Research Article

A Numerical Study of MHD Carreau Nanofluid Flow with Gyrotactic Microorganisms over a Plate, Wedge, and Stagnation Point

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This article addresses the numerical exploration of steady and 2D flow of MHD Carreau nanofluid filled with motile microorganisms over three different geometries, i.e., plate, wedge, and stagnation point of a flat plate. The influence of magnetic field, viscous dissipation, thermophoresis, and Brownian motion is considered for both cases, i.e., shear thinning and shear thickening. A set of relevant similarity transformations are utilized to obtain dimensionless form of governing coupled nonlinear partial differential equations (PDEs). The transformed system of ordinary differential equations (ODEs) is then numerically solved by bvp4c via MATLAB based on shooting technique and Runge–Kutta–Fehlberg (RKF) scheme via MAPLE. Also, a numerical analysis has been made for skin friction factor, heat, and mass transfer rates. Results elucidate that all the profiles except velocity show decreasing behavior for higher values of magnetic field parameter. Among all three flow geometries for both shear thinning and shear thickening cases, the flow over a plate has lesser skin friction factor. The nanoparticle concentration and density of motile microorganism decrease in both shear thinning and shear thickening cases, for increasing values of Brownian motion (Nb), but reverse trend is observed for rising values of thermophoresis parameter (Nt). Furthermore, it is observed that, as we increase the values of suction/injection parameter (S), the velocity of fluid increases but decreases the fluid temperature, concentration of mass and density of motile organisms over a plate, wedge, and stagnation point of a flat plate. Also, we observed that shear thinning nanofluid has higher rate of heat, mass, and motile microorganisms mass transfers than shear thickening fluid. Both shear thinning and thickening nanofluid have a low rate of heat/mass and gyrotactic microorganisms mass transfer over plate among wedge and stagnation point flow.

1. Introduction

The heat transfer phenomenon has gained extensive attraction for researchers due to its vital range of applications and implementations in industrial and manufacturing processes particularly in thermal insulations, nuclear waste storage, crude oil extraction, geothermal systems, enhanced oil recovery, heat exchangers, ground water pollution, etc. In prior work, boundary layer (BL) theory was related the flows driven by stream-wise pressure gradient. In fluid dynamics, a classical problem of fluid flow past a stationary plate is the Blasius problem in which the free stream is parallel to the plate and its velocity is constant. Falkner and Skan [1] had proved that their problem confessed similarity solution same like Blasius problem. Initially, they employed the Prandtl theory to transform the governing system and considered 2D flows over a wedge. They introduced a suitable similarity method in which the PDEs were converted to a nonlinear 3 rd-order ODEs and then solved by numeric techniques.

In 1937, Hartee [2] discussed thoroughly the same problem and presented some useful results. Later, Lin et al. [3] had explored the heat transfer characteristics in force convectional flow for variable Prandtl number less than a static wedge. Na [4] by using a set of transformations converted boundary value problem (BVP) to an initial value problems and applied forward integration scheme. Rajagopal et al. [5]
explored Falkner–Skan flow for 2nd-grade fluid over a wedge positioned in symmetric way with respect to the flow direction. In addition, Kuo [6] and many more researchers presented numerical and analytical precise solutions of BVP and discussed heat/mass transfer behaviors of the flow along a wedge. Ishak et al. [7] explored 2D steady MHD flow past a wedge and plate along a variable wall temperature.

The fluids are considered as non-Newtonian fluids, when “Newton law of viscosity” is disobeyed. In non-Newtonian fluids, the shear stress and shear rate are unsystematic (highly nonlinear); in contrast, the Newtonian fluids are linear. The custard, blood, toothpaste, shampoo, honey, and paint all are non-Newtonian fluids. The classification of non-Newtonian fluids comprises viscoelastic fluid, and it covers lubricants, whipped cream, etc. The rheopetic and thixotropic (including yogurt, gelatin gels, pectin gels, peanut butter) non-Newtonian fluids can also be categorized into shear thickening (dilatant) like oobleck (suspension of cornstarch and water) and shear thinning (pseudoplastic) such as nail polish, sand in water, paper pulp in water, and micropolar fluids, but from research point of view, non-Newtonian micropolar fluids yet encapsulated a small attention.

