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Buoyancy Effects on MHD Flow of a Nanofluid over a Stretching Sheet with Chemical Reaction

Adamu Gizachew Chanie¹, Bandari Shankar²

PhD Student, Department of Mathematics, Osmania University, Hyderabad, India¹

Professor, Department of Mathematics, Osmania University, Hyderabad, India²

ABSTRACT: In this article, the effect of buoyancy on an MHD nanofluid flow over a stretching sheet in the presence of a chemical reaction is investigated. Furthermore, the effect of thermophoresis and Brownian motion on the fluid flow has been taken into account. The governing PDE's is transformed into an ordinary differential equation using a suitable similarity variable. The transformed equation with the assumption of boundary conditions is computed by Runge-Kutta fourth order method along with shooting technique. The results obtained are explained through tables and graphs mainly for the distribution of concentration, velocity, and temperature for various values of the governing parameters. It is indicated that both thermal and solutal buoyancy parameters enhance the velocity distribution of the fluid. To check the validity of the method the Nusselt number has been compared with the available results and it is found in excellent agreement.

KEYWORDS: Nanofluid; Numerical solution; buoyancy; Lewis number; suction.

I. INTRODUCTION

The knowledge of heat transfer flow has drawn the concentration of many investigators for several decades because of its use for engineering process. Some of its applications are chemical reaction process, industry process, transport phenomena etc. Methods of heat transfer are classified as radiation, convection, and conduction. Conduction is a heat transfer through direct contact of molecules. Convection occurs during the movement of the fluid and solid body, and radiation is a method of heat transfer through electromagnetic waves with the absence of a medium. The first scientist who discovered heat was James Prescott Joule an English Physicist. The force applied on an object that is wholly or partly submerged in a fluid is known as Buoyancy. Its SI unit is Newton[N]. It is occurred due to a pressure difference acting on opposite sides of an object submerged in a static fluid. According the principle of Archimedes the Buoyant force amount on an object is equivalent to the fluid weight it displaces. Buoyancy is influenced by different reasons. Some of the reasons are the density of the fluid, the volume of the fluid displaced, and the local accelerations due to gravity. Mass of the submerged object and density of the submerged object do not affect the Buoyancy force.

II. RELATED WORK

The characteristics of heat transfer on different types of flow were examined by a number of investigators. The flow of heat transfer characteristics of a laminar viscous fluid on a stretching surface with variable wall temperature in the hypothesis of suction or blowing was studied by Vajvauel and Hadjinicolaou [1]. Later on, Qasim [2] carried out his study on the behavior of a Jeffery fluid flow on a stretching sheet under the influence of heat source/sink. His results indicated that the temperature distribution of the fluid decreases as the Deborah number increases. Magnetohydrodynamics (MHD) is a science that studies the magnetic properties of fluids which are electrically conducting, example liquid metals, plasmas, electrolytes and salt water.

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The involvement of magnetic field in the flow problem enhances the thermal conductivity and heat transfer of a fluid. Plentiful investigations have been studied on it. Daniel et al. [3] analysed the MHD flow of a fluid on a stretching sheet through a porous media using homotopy analysis method (HAM) with an impact of thermal radiation and buoyancy. Their result designated that an enhancement of thermal radiation raises the fluids thermal boundary layer thickness. Later on, Gizachew and Shankar [4] presented their study on a laminar steady non-Newtonian viscoelastic fluid flow and the characteristics of the heat transfer through a horizontal expanded plane. Their outcome illustrated that the thermal conductivity of a fluid was enhanced by an increase of viscoelastic and magnetic field parameter. Moreover, MHD fluid flow, the heat and mass transfer features on a vertical stretching sheet with an influence of radiation and buoyancy using HAM were analyzed by Rashidi et al. [5]. Correspondingly, Sulochana and Kumar [6] examined MHD fluid flow, characteristics of heat and mass transfer with radiation and chemical reaction influences. In their examination, they obtained that thermal radiation enhances the thermal boundary layer thickness of a fluid. Also, Reddy et al. [7] investigated MHD fluid flow behaviors on a porous inclined vertical plate. Furthermore, a magnetic field effect on different fluid flows is explained by several investigators in the references [8]-[13].

