263
					0.5		-0.079416000	0.350641798	0.404712466
					1		-0.082468891	0.494315271	0.366461989
						0	-0.087744784	0.347664129	0.262434448
						0.2	-0.083662558	0.349138024	0.331308281
						0.4	-0.080646877	0.495270391	0.383203226

Table 3
Numerical values of local skin friction coefficient, reduced Nusselt number and reduced Sherwood number for different parameters with $\epsilon = \gamma = \mathrm{Sc} = \mathrm{Q} = 0.5, \mathrm{Gc} = \mathrm{Gr} = \mathrm{M} = \mathrm{Ec} = 0.1, \mathrm{Rd} = 0.2, \mathrm{Pr} = 7$

Ec	Pr	λ_u	λ_t	λ_p	C_{fr}	Nur	Shr
1					-0.0797998673	0.3438522557	0.4047298009
5					-0.0816072736	0.3118872978	0.4048114207
10					-0.0841399549	0.3777467457	0.4049257890
	5				-0.0816312156	0.3207173547	0.4048136001
	7				-0.0794160001	0.3506417977	0.4047124656
	10				-0.0774128231	0.5410973784	0.4046243767
		1			-0.0794160001	0.3506417977	0.4047124656
		5			-0.0284833935	0.3351920196	0.4065219176
		10			-0.0158448890	0.4678204549	0.4069864947
			0.1		-0.0871473309	-0.0871473309	0.4050179758
			0.5		-0.0825767445	-0.0825767445	0.4048372382
			1		-0.0794160001	-0.0794160001	0.4047124656
				0.1	-0.0908487339	0.3467070161	0.6378609872
				0.5	-0.0844683730	0.3489243552	0.5077437946
				1	-0.0794160001	0.4958823858	0.4047124656

Figure 2 and Figure 3 illustrate how the magnetic field parameter affects the fluid's velocity and temperature. Improving the magnetic parameter as can be seen in the figures, M decreases fluid velocity while increasing temperature. The magnetic field Lorentz law may be responsible for this. The Lorentz force increases as the magnetic field intensity increases, causing the fluid to flow in the opposite direction. As a result, the fluid's velocity decreases, and its temperature and species concentration increase.

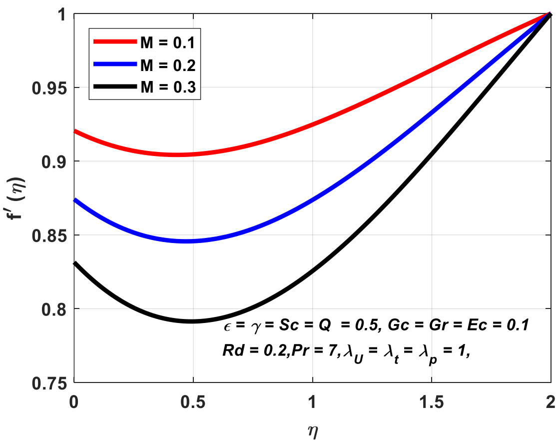

Fig. 2. Variation of velocity $f'(\eta)$ with η with several values of M

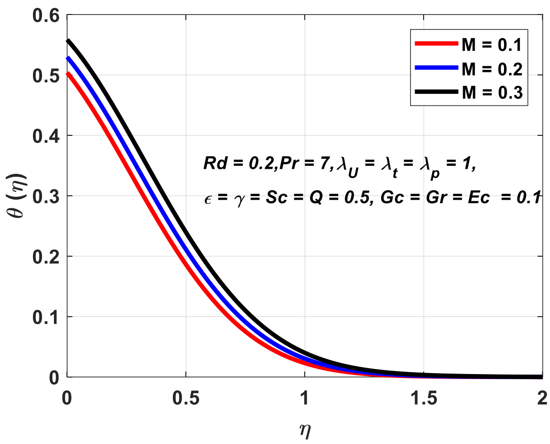

Fig. 3. Variation of temperature $\theta(\eta)$ with η with several values of M

The temperature profile of the nanofluid is affected by the thermal radiation parameter Rd, as shown in Figure 4. An increase in heat radiation increases the conduction influence and increases the thickness of the thermal layer. The temperature rises at every point away from the permeable top surface. This causes an increase in the distribution by adding more heat to the fluid molecules and nanoparticles already there.

