

Article

Stratified Flow of Micropolar Nanofluid over Riga Plate: Numerical Analysis

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Abstract: In this article, we present a numerical analysis of the energy and mass transport behavior of microrotational flow via Riga plate, considering suction or injection and mixed convection. The thermal stratified parameters of nanofluid are captured using an interpretation of the well-known Keller box model, which helps us to determine the characteristic properties of the physical parameters. The formulated boundary layer equations (nonlinear partial differential equations) are transformed into coupled ODEs with nonlinearities for the stratified controlled regimes. The impact of embedded flow and all physical quantities of practical interest, such as velocity, temperature, and concentration profile, are inspected and presented through tables and graphs. We found that the heat transfer on the surface decreases for the temperature stratification factor as mass transfer increases. Additionally, the fluid velocity increases as the modified Hartmann number increases.

Keywords: Riga plate; double stratification; Brownian motion; thermophoresis; mixed convection; suction or injection



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1. Introduction

A large number of examinations on non-Newtonian fluids with applications in many areas including materials science, fluid mechanics, chemistry, and biology have been carried out in recent years. Different studies aimed to identify the mixed convection effects on the squeezed flow of Sutter by fluid in the presence of double stratification. The double stratification of liquid occurs due to the concentration and temperature differences. Thermal stratification happens when two kinds of streams come in to contact with different temperatures. Their temperature distinction makes the colder and heavier water settle at the lower part of the liquid surface, while permitting the hotter and lighter liquid to drift over the cold liquid [1]. From a modern perspective, numerous applications use the idea of double stratification, for example, heat dismissal from climate nuclear power storing frameworks and sun-based energy as better stratification results in the higher energy execution. Numerous studies have been performed to explore the numerical analysis of double stratified convective flow [2–5]. Waqas et al. [6] studied stratified Oldroyd-B nanofluid flow via the homotopy technique. Daniel et al. [7] considered double stratification with additional slip effects for nanofluids. Recently, Eswaramoorthi et al. [8] studied double-stratification impacts on Williamson liquid for Riga surface. Mutuku and Makinde [9] conducted a numerical study of double-stratification effects for the Buongiorno model. Aaiza et al. [10] examined energy transfer in a mixed convection MHD flow of nanofluid containing different shapes of nanoparticles. They considered the fluid a channel filled

with saturated porous medium. In addition, Hayat et al. [11] investigated nanoliquids over an extended surface by incorporating stratified impacts.

The poor temperature conductivity of traditional coolants such as water, crude oil, mineral oil, etc., has limited the cooling capabilities of heat transfer devices. Notably, metals have somewhat high thermal conductivity compared to liquids. Hence, dissipating nanometer-sized metallic particles in liquids is perhaps the best method to further develop heat movement. The concept of nanofluid was introduced by Choi and Eastman [12] to address most problems of practical interest. Over the past few centuries, engineers and scientists have successfully investigated nanofluid convective heat transfer [13–17]. Recently, Rafique et al. [18] investigated micropolar nanofluid flow over a slanted surface and portrayed the inclination effect.

Nowadays, numerous issues in different fields of engineering and industry need to be addressed due to their significant applications in daily life, such as controlling an engine's temperature, machine speed, construction, and other scientific uses. The model of micropolar liquid might be used to develop models of the dust or smoke particles in gas or the environment. Unfortunately, these issues or models have some complicated nonlinear terms that are difficult to tackle logically. A few techniques can be utilized to address such problems: a notable technique is the Keller box technique. Rafique et al. [19] studied the characteristics of the microrotational effect on heat and mass transport rates via the Keller box scheme. Recently, Koriko et al. [20] investigated bioconvection flow by considering nanoparticles and gyrotactic micro-organisms. Mabood et al. [21] examined micropolar fluid flow for a moving plate and drawn streamlines. In addition, micropolar fluid flow on a wavy slanted surface was discussed by Srinivasacharya and Ramana [22].

In addition to all the key problems experienced with linear extending sheets, the available literature also describes the flow produced via an exponential extending surface as a significant factor in the vast field of engineering and processing. Initially, Magyari and Keller [23] started the analysis of flow through an exponentially stretching surface. They studied the energy and mass exchange phenomenon of fluid flow over a surface that is stretched with an exponential velocity. Later, Elbashbeshy [24] extended their work for heat transport with the addition of the suction/injection factor. Bidin and Nazar [25] numerically investigated the exponential extending surface with the influence of radiation. Hayat et al. [26] examined a stretching Riga plate by incorporating variable thickness effects. Shaw et al. [27] investigated an extending Riga surface with variable effects. Nadeem et al. [28] considered an exponential stretching Riga plate for the nanofluid regime. Moreover, Eid [29] discussed the extending Riga surface with the impacts of radiation. Recently, Abbas et al. [30] studied nanofluid flow for an exponentially extending Riga surface. The latest work on a stretching Riga plate was performed by Alotaibi and Rafique [31] considering mixed convection impacts.

To the best of our knowledge, no previous studies of the micropolar nanofluid flow generated by exponentially stretching Riga plate for double stratification have been reported. The impact of stratification is a significant aspect in energy and mass exchange investigations. Double stratification occurs due to different densities, different temperatures, and different concentrations of liquids. In the phenomenon of energy and mass transport, it is important to analyze the impact of double stratification on flow. The study of mixed convection in a double-stratified medium is a research hotspot due to its significance in nuclear power, solar ponds, geophysical flows etc. [32]. In this study, we aimed to address such limitations and develop and provide theoretical support for and to further develop the study of non-Newtonian fluids with practical applications. The system of equations was numerically solved using the boundary value problem solver (Keller box), which is available in MATLAB. A direct comparison with the findings in the literature for specific conditions confirmed the accuracy of our current work. This study's findings will be useful in chemical and biomedical applications, such as breast cancer tumors and human thermal plumes, and other engineering applications.

