

Impact of Gyrotactic Microorganisms on Bidirectional Tangent Hyperbolic Fluid with Nield Boundary Conditions

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Abstract: The present study deals with the synergistic influence of gyrotactic microorganisms and bimolecular reactions on the bidirectional flow of tangent hyperbolic fluids under Nield boundary conditions. Further, the flow characteristic of the non-Newtonian fluid is enhanced by incorporating the impact of thermal radiation, heat sources, Brownian motion, and thermophoresis. The presentation of these phenomena is vital for an extensive range of applications, including industrial processes, biomedical engineering, and environmental management. The analysis employs advanced mathematical modelling which needs suitable transformation rules to get the non-dimensional form and further numerical simulation is presented with the assistance of the “shooting-based fourth-order Runge-Kutta technique”. The results are depicted for the several contributing factors via the built-in in-house function `bvp4c` in “MATLAB”. The authentication of the study with the prior research is a benchmark to precede further research in this direction.

Keywords: Bidirectional Tangent Hyperbolic Fluid; Gyrotactic Microorganisms; Thermal Radiation; Brownian motion and Thermophoresis; Nield Boundary Conditions.

I. Introduction:

The primary objective of developing and studying nanofluids is to enhance the thermal properties of base fluids for various industrial and engineering applications. Nanofluids aim to significantly increase the thermophysical properties and heat transfer coefficient of traditional fluids, by improving the thermal properties, nanofluids can help reduce energy consumption in systems such as cooling and heating applications. Nanofluids are used to improve the cooling system in applications like electronic cooling. Beyond thermal conductivity, nanofluids can exhibit other beneficial properties such as enhanced electrical conductivity, magnetic properties, and improved lubrication. Reza et al. [1] scrutinized the nonlinear radiative boundary layer flow phenomena in second-grade nanofluids. Flow phenomena are enhanced by some factors i.e., bimolecular reaction, a sinusoidal magnetic-induced field, and an extended surface. In such a way the basic equations are altered and the explicit “finite difference method” is utilized for numerical calculation. Additionally, precise constancy and merging criteria have been established to ensure the solution's convergence. In another detailed work, Haq et al. [2] demonstrated that the combination of bimolecular reaction, heat flow, radiating heat energy influenced the heat flow rate capabilities of magnetised Darcy-Forchheimer hybrid nanomaterials. Reza-E-Rabbit et al. [3] researched the effect of radiative heat energy as well as bimolecular reaction on Casson liquid, as it enhanced the Lorentz force, thereby influencing the momentum distribution. Chabani [4] considered a numerical scrutinization of the laminar flow of nanomaterials, examining the interpretation of their thermal properties on convective heat flow. Additionally, they have employed the “Darcy-Forchheimer-Brinkmann model” and the “finite element method” to solve the non-dimensional equations. A study was conducted by Hameed et al. [5] to study the behavior of an analysis of the magnetism, and heat dissipation influences on a couple of stress Casson hybridised nanomaterials over an expanding sheet. Tangent hyperbolic nanofluid is a type of non-Newtonian fluid characterized by its shear-thinning behavior, described mathematically by the tangent hyperbolic model. This fluid model is particularly useful in representing fluids that exhibit both viscosity and elasticity, making it suitable for various industrial and engineering applications. By incorporating nanoparticles into a tangent hyperbolic fluid, the resultant nanofluid benefits from enhanced flow phenomenon, like as increased thermal conductivity and improved heat transport phenomena. In particular, Ramasekhar et al. [6] analysis deliberated the association of activation energy and Joule heating on tangent hyperbolic nanomaterial presence of motile microorganisms. Additionally, their work examines the association of a Riga plate, heat generation, thermal radiation, and variable thermal conductivity to provide comprehensive insights. Panda et al. [7] scrutinized the control of thermal stratification and radiative heat considering Powell-Eyring non-Newtonian fluid via Riga plate to utilizing “Cattaneo-Christov heat flux model”. Moreover, the inclusion of energy flow phenomena along with radiative heat energy significantly enhances the scope of the study. The subsequent governing equations are altered into ODEs and solved numerically by the “Runge-Kutta method” in conjunction with a “shooting approach”, a flexible numerical technique. Baithalu and colleagues [8] investigated the flow behavior of a nanoliquid that combines magneto and polar properties on a flexible surface. Moreover, their work explored a couple of stresses and shear rates that significantly influence the flow dynamics. Dharmiah et al. [9] depicted the flow of an incompressible nanofluid in a transient 2D flow over a cone. The numerical solution employed the `bvp4c` method to solve the converted coupled nonlinear equations. Zehra et al. [10] explored the heat transport phenomena of nanofluid using the “Casson nanofluid model”, incorporating the “double diffusional Cattaneo-Christov heat flux model”. Their study focused on a curved tube that either shrinks or widens.

The concept of activation energy in chemical reactions has been extremely valuable in various fields, including oil preservation, biodiesel production, geothermal energy, oil processing, food manufacturing, oil blending, sewage treatment, and as a key

renewable energy source. Hussain et al. [11] examined the imposition of magnetohydrodynamics on 3D tangential hyperbolic nanomaterial flows over an expanding sheet with gyrotactic microorganisms, incorporating new mass flux conditions. Utilizing Rosseland's approximation, thermal radiation, and activation energy is also involved in the chemical reaction. A new mathematical model has been anticipated by Ramzan et al. [12] for the 3D flow of tangent hyperbolic nanomaterial, considering the effective interaction of Hall current and ion slip under the influence of a strong magnetic field, via an elastic sheet. Furthermore, the "finite element analysis" of the transient magnetic-induced 3D spinning flow nanomaterials via a two-way extending sheet, incorporating the "Cattaneo-Christov heat flux model", has been investigated by Ali et al. [13]. The chemically reactive fluid flow of Eyring-Powell nanomaterial has been studied by Khan et al. [14]. Their study investigates heat transport phenomena by using thermal radiation. Moreover, the characteristics of reacting agent as well as activation energy are considered for their physical significance. Panda et al. [15] anticipated the free convective motion of a conducting material, influenced by radiating heat energy and magnetic field, demonstrating a significant role in the flow dynamics. Shamsuddin et al. [16] considered the characteristics of Williamson-micropolar nanofluid and concluded a bi-directional expanding surface, considering the effects of radiative heat with a heat source, and multiple slip conditions. Furthermore, the Navier stokes equations are solved utilizing the "Homotopy Analysis Method (HAM)". Eegunjobi and Makinde [17] deliberated the Couette flow in parallel pipes, considering the impact of entropy. Moreover, the Nonlinear partial differential equations governing the system were subsequently identified using "Runge-Kutta" and "finite difference methods". Furthermore, a thermodynamic irreversibility and the resultant entropy generation were conducted. Srinivasacharya and Hima-Bindu [18] investigated the micropolar material under the imposition of a magnetisation and entropy generation. Mehmood et al. [19] discussed the circulation of a micropolar material among two parallel plates under the influence of an external heat source and induced magnetism. They solved the PDEs via the "Optimal Homotopy Analysis Method (OHAM)". Yari [20] explored the entropy formation in microannulus flow, examining the influences of temperature variations, velocity slip, and viscous dissipation. Their work revealed that as the Knudsen number rises, entropy production decreases.

Approaches lead to Novelty: The assumptions and presentation of the proposed model shows its creative approach due to the followings

The unique presentation of the gyrotactic microorganisms, and binary chemical reactions, itself shows the novelty over earlier works.

The exploration of the interactions between several physical phenomena, including thermal radiation, heat sources, enriches the flow phenomena.

The irregular motion of the particles within the flow domain causing the effective role of Brownian motion, and thermophoresis enhances the thermal properties.

The study leads to advanced mathematical modeling to provide a detailed analysis of the factors involved in it.

The practical applications in diverse fields' likely biomedical engineering, environmental management, and industrial processes, emphasizing real-world applicability.

By focusing on bidirectional tangent hyperbolic fluids, the study contributes a novel characteristic of the non-Newtonian fluid including multiple factors.