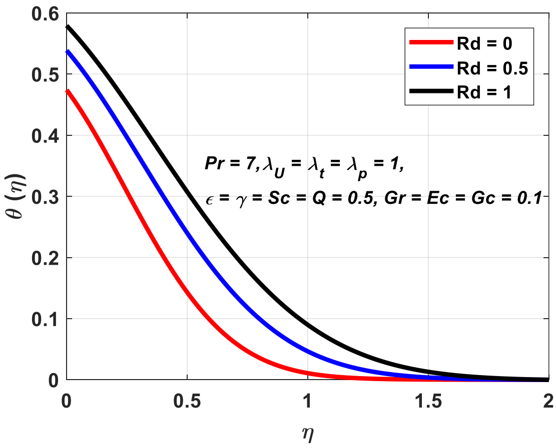

Fig. 4. Variation of temperature $\theta(\eta)$ with η with several values of Rd

In Figure 5, the influence of Q on temperature is examined. It demonstrates that as the value of heat generation Q rises, so does the temperature profile. It is observed that the estimation of the heat generation parameter Q causes the temperature of the nanofluid to rise.

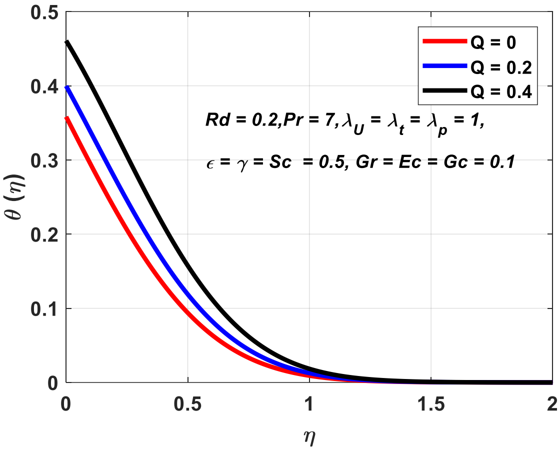

Fig. 5. Variation of temperature θ (η) with η with several values of Q

Figure 6 and Figure 7 show how the fluid's velocity and concentration profile change with an increasing Schmidt number. The ratio of momentum diffusivity to mass diffusivity is known as the Schmidt number. As a result, as the Schmidt number increases, the velocity profile reduces and the concentration profile increases.

