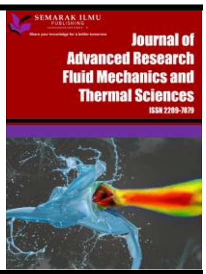
SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Investigation of Bioconvection in a Non-Newtonian Fluid Flow with Different Slip Effects over a Vertical Cylinder with Suction or Injection

Nayema Islam Nima[1,*], Mohammad Ferdows[2]

[1] Department of Physical Sciences, Independent University, Bangladesh
[2] Research Group of Fluid Flow Modelling and Simulation, Department of Applied Mathematics, University of Dhaka, Dhaka, Bangladesh

ARTICLE INFO

Article history:
Received 25 April 2024
Received in revised form 18 August 2024
Accepted 27 August 2024
Available online 15 September 2024

Keywords:
Mixed convection; non-Newtonian fluid; gyrotactic microorganism; slip effects; suction/injection

ABSTRACT

This work explores the interaction of mixed bio convection and non-Newtonian fluid flow around a vertical cylinder. It considers different slip effects and the impact of suction/injection boundary conditions. The inquiry is driven by the substantial implications of comprehending the interconnected dynamics of living organisms and non-Newtonian fluids, with wide-ranging applications in biotechnology, medicine, and environmental science. The study incorporates the intricacies of shear-thinning or shear-thickening fluids by utilizing the generalized power-law model to capture non-Newtonian rheological phenomena. The vertical cylinder, selected as the archetype geometry, functions as a fundamental structure encountered in several engineering applications. The slip effects, which can vary from no-slip to full slip, are included in the model to represent the interactions between the fluid and solid. Additionally, the suction/injection boundary conditions are used to simulate external forces that are provided to govern the motion of the fluid. The study utilizes similarity transformations to convert the governing equations and employs the MATLAB BVP4c scheme to solve the resulting ordinary differential equations. It investigates a parameter space that encompasses non-Newtonian parameters, slip coefficients, bio convection parameters, and suction/injection parameters. The results demonstrate intricate relationships between bio convection, non-Newtonian rheology, slip effects, and suction/injection. These findings state the suction parameter (s>1) and dilatant fluid (n>1) have great influence on heat, mass and motile microorganism rate and also slip parameters are responsible for reducing flow profiles. The study's findings enhance our comprehension of intricate fluid dynamics when biological activity and non-Newtonian behaviour are present. This provides valuable insights for the efficient design and optimization of processes involving vertical cylinders in fields such as biotechnology, medicine, and environmental engineering.

1. Introduction

Mixed convection, an intricate blend of buoyancy-driven and forced convection, stands as a vital phenomenon with widespread implications in engineering and environmental domains. Mixed

* *Corresponding author.*
E-mail address: nayema@iub.edu.bd

https://doi.org/10.37934/arfmts.121.1.202213

convective flow with gyrotactic microorganism represents a fascinating interdisciplinary field that combines heat transfer, and biological interactions. Mahdy and Nabwey [1], Nabwey *et al.,* [2], Rashad and Abdou [3] explores the unique characteristics of mixed convection in the presence of gyrotactic microorganisms, examining the interplay between buoyancy-driven and forced convection, while considering the influence of microorganism behavior. In a colony or single cell, microorganisms move in a process called bio-convection. Enzyme biosensors, ethanol, and biofuel biotechnology for mass transit are just a few of the industrial and environmental systems that efficiently utilize the physical implications of bio-convection by several authors [4-6]. Bioconvective flow occurs when motile microorganisms, which are typically denser than water, travel in an upward direction, causing the formation of unsteady, large density stratification in the upper region. Thermo-bioconvection plays a significant role in geophysical events, such as in hot springs inhabited by motile microorganisms known as thermophiles, which are bacteria that thrive in high temperatures. Another use involves the utilisation of nutrients and microorganisms in oil-bearing strata to modify the permeability difference, namely in the field of microbial assisted oil recovery. Several studies have been conducted on gyrotactic bacteria [7-12].

Various industries, such as food processing, electrical appliance cooling, petroleum drilling, and science and engineering, have raised concerns regarding the utilisation of fluid suction and injection in channels. Jabeen *et al.,* [13] conducted a study on gyrotactic microorganisms in the context of Casson nanofluids, examining both injection and suction methods. Mehmood *et al.,* [14] discovered that microorganisms moving on a vertically elongated surface exhibited suction and injection effects. The consequences of injection and suction on a vertical cone were similarly seen by Ravindran *et al.,* [15]. Recent years have seen a proliferation of new industrial research areas that make use of micro-scale fluid dynamics. The fluid's motion at tiny scales is still described by the Navier-Stokes equations, but with boundary conditions based on the slip velocity. Non-Newtonian fluids, fluids containing nanoparticles, and microorganisms are all fluids that do not do well in no-slip situations. Hayat *et al.,* [16] first proposed the concept of thermal slip across a stretching sheet. Magnetohydrodynamic (MHD) nanofluid flow was studied by Ibrahim and Shankar [17], with slip in velocities, temperatures, and solutal boundary conditions taken into consideration. Rai and Mishra [18] observed mixed convective nanofluid slip flow over moving vertical plate, Seethamahalakshmi *et al.,* [19] examined MHD slip flow with Casson and Maxwell nanofluid effects. Khan *et al.,* [20] studied velocity slip in nanofluid with gyrotactic organisms. Mabood *et al.,* [21] examined Casson fluid flow under different slip boundary conditions. Sk *et al.,* [22] found numerous slip effects using microorganisms.

All of the studies concerned Newtonian fluid, as shown in the preceding paragraph. The majority of the published research on power-law fluids also involves mixed convection. Gangawane and Oztop [23] investigated the impact of the power-law index on mixed convection heat transmission. Recent research has shown that non-Newtonian fluids can induce free, forced, mixed convection as reported by Roy *et al.,* [24], and non-Newtonian Casson fluids can flow with gyrotactic microorganisms as observed by Lone *et al.,* [25]. Non-Newtonian fluid flow over a spinning cylinder was investigated by Kumar and Sahu [26]. One such group that looked at non-Newtonian mixed convective flow via an inclined cylinder was Rehman and Shatanawi [27]. Dual solution through vertical cylinder in case of opposing flow was analysed by Alsenafi and Ferdows [28]. The purpose of our present study is to extend the work of Alsenafi and Ferdows [28] for non- Newtonian combined convection flow considering multiple slip effects in case of assisting flow only because assisting flow predicts the physically stable solutions as mentioned in a study by Nima and Ferdows [29].