Problem description: This study examines the significance of bioconvective flow of motile microorganisms considering a non-Newtonian tangent hyperbolic fluid through an elongating surface. The conducting fluid with the imposition of transverse magnetisation association with radiating heat energy enriches the flow phenomena. The main flow direction of the bidirectional fluid is xy -plane where the plate is elongating in both the direction of x and y with stretching velocity $U_w = ax$, $V_w = by$ respectively. Here $z > 0$ is the normal direction of the flow and the surface embedding with porous matrix. Additionally, it addresses heat generation/absorption properties and the velocity slip along with convective boundary condition are also consider. The initial fluid temperature at the surface along with concentration are assumed to be T_w and C_w respectively while T_∞ and C_∞ are far away from it (Fig.1).

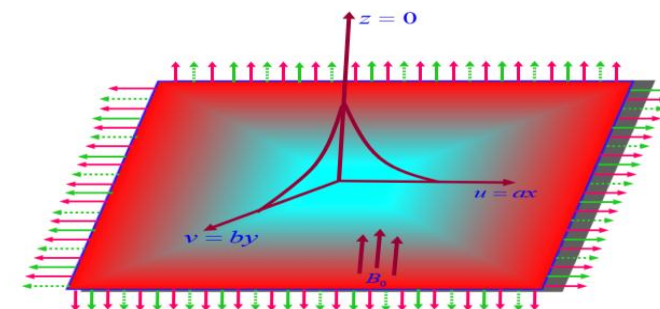


Fig.1 Flow geometry

The flow phenomena governed by the aforesaid assumptions lead to

$$u_x + v_y + w_z = 0 \quad (1)$$

$$uu_x + vv_y + ww_z = \nu(1-n)u_{zz} + \sqrt{2\nu n}\Gamma(u_z)u_{zz} - \sigma_f B_0^2 / \rho_f (u) - \mu / \rho k_p^* (u) \quad (2)$$

$$uv_x + vw_y + ww_z = \nu(1-n)v_{zz} + \sqrt{2\nu n}\Gamma(v_z)v_{zz} - \sigma_f B_0^2 / \rho_f (v) - \mu_{hnf} / \rho_{hnf} k_p^* (v) \quad (3)$$

$$uT_x + vT_y + wT_z = \alpha_1 T_{zz} + \tau \left[D_B T_z C_z + (T_z)^2 (D_T / T_\infty) \right] - \frac{1}{(\rho C)_f} (q_r)_z + \frac{1}{(\rho C)_f} q''' \quad (4)$$

$$uC_x + vC_y + wC_z = D_B C_{zz} + \frac{D_T}{T_\infty} T_{zz} - \left(\frac{T}{T_\infty} \right)^m k_r^2 e^{\left(\frac{-E_a}{kT} \right)} (C - C_\infty) \quad (5)$$

$$uN_x + vN_y + (NC_z)_z \frac{W_c b}{(C_w - C_\infty)} + wN_z = (D_m N_z)_z \quad (6)$$

The appropriate surface conditions relating to the model are:

$$\left. \begin{aligned} u &= ax + L \frac{\partial u}{\partial z}, v = V_w = by, w = 0, -kT_z = h_f (T_w - T), -D_B C_z + \frac{D_T}{T_\infty} T_z, N = N_w, \text{ at } z = 0, \\ u &\rightarrow 0, v \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty, N \rightarrow N_\infty \quad \text{as } z \rightarrow \infty. \end{aligned} \right\} \quad (7)$$

Whenever

$$q_r = -\frac{16\sigma^* T_\infty^3}{3k^*} T_z \quad (8)$$

The following similarity rules are appropriate to prepare the nondimensionalization of the governing equation

$$\left. \begin{aligned} T &= (T_w - T_\infty)\theta(\eta) + T_\infty, u = axf'(\eta), w = -[f(\eta) + g(\eta)]\sqrt{av}, N = (N_w - N_\infty)\chi(\eta) + N_\infty, \\ C &= (C_w - C_\infty)\phi(\eta) + C_\infty, \eta = z \left(\frac{a}{\nu} \right)^{\frac{1}{2}}, v = ayg'(\eta), \end{aligned} \right\} \quad (9)$$

Implementing the above similarity function in Eqs. (2-7)

$$(1-n+nWef'')f''' + (f+g)f'' - (f')^2 - (M+Da)f' = 0 \quad (10)$$

$$(1-n+nWe_1g'')g''' + (f+g)g'' - (g')^2 - (M+Da)g' = 0 \quad (11)$$

$$\left[1 + \frac{4}{3} Rd \right] \theta'' + Pr [Nb\theta'\phi' + 2Nt\theta'^2] + Pr(f+g)\theta' + (Af' + B\theta) = 0 \quad (12)$$

$$\phi'' + Pr Le(f+g)\phi' + \frac{Nt}{Nb} \theta'' - Pr Le \sigma [1 + \delta_1 \theta]^m \phi e^{\left(\frac{E}{1+\delta_1 \theta} \right)} = 0 \quad (13)$$

$$\chi'' + Lb\chi'(f+g) - Pe[\phi''(\chi + \delta_2) + \phi'\chi'] = 0 \quad (14)$$

$$\left. \begin{aligned} f(0) &= 0, f'(0) = (1 + \delta f''), g(0) = 0, g'(0) = \alpha, \theta'(0) = -\gamma[1 - \theta(0)], Nb\phi'(0) + Nt\theta'(0) = 0, \chi(0) = 1 \\ f'(\infty) &\rightarrow 0, g'(\infty) \rightarrow 0, \theta(\infty) \rightarrow 0, \phi(\infty) \rightarrow 0, \chi(\infty) \rightarrow 0, \end{aligned} \right\} \quad (15)$$

Where the dimensionless factors are expressed as

$$\left. \begin{aligned} Pr &= \frac{\nu}{\alpha_1}, R = \frac{4\sigma^* T_\infty^3}{3kk^*}, Nb = \frac{\tau D_T (T_w - T_\infty)}{\nu T_\infty}, M = \frac{\sigma^* B_0^2}{\rho_f a}, E = \frac{E_a}{kT_\infty}, We = \frac{\sqrt{2a}\Gamma U_w}{\sqrt{\nu}} \\ \alpha &= \frac{b}{a}, Nt = \frac{\tau D_B (C_w - C_\infty)}{\nu}, Pe = \frac{bWc}{D_m}, \delta_2 = \frac{N_\infty}{(N_w - N_\infty)}, Le = \frac{\alpha_1}{D_B}, \gamma = \frac{h_f}{k} \sqrt{\frac{\nu}{a}}, \\ Lb &= \frac{\nu}{D_m}, \sigma = \frac{k_r^2}{a}, \delta = \frac{Q_0}{\alpha(\rho Cp)_f}, Da = \frac{\nu}{k_p^* a}, Nb = \frac{\tau D_B (T_w - T_\infty)}{\nu T_\infty} \end{aligned} \right\} \quad (16)$$

Physical quantities

Shear stress

$$\begin{aligned} Cf_x &= \frac{2\mu}{U_w^2 \rho_f} \left[(1-n)u_z + \frac{\Gamma n}{\sqrt{2}} (u_z)^2 \right]_{z=0}, \\ Cf_y &= \frac{2\mu}{V_w^2 \rho_f} \left[(1-n)v_z + \frac{\Gamma n}{\sqrt{2}} (v_z)^2 \right]_{z=0} \end{aligned} \quad (17)$$

Dimensionless form of above-mentioned quantities are

$$\begin{aligned} Re_x^{-\frac{1}{2}} Cf_x &= 2 \left[(1-n)f''(\eta) + \frac{n}{2} We_1 \{f''(\eta)\}^2 \right]_{\eta=0}, \\ Re_y^{-\frac{1}{2}} Cf_y &= 2 \left[(1-n)g''(\eta) + \frac{n}{2} We_2 \{g''(\eta)\}^2 \right]_{\eta=0} \end{aligned} \quad (18)$$