For the increment of a heat transfer and thermal conductivity of fluids, Choi [14] introduced a new technique, i.e., adding nanoparticles to a base fluid, the resulting fluid which he called it nanofluids. The base fluids that are employed for this function are like toluene, water, oil, and ethylene mixture, and the nanoparticles that are applicable for a nanofluid can be solid viz. silver, aluminum, gold and copper, metallic liquid like sodium and it can be non-metallic like Silicon (SiO), alumina (Al_2O_3). Besides the development of heat transfer, the causes have were examined out by Boungiorno [15]. His results have shown that in addition to nanofluids, thermophoretic and Brownian motion parameter contributes to the enhancement of heat transfer. Later on, Kandasamy et al. [16] investigated a mixed convective MHD flow of a nanofluid and its properties with an impact of thermophoresis and Brownian motion. Equally, Yazdi et al. [17] explored the cause of Brownian motion on alumina-water which are naturally convective. Their numerical result showed that an enhancement of Rayleigh number raises the Nusselt number. Furthermore, an MHD flow of a Maxwell fluid containing nanoparticles due to a stretching sheet with the effect of radiation and a chemical reaction was studied by Ramesh et al. [18]. Moreover, Ibrahim et al. [19] analyzed the magnetic field impacts on a nanofluid near stagnation point and transfer of heat on a stretching sheet. Generally, several studies on nanofluids were studied in the references [20]-[27]. This study aimed to examine the effect of buoyancy on the MHD flow of nanofluids with chemical reaction on a stretching sheet. Furthermore, the study looked at the effect of other parameters on the transfer properties of heat. Under the assumption of a similarity variable, the governing PDEs were changed into a couple of ODEs. The resulting equation is computed numerically using Runge-Kutta fourth order method along with shooting technique. The effect of the parameters involved on the fluid flow problems is computed by tables and graphs.

III. MATHEMATICAL FORMULATION

We considered MHD flow of an incompressible nanofluid which is steady two-dimensional on a stretching sheet. The direction of the flow is supposed to be along a sheet which is stretching and the flow of a nanofluid is taken place in the region. The introduction of two forces which are opposite and equal along the axis as a result of the stretching sheet causes the fluid flow to be produced. Holding the origin fixed, the sheet material is then stretched at a distance from the slit with a certain speed that varies linearly. In the direction normal to the sheet a magnetic field of strength B_0 is applied. Because of low magnetic Reynolds number and no external applied electric field assumption, both the magnetic field and electric field are excluded from the present study. In addition, the impact of Buoyancy on the fluid flow are extensively viewed in the considered model. The equation of continuity, momentum, energy, and concentration is considered as follows.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

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$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - \nu \frac{\partial^2 u}{\partial y^2} + \frac{\sigma B_0^2}{\rho_f} u = g\beta_t(T - T_\infty) + g\beta_n(C - C_\infty) \quad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} - \alpha \frac{\partial^2 T}{\partial y^2} - \frac{\mu_f}{(\rho c_p)_f} \left(\frac{\partial u}{\partial y} \right)^2 = \frac{(\rho c_p)_s}{(\rho c_p)_f} \left[D_B \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} + \left(\frac{D_T}{T_\infty} \right) \left(\frac{\partial T}{\partial y} \right)^2 \right] \quad (3)$$

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

In the above equations, u and v denotes the velocity components in the direction of x and y axes in accordance with their order. Furthermore, $g, \beta_t, \beta_n, \sigma, T, C, \rho_f, \alpha_t$, and μ_f denotes acceleration due to gravity, the coefficient of thermal expansion, the coefficient of concentration expansion, the electrical conductivity of the nanofluid, the temperature, concentration, density of the fluid, thermal diffusivity, and the dynamic viscosity of the base fluid respectively. The ambient temperature and concentration are denoted by T_∞ and C_∞ respectively, and the Brownian diffusion coefficient is denoted by D_B , D_T is the thermophoresis diffusion coefficient, $(\rho c_p)_s$ is the effective heat capacity of the nanosolid particle, $(\rho c_p)_f$ is the effective heat capacity of the base fluid, R is the chemical reaction rate coefficient.