2. Materials and Methods

In this study, we adopted a 2D-steady micropolar nanofluid with an exponentially stretching sheet, considering double stratification and suction or injection. We assumed that the velocity of the stretching plate has an exponential form, i.e., $u_w(x) = u_0 e^{\frac{x}{2l}}$. The velocities field along the x and y axis are u , and v , respectively. The flow is characterized by velocity, which is governed by a randomly expanding surface. The fluid elements in the micropolar nanofluid have a stronger ability to stay in place before colliding with another fluid molecule, resulting in gyration effects as these molecules spin in the fluid continuum [33]. The gyration vector in a micropolar nanofluid is an ideal replacement for exhibiting the conjugate effects of heat and mass transport. The Riga plate structure presented in Figure 1, while the physical model of current flow presented in Figure 2. The equations defining the computational domain are provided below.

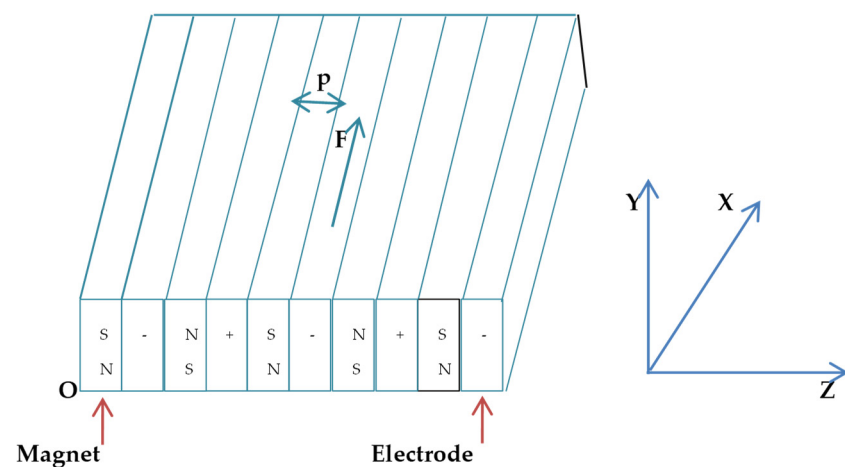


Figure 1. Physical structure of Riga plate.

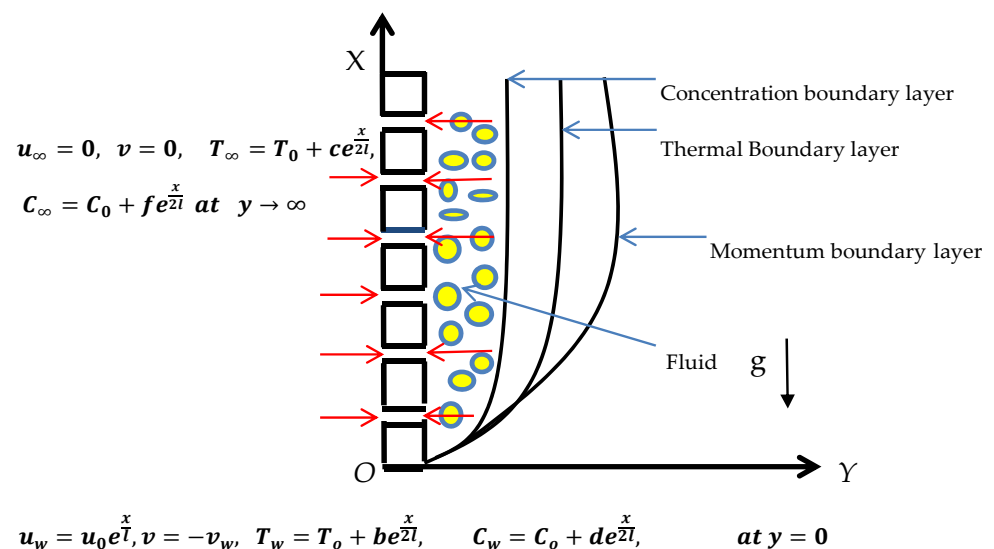


Figure 2. Geometry of the physical configuration.

The basic equations were developed from [34]:

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \left(\frac{\mu + k_1^*}{\rho} \right) \frac{\partial^2 u}{\partial y^2} + \left(\frac{k_1^*}{\rho} \right) \frac{\partial N^*}{\partial y} + g[\beta_t(T - T_\infty) + \beta_c(C - C_\infty)] + \left(\frac{\pi j_0 M_0}{8\rho} \right) e^{-\frac{y\pi}{p}} \quad (2)$$

$$u \frac{\partial N^*}{\partial x} + v \frac{\partial N^*}{\partial y} = \left(\frac{\gamma^*}{j^* \rho} \right) \frac{\partial^2 N^*}{\partial y^2} - \left(\frac{k_1^*}{j^* \rho} \right) \left(2N^* + \frac{\partial u}{\partial y} \right) \quad (3)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \tau \left[D_B \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} + \frac{D_T}{T_\infty} \left(\frac{\partial T}{\partial y} \right)^2 \right] \quad (4)$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_B \frac{\partial^2 C}{\partial y^2} + \frac{D_T}{T_\infty} \frac{\partial^2 T}{\partial y^2} \quad (5)$$