Nusselt number

$$Nu_x = \left(-\frac{x}{(T_w - T_\infty)} T_z + \frac{xq_r}{(T_w - T_\infty)} \right) \Big|_{z=0} \quad (19)$$

We obtained

$$Re_x^{-\frac{1}{2}} Nu_x = -\left(1 + \frac{4}{3} Rd \right) \theta'(0) \quad (20)$$

Sherwood number

We write

$$Sh_x = -\frac{x}{(C_w - C_\infty)} C_z \Big|_{z=0} \quad (21)$$

Utilising the above-obtained

$$Re_x^{-\frac{1}{2}} Sh_x = -\phi'(0), \quad (22)$$

Motile number

$$Nn_x = -\frac{x}{(N_w - N_\infty)} N_z \Big|_{z=0} \quad (23)$$

dimensionless format of above term

$$\text{Re}_x^{-\frac{1}{2}} Nn_x = -\chi'(0), \quad (24)$$

$$\text{Where } (\text{Re}_x, \text{Re}_y) = \left(\frac{ax^2}{\nu}, \frac{ay^2}{\nu} \right)$$

Table-1: Comparative analysis of $f''(0)$ for diverse values of M with previous studies at $We = n = Da = A = B = 0$

M	Hussain et al. [21]	Akbar et al. [22]	Present
0	-1	-1	-1
0.25	-1.1232	-1.11803	-1.11845645
1	-1.4165	-1.41421	-1.41447456
5	-2.4497	-2.449449	-2.44943453
10	-3.3186	-3.31663	-3.31634346
100	-10.049	-10.0498	-10.0436344
500	-22.3887	-22.38303	-22.3833656
1000	-31.6388	-31.63859	-31.6384577

Comparative analysis with discussion

The bidirectional flow of tangent hyperbolic nanomaterial via an expanding surface embedding with porous medium under the action of Neild surface condition is analyzed in the existing study. The non-Newtonian electrically conducting liquid in association with the radiative heat energy and external heat source energies the flow dynamics. In addition to that the cross-diffusion flow for the occurrence of Brownian and thermophoresis, binary chemical reactions also customize the study. To get the physical significance of the flow profiles, the “shooting-based Runge-Kutta technique” is employed for the transformed phenomena utilizing the bvp4c built-in function in MATLAB. The comparative analysis among the profiles of the current and the prior work of Hussain et al. [21] and Akbar et al. [22] is obtained numerically and the simulated outputs are described in **Table-1**. This shows the validation of the output in a specific scenario which conforms to the convergence criteria of the existing applied technique. Further, the physical significance of the contributing factors of the study is obtained graphically and these are gained for the fixed values of all the factors except the behavior of the precise one in the concerned graph.

The detailed explanation of the variation of magnetic parameters combined with the impact of porosity affecting the axial and transverse fluid velocity of tangent hyperbolic nanofluid is depicted in **Fig.2 and Fig.3** respectively. The influence of the external magnetism through the magnetisation factor M is presented considering the range of $M \in [0, 3]$. The allocated numeric value of M , $M = 0$ is the consideration of non-magnetization and the non-zero value suggests the behavior of the magnetic field. Further, this behavior is depicted for the circumstance of $Da = 0$, the flow via an impermeable medium and the $Da = 1$ clarifies the significance of the study within the permeable medium. The magnetic parameter directly affects the Lorentz force acting on the fluid which in turn influences the momentum profile. As the magnetisation augments the profile potentially leads to a decrease in fluid velocity due to enhanced Lorentz force acting as a resistive force. The retardation in the fluid velocity occurs in both the situation of permeability and the comparison reveals that in the presence of porosity, the amount of retardation is stronger than the absence. The fact is that, as per the magnetic parameter porosity also is a resistive force which attenuates the profile. **Fig.3** portrays the similar tendency for the transverse velocity in varying magnetization with respect to the presence/absence of permeability. The increasing permeability also provides greater retardation in comparison to the impermeable medium.

Fig.4 and Fig.5 portray the characteristic of the non-Newtonian Weissenberg number on the axial as well as the transverse fluid velocity depicting the variation of the slip velocity factor and the velocity ratio factor respectively. The Weissenberg number is a non-dimensional parameter that exemplifies the relative importance of the elastic forces in comparison to the viscous force within the flow. The projected range of the parameter is $We \in [0, 3]$. Here, $We = 0$ suggests the flow behaviour of a Newtonian fluid and $We \in [0, 3]$ carries out the behavior of a non-Newtonian. The discrepancy of the parameter is demonstrated in two dissimilar conditions such as the no-slip ($\delta = 0$) and slip ($\delta \neq 0$) condition. For the low We $We = 0, 1$ the velocity profile is primarily induced by viscous forces. slip velocity causes a slight movement of the velocity profile making fluid move faster near the boundary in comparison to the no-slip condition. For the high elastic forces, $We = 2, 3$ the fluid exhibits strong resistance to deformation

and the profile becomes flattened. Further, with increasing slip the velocity distribution attenuates significantly. **Fig.5** shows a reverse impact on the transverse velocity for the association of the velocity ratio factor. The variation of velocity ratio is projected as $\alpha = 0$, indicating that no flow occurs towards the transverse direction and $\alpha \neq 0$ exhibits the velocity variation towards the transverse direction of the flow. The increasing velocity ratio shows a greater impact on the momentum profile causing a rise in the bounding surface thickness.