The boundary conditions considered in this study are as follows:

$$\left. \begin{aligned} u = u_w(x) = bx, \quad v = v_w, \\ T = T_w, \quad C = C_w \end{aligned} \right\} \text{ at } y = 0 \quad (5)$$

$$u \rightarrow 0, v \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty \text{ as } y \rightarrow \infty \quad (6)$$

$u_w(x) = bx$ is assumed to be the stretched velocity, b is a positive constant named stretched rate. Under the assumption of the following similarity transformations and substitution

$$\left. \begin{aligned} \psi = f(\eta)x\sqrt{bv_f}; \eta = y\sqrt{\frac{b}{v_f}}; \\ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}; \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \end{aligned} \right\} \quad (7)$$

where $\frac{\partial \psi}{\partial y} = u$ and $\frac{\partial \psi}{\partial x} = -v$, ψ is the dimensional stream function.

The above non-linear partial differential Eqs. (2) to (4) are transformed into

$$f'''' + ff'' - f'^2 - Mf' + R_t\theta + R_s\phi = 0 \quad (8)$$

$$\theta'' + Pr[f\theta' + Nb\theta'\phi' + Nt\theta'^2 + Ec\phi'^2] = 0 \quad (9)$$

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$$\phi'' + Le Pr(f\phi' - \gamma\phi) + \frac{Nt}{Nb}\theta'' = 0 \quad (10)$$

Based on the similarity transformation the boundary condition is also transformed into

$$\left. \begin{aligned} f'(\eta) = 1, f(\eta) = S, \theta(\eta) = 1, \phi(\eta) = 1 \\ \text{at } \eta = 0 \end{aligned} \right\} \quad (11)$$

$$\left. \begin{aligned} f'(\eta) \rightarrow 0, \theta(\eta) \rightarrow 0, \phi(\eta) \rightarrow 0 \\ \text{as } \eta \rightarrow \infty \end{aligned} \right\} \quad (12)$$

where $f(\eta)$, $\theta(\eta)$ and $\phi(\eta)$ represents the dimensionless stream function, the dimensionless temperature, and the dimensionless concentration in accordance with their order and the prime denotes its differentiation with respect to η only. The non-dimensional parameters that are contained in the above equation are defined as follows:

$M = \frac{\sigma B_0^2}{b\rho_f}$ is the magnetic parameter, $R_t = \frac{Gr_x}{Re^2 x} = \frac{g\beta_t(T_\omega - T_\infty)}{b^2}$, the thermal buoyancy parameter,

$R_s = \frac{Gn_x}{Re^2 x} = \frac{g\beta_n(C_\omega - C_\infty)}{b^2}$, is the solutal buoyancy parameter, $Nt = \frac{(\rho c_p)_s}{(\rho c_p)_f} \frac{D_T}{T_\infty} \frac{T_\omega - T_\infty}{v_f}$, thermophoresis

parameter, $Nb = \frac{(\rho c_p)_s}{(\rho c_p)_f} \frac{D_B(C_\omega - C_\infty)}{v_f}$, Brownian motion parameter, $Le = \frac{v_f}{D_\beta}$ is the Lewis number, where,

$Gr_x = \frac{g\beta_t(T_\omega - T_\infty)x^3}{v_f^2}$ is the local Grashof number, $Gn_x = \frac{g\beta_n(C_\omega - C_\infty)x^3}{v_f^2}$ is the local modified Grashof

number, $Ec = \frac{u_\omega^2}{c_p(T_\omega - T_\infty)}$ is the Eckert number, $Pr = \frac{v_f}{\alpha}$ is the Prandtl number, $\gamma = \left(\frac{R}{C}\right)$ is the chemical

reaction parameter $Re x = \frac{u_\omega}{v_f} x$ is the Reynolds number. $S = \frac{-v_\omega}{\sqrt{b}v_f}$ is the suction parameter. The essential physical

quantities that arises in this problem are the local skin friction coefficient C_f , the local Nusselt number Nu , and the local Sherwood number Sh which are defined by

$$C_f = \frac{\tau_\omega}{\mu_f u_\omega(x) \sqrt{\frac{b}{v_f}}} = f'''(0) \quad (13)$$

where, $\tau_\omega = \mu_f \left(\frac{\partial u}{\partial y}\right)_{y=0} = \mu_f b x \sqrt{\frac{b}{v_f}} f'''(0)$