The fundamental equations for the non-newtonian fluid flow are much complicated and highly nonlinear and imply the high-order terms. The momentum equations are incompetent to explicate the flow ability of non-Newtonian fluids. This fact is on account of complex rheological effects. This complexity can be overwhelmed as different rheological models are presented. Few of the models are Casson fluid, Maxwell fluid, Walter’s B fluid, Carreau fluid, cross fluid, the power law fluid, etc. The constitutive relation of power-law is uncomplicated but it has the deficiency that it cannot accurately predict viscosity for extremely high or low rates of shear. To overcome the limitation, another model was considered, i.e., Carreau rheological model (a combination of Newtonian and power law properties) proposed by Carreau [8]. Due to multiple characteristics, Carreau fluid has its own importance in literature. Carreau fluid is better to depict several kinds of physical issues because this fluid model has the ability to reveal the rheology of multiple specific fluids such as fluids with brief-chain suspension particles, detergents, fluid crystals, and blood in humans and animals. This flow model has gained notable attention due to its significance in extrusion of a polymer, tumors treatment, bitumen for road construction, cosmetics, etc. In the Carreau model, the essential conditions retain at high and low shear rates unlike power law fluid. Accordingly, this fluid has received a widespread adoption in research these days. For free surface flow, the fundamental relation of Carreau model is suitable enough. The reason behind the fact is that, in Carreau model, when the shear rate approaches zero, viscosity remains finite. This fluid possesses shear thinning ($n < 1$) shear thickening ($n > 1$) and Newtonian ($n = 0$) fluid properties. At high shear rate, the non-Newtonian fluids exhibit thickening while at low shear rate and exhibit the thinning properties which makes sense that its viscosity is highly dependent on shear rate. Different researchers in different times discussed Carreau fluid. In [9], Raju explained MHD Carreau fluid with cross diffusion over a wedge and concluded that velocity field grows for increasing wedge angle parameter. Sandeep [10] had a detailed work for the consequences of nonlinear thermal radiation and an uncertain heat source, sink in the presence of homogenous and heterogeneous phenomenon. Khan et al. [11] used Buongiorno model to predict the time-dependent Carreau nanofluid along a wedge and found that Weissenberg number enhances the temperature of fluid. Waqas et al. [12] have explored two different characteristics of MHD Carreau nanofluid. Khan et al. [13] have studied and analyzed numerically the effects of heat generation/absorption and melting phenomenon of Carreau nanofluid over a wedge and noted that nanoparticle concentration field decreases by enhancing melting parameter. Khan et al. [14] have studied the MHD Carreau nanofluid transport properties for solar energy application over a 3D extending sheet. Tanmay [15] represented his work for the stability criteria of the non-Newtonian fluid taking into account the whole analysis of arbitrary Reynolds number. In [16–18], authors addressed 2D and 3D flow of MHD Carreau nanofluid with chemical reaction over an exponential surface and presented detailed discussion upon physical outcomes of various parameters such as Weissenberg number, thermal and concentration Biot numbers, Brownian movement thermophoresis, Schmidt and Prandtl numbers, thermal radiation and temperature ratio parameter for primary and secondary velocities, concentration and temperature, and for both $n = 1.5$ and $n = 0.5$ flows.

Bhatti [19] explored the heat transfer on the electromagnetic hydrodynamic (EMHD) Carreau fluid flow over a rectangular plates. For physical modeling, he considered a Darcy–Brinkman–Forchheimer medium and solved the formulated flow system by numerical and semi-analytical schemes. In his work, the author observed the Forchheimer and MF suppress the flow. Also, he concluded that the We and $n$ retard the velocity of fluid but enhance the temperature profile. He declared that DTM is more powerful technique [20, 21]. Due to vast number of applications in the industrial, technological, and engineering developments, the Carreau model was further worked out by numerous researchers/authors in the last decades [22–26].

A little while back, nanotechnology played an indispensible role of heat dissipation processes in numerous fields. In this developed era, the ultimatum of energy increasing was unwaveringly. Nanotechnology made its in-digeneous efforts for this ultimate demand and its most credible achievement leads us to nanoparticles. The word “nano” means “billionth part of a meter” and is denoted by a factor $0.000000001\text{ m}$. The nanofluids contain nanosized particles. A very small amount, almost less than 100 nm of guest nanoparticles dispersed uniformly and suspended stably in the host liquid, comes up with a dramatic improvement in the thermal possessions of the host fluid and finally gives nanofluids which are most stable and hold high possible thermal properties with smallest volume fraction of the nanoparticles and expose rapid heat dissipation than conventional fluids. The commonly known base (conventional) fluids are oil, water, and some other lubricants,
polymer solutions, biofluids, ethylene glycol, etc. This sudden rise in thermal conductive property after the emulsion of nanoparticles into the conventional fluids is owing to the fact of Brownian motion that develop the micromixing, volume fraction of particles, interfacial layer. The term was brought into being by Choi [27] at Argonne National Laboratory of USA. Nanofluids have innovative possessions that make them capable of being potentially convenient. The more relative surface area of nanoparticles, unlike the ordinary particles, not only enhances the credibility of heat dissipation but also improves the strength and stability of suspension. The desirability of nanofluids is having high specified surface area, high dispersion stability, adaptable properties which differ in the concentration of nanoparticles, and exhibiting lower pumping power as compared to the conventional fluid. The particular applications of nanofluid are in engine cooling, cooling of transformer oil, cooling of electronics, improving efficiency of diesel generator, in grinding, fuel cells, domestic refrigerator, chillers, space and defence, cooling of microchips, etc. Initially, the usage of nanofluids in heat transmit applications was too much common, but with the enhancement in worldwide development, nanofluids find their way also in biomedical engineering such as in diagnosis and therapy. Magnetic nanofluid system is a consequential track for targeted drug transportation, hyperthermia (a physiological state), and differential diagnosis. Nanofluid found its extreme way as a powerful antiseptic factor to overthrow antibacterial resistance. Therefore, this transformation of conventional fluids to the nanofluids has stimulated chemists, physicists, and engineers around the globe and is a stunning out-turn of such continuance. New areas of research in which nanofluids are developed include bioconvection, inorganic-based nanomaterials, tissue engineering, regenerative medicine, stem cells, etc. Falkner–Skan nanofluid flows along a wedge with various properties, such as heat source/sink, suction/injection, magnetic field, slip/no slip, thermophoresis, and chemical reaction were studied by many authors [28–31].