2. Methodology
2.1 Mathematical Formulation

This study specifically examines the consistent flow in two dimensions of a non-compressible non-Newtonian power-law substance around a vertical cylinder with radius R^* in presence of slip effects. The media contains gyrotactic microorganisms, as depicted in Figure 1. The x^* axis is aligned with the axial flow of the cylinder, whereas the r axis is perpendicular to it. It is postulated that the mainstream velocity $U_e(x^*)$ and the concentration of fluid C_w and motile microorganisms m_w on the cylinder surface remain constant at temperature T_w.

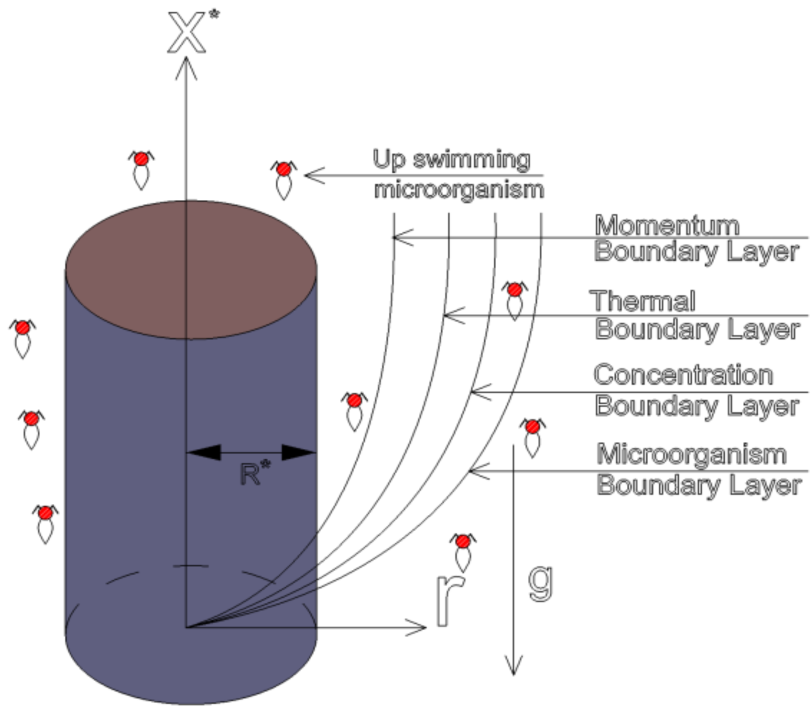


Fig. 1. Physical Model

The system of equations that describes the motion of steady mixed convection flow of a non-Newtonian fluid containing microorganisms over a vertical cylinder embedded in Darcy porous media taking into account slip effects can be represented using the formulations provided by Alsenafi and Ferdows [28], as well as Nima and Ferdows [29,30].

$$\frac{\partial(ru^*)}{\partial x^*}+\frac{\partial(rv^*)}{\partial r}=0 \tag{1}$$

$$\frac{\partial u^{*n}}{\partial r}=\pm\frac{gk}{\nu}(\beta_{Th}\frac{\partial T}{\partial r}+\beta_C\frac{\partial C}{\partial r}+\beta_m\frac{\partial m}{\partial r}) \tag{2}$$

$$u^*\frac{\partial T}{\partial x^*}+v^*\frac{\partial T}{\partial r}=\alpha^*(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T}{\partial r})) \tag{3}$$

$$u^*\frac{\partial C}{\partial x^*}+v^*\frac{\partial C}{\partial r}=D_c(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial C}{\partial r})) \tag{4}$$

$$u^* \frac{\partial m}{\partial x^*} + v^* \frac{\partial m}{\partial r} + \frac{bW_c}{\nabla C}\left(\frac{\partial}{\partial r}\left(m\frac{\partial C}{\partial r}\right)\right) = D_m\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial m}{\partial r}\right)\right) \tag{5}$$

Given that the boundary conditions are expressed as follows:

$$v^* = v_w, T = T_w + B^*\left(\frac{\partial T}{\partial r}\right)_{r=R^*}, C = C_w + B^*\left(\frac{\partial C}{\partial r}\right)_{r=R^*}, m = m_w + B^*\left(\frac{\partial m}{\partial r}\right)_{r=R^*} \text{ at } r = R^* \tag{6}$$

$$u^* \to U_e(x^*),\ T \to T_\infty,\ C \to C_\infty,\ m \to m_\infty \text{ at } r = \infty \tag{7}$$

In accordance with the research conducted by Alsenafi and Ferdows [28], this work assumes the utilization of dimensionless quantities.

$$\eta = \frac{r^2 - R^{*2}}{2R^*L} Pe^{\frac{1}{2}},\ \psi = \alpha^* R^* Pe^{\frac{1}{2}} \frac{x^*}{L} f(\eta) \tag{8}$$

$$T = T_\infty + \frac{x^{*n}\nabla T}{L^n}\theta(\eta), C = C_\infty + \frac{x^{*n}\nabla C}{L^n}\varphi(\eta), m = m_\infty + \frac{x^{*n}\nabla n}{L^n}\zeta(\eta) \tag{9}$$

By employing the aforementioned dimensionless quantities, the Eq. (1) to Eq. (7) are in the following structure:

$$n(f')^{n-1} f'' = \lambda^n[\theta' + N_c\phi' + N_m\chi'] \tag{10}$$

$$(1+\varepsilon\eta)\theta'' + \varepsilon\theta' + nf\theta' - f'\theta = 0 \tag{11}$$

$$(1+\varepsilon\eta)\varphi'' + \varepsilon\varphi' + Le.nf\varphi' - Le.f'\phi = 0 \tag{12}$$

$$(1+\varepsilon\eta)\varsigma'' + \varepsilon\zeta' + Lb.nf\zeta' - Lb.f'\zeta - Pb((1+\varepsilon\eta)\phi'\zeta' + (\zeta + A)(\zeta\varphi' + (1+\varepsilon\eta)\phi'')) = 0 \tag{13}$$