The suitable boundary conditions for this flow regime are given as

$$u = u_w(x), v = -v_w(x), N^* = -m_0 \frac{\partial u}{\partial y}, T = T_w(x), C = C_w(x) \text{ at } y = 0, u \rightarrow 0, v \rightarrow 0, N^* \rightarrow 0, T \rightarrow T_\infty(x), C \rightarrow C_\infty(x) \text{ at } y \rightarrow \infty \quad (6)$$

where

$$T_\infty(x) = T_0 + ce^{\frac{x}{2l}}, C_\infty(x) = C_0 + fe^{\frac{x}{2l}}, T_w(x) = T_0 + be^{\frac{x}{2l}}, C_w(x) = C_0 + de^{\frac{x}{2l}}$$

Applying

$$u = u_0 e^{\frac{x}{2l}} f'(\eta), v = -\sqrt{\frac{v u_0}{2l}} \{f(\eta) + \eta f'(\eta)\} e^{\frac{x}{2l}}, \eta = y \sqrt{\frac{u_0}{2lv}} e^{\frac{x}{2l}} \quad (7)$$

$$\theta(\eta) = \frac{T - T_0}{T_w - T_0}, \phi(\eta) = \frac{C - C_0}{C_w - C_0}, N^* = \left(\frac{u_0}{2lv} \right) e^{\frac{3x}{2l}} \sqrt{2lv u_0} h(\eta)$$

with the use of Equation (7), Equations (2)–(5) take the above form, and Equation (1) is identically satisfied.

$$(1 + K)f''' + ff'' - 2f'^2 + kh' + Me^{-m\eta} + (\lambda\theta + \delta\phi) = 0 \quad (8)$$

$$\left(1 + \frac{K}{2} \right) h'' + h'f - hf' - K(2h + f'') = 0 \quad (9)$$

$$\theta'' + PrNb\phi'\theta' + PrNt\theta'^2 + Pr(f\theta' - f'\theta) - St_1 f' = 0 \quad (10)$$

$$\phi'' + Nt_b\theta'' + Le(f\phi' - f'\phi) - St_2 f' = 0 \quad (11)$$

In the previous dimensionless equations, the prime emphasizes differentiation with respect to η , and ρ is the fluid's kinematic viscosity; M denotes the modified Hartmann number; Pr is the Prandtl quantity; $m = \frac{\pi}{p} \sqrt{\frac{v}{a}}$ is the dimensionless parameter; Le is the Lewis quantity; K is the dimensionless vortex viscosity; λ denotes the local Grashof number; δ denotes the modified Grashof number; $Nt_b = \frac{Nt}{Nb}$, where Nb denotes Brownian motion and Nt denotes thermophoresis variable; and St_1, St_2 are stratification parameters.

$$\nu = \frac{\mu}{\rho_f}, Pr = \frac{\nu}{\alpha}, Nb = \tau \frac{D_B (C_w - C_\infty)}{V}, Nt = \tau \frac{D_T (T_w - T_\infty)}{VT_\infty}, K = \frac{k_1^*}{\mu}, j^* = \frac{\nu}{\alpha}, \quad (12)$$

$$\lambda = \frac{2l}{Re^2} g\beta_t (T_w - T_\infty), St_1 = \frac{c}{b}, St_2 = \frac{f}{d}, \delta = \frac{2l}{Re^2} g\beta_c (C_w - C_\infty), M = \frac{l\pi j_0 M_0}{4\rho u_w^2}$$

The boundary conditions (6) are changed to:

$$f(\eta) = S, f'(\eta) = 1, h(\eta) = 0, \theta(\eta) = 1 - St_1, \phi(\eta) = 1 - St_2 \text{ at } \eta = 0 \quad (13)$$

$$f'(\eta) \rightarrow 0, h(\eta) \rightarrow 0, \theta(\eta) \rightarrow 0, \phi(\eta) \rightarrow 0 \text{ as } \eta \rightarrow \infty$$

We signify the following quantities associated with local Nusselt number, local Sherwood number, and skin friction;

$$Nu_x = \frac{xq_w}{k(T_w - T_\infty)}, \quad q_w = -k \frac{\partial T}{\partial y}$$

$$Sh_x = \frac{xq_m}{D_B(C_w - C_\infty)}, \quad q_m = -D_B \frac{\partial C}{\partial y}$$

$$C_f = \frac{t_w}{\rho u_w^2}, \quad \tau_w = (\mu + k_1^*) \frac{\partial u}{\partial y} + k_1^* N^*$$

The above relation can also be written in the form:

$$-\theta'(0) = \frac{Nu_x}{\sqrt{Re}}$$

$$-\phi'(0) = \frac{Sh_x}{\sqrt{Re}}$$

$$C_{fx} = C_f \sqrt{Re_x}$$

The local Reynolds number is $Re = \frac{u_w x}{\nu}$.