In viscous fluid flow, microorganisms are considered as the research domain to researchers, scientists, chemists, and engineers to an extensive range in the fields like agronomy, industrial point of view, or scientifically establishing a power in research area, as microorganisms play an indispensable role in plenty ways like to get rid of toxins, in digestion of food, etc. Moreover, magnetic field is essential in some of the applications of fluid flow. Furthermore, microorganism particles can be used in various commercial and industrial products, for example, biofuel, biodiesel, biofertilizers, ethanol, and bio-microsystems.

An erratic and crooked pattern of countless swimming microorganisms is the cause for bioconvection. It is the phenomenon in which microorganism shows movement in upward and downward directions. Just because of the denseness behavior, bioconvection is basically correlated with the minuscule convection of these microorganisms. Generally, the motion of such unicellular microbes is categorized as taxis based on its incentive and stimulant motion. Moreover, these taxis are further compartmentalized into gravitaxis, gyrotaxis, and phototaxis. Such distinguished and eminent applications stimulate many of the analysts to put their benefactions in this domain. The conceptualization of nanofluid bioconvection was first presumably given by “Kuznetsov” [32, 33], and his center of attraction is to work on nanofluids containing gyrotactic microorganisms, corroborating that the locomotion of the fluid on extensive scale due to self-sustained motile microorganisms intensifies the merging and prohibits the agglomeration of nanoparticles in nanofluid. This phenomenon arises as the infinitesimal microorganisms, that are more dense with the base fluid, and the base fluid here is water float upwardly due to density gradient establishing the fact that very small microorganism of insignificant settling velocity cast no distinguishable outcome on bioconvection, also the particles with extraordinary settlement have no further possessions on bioconvection, regardless this, the particles with much appropriate and optimal size and its gravitational settlement must emulate with Brownian diffusion, so very these particles can proficiently slows down bioconvection. In short, the phenomenon of bioconvection come about to happen due to unreliable stratification, that sequentially leads to the evolution of indiscernible radiative-motion. Bioconvection involves wide range of applications in biological and biosystems such as enzymes, biofuels, biosensors, oil recovery, fertilizer, and various fields of life where it shows significant and notable applications. Beside this, bioconvection flows play a key role in fuel cells, biological polymer synthesis, and environmental systems [34]. Other important advantages of bioconvection are to enhance the mass transfer process and being used to solve the mixing hurdles in microsystems.

Bhatti [35] solved the flow system by perturbation method to investigate the bioconvection flow of blood nanofluid in an annulus with gyrotactic microorganism and have seen that, for enhancing the Peclet number, microorganism density decays. Raju [36] studied a numerical study to explore the Casson nanofluid transport properties filled by gyrotactic microorganisms [37] and declared that increasing wedge angle parameter causes reducing the density of microorganisms. Ullah [38] scrutinized his model for protrusion system regarding with the bio-convention flow, using the same idea as he proposed, which may be used for intensification of extrusion system. Wang [39] did great work in medicinal field and in rheology carrying the square channel for simulation. Kotha [40] employed magnetohydrodynamics and heat and mass transfer sensations assuming the gyrotactic microorganisms in a water based nanofluid suspension in a vertical manner of a plane that comes out in form of partial differential fundamental equations, that are transformed using similarity possessions and turn into non-linear ODEs. Few works associated with bioconvection Carreau nanofluid over a wedge/plate/stagnation of the plate can be seen in [41–50].

The present survey explores the impacts of shear-thinning/shear-thickening characteristics of Carreau nanofluid filled with gyrotactic microorganisms over three different geometries, i.e., (i) flat plate, (ii) over a wedge, and (iii) at stagnation point in the presence of magnetic field, suction/
injection, thermophoresis, and Brownian motion. This analysis casts a noteworthy attention as the present work involves nanofluid in view of the fact that the nanofluids are of significant worth due to their high thermal conductivity. The substructure of the whole work is to visualize the impacts on Falkner–Skan flow assuming a wedge, stagnation point, and plate of the plate with shear thinning and shear thickening cases. Appropriate similarity transformations are applied to transmute the fundamental PDEs into ODEs and used RKF and bvp4c techniques that lead to the convergence. The fluid velocity, concentration, temperature, stream function, rate of heat, and mass transfer are scrutinized with rising parameters, and their evaluations and outcomes are properly discussed using graphical approach. Evaluated graphical scheme evidently announces that the perspective shear thinning/thickening fluid exhibit an opposed behavior in both fluid velocity and temperature for inflated values of Weissenberg # for the cases of shear thinning and shear thickening, respectively. The flow of Carreau nanofluid with magnetic field and suction/injection can be beneficial for improving solar energy efficiency. The scientific results investigated in this work may provide improvement in energy consumption, solar systems, and heat extrusion systems.

This paper is divided into three sections: (i) formulation of flow model, (ii) graphical and tabular representation, and (iii) results and discussion.

2. Formulation of Flow Model

The schematic configuration of three different geometries can be seen in Figure 1. The flow of 2D, viscous, incompressible, and time independent non-Newtonian Carreau nanofluid having gyrotactic microorganisms for both shear thinning and thickening cases is considered in this study. The mass/heat transfer characteristics under the impacts of viscous dissipation, suction/injection, thermal radiation, Brownian, and thermophoresis motion are studied thoroughly.