Boundary conditions

$$\eta = 0, f = s, \theta = 1 + b_s\theta', \phi = 1 + c_s\phi', \zeta = 1 + d_s\zeta'$$

$$\eta \to \infty, f' \to 1, \theta \to 0, \phi \to 0, \zeta \to 0 \tag{14}$$

The defining parameters are

$$\lambda = \frac{Ra}{Pe},\ Ra = \left(\frac{g\beta_{Th}k\nabla T}{\upsilon}\right)^{\frac{1}{n}} \frac{L}{\alpha^*}, Pe = \frac{u_\infty L}{\alpha^*},\ \varepsilon = \frac{2}{R^*}\sqrt{\frac{\alpha^* L}{u_\infty}}, Le = \frac{\alpha^*}{D_c},\ Lb = \frac{\alpha^*}{D_m},\ Pb = \frac{bW_c}{D_m},$$

$$b_s = B^* \frac{Pe^{\frac{1}{2}}}{L}, c_s = C^* \frac{Pe^{\frac{1}{2}}}{L}, d_s = D^* \frac{Pe^{\frac{1}{2}}}{L}$$

2.2 Numerical Procedure

The controlling PDEs were simplified into ordinary differential equations by applying similarity transformations. Subsequently, the bvp4c solver in Matlab was employed to computationally solve these equations. The function sol = bvp4c(odefun,bcfun,solinit) utilizes an initial solution guess, solinit, to numerically integrate a system of differential equations over the interval [p,q]. The system is subject to general two-point boundary conditions of the form bc(y(p), y(q)) = 0. Within the framework of the aforementioned bvp4c function, it is necessary to convert the governing equations into first-order differential equations by substituting η for x and also considering

$$h_1 = f, h_2 = f', h_3 = \theta, h_4 = \theta', h_5 = \phi, h_6 = \phi', h_7 = \zeta, h_8 = \zeta'$$

So, the first order equations are

$$\frac{dh_1}{dx} = f' = h_2, \frac{dh_2}{dx} = f'' = \lambda^n * (h_4 + N_c * h_6 + N_m * h_8) / n * (h_2)^{n-1}$$
$$\frac{dh_3}{dx} = \theta' = h_4, \frac{dh_4}{dx} = \theta'' = (h_2 * h_3 - \varepsilon * h_4 - n * h_1 * h_4) / (1 + \varepsilon * \eta)$$
$$\frac{dh_5}{dx} = \phi' = h_6, \frac{dh_4}{dx} = \phi'' = (Le * h_2 * h_5 - \varepsilon * h_6 - Le * n * h_1 * h_6) / (1 + \varepsilon * \eta)$$
$$\frac{dh_7}{dx} = \zeta' = h_8, \frac{dh_8}{dx} = \zeta'' = (Lb * h_2 * h_7 - \varepsilon * h_8 - Lb * n * h_1 * h_8) + Pb * ((1 + \varepsilon * \eta) * h_6 * h_8$$
$$+ (h_7 + A) * (\varepsilon * h_6 + (1 + \varepsilon * \eta) * (-\varepsilon * h_6 - Le * h_1 * h_6 + Le * h_2 * h_5) / (1 + \varepsilon * \eta)$$

Boundary conditions

$$hp(1) - s = 0, \qquad hq(2) - 1 = 0$$
$$hp(3) - 1 - b_s hp(4) = 0, \qquad hq(3) = 0$$
$$hp(5) - 1 - c_s hp(6) = 0, \qquad hq(5) = 0$$

The variable hp represents the boundary on the left side, while hq represents the boundary on the right side.

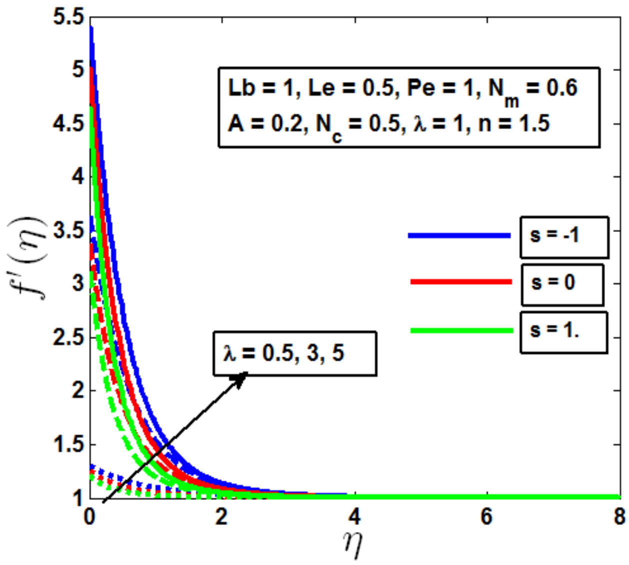
In order to verify the accuracy of our findings, we conducted a comparison between our current results for the specific scenario and the findings of Alsenafi and Ferdows [28] as presented in Table 1. This comparison demonstrates a strong agreement and high level of accuracy in our numerical computations.