3. Results

Numerical simulation was performed to obtain the energy and mass exchange characteristics of the flow field against different parameters. The current investigation incorporated physical parameters such as the Brownian motion parameter Nb ; the thermophoresis parameter Nt , the stratification coefficients St_1 , St_2 ; the suction parameter S ; the Prandtl number Pr ; the material parameter K ; the modified Hartmann number M ; and the Lewis number Le . For the approximate solution of ordinary differential equations that are nonlinear Equations (8)–(11) influenced by boundary conditions (13), we performed a numerical procedure using the Keller box method. Table 1 compares our results with those in the literature, whereas Table 2 presents the impacts of incorporating parameters of energy and mass exchange changes. In this study, we aimed to investigate the heat and mass exchange rates in the presence of double stratification and exponential velocity over a Riga plate. Figure 3 depicts the behavior of velocity field with respect to η for numerous variations in the modified Hartmann number M . An acceleration was produced in velocity as we increased the strength of M . This concurs well with the physics of the problem, because $M > 0$ helps the flow phenomenon during flow distribution. The pattern in this figure shows that with increasing strength of M , the external electric field strengthened. As a result, the velocity profile increased. In such circumstances, as the magnetic strength increased, there was an equivalent increase in the electromagnetic field. Moreover, the Lorentz powers prompted by Riga plate, corresponding to the surface, produced more surface strain; accordingly, the liquid speed increased. Figure 4 presents the impact of suction/injection factor S on the velocity field. We found that the boundary layer thickness decreased with the increase in $S > 0$, while the opposite behavior was observed in the case of injection $S < 0$.

Figures 5 and 6 show that the temperature profiles increased with increasing values of Nb and Nt respectively. As Brownian motion is the random movement of the fluid particles, in return, more heat was generated and temperature distribution was enhanced. If the particles had kinetic energy, this would lead to a collision of particles, because thermophoresis causes tiny particles to move away from hotspots to cold surfaces. Figure 7 depicts the effects of thermal stratification St_1 on the temperature profile, showing that the temperature profile decreased for increases in St_1 , since increases in St_1 decreased surface temperature and decreased the thickness of the thermal boundary layer. Figure 8 displays the behavior of Nb , where the concentration profile declines as the Nb value increases. Figure 9 shows the effect of Nt : the concentration distribution increases and increase the

value of Nt . Figure 10 shows the result of the stratified parameter on the concentration profile, where the concentration profile decreases with the growth in St_2 . It is clear that increases in St_2 reduce the concentration difference between the liquid and sheet.

Table 1. Comparison of our result with those previously published when $Nb = Nt = Le = \delta = K = \lambda = \eta = m = S = St_1 = St_2 = 0$.

Pr	M	Bidin and Nazar [25]	Present Results
		$-\theta'(0)$	$-\theta'(0)$
1	0	0.9548	0.9548
2	0	1.4714	1.4714
3	0	1.8691	1.8691

Table 2. Values of $-\theta'(0)$, $-\phi'(0)$, and $C_{fx}(0)$.

Nb	Nt	Pr	Le	M	K	S	St_1	St_2	m	λ	δ	η	$-\theta'(0)$	$-\phi'(0)$	$C_{fx}(0)$
0.1	0.1	6.5	5.0	0.1	1.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	0.9752	0.3786	0.8619
0.5	0.1	6.5	5.0	0.1	1.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	0.4772	0.6934	0.9391
0.1	0.5	6.5	5.0	0.1	1.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	0.4795	0.9095	0.6288
0.1	0.1	10.0	5.0	0.1	1.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	1.0108	0.3957	0.8560
0.1	0.1	6.5	10.0	0.1	1.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	0.9090	0.7549	0.9376
0.1	0.1	6.5	5.0	0.5	1.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	1.0068	0.4239	0.3894
0.1	0.1	6.5	5.0	0.1	3.0	0.1	0.1	0.5	1.0	0.1	1.0	0.1	0.9896	0.3971	1.2545
0.1	0.1	6.5	5.0	0.1	1.0	0.5	0.1	0.5	1.0	0.1	1.0	0.1	0.2550	0.4297	0.6916
0.1	0.1	6.5	5.0	0.1	1.0	0.1	0.5	0.5	1.0	0.1	1.0	0.1	0.5881	0.4757	0.9169
0.1	0.1	6.5	5.0	0.1	1.0	0.1	0.1	0.7	1.0	0.1	1.0	0.1	1.0369	0.0518	0.9238
0.1	0.1	6.5	5.0	0.1	1.0	1.0	0.1	0.5	2.0	0.1	1.0	0.1	0.9742	0.3771	0.8749
0.1	0.1	6.5	5.0	0.1	1.0	1.0	0.1	0.5	1.0	0.5	1.0	0.1	0.9804	0.3823	0.7440
0.1	0.1	6.5	5.0	0.1	1.0	1.0	0.1	0.5	1.0	0.1	1.5	0.1	0.9871	0.3884	0.6191
0.1	0.1	6.5	5.0	0.1	1.0	1.0	0.1	0.5	1.0	0.1	1.0	0.5	0.9771	0.3770	0.7896

The bold letters present the variations in involved parameters where remaining parameters are fixed.