The Carreau nanofluid particles get influenced by magnetic force of strength \( B_0 \), Brownian motion, and thermophoresis mechanism. Total wedge angle is \( \Omega = \pi y \) where \( y = (2m/m + 1) \) is the parameter of wedge angle or measure of pressure gradient (d\( p/dx \)). In other words, \( m = (y/2 - y) \) is the Hartree pressure gradient. Here, \( y = 0, 0.5, 1 \) represents the fluid flow over a plate, wedge, and stagnation point. Further suppose that \( U_e = ax^n \) is the free stream velocity of the potential flow where \( a \) and \( m(0 \leq m \leq 1) \) are constants. The surface temperature, density of motile microorganisms, and nanoparticle concentration at free stream and boundary are \( T_{\infty}, N_{\infty}, C_{\infty} \) and \( T_w, N_w, C_w \), respectively. Also, it is assumed \( T_{\infty}, C_{\infty}, N_{\infty} \) are fixed and greater than \( T_w, C_w, N_w \) (Figure 1).

Based on aforementioned situation, the problem is formulated upon the following assumptions:

(i) The MHD Carreau nanofluid flow filled with gyrotactic microorganisms is steady, laminar, and incompressible
(ii) Flow has no slip behavior
(iii) No body force is considered in the momentum equation
(iv) On surface, suction/injection can happen
(v) The famous Buongiorno nanofluid model is considered to investigate the Nanofluid features, i.e., Brownian and thermophoresis movement
(vi) The modeled equations for the abovementioned flow problem are numerically handled by imposing RKF and bvp4c

The fluid transport system, containing the gyrotactic microorganisms, nanoparticles concentration, momentum, and energy equations, is expressed as follows:
The constitutive problem proceeds with the following BCs:

\[
\begin{aligned}
\eta &= \sqrt{\frac{(m + 1)U_e}{2yx}} y, \\
\Psi &= f(\eta) \sqrt{\frac{2yxU_e}{m + 1}}, \\
u &= U_e f' (\eta), \\
v &= -\sqrt{\frac{2yxU_e}{(m + 1)x} \left[ \frac{m + 1}{2} f + \frac{m - 1}{2} \eta f' \right]}, \\
\theta(\eta) &= \frac{T - T_\infty}{T_w - T_\infty}, \\
\phi(\eta) &= \frac{C - C_\infty}{C_w - C_\infty}, \\
\psi(\eta) &= \frac{N - N_\infty}{N_w - N_\infty}.
\end{aligned}
\]

(6) (7)

2.1. Similarity Transformations. We introduce the similarity transformations [36, 37]:

Using PDEs ((1)–(5)) and associated BCs (7), the transformed system of ODEs is as follows:

\[
\begin{aligned}
\left(1 + \text{We}^2 f''\right)^{(\alpha - 3/2)} \left(1 + n \text{We}^2 f''\right) f'' + f f'' + \gamma \left(1 - f''\right) + M \left(1 - f'\right) = 0, \\
\left(1 + \frac{4}{3} R\right) \theta'' + \text{Pr} \left( f \theta' + N_b \theta' \phi' + N_t \theta' \phi'' + \text{Ec} f \phi'' \left(1 + \text{We}^2 f''\right)^{(\alpha - 1/2)}\right) = 0, \\
\phi'' + \text{Sc} f \phi' + \left(\frac{N_t}{N_b}\right) \theta'' = 0, \\
\Psi'' + \text{Sc} f \Psi' - \text{ScPe} (\phi' \Psi' + (\beta_1 + \Psi) \phi'') = 0.
\end{aligned}
\]

(8)

Also, the transformed boundary conditions are
\[ f(0) = S, \]
\[ f'(0) = 0, \]
\[ f'(\infty) = 1, \]
\[ \theta(0) = 1, \]
\[ \theta(\infty) = 0, \]
\[ \phi(0) = 1, \]
\[ \phi(\infty) = 0, \]
\[ \Psi(0) = 1, \]
\[ \Psi(\infty) = 0, \]
\[ \tau_w = \left[ \mu \left( \frac{\partial u}{\partial y} \right) \left( 1 + \frac{x^2}{2} \frac{\partial u}{\partial y} \right)^{(n-1)/2} \right]_{y=0}, \]
\[ q_w, q_m, \text{ and } q_n \text{ are surface heat and mass fluxes defined as} \]
\[ q_w = -k \frac{\partial T}{\partial y} \bigg|_{y=0} - \left( \frac{16\pi^2}{3\kappa^2} \left( \frac{T}{T_{\infty}} \right)^{\frac{3}{2}} \right) \bigg|_{y=0}, \]
\[ q_m = -D_B \frac{\partial C}{\partial y} \bigg|_{y=0}, \]
\[ q_n = -D_N \frac{\partial N}{\partial y} \bigg|_{y=0}. \]