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$$Nu = \frac{q_\omega}{k \sqrt{\frac{b}{\nu_f}} (T_\omega - T_\infty)} = -\theta'(0) \quad (14)$$

$$q_\omega = -k \left(\frac{\partial T}{\partial y} \right)_{y=0} = -k \sqrt{\frac{b}{\nu_f}} (T_\omega - T_\infty) \theta'(0)$$

and
$$Sh = \frac{J_\omega}{D_B (C_\omega - C_\infty) \sqrt{\frac{b}{\nu_f}}} = -\phi'(0) \quad (15)$$

$$J_\omega = -D_B \left(\frac{\partial C}{\partial y} \right)_{y=0} = -D_B (C_\omega - C_\infty) \sqrt{\frac{b}{\nu_f}} \phi'(0)$$

The letters τ_ω , q_ω , and J_ω represents the shearing stress, surface heat flux and mass flux respectively.

IV. NUMERICAL SOLUTION

In order to solve the transformed non-linear ordinary differential equations (8)-(10) together with boundary conditions (11) and (12), we apply Runga-Kutta fourth order method along with shooting technique. To apply this method on the given problem the following assumptions are made

$$\left. \begin{aligned} f(1) &\rightarrow f, f(2) \rightarrow f', f(3) \rightarrow f'', \\ f(4) &\rightarrow \theta, f(5) \rightarrow \theta', f(6) \rightarrow \phi, f(7) \rightarrow \phi' \end{aligned} \right\} \quad (16)$$

And rewriting equations (8)-(10) with their boundary conditions in the form of

$$\begin{aligned} f''' &= -ff'' + f'^2 + Mf' - R_t \theta - R_s \phi \\ \theta'' &= -Pr [f\theta' + Nb\theta'\phi' + Nt\theta'^2 + Ec f'^2] \\ \phi'' &= -Le Pr (f\phi' - \gamma\phi) - \frac{Nt}{Nb} \theta'' \\ &= -Le Pr (f\phi' - \gamma\phi) + \frac{Nt}{Nb} Pr [f\theta' + Nb\theta'\phi' + Nt\theta'^2 + Ec f'^2] \end{aligned}$$

$$\left. \begin{aligned} f_a(1) &= S, f_a(2) = 1, f_a(4) = 1, f_a(6) = 1, \\ f_b(2) &= 0, f_b(4) = 0, f_b(6) = 0 \end{aligned} \right\} \quad (17)$$

Where a and b are the initial and boundary condition points i.e. $a = 0, b = \infty$. Before solving the problem by the explained method using Matlab program, we assumed the step size $\Delta\eta = 0.01$ and the accuracy convergence criteria to be a five decimal value.

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V. RESULTS AND DISCUSSIONS

In this article, we studied MHD flow of nanofluid and the properties of heat transfer under the influence of various parameters. To analyse the flow model of the above system of non-linear coupled differential equations (8)-(10) for various values of governing parameters viz, magnetic field parameter M , thermal buoyancy parameter Rt , solutal buoyancy parameter Rs , Brownian motion parameter Nb , thermophoresis parameter Nt , chemical reaction parameter γ , and as well as a Lewis number Le , we used an efficient Runge-Kutta fourth order method along with shooting technique.

Table-I. Comparison results of local Nusselt number ($-\theta'(0)$) when $M=S=Ec=Rt=Rs=\gamma=0, Le=1, Pr=1, Nb=0.1$.

Nt	Present (Nu)	Ramesh et al. [18] (Nu)	Khan and Pop [28] (Nu)	Sherwood Number (Sh)
0.1	0.952366	0.9523	0.9524	2.129424
0.3	0.520074	0.5200	0.5201	2.528654
0.5	0.321050	0.3210	0.3211	3.035162

Table II. Comparison results of skin friction coefficient $-f''(0)$, local Nusselt number ($-\theta'(0)$), and Sherwood number ($-\phi'(0)$) for various values of the governing parameters.