Table 1
Curvature Parameter ε effect on $-\theta'(0)$ for the regular fluid n=1 in case of opposing flow

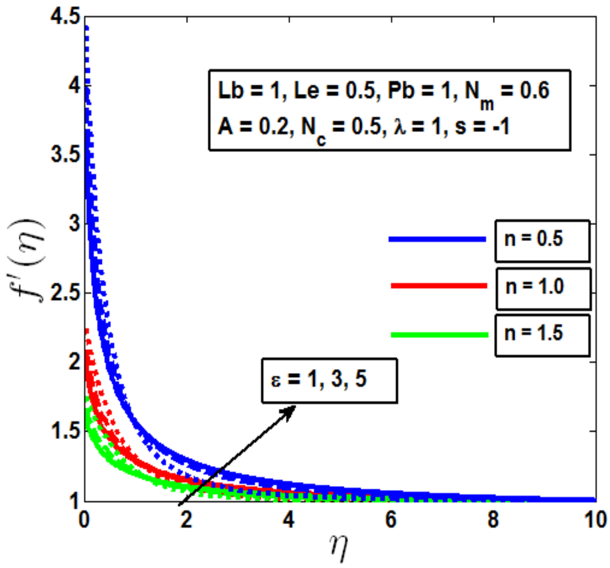
λ	ε	$-\theta'(0)$	
		(Present Result)	Alsenafi and Ferdows [28]
-1	0.0	0.731408	0.731408
-1	0.5	0.873552	0.873551
-1	1.0	1.000111	1.000111
-1	3.0	1.436532	1.436533
-1	5.0	1.824376	1.824377

3. Results

The velocity profile in Figure 2(a) illustrates how an increase in the mixed convection parameter results in an increased buoyancy force, especially when s = -1, which indicates injection, as opposed to suction (s>1) and impermeability (s=0) scenarios where the value of s is zero. The phenomenon can be explained by the fact that when a higher blowing force is applied, the heated fluid is pushed away from the wall, allowing the buoyant forces to accelerate the flow with less interference from viscosity. This phenomenon enhances the shear stress by amplifying the maximum velocity within the boundary layer. In Figure 2(b), For values of n less than 1, the non-Newtonian nanofluid exhibits shear thinning behaviour, also known as pseudo-plasticity, resulting in a viscosity lower than that of Newtonian fluids with n=1. This results in fluid acceleration. On the other hand, when n is greater than 1, the fluid exhibits shear thickening behaviour (also known as dilatant) and has an increased viscosity, resulting in a slowdown of the flow. At high values of the curvature parameter ε, the fluid velocity demonstrates an arousing characteristic. For increasing values of ε, the radius of the cylinder decreases, resulting in reduced interaction between fluid particles and the cylindrical surface. This leads to a decrease in resistance to fluid flow. Consequently, the velocity of the fluid experiences a substantial increase.



(a)



(b)

Fig. 2. (a) Mixed convection parameter λ with s, (b) Curvature parameter εimpact with n on velocity profile

The effect of ε on the temperature distribution is illustrated in Figure 3(a). Clearly, as ε increases, there is a discernible upward trend in temperature. A reduction in ε signifies a corresponding decrease in the resistance encountered by fluid particles due to a decrease in the surface contact area exposed to them. Their average velocity consequently increases. An elevation in temperature ensues due to the fact that the Kelvin temperature is established by the average kinetic energy. Additionally, a greater impact of dilatant fluid on the temperature profile is noted. As the value of n increases, the thermal energy transmitted from the fluid regime to the plate causes a reduction in the thickness of the boundary layer. As the value of n drops, the temperature profile near the surface wall lowers, while it increases further away from the wall. Figure 3(b) depicts the correlation between the thermal slip coefficient b_s and the impact of temperature for different values of the suction/blowing parameter s. In these instances, a rise in the thermal slip parameter results in a drop in the temperature profile in the suction and blowing parameters. An increase in the thermal slip parameter leads to a higher rate of heat transfer accompanied by a drop in temperature profiles.

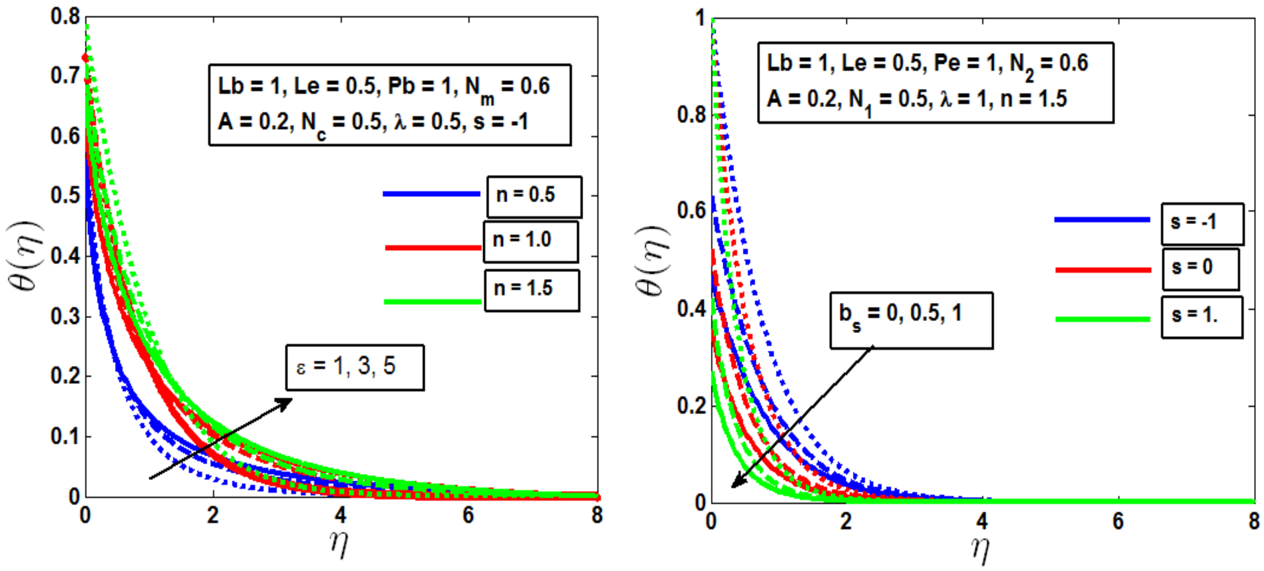
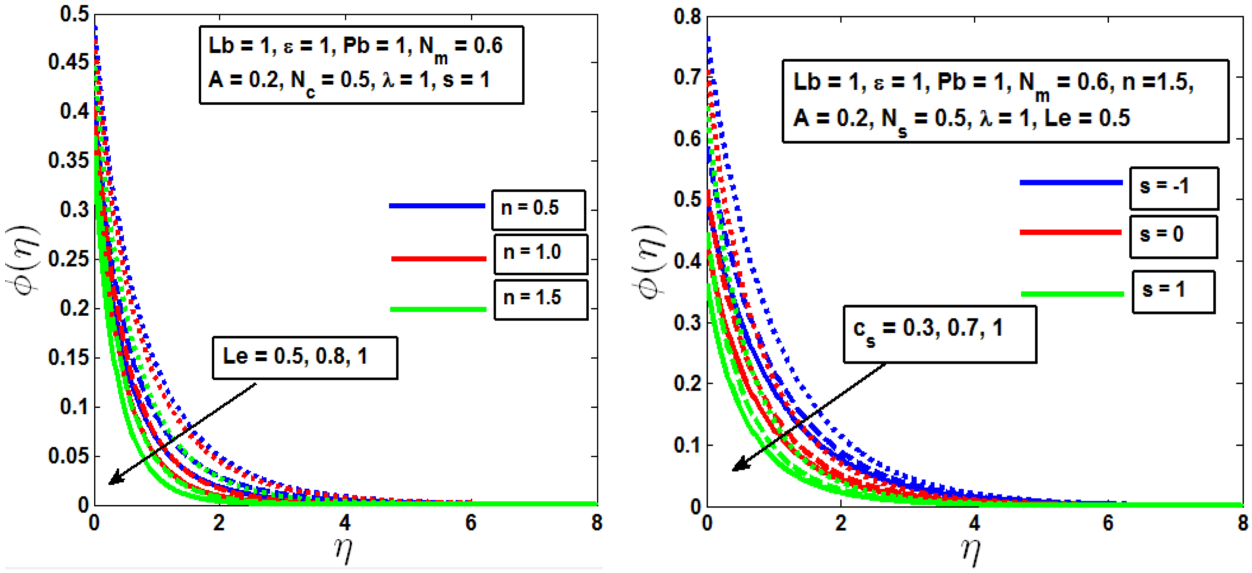