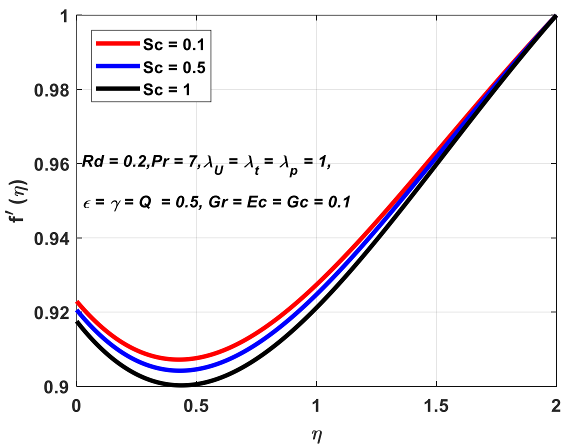

Fig. 6. Variation of velocity f ′ (η) with η with several values of Sc

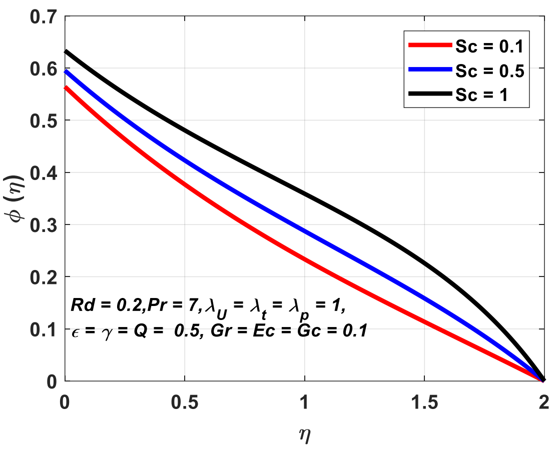

Fig. 7. Variation of concentration ϕ(η) with η with several values of Sc

Figure 8 and Figure 9 show the effect of the thermal Grashof number on flow velocity and temperature profiles. It is clear that as the thermal Grashof number increased, we saw a decrease in velocity and an increase in the concentration profiles of the flow. This is because an increase in the thermal Grashof number generates buoyancy forces, which reduce the thickness of the boundary layer.

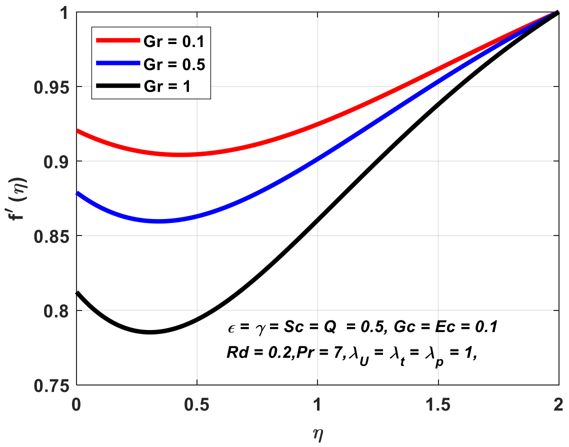

Fig. 8. Variation of velocity f ′ (η) with η with several values of Gr

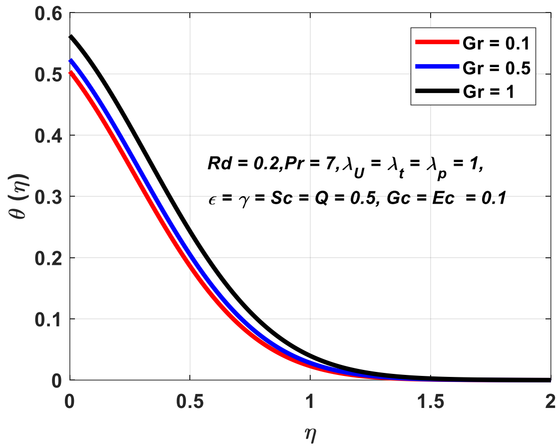

Fig. 9. Variation of temperature θ (η) with η with several values of Gr

Figure 10 illustrates the relationship between the fluid's velocity and the value of the chemical reaction parameter. Figure 11 shows that the concentration of the fluid will be suppressed as the chemical reaction parameter is increased. Less diffusion results from higher values of γ, which cause the chemical molecule's diffusivity to decrease. With an increase in the chemical reaction parameter, the concentration distribution falls at all points of the flow field.