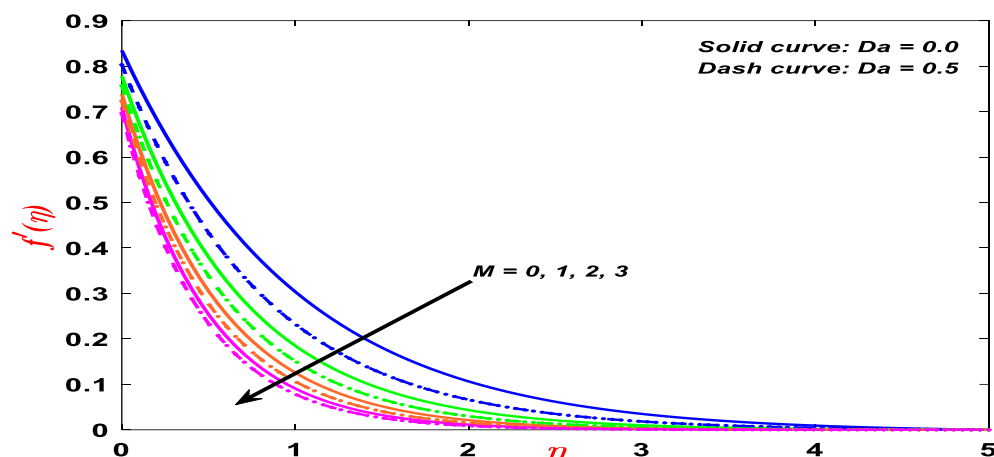


Fig. 2 M on $f'(\eta)$

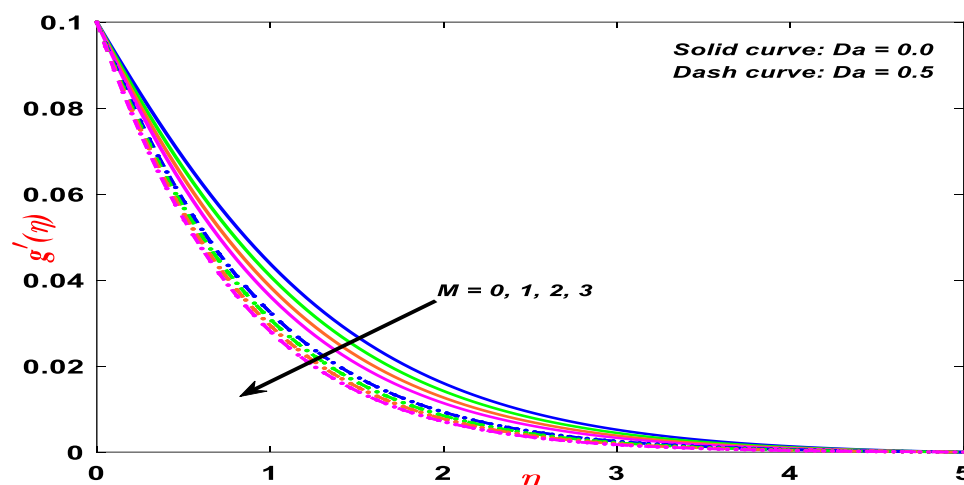


Fig. 3 M on $g'(\eta)$

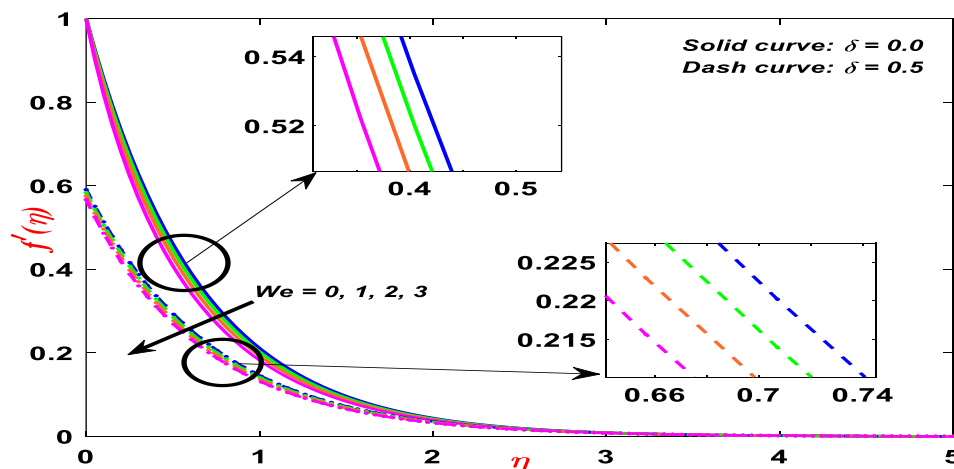


Fig. 4 We on $f'(\eta)$

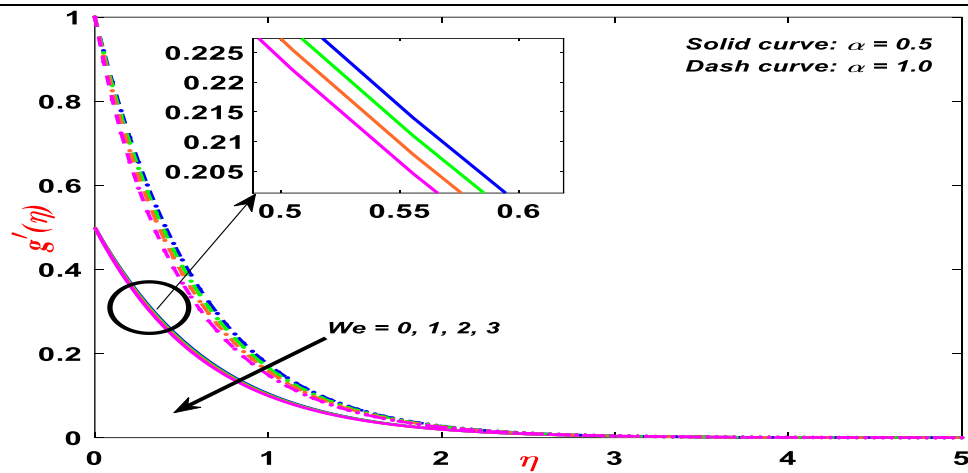


Fig. 5 We on $g'(\eta)$

Fig.6 exhibits the interpretation of the power-law index in a tangent hyperbolic fluid model which signifies the shear thinning behavior on the momentum distribution. The behavior is followed by two situations, considering no slip vis-a-vis slip velocity conditions. Here, $\delta = 0$ suggests no-slip i.e., the momentum of the surface and the momentum of the fluid at the surface are either zero or the same. Further, $\delta \neq 0$ indicates slip velocity where the fluid momentum at the surface and the surface velocity differs. At a low power-law index i.e., $n = 0$, the fluid exhibits extremely shear-thinning behavior where the fluid viscosity diminishes rapidly with growing shear rate. With the no-slip condition, the velocity profile shows a flat profile indicating low resistance. Further, in the case of slip condition the profile attenuates greatly than that of the no-slip condition.

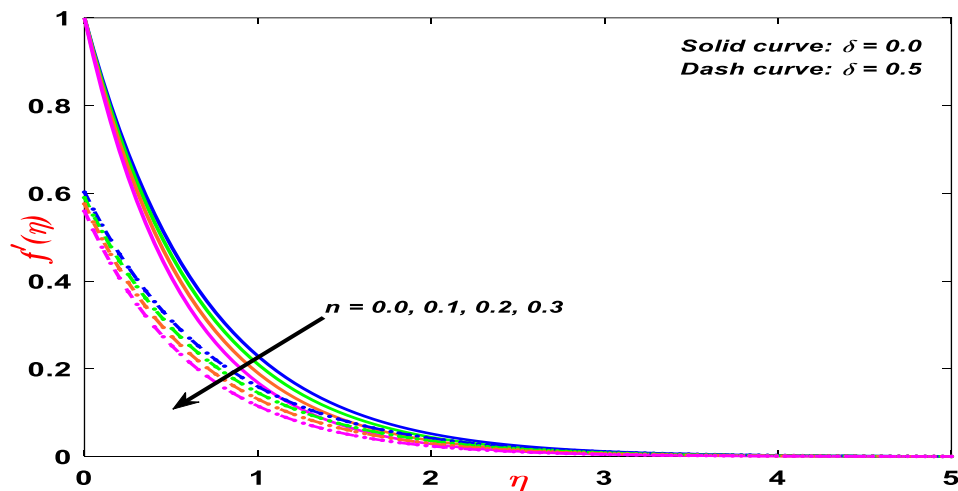


Fig. 6 n on $f'(\eta)$

The variation of fluid temperature for the diversified factors intricate in the flow phenomena is depicted through figures. **Fig.7** and **Fig.8** respectively deployed for the association of the fluid temperature which is affected by the variation of thermal radiation and thermal Biot number. However, the results are depicted in varying the space and temperature-dependent heat source/sink. The characteristic of the non-uniform heat generation/sink has an extensive range of applications in biomedical as well as industries. The variation of the thermal radiation is shown for the range of $Rd \in [0, 1.5]$. The numerically assigned thermal radiation $Rd = 0$ represents the non-existence of the radiative heat and further, the non-zero variation of thermal radiation shows the existence. With increasing Rd , radiative heat transfer becomes more significant. Higher Rd results in a more uniform temperature distribution due to enhanced radiative heat flux. This behavior is exhibited for both the scenario of heat source/sink within the fluid. The comparative analysis reveals that for the increasing heat source, the profile temperature significantly increases than that of the scenario of sink. Further, Biot number (**Fig.8**) suggests the proportion of the internal thermal resistance within the body to the thermal resistance at its boundary. The variation of the Biot number is presented within the range of $Bi \in [0.1, 0.5]$. The enhanced Biot number indicates more significant heat flow at the boundary. The situation of heat source augments significantly in comparison to heat sink.