Fig. 3. Effect of (a) Curvature parameter ε with different values of n, (b) Thermal slip parameter b_s with different values of s on temperature profile

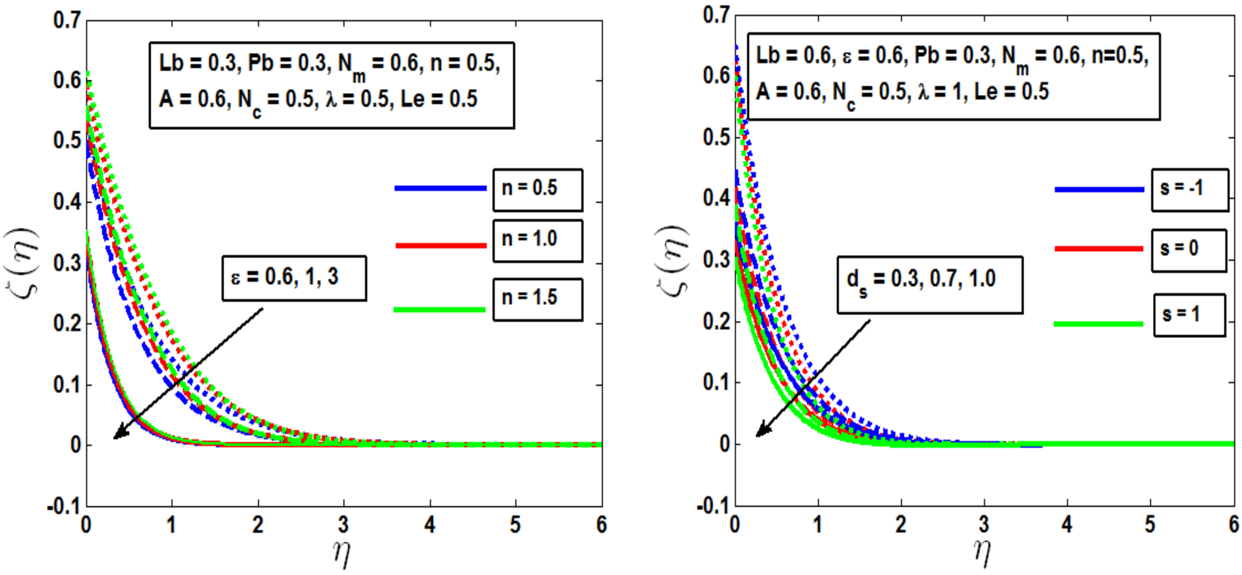
As the Lewis parameter Le increases, the solid volume fraction of the concentration profile decreases, as shown in Figure 4(a). The increase in the Lewis number (Le) leads to a higher mass transfer rate, which in turn increases the concentration gradient at the surface. Consequently, as the Le rises, the concentration of fluid at the surface decreases.An elevation in n, signifying progressively more intense non-isoconcentration conditions at the surface, results in a decrease in concentration. The concentration diminishes as the transfer of mass from the plate to the fluid diminishes, due to the increasing impact of solutal slip. The concentration profile shows a consistently decreasing connection with the suction parameter s. This occurs because the fluid experiences resistance when the friction between its layers intensifies. As a result, there is a decrease in focus.

Figure 5(a) demonstrates that an increase in the curvature parameter leads to an increase in the rate of microbe transfer, thereby resulting in a decrease in the quantity of microorganisms near the surface. Pseudoplastic, Newtonian, and dilant fluids have a comparable effect on the profile of microorganisms. As the suction parameter increases, the microorganism profile diminishes in Figure 5(b). The suction parameter exerts a force that causes the scattering of microbes and reduces the segregation of microorganisms, resulting in a decrease in their concentration.