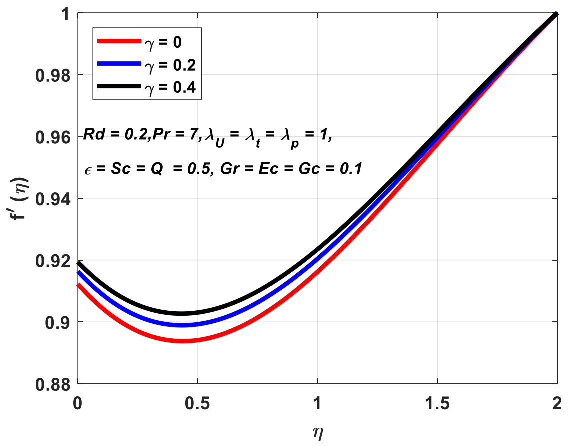

Fig. 10. Variation of velocity f ′ (η) with η with several values of γ

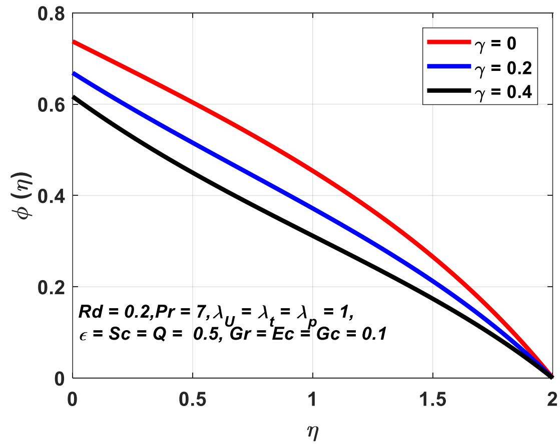

Fig. 11. Variation of concentration ϕ(η) with η with several values of γ

As the Prandtl number rises, velocity also rises, as shown in Figure 12. (Pr). The Prandtl number's effect on the temperature profile was depicted in Figure 13 A fluid's Pr property indicates that it has greater thermal diffusivity when it has a low Pr value. Since the temperature and thickness of the thermal boundary layer drop as the Prandtl number rises, this phenomenon occurs.

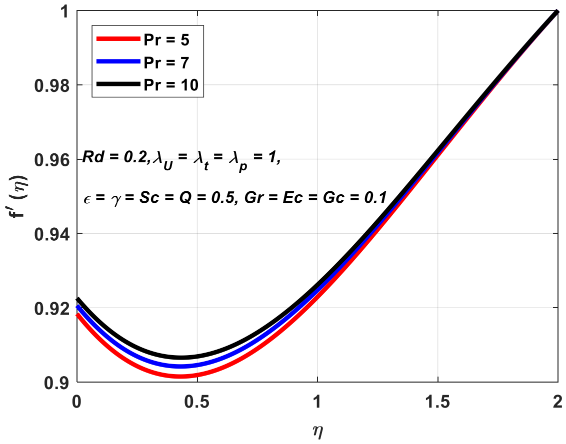

Fig. 12. Variation of velocity $f'(\eta)$ with η with several values of Pr

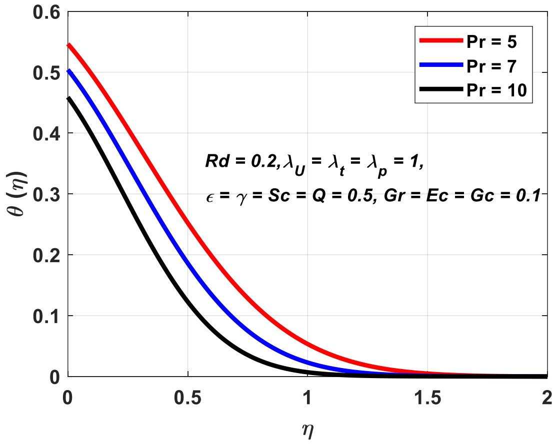

Fig. 13. Variation of temperature $\theta(\eta)$ with η with several values of Pr

Figure 14 demonstrates how the velocity profile decreases with increasing values of λ_u. As λ_u is increased, the slip velocity rises. Fluid velocity decreases when slip velocity rises because the moving plate's surface moves at a different rate than the flow near it. Increases in slip velocity but decreases in fluid velocity arise from raising the slip velocity parameter.

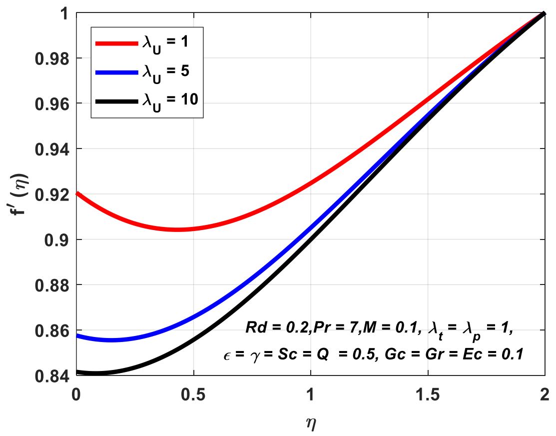

Fig. 14. Variation of velocity $f'(\eta)$ with η with several values of λ_u

Figure 15 shows how the temperature profile at the boundary surface is affected by velocity slip. The results demonstrate that as the slip parameter rises, the boundary surface temperature profile does as well. It's because a rise in velocity slip causes nanoparticles to diffuse into the boundary layer.