Upon fixing the local Reynolds's number \( \text{Re}_x = (ax/y) \) and using the above defined relations, we have
\[ \left( \text{Re}_x \right)^{1/2} C_{fx} = \frac{2 \left( \frac{\partial u}{\partial y} \right)(0)}{\sqrt{2 - \gamma}} (1 + \text{We}^2 \left( \frac{\partial u}{\partial y} \right)^2)^{(n-1)/2}, \]
\[ \left( \text{Re}_x \right)^{-1/2} N_{ux} = -\left( 1 + \frac{4}{3} R \right) \frac{\theta'(0)}{\sqrt{2 - \gamma}}, \]
\[ \left( \text{Re}_x \right)^{-1/2} S_{hx} = -\frac{\phi'(0)}{\sqrt{2 - \gamma}}, \]
\[ \left( \text{Re}_x \right)^{-1/2} N_{nx} = -\frac{\psi'(0)}{\sqrt{2 - \gamma}}. \]

### 3. Results and Discussion

In the presence of the above literature and the present work, the ingenuity of the conventional problem is to address the impacts of active parameters on fluid properties over a wedge where thermal jump and viscous dissipation exist and all the exertions have been made to get solution for this problem via similarity function. Furthermore, the considered physical problem gives highly nonlinear and coupled temperature dependent flow equations, while these converted ODEs subject to BCss are then computed by two different methods, bvp4c (using MATLAB) and dsolve technique (on MAPLE). Our basic assumptions are a wedge, plate, and stagnation point with shear thinning \((n < 1)\) and shear thickening \((n > 1)\) cases. The fixed parameters are 

- \( M = 1, \lambda = 0.1, \text{We} = 1, \gamma = 0.1, \text{Pr} = 2, \text{Re} = 0.2, \) 
- \( E_c = 0.2, N_p = 0.3, N_i = 0.2, \text{Sc} = 2, \text{Pe} = 0.1 \)

and we elucidate their effects on fluid velocity \((f')\), temperature \((\theta)\), concentration \((\phi)\), and gyrotactic motile \((\psi)\), whereas the effects of the above-mentioned parameters are thoroughly investigated and are given in Tables 1–4 and their graphical outlook. To monitor the reliability of present work, we expose our results with the prior researches, Rajagopal [5], Kuo [6], and Masood [24] et al. After scrutinizing, our results are in good agreement with their results. Tables 1 and
### Table 1: Calculation of $-f''(0)$ of Carreau nanofluid for different values of $\gamma$ when $\beta \longrightarrow \infty$.

| $\gamma$ | Rajagopal [5] | Kuo [6] | Masood [24] | MATLAB | MAPLE |
|----------|----------------|---------|--------------|--------|-------|
| 0        | $-$            | 0.469600 | 0.469600     | 0.469600 | 0.469600 |
| 0.3      | 0.474755      | 0.775524 | 0.474755     | 0.774755 | 0.774755 |
| 0.6      | 0.995836      | 0.995757 | 0.995836     | 0.995836 | 0.995836 |
| 1.2      | 1.335722      | 1.333833 | 1.335722     | 1.335721 | 1.335721 |

### Table 2: Calculation of $(Re)^{(-1/2)}N_{ux}$ of Carreau nanofluid for different values of $Pr$ when $\beta \longrightarrow \infty M = We = S = \lambda = R = Nb = NT = Ec = 0$.

| Pr  | Kuo [6] | Raju [37] | Present | Kuo [6] | Raju [37] | Present |
|-----|---------|-----------|---------|---------|-----------|---------|
|     |         |           |         |         |           |         |
| 0.72| 0.41809 | 0.41868   | 0.418091| 0.5298  | 0.5296    | 0.529608| 0.529608|
| 1.0 | 0.46960 | 0.469600  | 0.469600| 0.60541 | 0.6052    | 0.605197| 0.605197|
| 10  | 1.02974 | 1.029745  | 1.029747| 1.4561  | 1.4588    | 1.455750| 1.455750|
| 30  | 1.4873  | 1.487319  | 1.487319| 2.1582  | 2.1580    | 2.157737| 2.157737|
| 100 | 2.2229  | 2.222906  | 2.222906| 3.2869  | 3.2873    | 3.286250| 3.286250|
| 1000 | 4.7901 | 4.790062 | 4.790062| 7.2225  | 7.2334    | 7.221173| 7.221173|

### Table 3: Calculation of $(Re)^{1/2}C_{fs}$, $(Re)^{(-1/2)}N_{ux}$, $(Re)^{(-1/2)}Sh_{x}$, and $(Re)^{(-1/2)}N_{ux}$ for different values of $We$.