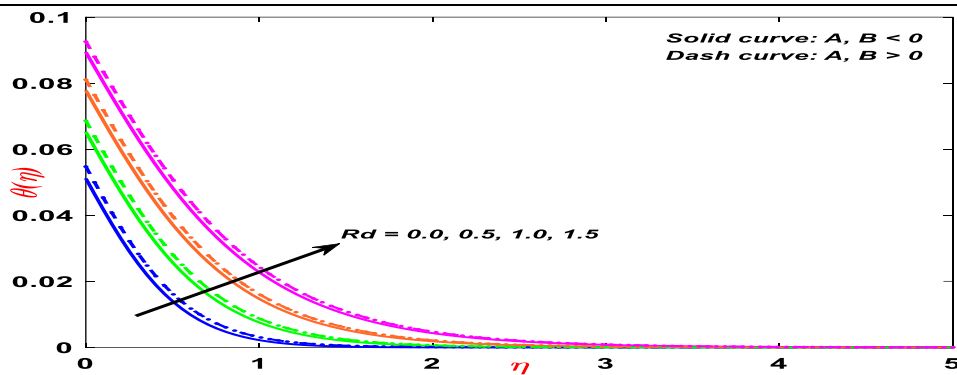


Fig. 7 Rd on $\theta(\eta)$

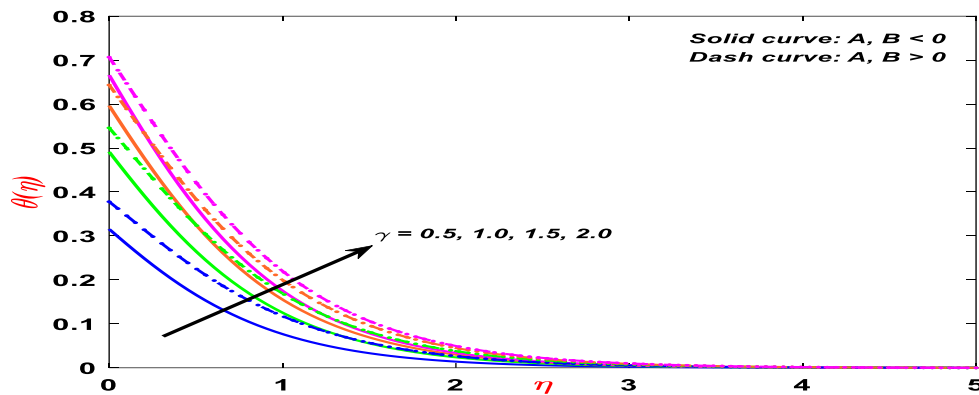


Fig. 8 γ on $\theta(\eta)$

The variation of the distinct factors affecting the fluid solutal concentration for the fixed values of certain factors contributes to the flow phenomena. **Fig.9** visualizes the characteristic of the concentration profile for the variation of the bimolecular reaction/activation energy in association with the Lewis number. The interpretation of the activation energy/bimolecular reaction lies in between the range of $E \in [0.1, 0.7]$ and the behavior is depicted for distinct values of Le as $Le = 1$ and $Le = 2$. At low activation energy ($E = 0.1$), the energy barrier for the chemical reaction is minimal which leads to a higher reaction rate, with increasing activation energy, the concentration profile increases significantly. The concentration of the fluid is expected to be flat with minimal gradient and diffusion becomes the dominant mechanism which increases the concentration significantly. This phenomenon is exhibited for both the high and low values of the Lewis number. The physical significance of the Lewis number shows the proportion of the diffusions obtained by the thermal and solutal. The rising Le indicates the lower solutal diffusivity which retards the concentration in comparison to the lower Le . **Fig.10** reveals the significant characteristic of the bilateral chemical reaction affecting the fluid concentration in the rising values of the Lewis number. The positive amount of the chemical reaction signifies the destructive chemical reaction and growing reacting agent retards the fluid concentration. In other words, the fluid concentration is controlled by the enhancement of the chemical reaction in either of the case of the Lewis number.

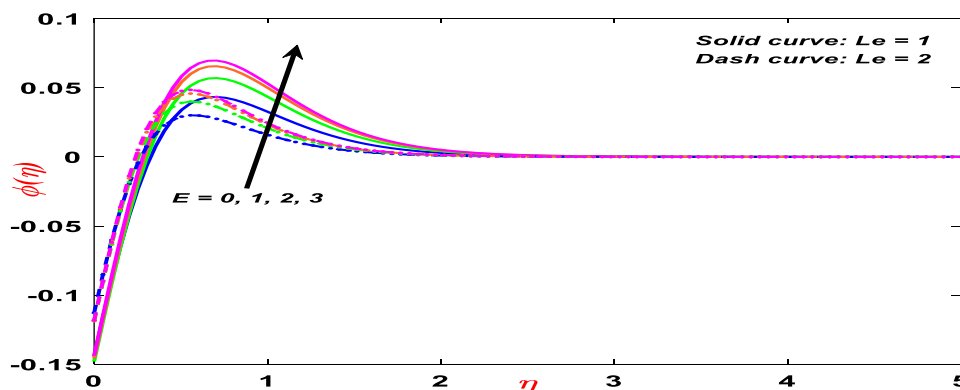


Fig. 9 E on $\phi(\eta)$

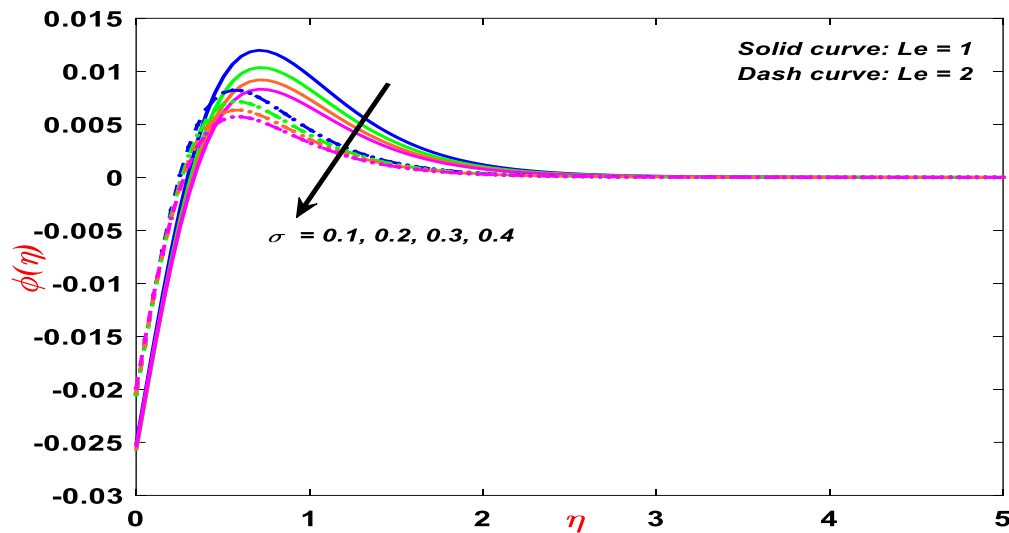


Fig. 10 σ on $\phi(\eta)$

The mutual association of Brownian diffusion and thermophoretic motion is projected on the fluid concentration is presented in **Fig.11**. In general Brownian motion refers to the irregular motion of the particles within the fluid and this arises due to the collisions with the molecules. The effect is significant for small particles and becomes more pronounced with decreasing size of the particle. In non-Newtonian fluids, the rate of diffusion is affected by the rheological properties. A dual characteristic is presented for the variation of the Nb and Nt on the fluid concentration. Thermophoresis refers to the shift of the particles from the region of higher temperature to a lower temperature region. Thermophoresis suggests a directional movement of the particles along the temperature gradient. therefore, increasing thermophoresis enhances the fluid concentration, and the opposite impact is rendered for the growing Brownian motion throughout the domain.