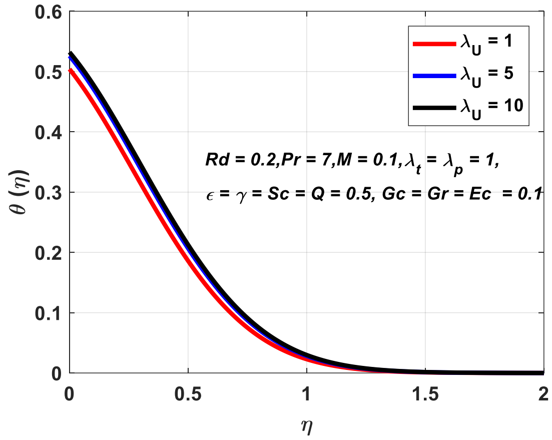

Fig. 15. Variation of temperature θ (η) with η with several values of λ_u

The impact of the thermal slip parameter λ_t on the dimensionless temperature and nanoparticle volume fraction is shown in Figure 16 and Figure 17. It is evident that as the values of $\lambda_t$are raised, the temperature falls and the concentration profiles rise. Even when just a little amount of heat is transported from the sheet to the fluid, the thermal boundary layer thickness decreases as the value of the thermal slip parameter rises.

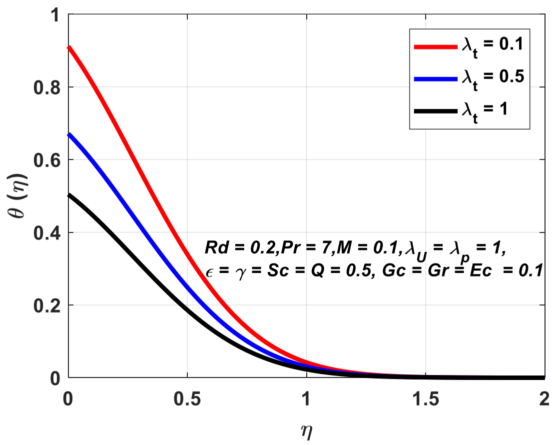

Fig. 16. Variation of temperature θ (η) with η with several values of λ_t

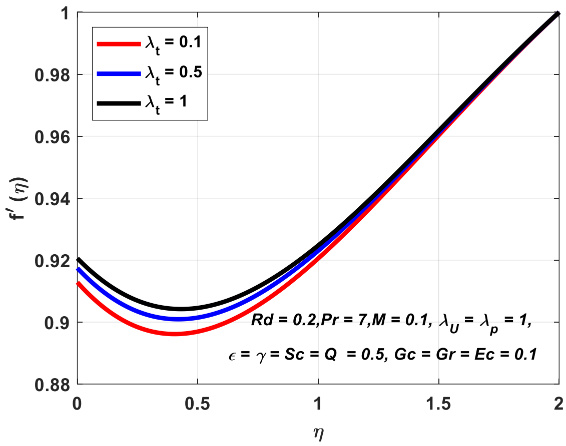

Fig. 17. Variation of concentration ϕ (η) with η with several values of λ_t

Figure 18 shows the inverse relationship between the temperature profile and the concentration slip parameter within the boundary layer region. Figure 19 shows how an impact has on the concentration profile. This is so because slip slows down fluid flow, which in turn slows down net molecule mobility. The decreased molecular mobility causes a drop in temperature and mass fraction.