S	M	Rs	Rt	Pr	Nb	Nt	Ec	γ	Le	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	0.5	0.5	0.5	3	0.1	0.1	0.02	0.2	1	0.830318	0.890637	1.055215
0.2										0.954776	1.206391	1.127328
0.4										1.088933	1.557611	1.188102
0.2	0	0.5	0.5	3	0.1	0.1	0.02	0.2	1	0.721994	1.240253	1.150813
	0.5									0.954776	1.206391	1.127328
	1									1.155138	1.177018	1.109487
0.2	0.5	0	0.5	3	0.1	0.1	0.02	0.2	1	1.153580	1.178263	1.110900
		0.3								1.033194	1.195704	1.120962
		0.5								0.954776	1.206391	1.127328
0.2	0.5	0.5	0	3	0.1	0.1	0.02	0.2	1	1.121885	1.186430	1.116637
			0.2							1.020969	1.198682	1.123125
			0.4							0.954776	1.206391	1.127328
0.2	0.5	0.5	0.5	0	0.1	0.1	0.02	0.2	1	0.513562	0.125000	0.125000
				1						0.790555	0.699329	0.503766
				3						0.954776	1.206391	1.127328
0.2	0.5	0.5	0.5	3	0.1	0.1	0.02	0.2	1	0.954776	1.206391	1.127328
					0.3					0.977633	0.843659	1.674930
					0.5					0.970582	0.576253	1.769149
0.2	0.5	0.5	0.5	3	0.1	0.1	0.02	0.2	1	0.954776	1.206391	1.127328
						0.2				0.899510	1.102956	0.649999
						0.3				0.850577	1.008460	0.328347

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0.2	0.5	0.5	0.5	3	0.1	0.1	0	0.2	1	0.955542	1.227330	1.109420
							0.01			0.955159	1.216854	1.118379
							0.02			0.954776	1.206391	1.127328
0.2	0.5	0.5	0.5	3	0.1	0.1	0.02	0	1	0.937894	1.227942	0.800339
								0.1		0.946866	1.216450	0.971430
								0.2		0.954776	1.206391	1.127328
0.2	0.5	0.5	0.5	3	0.1	0.1	0.02	0.2	0	0.513562	1.642362	-1.392362
									1	0.954776	1.206391	1.127328
									3	1.045345	1.096053	3.334767

In order to check the validity of the results obtained by using this numerical method, the Nusselt number ($\theta'(0)$) for various values of Nt is compared with the previously published results (table-I) and it is found in an excellent agreement. In Table-II, we have presented the comparison of skin friction coefficient, Nusselt number, and Sherwood number for various values of parameters. From the table, it is obtained that Prandtl number Pr enhances heat transfer rate, while the magnetic field parameter M reduces it. In figures (1)-(4) the velocity profile results for various parameter effect is shown. Figure 1 depicts that an increase of the suction parameter S reduces the velocity distribution of the fluid.

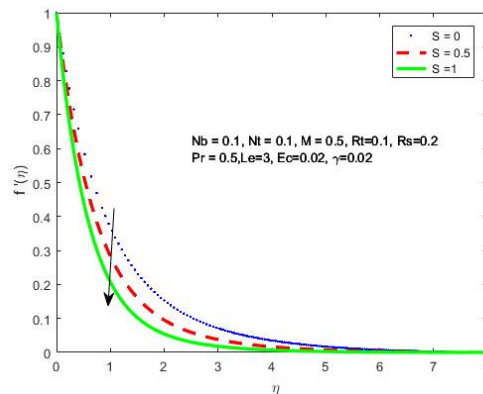


Figure 1. Velocity profiles as a function of S .

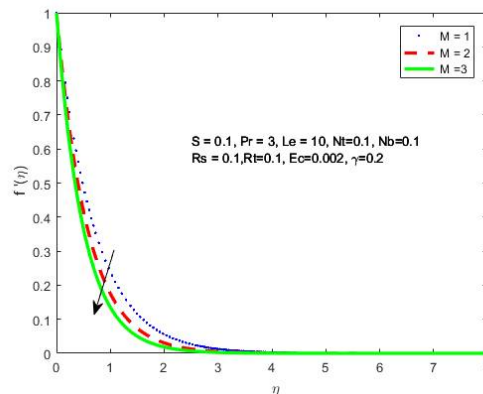


Figure 2. Velocity profiles as a function of M .