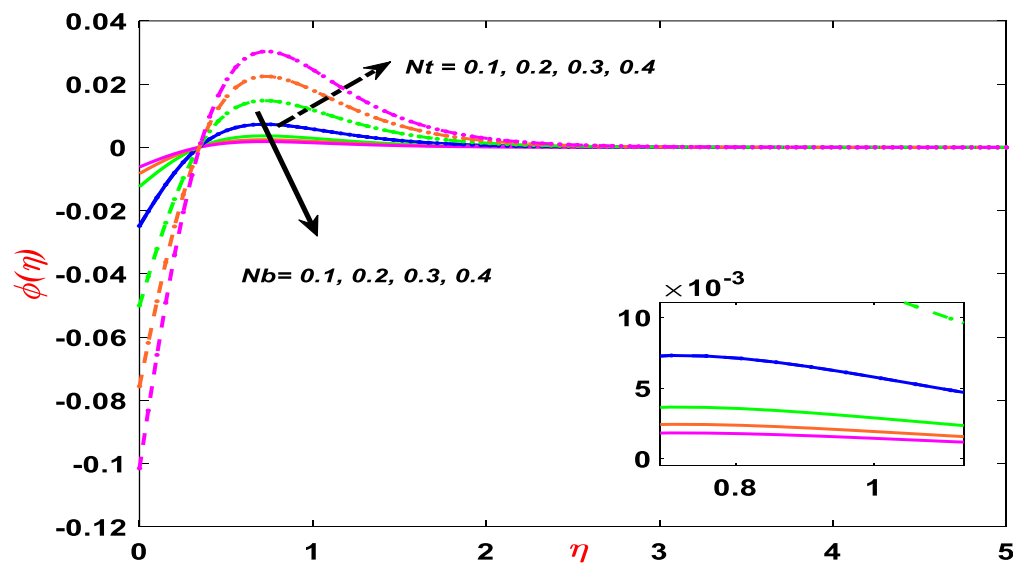


Fig. 11 Nb, Nt on $\phi(\eta)$

Fig.12 and **Fig.13** illustrate the variation of the bioconvection Lewis number and the solutal Peclet number on the profile of motile microorganisms of the non-Newtonian fluid. The bio-convection lewis number is the thermal diffusivity ratio to the motile microorganism's diffusivity. At $Lb = 1$, both the diffusivity is equal and it suggests that the microorganism distribution is relatively uniform with the influence of thermal and mass diffusivity. For the higher Lb , the diffusivity of the microorganism is significantly lower than thermal diffusivity which causes a sharp retardation in the concentration of the microorganism. Therefore, increasing Lb retards the bioconvection profile. Further from **Fig.13** it is seen that Peclet number is the ratio of the convective to diffusive transport of the solutes. However, it signifies the dominance of the advection over diffusion in the microorganism movement. With $Pe > 1$, the convection is more dominant resulting in the microorganism is more advective creating a region of higher concentration where the flow is strong. Further, increasing Peclet number decelerates the bioconvection profile significantly.

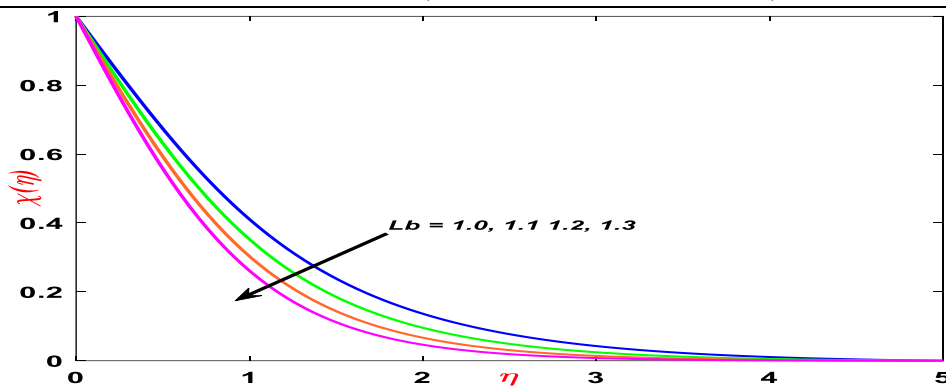


Fig. 12 Lb on $\chi(\eta)$

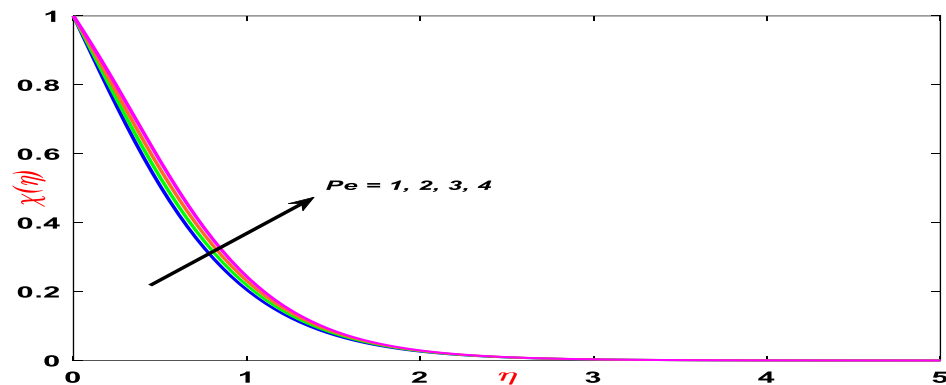


Fig. 13 Pe on $\chi(\eta)$

The numerical computation of the shear rate for the diversified factors affecting the flow profile is obtained and the outputs are depicted graphically with the inclusion of simulated numerical outputs. **Fig.14** and **Fig.15** portray the characteristics of the magnetic, porosity, and non-Newtonian Weissenberg numbers affecting the shear drag rate along the axial and transverse direction respectively. Both the resistive force for the imposition of the magnetisation and porosity with the variation of the Weissenberg parameter on the shear rates respectively. The output discloses that for the growing resistivity i.e. increasing magnetic and porosity enhances the profiles of shear rate but reverse impact is rendered for the enhanced Weissenberg number. From both the results presented in the figures, it is seen that the profile of axial velocity of shear rate dominates the profile presented for the transverse direction. **Fig.16** depicts the variation of the power-law index and the slip velocity on the shear rate profile along the axial direction is deployed. The augmentation in both the parameter and the profile retards significantly. **Fig.17** illustrates the graphical representation of the power-law index and the velocity ratio over the shear rate along the transverse direction. The presented numerical results show a greater enhancement in the profile for the increasing velocity ration throughout.