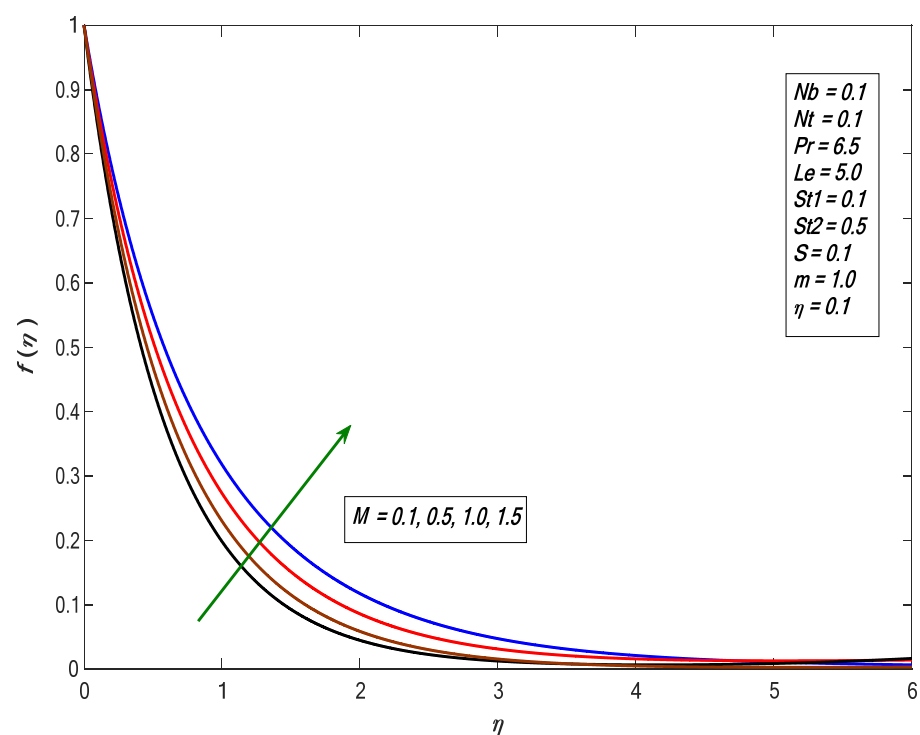


Figure 3. Impact of the modified Hartmann number M on velocity profiles against η .

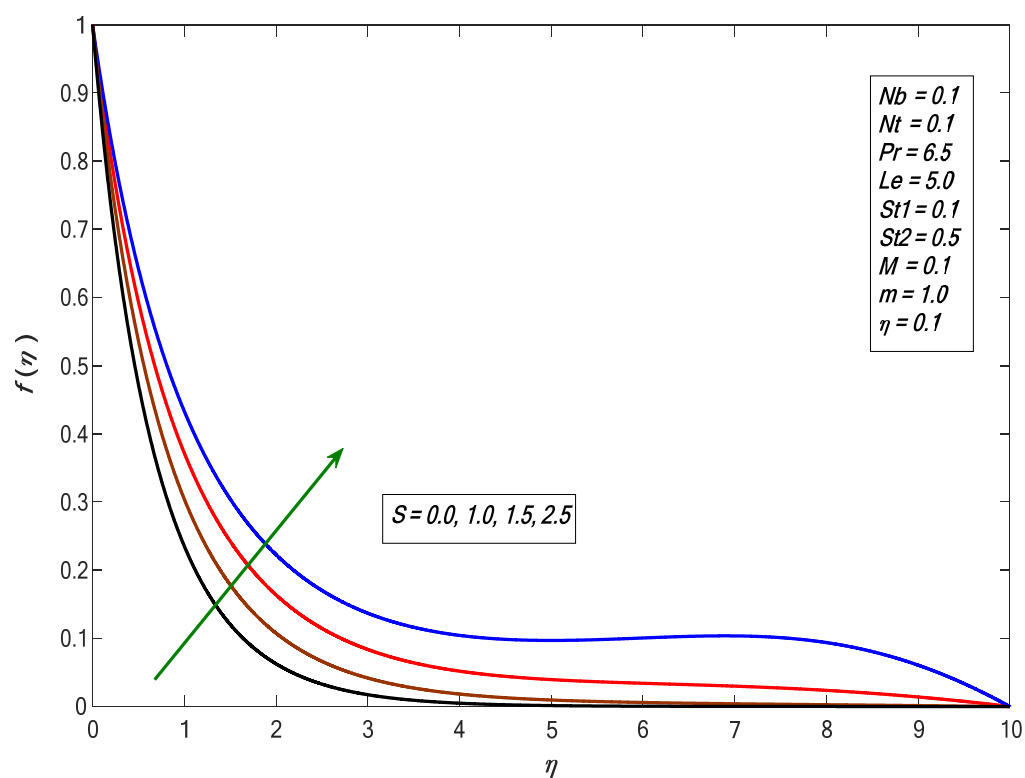


Figure 4. Impact of suction/injection S on velocity profiles against η .