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The magnetic field parameter M effect on the velocity profile is displayed in figure 2. It is shown that magnetic field slows down the motion of the fluid. It is due to the fact that the presence of a magnetic field creates a Lorentz force that opposes the motion of the fluid and resists the velocity of the fluid. Figure-3 revealed that an increase of the solutal buoyancy parameter rises the velocity profile of the fluid.

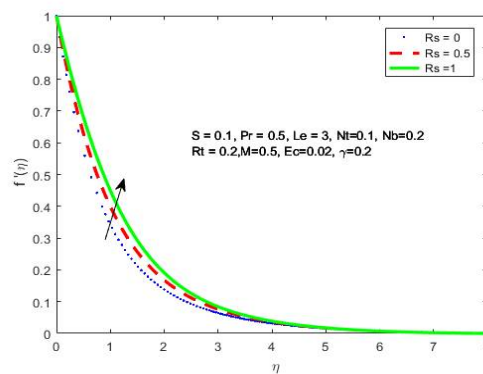


Figure 3. Velocity profiles as a function of R_s .

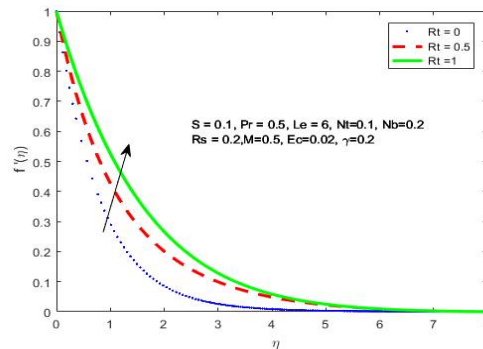


Figure 4. Velocity profiles as a function of R_t .

In figure 4 the thermal buoyancy effect on the velocity distribution of the fluid is shown. The graph has indicated that an increase of thermal buoyancy enhances the axial velocity of the fluid.

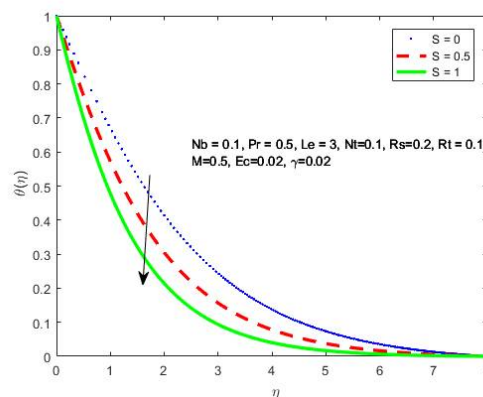


Figure 5. Thermal conductivity as a function of S .

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In figures (5)-(9) the parametric effect of suction S , magnetic field parameter M , solutal buoyancy Rs Brownian motion parameter Nb , and thermal buoyancy parameter Rt is presented. Figure 5 demonstrated that an increase of suction parameter S reduces the thermal conductivity of the fluid. Since an increase of suction S brought the fluid close to the surface.

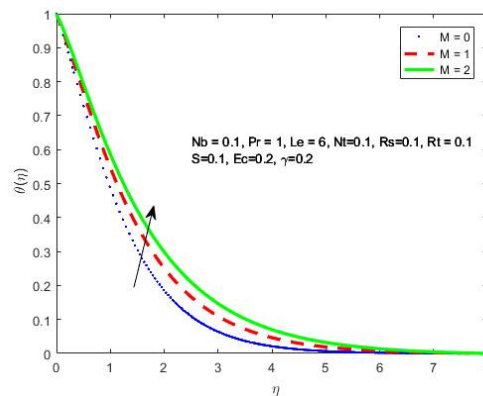


Figure 6. Thermal conductivity as a function of M .

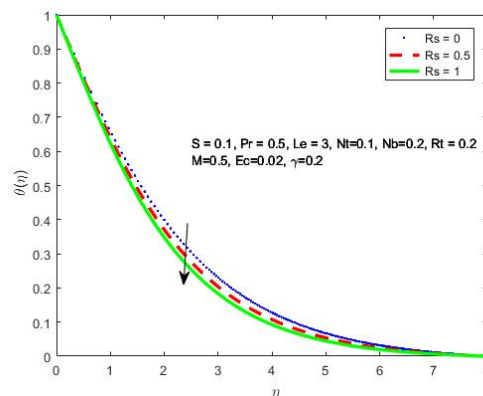


Figure 7. Thermal conductivity as a function of Rs .