(a) (b)

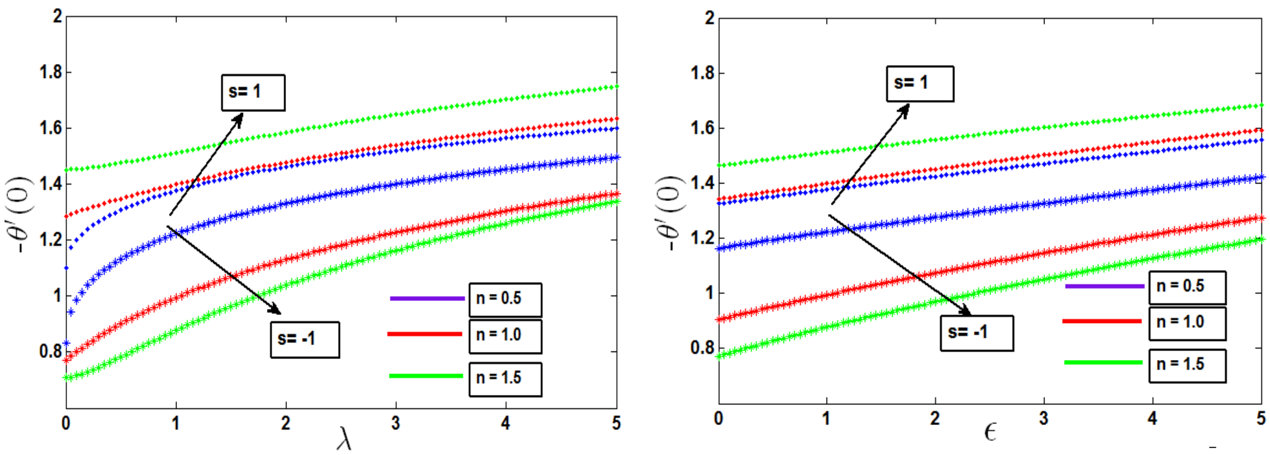
Fig. 4. Effect of (a) Lewis parameter Le with different values of n, (b) Solutal slip parameter c_s with different values of s on concentration profile



(a) (b)

Fig. 5. Effect of (a) Curvature parameter ε with different values of n, (b) Microbial slip parameter d_s with different values of s on microorganism profile

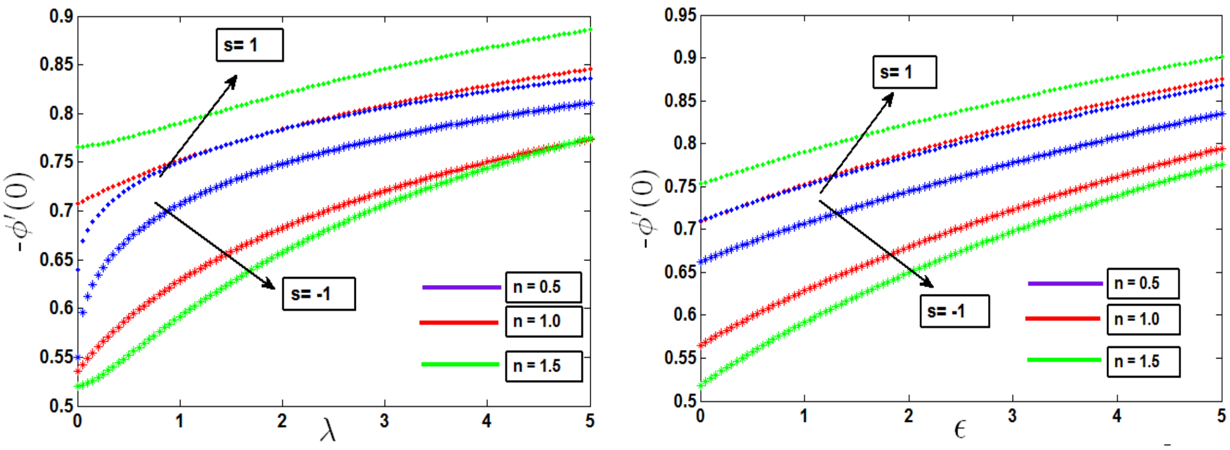
Raising λ and ε values in the flow zone considerably improves the heat transfer rate as shown in Figure 6. The transfer of heat from the surface to the fluid becomes more pronounced with increasing curvature. The heat transfer coefficient quantifies the rate at which energy is exchanged between the wall and the fluid, either in one direction or the other. As the suction injection parameter increases, there is a greater amount of fluid that is either sucked into or injected out of the wall. The heat transfer rate mostly increases for s = 1, and this increase is particularly significant for dilatant fluids. When s is equal to -1, the heat transfer rate exhibits an inverse phenomenon. For injection of a pseudoplastic fluid, the heat transfer rate is increased.



(a) (b)

Fig. 6. Effect of (a) mixed convection parameter λ, (b) curvature parameter ε with different values of n on heat transfer rate

Both the mass transfer rate and the density of motile microbe transfer rates are seen to rise with the mixed convection parameter and the curvature parameter, as seen in Figure 7 and Figure 8. This is something that can be noticed. It has been established that the density of motile microorganisms is greater than that of liquid, and it is typical for these organisms to swim in an upward manner toward the exterior of the cylinder wall. In light of this, the curvature parameter ε is responsible for a greater rise in the transfer rate of motile microorganisms in comparison to the mass transfer rate. The increment is significant for both the s = 1 and the dilatants fluid flow processes in both situations.



(a) (b)

Fig. 7. Effect of (a) mixed convection parameter λ, (b) curvature parameter ε with different values of n on mass transfer rate

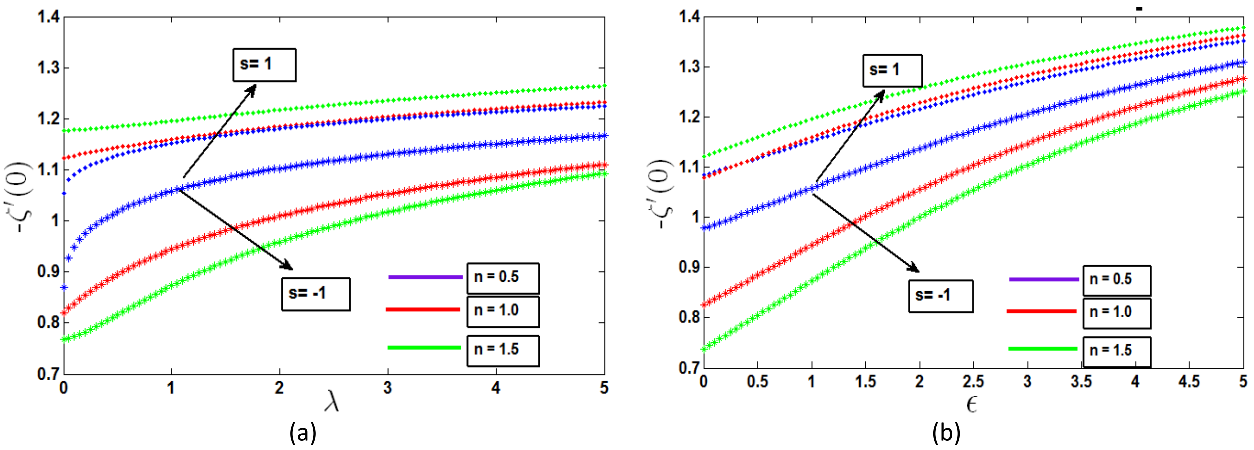


Fig. 8. Effect of (a) mixed convection parameter λ, (b) curvature parameter ε with different values of n on microorganism transfer rate