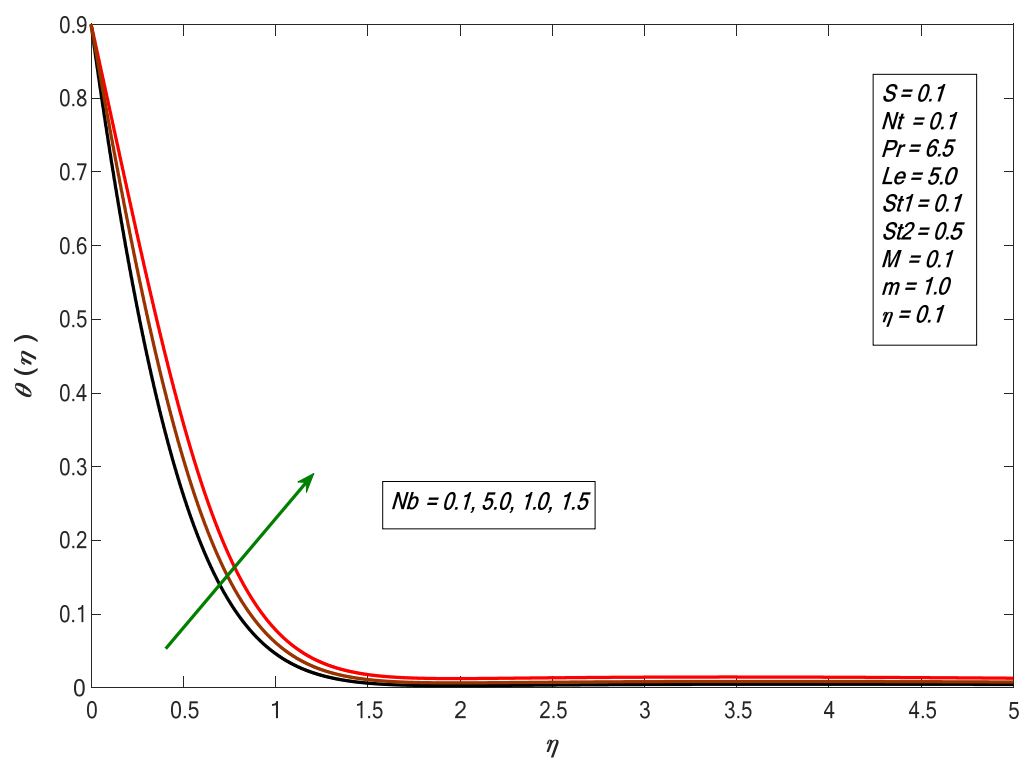


Figure 5. Impact of Brownian motion Nb on temperature profiles against η .

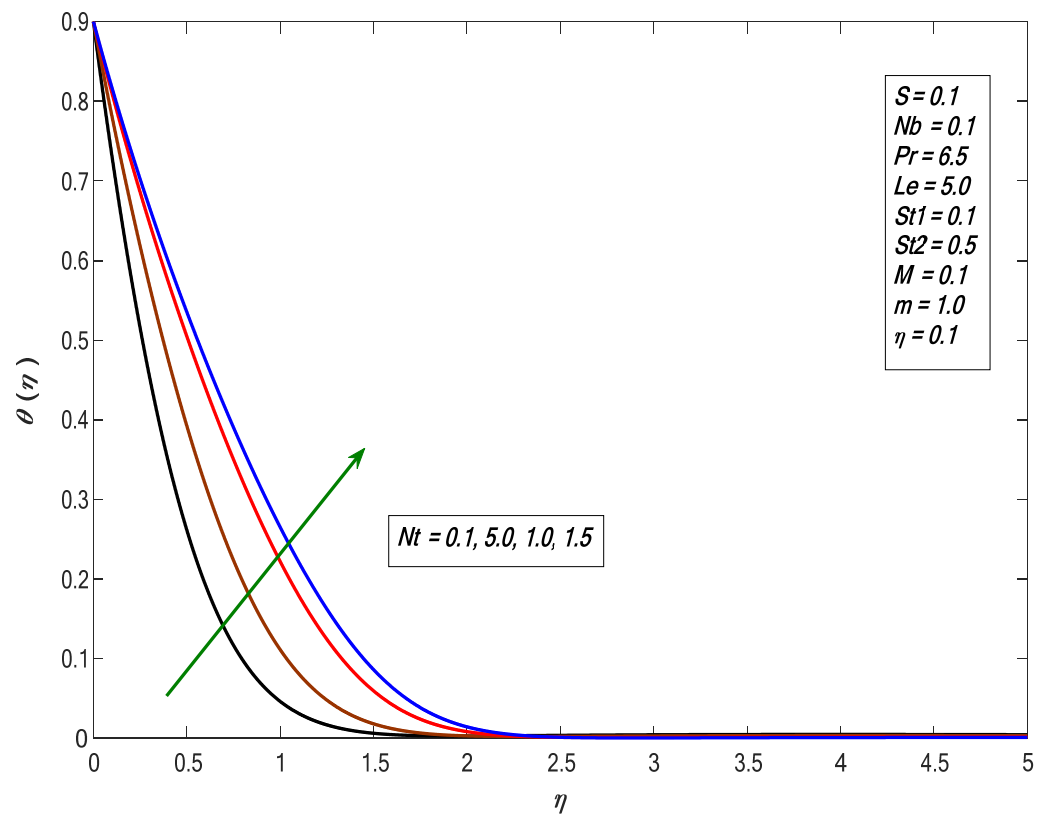


Figure 6. Impact of the thermophoresis factor Nt on temperature profiles against η .