| Plate | Wedge | Stagnation |
|-------|-------|------------|
|       | MATLAB | MAPLE      | MATLAB | MAPLE      | MATLAB | MAPLE      |
| Shear thinning |        | $(Re)^{(-1/2)}C_{fs}$ |        | $(Re)^{(-1/2)}N_{ux}$ |        | $(Re)^{(-1/2)}Sh_{x}$ | $(Re)^{(-1/2)}N_{ux}$ |
| We = 1 | 0.779657 | 0.779656 | 1.098775 | 1.098775 | 1.544226 | 1.544226 |
| We = 2 | 0.742201 | 0.742201 | 1.036636 | 1.036636 | 1.484262 | 1.484262 |
| We = 3 | 0.712195 | 0.712198 | 0.991033 | 0.991034 | 1.381483 | 1.381483 |
| We = 4 | 0.689058 | 0.689059 | 0.957061 | 0.957061 | 1.332688 | 1.332688 |
| Shear thinning |        | $(Re)^{(-1/2)}N_{ux}$ |        | $(Re)^{(-1/2)}Sh_{x}$ |        | $(Re)^{(-1/2)}N_{ux}$ |
| We = 1 | 0.359687 | 0.359688 | 0.401976 | 0.401976 | 0.473756 | 0.473756 |
| We = 2 | 0.370326 | 0.370327 | 0.417153 | 0.417153 | 0.495277 | 0.495277 |
| We = 3 | 0.379118 | 0.379120 | 0.428921 | 0.428921 | 0.511341 | 0.511341 |
| We = 4 | 0.386060 | 0.386061 | 0.437996 | 0.437996 | 0.523556 | 0.523556 |
| Shear thinning |        | $(Re)^{(-1/2)}Sh_{x}$ |        | $(Re)^{(-1/2)}N_{ux}$ |
| We = 1 | 0.592494 | 0.592493 | 0.744520 | 0.744520 | 0.970189 | 0.970189 |
| We = 2 | 0.596715 | 0.596715 | 0.747650 | 0.747649 | 0.971433 | 0.971433 |
| We = 3 | 0.599205 | 0.599205 | 0.748616 | 0.748616 | 0.970419 | 0.970419 |
| We = 4 | 0.600708 | 0.600709 | 0.748788 | 0.748788 | 0.968957 | 0.968957 |
| Shear thinning |        | $(Re)^{(-1/2)}N_{ux}$ |
| We = 1 | 0.703413 | 0.703413 | 0.856238 | 0.856239 | 1.087959 | 1.087959 |
| We = 2 | 0.714318 | 0.714319 | 0.869533 | 0.869530 | 1.104199 | 1.104199 |
| We = 3 | 0.722319 | 0.722317 | 0.878400 | 0.878401 | 1.114421 | 1.114421 |
Table 3: Continued.

|                  | MATLAB | MAPLE | MATLAB | MAPLE | MATLAB | MAPLE |
|------------------|--------|-------|--------|-------|--------|-------|
| **We = 4**       | 0.728184 | 0.728186 | 0.884688 | 0.884688 | 1.121540 | 1.121540 |
| **Shear thickening** |        |       |        |       |        |       |
| **We = 1**       | 0.678455 | 0.678455 | .820446 | .820446 | 1.038309 | 1.038309 |
| **We = 2**       | 0.659986 | .659987 | 0.797830 | 0.797830 | 1.010170 | 1.010170 |
| **We = 3**       | 0.646851 | .646851 | .782502 | .782503 | .991659 | .991659 |
| **We = 4**       | 0.637043 | 0.637043 | .771270 | .771270 | .978246 | .978246 |

Table 4: Calculation of \((Re_x)^{-1/2}N_{ux}\) and \((Re_x)^{-1/2}N_{nx}\) for different values of \(N_t\) and \(Pe\).

|                  | MATLAB | MAPLE | MATLAB | MAPLE | MATLAB | MAPLE |
|------------------|--------|-------|--------|-------|--------|-------|
| **Shear thinning** |        |       |        |       |        |       |
| \(N_t = 0.1\)    | 0.381564 | 0.381566 | 0.427964 | 0.427965 | 0.506142 | 0.506144 |
| \(N_t = 0.2\)    | 0.359687 | 0.359688 | 0.401976 | 0.401977 | 0.473756 | 0.473757 |
| \(N_t = 0.3\)    | 0.338546 | 0.338547 | 0.376876 | 0.376877 | 0.442485 | 0.442486 |
| \(N_t = 0.4\)    | 0.318183 | 0.318183 | 0.352709 | 0.352710 | 0.412382 | 0.412383 |

|                  | MATLAB | MAPLE | MATLAB | MAPLE | MATLAB | MAPLE |
|------------------|--------|-------|--------|-------|--------|-------|
| **Shear thickening** |        |       |        |       |        |       |
| \(N_t = 0.1\)    | 0.358586 | 0.358587 | 0.391480 | 0.391482 | 0.450192 | 0.450194 |
| \(N_t = 0.2\)    | 0.337408 | 0.337408 | 0.366525 | 0.366526 | 0.419309 | 0.419311 |
| \(N_t = 0.3\)    | 0.316979 | 0.316980 | 0.342489 | 0.342490 | 0.389590 | 0.389600 |
| \(N_t = 0.4\)    | 0.297334 | 0.297336 | 0.319408 | 0.319410 | 0.361101 | 0.361102 |

|                  | MATLAB | MAPLE | MATLAB | MAPLE | MATLAB | MAPLE |
|------------------|--------|-------|--------|-------|--------|-------|
| **Shear thinning** |        |       |        |       |        |       |
| \(Pe = 0.1\)     | 0.703413 | .703413 | .856238 | .856238 | 1.087959 | 1.087959 |
| \(Pe = 0.2\)     | 0.800922 | 0.800926 | .980401 | .980401 | 1.251472 | 1.251472 |
| \(Pe = 0.3\)     | 0.900387 | 0.900388 | 1.106908 | 1.106908 | 1.417923 | 1.417923 |
| \(Pe = 0.4\)     | 1.001706 | 1.001706 | 1.235637 | 1.235637 | 1.587159 | 1.587160 |