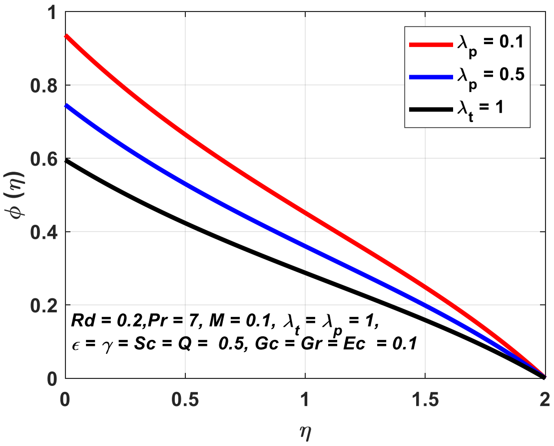

Fig. 18. Variation of temperature θ (η) with η with several values of λ_p

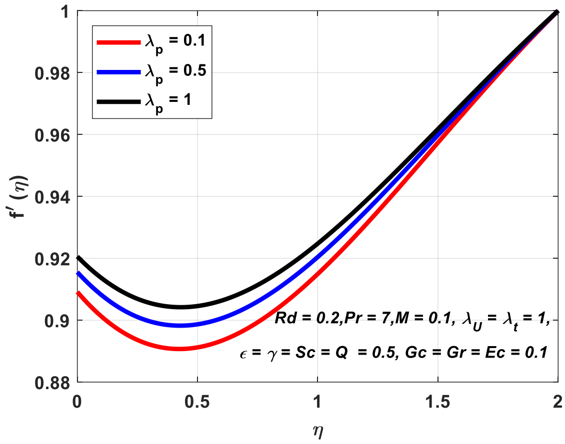

Fig. 19. Variation of concentration ϕ (η) with η with several values of λ_p

4. Conclusions

The numerical study of the boundary layer flow of a nanofluid across a Vertical moving plate with the effects of radiation, chemical reaction, velocity slip, temperature slip, concentration slip, magnetic field, and viscous dissipation. The impacts of fluid flow factors on velocity, temperature, and concentration profiles are investigated. $\mathrm{M}, \mathrm{Gc}, \mathrm{Gr}, \mathrm{Sc}, \mathrm{Q}, \mathrm{Rd}, \gamma, \varepsilon, \lambda_u, \lambda_t, \lambda_p$ and Pr are studied on different profiles. The results are as follows:

(i) The Lorentz force causes the velocity profile to decrease as the magnetic parameter M is increased, while temperature profiles increase.
(ii) With the existence of viscous dissipation, velocity and temperature profiles rise.
(iii) For rising values of the velocity slip parameter, the velocity profile drops. It also increases the thickness of the concentration boundary layer.
(iv) Temperature reduces and concentration rises when the thermal slip parameter is enhanced.
(v) Temperatures increase and concentration reduces as concentration slip parameter is increased.
(vi) Velocity drops and temperature increases as the thermal and concentration Grashof numbers are enhanced.
(vii) As Schmidt number increases, the velocity profile reduces and the concentration profile increases.
(viii) As the value of heat generation Q rises, so does the temperature profile.
(ix) When the Chemical reaction parameter γ increases, the velocity profile increases and the temperature profile decreases.
(x) Increasing the Prandtl number, increases velocity and decreases the temperature profile.
(xi) Temperatures increase as the radiation parameter (Rd) is increased.

This analysis has numerous practical applications in engineering and science. The following are few of them:

(i) Cooling systems in electronic devices such as laptops and smartphones, which use nanofluids to enhance heat transfer efficiency.
(ii) Nuclear reactor cooling systems, where nanofluids can be used to improve heat transfer and reduce the likelihood of overheating.
(iii) Oil and gas industry, where the analysis can be used to study the flow of fluids through pipes and the efficiency of heat transfer.

(iv) Aerospace industry, where the analysis can be applied to the design of thermal protection systems for spacecraft.
(v) Biomedical engineering, where the analysis can be used to study the flow of blood through veins and arteries and the effects of radiation and chemical reactions on the flow.

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