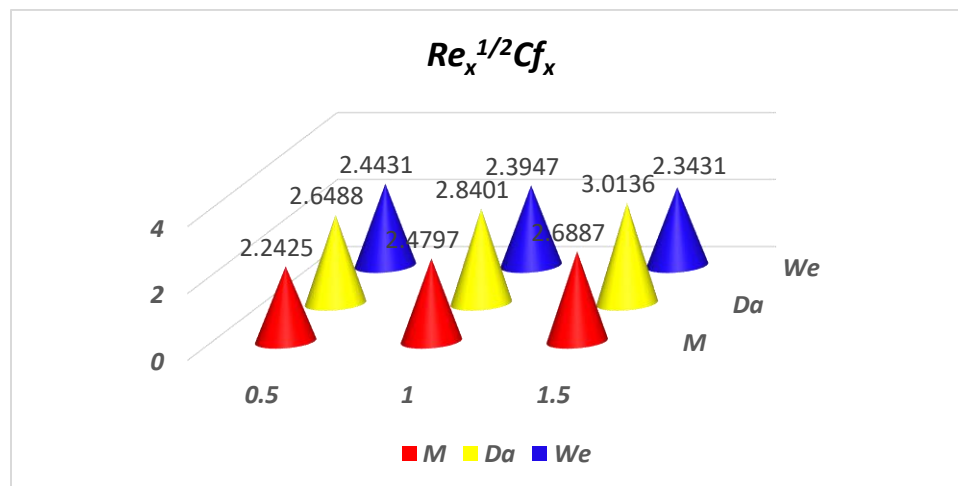


Fig. 14 M, Da, We on $Re_x^{1/2} Cf_x$

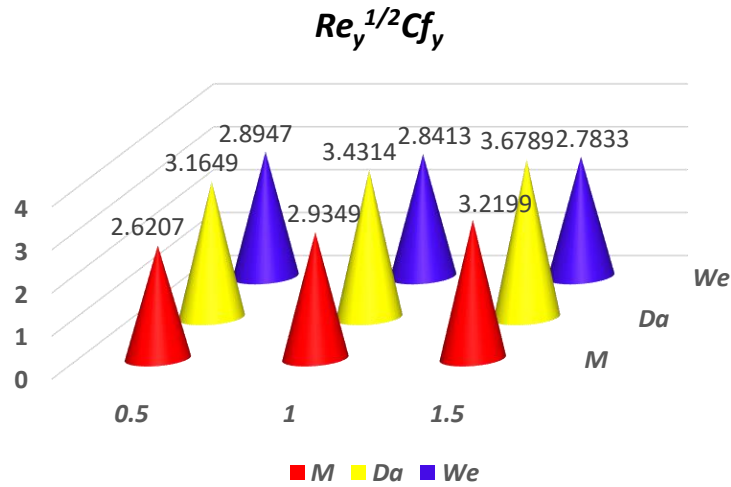


Fig. 15 M, Da, We on $Re_y^{1/2} Cf_y$

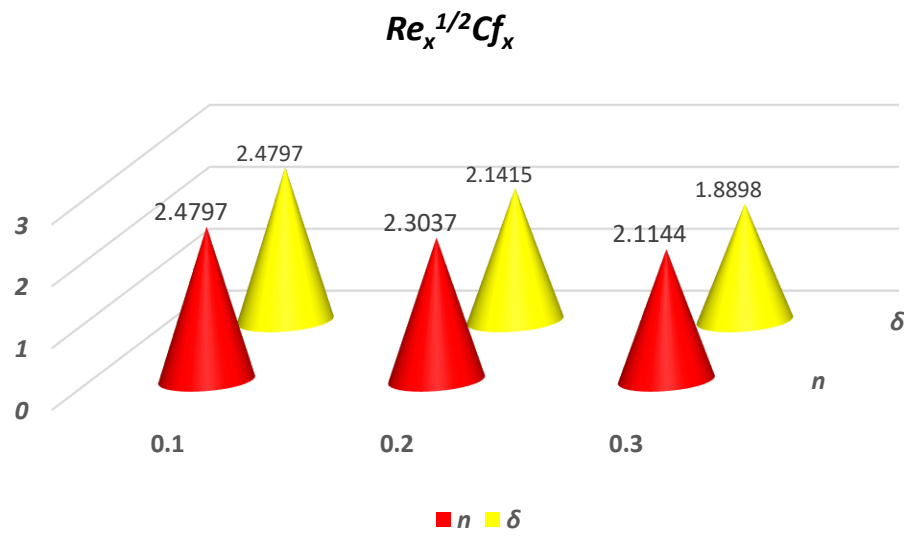


Fig. 16 n, δ on $Re_x^{1/2} Cf_x$

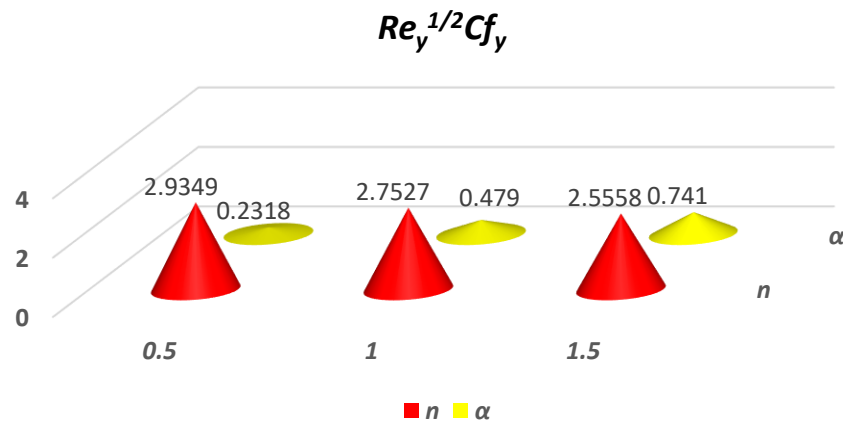


Fig. 17 n, α on $Re_y^{1/2} Cf_y$

The simulation of the heat flow rate for the variation of the characterizing term is vital in this study. **Fig.18** describes the significant variation in the factors of Rd , and the heat source for the inclusion of an irregular heat source affecting the heat flow rate. The result shows that increasing thermal radiation significantly boosts the heat flow rate but the coefficient retards significantly for the increasing heat source for both the space and temperature-dependent heat source. **Fig.19** carries out the behaviour of the Prandtl number and the thermal Biot number on the profiles of heat flow rate. Prandtl number is expressed as the ratio of the kinematic viscosity and thermal diffusivity. The increasing Pr is due to the enhanced kinematics diffusion which enriches the profile. Further, significant enhancement is rendered for the increasing thermal Biot number.

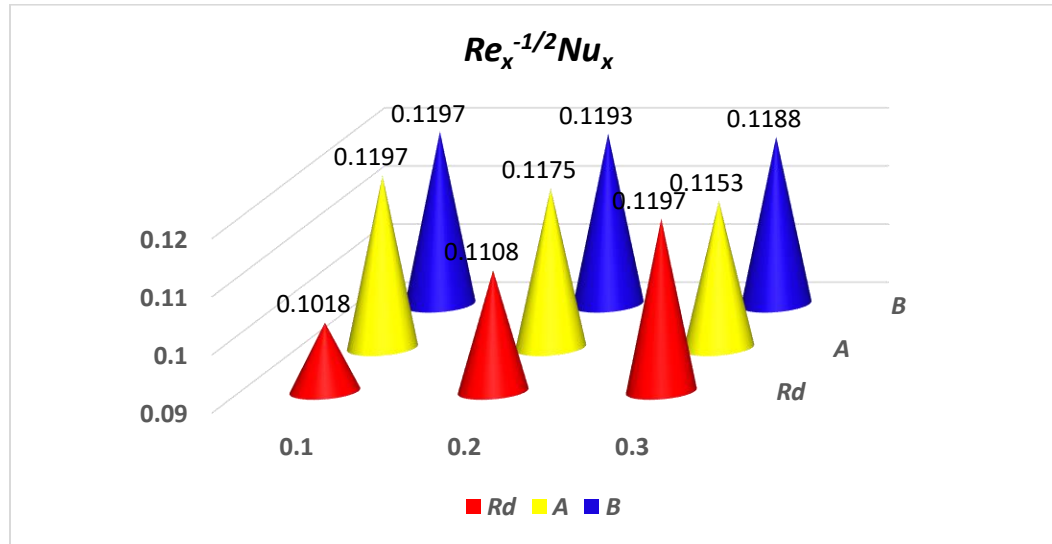


Fig. 18 Rd, A, B on $Re_x^{-1/2} Nu_x$

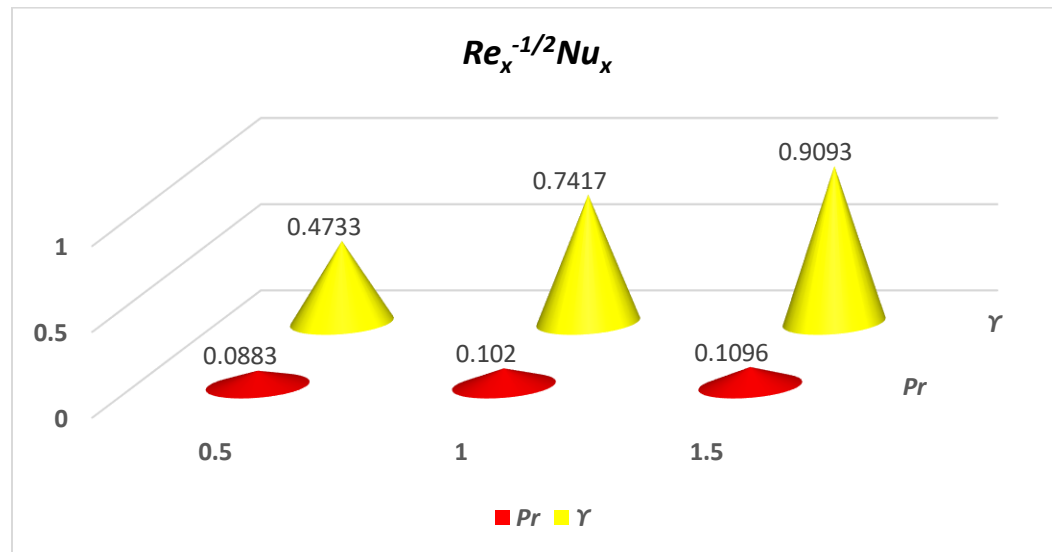


Fig. 19 Pr, γ on $Re_x^{-1/2} Nu_x$

Significant behavior of the characterizing factors affecting the flow profile is presented in simulating the solutal transfer rate. The graphical illustration of the Lewis number, Brownian motion, and thermophoresis on the profile of the Sherwood number is depicted in **Fig.20**. An increasing Le , the solutal diffusivity increases and this causes a greater enhancement in the solutal transfer rate. The irregular motion of the particles present within the flow domain characterizes the role of Brownian diffusion affecting the Sherwood number. The enhanced Nb retards the profile. Further, the analysis of the thermophoresis affecting the solutal transfer rate is deployed graphically and the enhanced thermophoresis drastically enhances the profile. Fig.21 characterizes the behaviour of activation energy and the chemical reaction on the profiles of solutal rate. The computed numerical result shows that the increasing E and γ , significantly retards the solutal transfer rate. Fig.22 depicts the variation of the solutal Peclet number and bioconvection Lewis number on the motile microorganism rate profile. The significant enhancement in the profile is rendered for the growing values of all the factors.