4. Conclusions

The effects of heat, mass, and microorganism slip are investigated in a gyrotactic microorganism flow study on a vertical cylinder with a non-Newtonian fluid. The following are the most important results

i. The velocity profile is positively correlated with the mixed convection parameter λ and the curvature parameter ε. The occurrence of increasing phenomena is primarily observed in the situation of injection ($s < 1$), particularly with pseudoplastic fluids($n < 1$).
ii. Temperature profile increases with ε. The increase in the curvature parameter leads to an augmentation in the thickness of the boundary layer of the temperature profile, which is mostly caused by the dilatant fluid ($n > 1$).
iii. As the slip parameters grow from 0 to 1, the thermal, concentration, and microbiological boundary layer thickness decrease. These occurrences occur when a suction effect ($s > 1$) is present.
iv. The transfer rates of heat, mass, and microorganisms predominantly increase due to the suction effect when dilatant fluids are present.

References

[1] Mahdy, A., and Hossam A. Nabwey. "Microorganisms time-mixed convection nanofluid flow by the stagnation domain of an impulsively rotating sphere due to Newtonian heating." *Results in Physics* 19 (2020): 103347. https://doi.org/10.1016/j.rinp.2020.103347
[2] Nabwey, Hossam A., S. M. M. El-Kabeir, A. M. Rashad, and M. M. M. Abdou. "Gyrotactic microorganisms mixed convection flow of nanofluid over a vertically surfaced saturated porous media." *Alexandria Engineering Journal* 61, no. 3 (2022): 1804-1822. https://doi.org/10.1016/j.aej.2021.06.080
[3] Rashad, A. M., and M. M. M. Abdou. "Gyrotactic microorganisms mixed convection flow of nanofluid over a vertically surfaced saturated porous media." *AEJ-Alexandria Engineering Journal* (2021).
[4] Xu, Yun-Jie, Muhammad Bilal, Qasem Al-Mdallal, Muhammad Altaf Khan, and Taseer Muhammad. "Gyrotactic micro-organism flow of Maxwell nanofluid between two parallel plates." *Scientific Reports* 11, no. 1 (2021): 15142. https://doi.org/10.1038/s41598-021-94543-4
[5] Lv, Yu-Pei, Ebrahem A. Algehyne, Maryam G. Alshehri, Ebraheem Alzahrani, Muhammad Bilal, Muhammad Altaf Khan, and Muhammad Shuaib. "Numerical approach towards gyrotactic microorganisms hybrid nanoliquid flow with the hall current and magnetic field over a spinning disk." *Scientific Reports* 11, no. 1 (2021): 8948. https://doi.org/10.1038/s41598-021-88269-6
[6] Lakshmi, S. K. Prasanna, Sreedhar Sobhanapuram, S. V. V. Rama Devi, and Shaik Mohammed Ibrahim. "Investigation of Magneto Hydrodynamics Properties of Reiner-Philippoff Nanofluid with Gyrotactic Microorganism in a Porous Medium." *CFD Letters* 16, no. 6 (2024): 1-19. https://doi.org/10.37934/cfdl.16.6.119

[7] Alharbi, Khalid Abdulkhaliq M., Muhammad Bilal, Aatif Ali, Sayed M. Eldin, Alhanouf Alburaikan, and Hamiden Abd El-Wahed Khalifa. "Significance of gyrotactic microorganisms on the MHD tangent hyperbolic nanofluid flow across an elastic slender surface: Numerical analysis." *Nanotechnology Reviews* 12, no. 1 (2023): 20230106. https://doi.org/10.1515/ntrev-2023-0106

[8] Loganathan, Karuppusamy, Reema Jain, S. Eswaramoorthi, Mohamed Abbas, and Mohammed S. Alqahtani. "Bioconvective gyrotactic microorganisms in third-grade nanofluid flow over a Riga surface with stratification: An approach to entropy minimization." *Open Physics* 21, no. 1 (2023): 20230273. https://doi.org/10.1515/phys-2023-0273

[9] Algehyne, Ebrahem A., Anwar Saeed, Muhammad Arif, Muhammad Bilal, Poom Kumam, and Ahmed M. Galal. "Gyrotactic microorganism hybrid nanofluid over a Riga plate subject to activation energy and heat source: Numerical approach." *Scientific Reports* 13, no. 1 (2023): 13675. https://doi.org/10.1038/s41598-023-27562-y

[10] Kada, Belkacem, Iftikhar Hussain, Amjad Ali Pasha, Waqar Azeem Khan, Muhammad Tabrez, Khalid A. Juhany, Mostafa Bourchak, and Ramzi Othman. "Significance of gyrotactic microorganism and bioconvection analysis for radiative Williamson fluid flow with ferromagnetic nanoparticles." *Thermal Science and Engineering Progress* 39 (2023): 101732. https://doi.org/10.1016/j.tsep.2023.101732

[11] Reddy, P. Sudarsana, and P. Sreedevi. "Unsteady gyrotactic microorganisms and magnetic nanofluid heat and mass transfer analysis inside a chamber with thermal radiation." *International Journal of Ambient Energy* 45, no. 1 (2024): 2277301. https://doi.org/10.1080/01430750.2023.2277301

[12] Sravanthi, Poludasu Madhu, Maddali Radha Madhavi, and Sridhar Wuriti. "Effect of Chemical Reaction and Variable Thermal Conductivity in MHD Williamson Nanofluid Flow with Gyrotactic Microorganisms." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 113, no. 1 (2024): 67-81. https://doi.org/10.37934/arfmts.113.1.6781