Figure 6 depicts that when the magnetic field parameter M increases the temperature distribution of the fluid increases. It is because the existence of the magnetic field creates a Lorentz force that opposes the motion of a fluid and increases the thermal conductivity of the fluid. The solutal buoyancy parameter Rs effect on the temperature profile is shown in figure 7. It is seen that an increase of solutal buoyancy parameter Rs decelerates the thermal conductivity of the fluid. Figure 8 displays the Brownian motion Nb effect on the temperature profile. The results have shown that an increase of Nb facilitates the temperature distribution of the fluid. The thermal buoyancy parameter Rt effect on the fluid temperature is revealed using figure 9. It is found that an increase of the thermal buoyancy parameter Rt decreases the thermal conductivity of the fluid. In figure (10)-(14) the concentration profile results due to an increase of the parameters like Brownian motion parameter Nb , thermophoresis parameter Nt , Lewis number Le etc. are presented.

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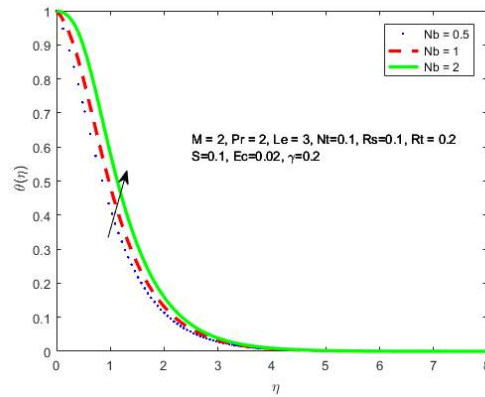


Figure 8. Thermal conductivity as a function of Nb .

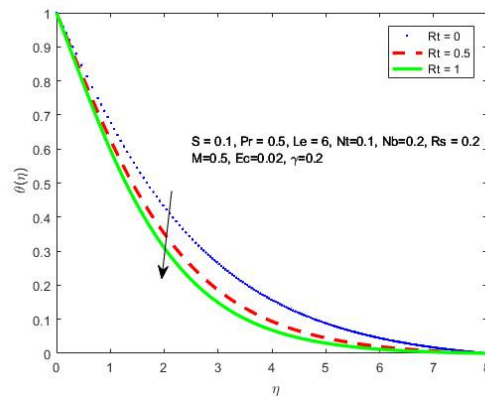


Figure 9. Thermal conductivity as a function of Rt .

From figure 10, it is indicated that the fluid concentration decreases due to an increase of the Brownian motion parameter Nb . It is due to the fact that the net movement of particles in base fluids makes the nanofluid to be less concentrated.

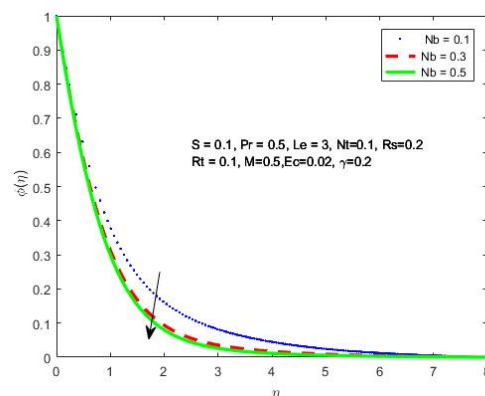


Figure 10. Concentration profiles as a function of Nb .

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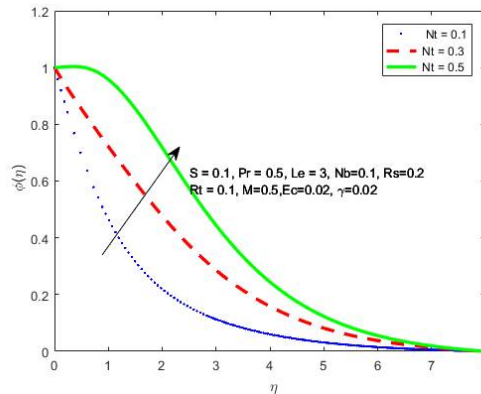


Figure 11. Concentration profiles as a function of Nt .