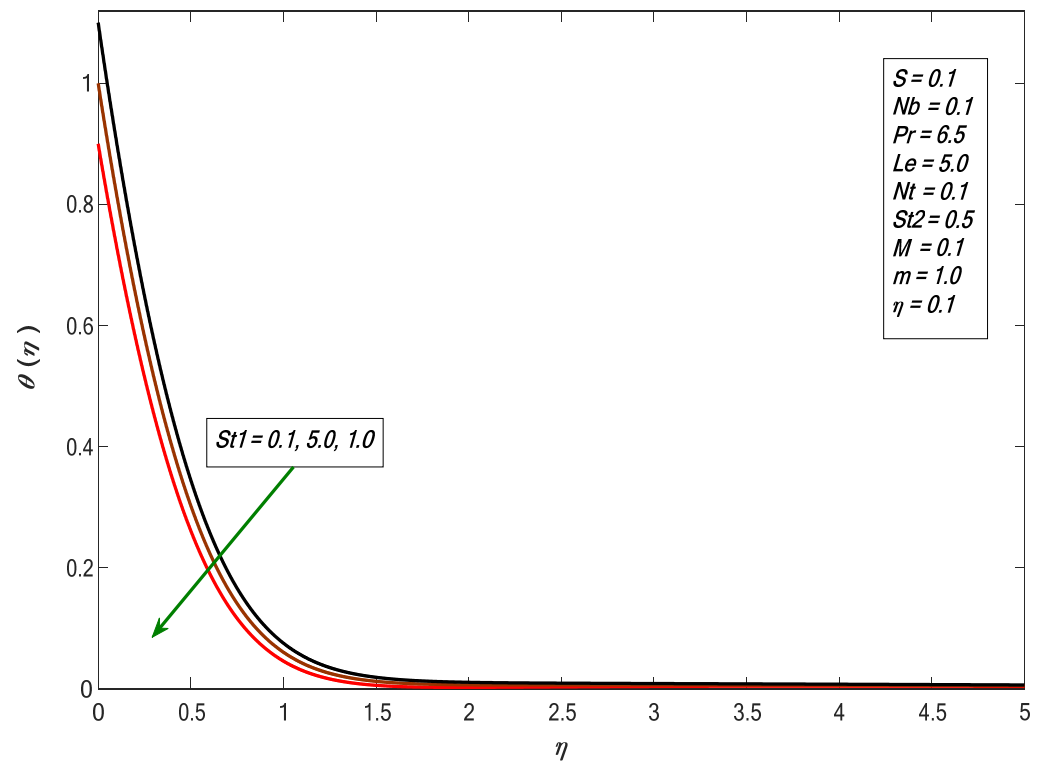


Figure 7. Impact of stratification St_1 on temperature profiles against η .

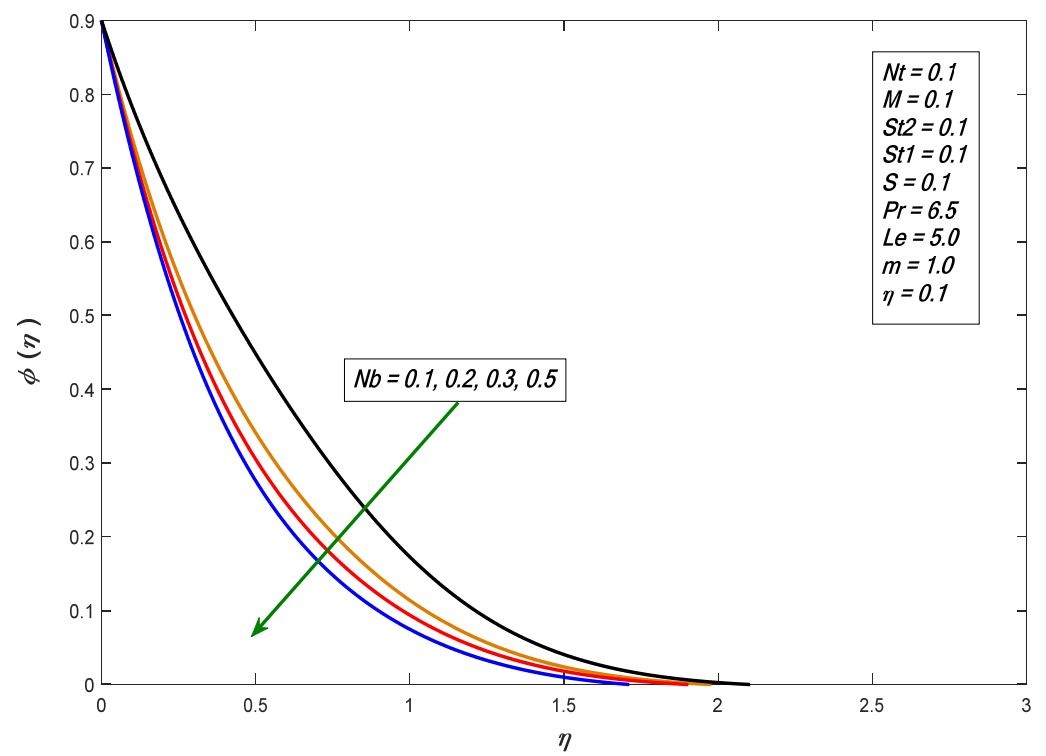


Figure 8. Impact of Brownian motion Nb on concentration profiles against η .