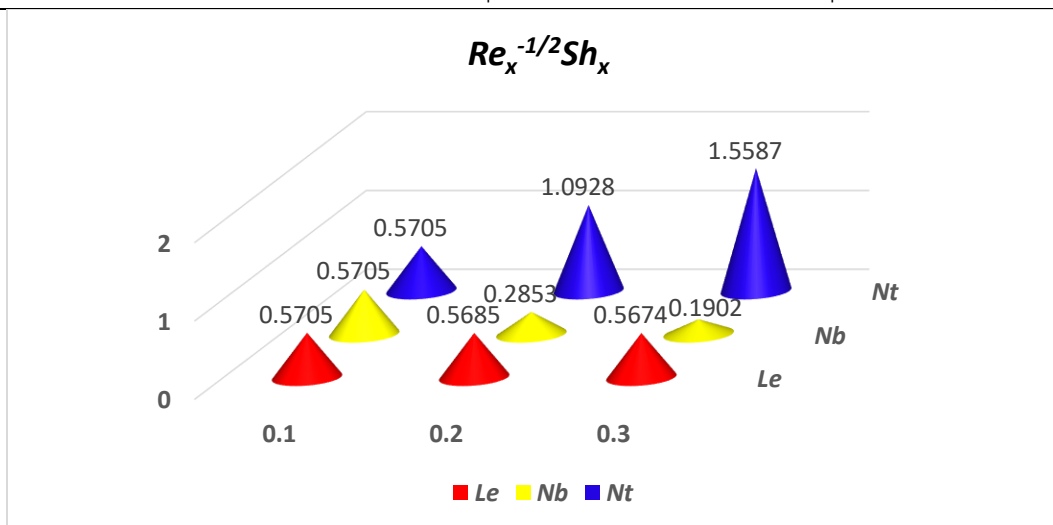


Fig. 20 Le, Nb, Nt on $Re_x^{-1/2} Sh_x$

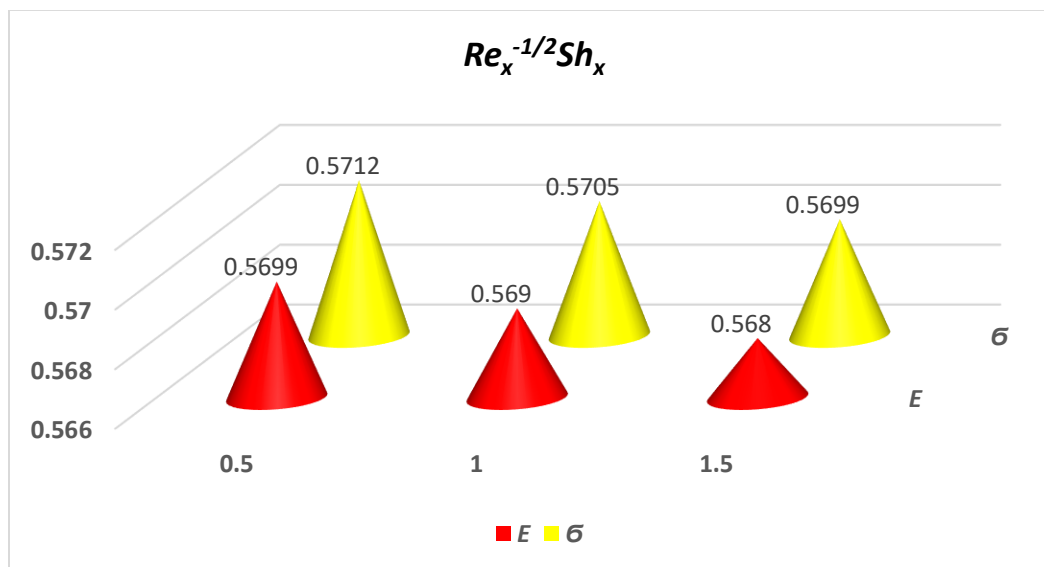


Fig. 21 E, σ on $Re_x^{-1/2} Sh_x$

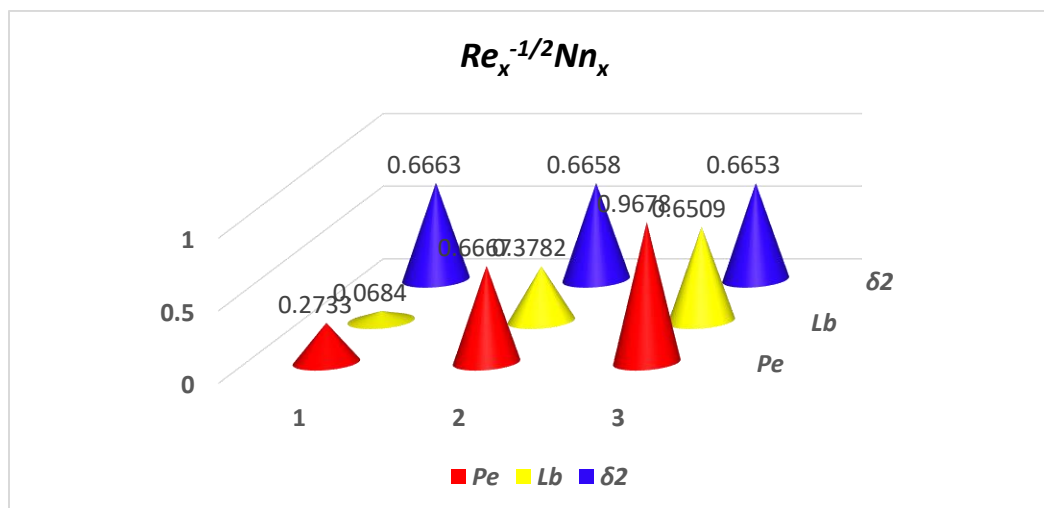


Fig. 22 Pe, Lb, δ_2 on $Re_x^{-1/2} Nn_x$

Conclusive remark

The significant contribution of the factors involved in the flow dynamics and their behaviour is visualized graphically and discussed briefly in the results and discussion section. Further, the major outcomes obtained from this discussion are laid down as below;

The comparative analysis between the numerical results obtained at present with the earlier investigation coincides with each other conforming to the validation of the result and the convergence criteria of the current methodology.

The resistivity of the magnetization in combination with the porosity decelerates the axial and transverse fluid velocity which has a greater control in resisting the fluid velocity.

The enhanced non-Newtonian characteristic due to the increasing Weissenberg number favors decelerating the fluid velocity.

A dual behaviour in the profile of axial and transverse velocity is projected for the variation of the slip velocity and velocity ratio parameter.

The enhanced thermal Biot number due to the consideration of convective boundary conditions along with thermal radiation augments the heat transfer properties.

The bioconvection Lewis number is favorable in controlling the motile microorganism profile but enhances the motile number significantly.

The augmentation in the radiating heat overshoots the heat transfer rate whereas a significant attenuation in the profile is projected for the increasing non-uniform heat source.

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