Figure 11 displays the thermophoresis parameter Nt effect on the concentration of the fluid. It is observed that increasing thermophoresis parameter Nt decreases the concentration of the fluid. Since the thermophoresis parameter Nt for hot surfaces tends to blow the concentration boundary layer of the fluid far from the surface. This causes, the fluid concentration to be created outside.

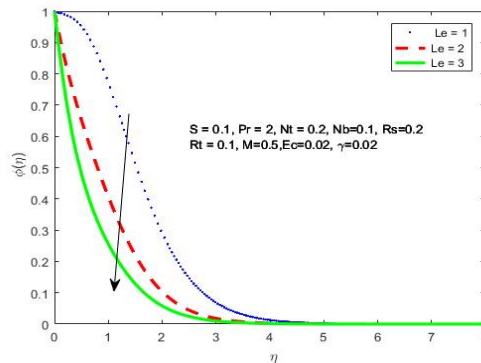


Figure 12. Concentration profile as a function of Le .

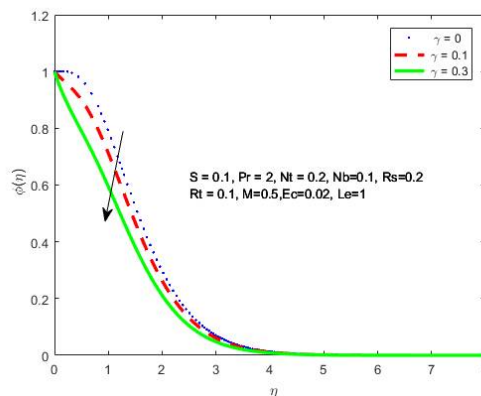


Figure 13. Concentration profiles as a function of γ .

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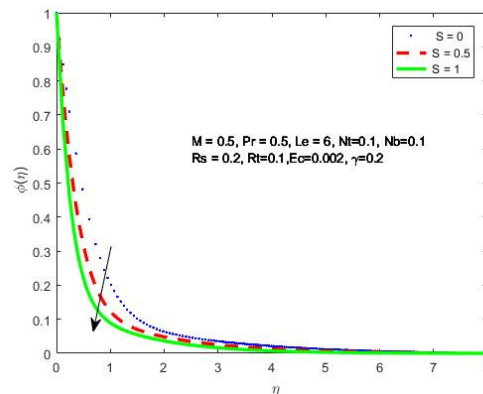


Figure 14. Concentration profiles as a function of S .

Figure 12 illustrates Lewis effect on the concentration of the fluid. An increase of Lewis number Le lowers the concentration profile of the fluid. This is because the mass diffusivity of the fluid is inversely proportional to Lewis number. Figure 13 shows the influence of chemical reaction γ on the concentration profile. The result has shown that an increase in chemical reaction γ reduces the fluid concentration. It is due to the fact that the process of chemical reaction that is taken place in the fluid gives fluid particles to move freely. Finally, the effect of suction on the concentration of the fluid is displayed in figure 14. From the figure, it is observed that an increase in the suction parameter S reduces fluid concentration.

VI. CONCLUSION

The effect of thermal and solutal buoyancy parameters on the nanofluid flow, heat, and mass transfer characteristics due to a stretching sheet in the presence of a magnetic field was the main focus of the study. In addition, the effect of thermophoretic, Brownian motion, Lewis number, and chemical reaction parameters have been taken into account. The governing transformed differential equations were computed numerically using Runge-Kutta fourth order method along with shooting technique. The obtained results have been presented using graphs and tables, it is summarized as follows.

- The magnetic field parameter enhances the thermal conductivity of the nanofluid while it reduces the velocity distribution of the fluid.
- The axial velocity of the fluid increases with an increase of both thermal and solutal buoyancy parameter while the thermal conductivity of the fluid decreases.
- Brownian motion parameter and thermophoresis parameter enhances the thermal conductivity of the fluid.
- An increase of suction parameter reduces the axial velocity, thermal conductivity, and concentration of the nanofluid.
- Brownian motion reduces the concentration of the fluid while thermophoresis parameter increases.
- Both Lewis number and chemical reaction parameter has a reducing effect on the concentration of the nanofluid.

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