|                  | MATLAB | MAPLE | MATLAB | MAPLE | MATLAB | MAPLE |
|------------------|--------|-------|--------|-------|--------|-------|
| **Shear thickening** |        |       |        |       |        |       |
| \(Pe = 0.1\)     | 0.678455 | 0.678455 | 0.820446 | 0.820449 | 1.038309 | 1.038309 |
| \(Pe = 0.2\)     | 0.774200 | .774197 | .942647 | .942646 | 1.199928 | 1.199928 |
| \(Pe = 0.3\)     | 0.871902 | 0.871898 | 1.067214 | 1.067214 | 1.364543 | 1.364543 |
| \(Pe = 0.4\)     | 0.971456 | .971459 | 1.194023 | 1.194023 | 1.531992 | 1.531992 |

Figure 2: Continued.
Figure 2: We effects on $f'(\eta)$ and $\theta(\eta)$.

Figure 3: Continued.
We = 1, 2, 3, 4

\( \eta \)

\( n = 0.75 \)

\( n = 1.75 \)

\( M = 0.1, 0.2, 0.3, 0.4 \)

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**Figure 3:** We effects on \( \phi(\eta) \) and \( \psi(\eta) \).

**Figure 4:** Continued.
Figure 4: Effects of $M$ on $f'(\eta)$ and $\theta(\eta)$.

Figure 5: Continued.
Figure 5: Effects of $M$ on $\psi(\eta)$ and $\phi(\eta)$.

Figure 6: Continued.

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Figure 6: Effects of $f'(\eta)$ and $\theta(\eta)$.

Figure 7: Continued.
Figure 7: Effects of $S \psi(\eta)$ and $\psi(\eta)$.

Figure 8: Continued.
Figure 8: Effects of $R$ for $n = 0.75$ and $n = 1.75$ on $\theta(\eta)$. 

Figure 9: Continued.
Figure 9: Effects of Sc and Pe on $\psi(\eta)$ and $\psi(\eta)$.

Figure 10: Continued.
are created for proving the authenticity of the present work with the already published work. It would be worth mentioning that all physical behavior of this flow problem coincides very well with already published literature either in graphical or in tabular representation.

Table 3 is created to show the numerically calculated results of $(Re_x)^{1/2}C_{fx}$, $(Re_x)^{-1/2}N_{ux}$, $(Re_x)^{-1/2}Sh_x$, and $(Re_x)^{-1/2}N_{nx}$ to see the impacts of Weissenberg number $(We)$ for both shear thinning and shear thickening cases with $n = 0.75$ and $n = 1.75$, respectively, by MATLAB bvp4c and MAPLE dsolve techniques. Both methods are in good agreement, and this shows the validity of present results. From this table, we observed that the skin friction factor is the decreasing function of $We$ in case of shear thinning fluid but in shear thickening case skin friction factor accelerates with rising values of $We$. But we noticed an opposite behavior in $(Re_x)^{-1/2}N_{ux}$, $(Re_x)^{-1/2}Sh_x$, and $(Re_x)^{-1/2}N_{nx}$. We also noticed that, among all the flow geometries (plate, stagnation point, and wedge), the plate experienced less skin friction when compared with wedge and stagnation point.

Table 4 is constructed to show the numerical results of $(Re_x)^{-1/2}N_{nx}$ for varying values of thermophoresis parameter $(Nt)$ and $(Re_x)^{-1/2}N_{nx}$ for selected values of Peclet number $(Pe)$ in both cases when $n < 1$ and $n > 1$. The density of motile microorganism increases in both the shear

Table 3

| $n$     | $(Re_x)^{1/2}C_{fx}$ | $(Re_x)^{-1/2}N_{ux}$ | $(Re_x)^{-1/2}Sh_x$ | $(Re_x)^{-1/2}N_{nx}$ |
|---------|----------------------|-----------------------|---------------------|-----------------------|
| $0.75$  | 0.1, 0.2, 0.3, 0.4    | 0.1, 0.2, 0.3, 0.4    | 0.1, 0.2, 0.3, 0.4  | 0.1, 0.2, 0.3, 0.4    |
| $1.75$  | 0.1, 0.2, 0.3, 0.4    | 0.1, 0.2, 0.3, 0.4    | 0.1, 0.2, 0.3, 0.4  | 0.1, 0.2, 0.3, 0.4    |

Table 4

| $n$     | $(Re_x)^{-1/2}N_{nx}$ |
|---------|-----------------------|
| $0.75$  | 0.1, 0.2, 0.3, 0.4    |
| $1.75$  | 0.1, 0.2, 0.3, 0.4    |

Figure 10: Effects of Nb $\theta(\eta)$, $\phi(\eta)$ and $\psi(\eta)$. 
Figure 11: Effects of Nt on $\theta(\eta)$, $\phi(\eta)$, and $\psi(\eta)$. 
thinning and shear thickening cases, for increasing values of Pe, but reverse trend is observed for rising values of Nt while calculating thermal gradient.

Figures 2–11 illustrate the fluid transport properties. The graphs are presented by dotted, dash, and solid lines orderly managed for plate, wedge, and stagnation point, manifesting the nano-fluid properties that whether these properties are increasing or decreasing, or remain constant throughout the phenomenon.