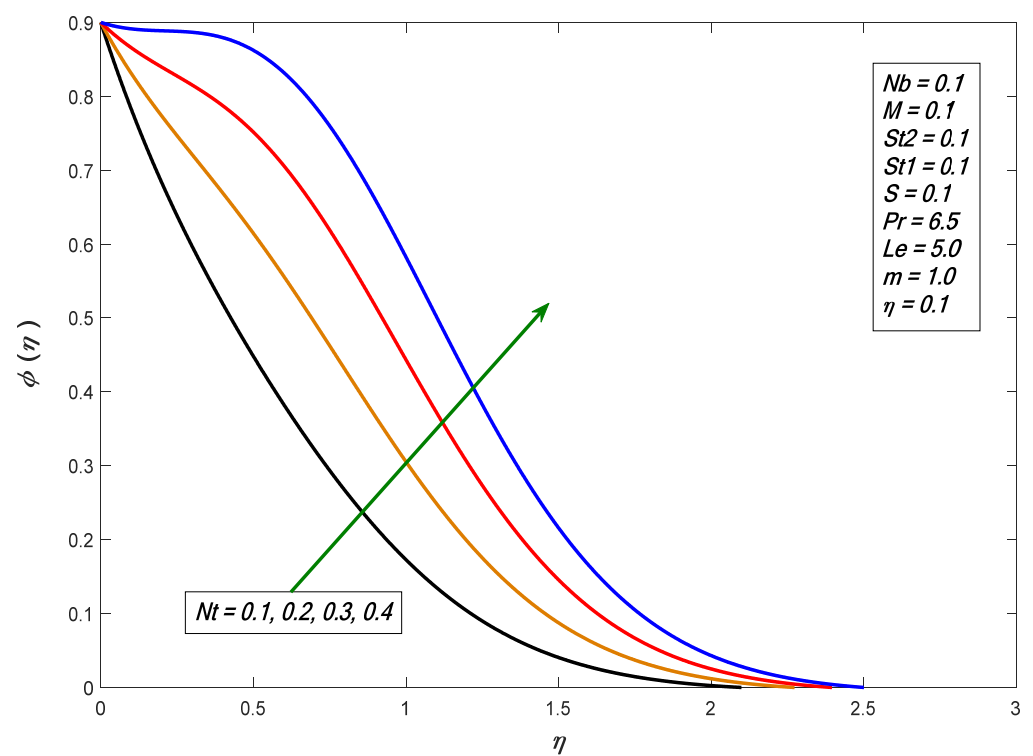


Figure 9. Impact of the thermophoresis factor Nt on concentration profiles against η .

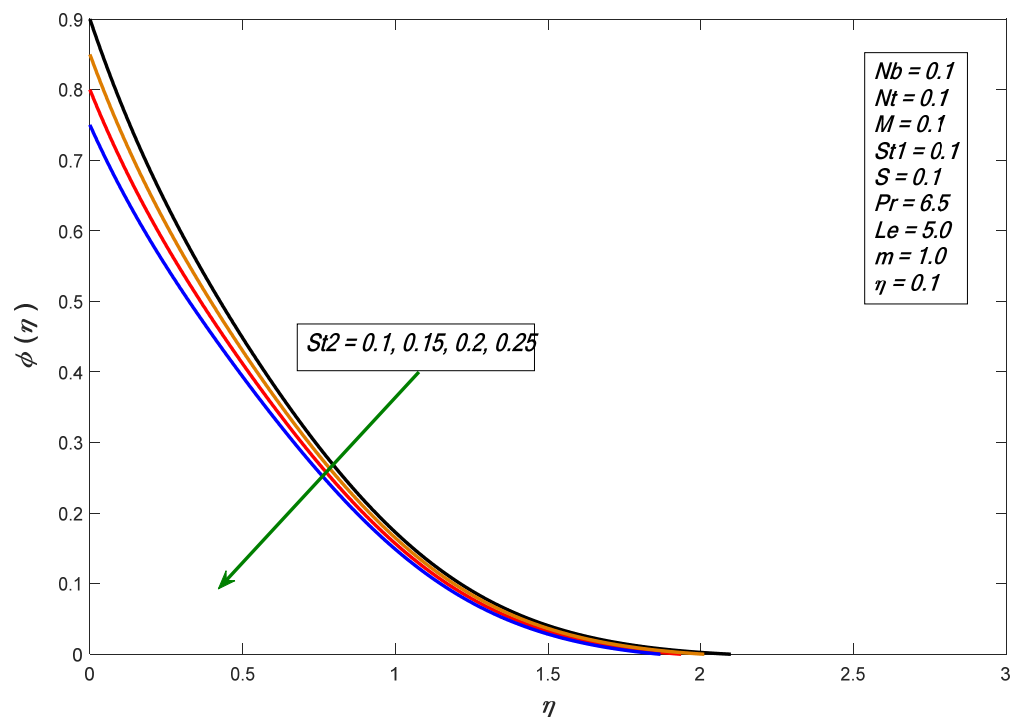


Figure 10. Impact of stratification St_2 on concentration profiles against η .

4. Conclusions

In this study, we addressed stratified micropolar nanofluid flow over an exponentially stretchable Riga surface. The Keller box scheme was applied to obtain the results of the modeled flow equations. From this analysis, our most important findings are summarized as:

- The thermal stratification factor St_1 decreases the energy exchange rate while the concentration stratification factor St_2 increases the mass exchange rate.
- Energy and mass transport rates are directly related to the local and modified Grashof numbers.
- The dimensionless factor (m) shows an inverse relationship with the energy and mass exchange rate.
- The temperature profile increases while the concentration profile decreases with increasing Nb .
- As Nt increases, both temperature and concentration increase.

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Nomenclature

C	fluid concentration
C_f	Skin friction
C_p	Specific heat at constant pressure
C_w	Surface volume fraction
C_∞	Ambient nanoparticle volume fraction
D_B	Brownian diffusion coefficient
D_T	Thermophoretic diffusion coefficient
f	Similarity function for velocity
g	Gravitational acceleration
J^*	Micro inertia per unit mass
K	Material parameter
k	Thermal conductivity
k_1^*	Vertex viscosity
l	Reference length
Le	Lewis number
M	Modified Hartmann number
N^*	Nondimensional angular velocity
N_b	Brownian motion parameter
N_T	Thermophoretic parameter
Nu	Nusselt number
Pr	Prandtl number
Re_x	Reynolds number
Sh	Sherwood number
St_1	Thermal stratification
St_2	Concentration stratification
T	Fluid temperature
T_w	Wall temperature
u	Velocity in the x direction
u_w	Wall Velocity
u_∞	Ambient velocity
v	Velocity in the y direction
x	Cartesian coordinate
α	Thermal diffusivity
β_c	Concentration expansion coefficient
γ^*	Spin gradient viscosity
δ	Modified Grashof number
λ	Local Grashof number
η	Similarity independent variable
ρ	Wall velocity
ν	Dynamic viscosity
σ	Electric conductivity
Θ	Dimensionless temperature
∞	Ambient condition
w	Condition at the wall
l	Differentiation with respect to η

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