[13] Jabeen, Kanwal, Muhammad Mushtaq, and R. M. Akram Muntazir. "Suction and injection impacts on Casson nanofluid with gyrotactic micro-organisms over a moving wedge." *Journal of Fluids Engineering* 144, no. 1 (2022): 011204. https://doi.org/10.1115/1.4051484

[14] Mehmood, Rashid, Iqra Ali, Shagufta Ijaz, Siddra Rana, and Ehnber Naheed Maraj. "Radiative slip transport of magnetized gyrotactic micro-organisms submerged with nano fluid along a vertical stretching surface with suction/injection effects." *Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanomaterials, Nanoengineering and Nanosystems* (2023): 23977914231176866. https://doi.org/10.1177/23977914231176866

[15] Ravindran, R., Satyajit Roy, and E. Momoniat. "Effects of injection (suction) on a steady mixed convection boundary layer flow over a vertical cone." *International Journal of Numerical Methods for Heat & Fluid Flow* 19, no. 3/4 (2009): 432-444. https://doi.org/10.1108/09615530910938362

[16] Hayat, T., M. Qasim, and S. Mesloub. "MHD flow and heat transfer over permeable stretching sheet with slip conditions." *International Journal for Numerical Methods in Fluids* 66, no. 8 (2011): 963-975. https://doi.org/10.1002/fld.2294

[17] Ibrahim, Wubshet, and Bandari Shankar. "MHD boundary layer flow and heat transfer of a nanofluid past a permeable stretching sheet with velocity, thermal and solutal slip boundary conditions." *Computers & Fluids* 75 (2013): 1-10. https://doi.org/10.1016/j.compfluid.2013.01.014

[18] Rai, Purnima, and Upendra Mishra. "Unveiling the Behavior of MHD Mixed Convective Nanofluid Slip Flow over a Moving Vertical Plate with Radiation, Chemical Reaction, and Viscous Dissipation." *CFD Letters* 15, no. 10 (2023): 93-109. https://doi.org/10.37934/cfdl.15.10.93109

[19] Seethamahalakshmi, V., Leelavathi Rekapalli, T. S. Rao, P. Naga Santoshi, G. V. R. Reddy, and A. S. Oke. "MHD slip flow of upper-convected Casson and Maxwell nanofluid over a porous stretched sheet: impacts of heat and mass transfer." *CFD Letters* 16, no. 3 (2024): 96-111. https://doi.org/10.37934/cfdl.16.3.96111

[20] Khan, W. A., O. D. Makinde, and Z. H. Khan. "MHD boundary layer flow of a nanofluid containing gyrotactic microorganisms past a vertical plate with Navier slip." *International Journal of Heat and Mass Transfer* 74 (2014): 285-291. https://doi.org/10.1016/j.ijheatmasstransfer.2014.03.026

[21] Mabood, F., W. A. Khan, and A. I. Md Ismail. "Multiple slips effects on MHD Casson fluid flow in porous media with radiation and chemical reaction." *Canadian Journal of Physics* 94, no. 1 (2015): 26-34. https://doi.org/10.1139/cjp-2014-0667

[22] Sk, Md Tausif, Kalidas Das, and Prabir Kumar Kundu. "Multiple slip effects on bioconvection of nanofluid flow containing gyrotactic microorganisms and nanoparticles." *Journal of Molecular Liquids* 220 (2016): 518-526. https://doi.org/10.1016/j.molliq.2016.04.097

[23] Gangawane, Krunal M., and Hakan F. Oztop. "Mixed convection in the semi-circular lid-driven cavity with heated curved wall subjugated to constant heat flux for non-Newtonian power-law fluids." *International Communications in Heat and Mass Transfer* 114 (2020): 104563. https://doi.org/10.1016/j.icheatmasstransfer.2020.104563

[24] Roy, Partha Pratim, Shuvra Chowdhury, Md Hossain Raj, Md Quamrul Islam, and Sumon Saha. "Forced, natural and mixed convection of Non-Newtonian fluid flows in a square chamber with moving lid and discrete bottom heating." *Results in Engineering* 17 (2023): 100939. https://doi.org/10.1016/j.rineng.2023.100939

[25] Lone, Showkat Ahmad, Sadia Anwar, Anwar Saeed, and Gabriella Bognár. "A stratified flow of a non-Newtonian Casson fluid comprising microorganisms on a stretching sheet with activation energy." *Scientific Reports* 13, no. 1 (2023): 11240. https://doi.org/10.1038/s41598-023-38260-0

[26] Kumar, Deepak, and Akhilesh Kumar Sahu. "Non-Newtonian fluid flow over a rotating elliptic cylinder in laminar flow regime." *European Journal of Mechanics-B/Fluids* 93 (2022): 117-136. https://doi.org/10.1016/j.euromechflu.2022.01.005

[27] Rehman, Khalil Ur, and Wasfi Shatanawi. "Non-newtonian mixed convection magnetized flow with heat generation and viscous dissipation effects: A prediction application of artificial intelligence." *Processes* 11, no. 4 (2023): 986. https://doi.org/10.3390/pr11040986

[28] Alsenafi, Abdulaziz, and M. Ferdows. "Dual solution for double-diffusive mixed convection opposing flow through a vertical cylinder saturated in a Darcy porous media containing gyrotactic microorganisms." *Scientific Reports* 11, no. 1 (2021): 19918. https://doi.org/10.1038/s41598-021-99277-x

[29] Nima, Nayema Islam, and Mohammad Ferdows. "A sustainable computational modeling on gyrotactic free forced bioconvective flow with various slip effects." *Journal of Interdisciplinary Mathematics* 25, no. 7 (2022): 1989-1997. https://doi.org/10.1080/09720502.2022.2133226

[30] Nima, Nayema Islam, and Mohammad Ferdows. "Dual solutions in mixed convection flow along non-isothermal inclined cylinder containing gyrotactic microorganism." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 87, no. 3 (2021): 51-63. https://doi.org/10.37934/arfmts.87.3.5163