Figures 2 and 3 illustrate the impacts on fluid velocity, temperature, concentration, and the gyrotactic motile microorganisms distribution signified by \( f', \theta, \phi, \psi \) for both shear thinning and shear thickening cases with \( n = 0.75 \) and \( n = 1.75 \), respectively. It was noticed that for varying values of We the velocity of the fluid declines in the case when \( n < 1 \) but it increases for increasing values of We when \( n > 1 \). Actually, We is the relation between relaxation time and the process in which time grows the fluid’s viscosity. Increasing the values of We enhances the relaxation time. So, there is a decrement in the fluid’s velocity due to dominating effects of viscosity which generates resistance in the fluid particles. Moreover, the plots of the variation in the thermal, solutal, and motile microorganisms distributions for various values of We can also be seen in Figures 2 and 3 for both types of fluids for three different geometries (\( y = 0, 0.5, 1 \)). These figures exhibit that the thermal, concentration, and motile microorganism layers thickness increases with increasing We in shear thinning case. Scientifically, ratio of elastic and viscous forces is known as We, so it elevates the thickness of fluid so temperature increases, while both profiles show decreasing trend for shear thickening fluids. It is necessary to mention here that We = 0 recovered Newtonian fluid.

The influence of magnetic parameter \( M \) on velocity, temperature, concentration, and gyrotactic motile microorganisms \( (f', \theta, \phi, \psi) \) contours is visualized graphically through Figures 4 and 5. In the BL flow of various conducting fluids, magnetic field utilization can play a vital role in controlling the momentum and heat transfer. From Figures 4 and 5, we can see the impacts of \( M \) on \( f', \theta, \phi, \psi \) for distinct values of \( M \) in both shear thinning and thickening cases. It is noteworthy to mention here that the fluid velocity rises for rising values of \( M \) in both flow cases but increasing \( M \) causes decelerating the \( \theta, \phi, \psi \) profiles for both cases. Physically, if less suppression of drag force is involved, it reduces the thermal, concentration, and gyrotactic motile microorganism profiles but elevates the velocity distribution with higher values of \( M \).

Figures 6 and 7 depict the behavior of suction parameter \( S \) for different flow geometries on boundary layer profiles for shear thinning and shear thickening cases of MHD Carreau nanofluid. It is seen that all the profiles are decreasing except the velocity distribution that is the only increasing function of \( S \) for \( n < 1 \) and \( n > 1 \) when the fluid is injected through a surface, but escalating values of \( S \) depreciating the boundary layer thickness of \( \theta, \phi, \psi \) over the plate, wedge, and stagnation point. Further, it is noticed that the stagnation point of a flat plate has a low temperature, concentration, and gyrotactic motile microorganism when compared with the plate and wedge.

Figure 8 depicts the effects of distinct values of Eckert number \( (E_c) \) and radiation parameter \( R \) on temperature profile \( (\theta) \), where in the figure the temperature propagates. The Eckert number pops up as coefficient of internal energy changes; therefore, the upsurge of temperature is obvious. The reason behind this upsurge temperature is that when heat is dispersed because of viscous force, the heat starts flowing towards the fluid, ensuring the case of increase in Eckert number, and follows to rise the temperature of the fluid. This divulges that temperature of fluid is going to be high when change in internal energy is negligible compared with the temperature of fluid where this change is consequent. So, for both discussed cases, temperature increases. Also, Figure 8 represents the curves of temperature field for several values of radiation parameter \( R \). Due to rise in radiation parameter, this will uplift the temperature of the fluid. As more heat is transmitted to the fluid when the phenomenon of radiation occurs, in shear thinning and shear thickening of the fluid, the temperature will rise when \( R \) parameter rises.

Figure 9 depicts the graphical behavior of Schmidt (Sc), and bioconvectional Peclet (Pe) numbers scrutinize that for positive values of Sc and Pe. As Sc increases, the concentration profile decreases. The above behavior of concentration profile is according to the existing physical situations. On explanatory note, the rate of mass transfer gets smaller when diffusion coefficient increases; this retards the concentration profile for both cases. Similarly, higher molecular motion leads to sharpening process of mass transportation which results in the deceleration in the concentration profile. The motile microorganism profile also shows a declined graph. This declined scratch for \( n < 1 \) and \( n > 1 \) is due to the fact that motile density dwindles due to the observed relation of Pe number with microorganism diffusivity.

Figure 10 highlights the effects of Brownian motion \( (N_b) \) on temperature, concentration, and density of motile microorganism profiles of the fluid for shear thinning and shear thickening. Nanoparticles with incremented values of \( N_b \) cast a stronger impact on heat transfer. The temperature of nanofluid escalates as the \( (N_b) \) parameter increases. However, \( N_b \) causes declining of the concentration BL because the nanoparticles diffuse away from the surface into the fluid which causes retardation in nanoparticle concentration and hence results in deceleration. Furthermore, it has been observed that, with increasing magnitude of \( N_b \) parameter, this uplifts the rate at which nanoparticles in the conventional fluids start to move themselves in irregular directions with disparate velocities. Also, Figure 10 demonstrates the graphical illustration of density of motile microorganisms of the flow due to uplifting Brownian motion parameter \( (N_b) \). We see that a strength in \( (N_b) \) parameter results in stifling the dispersion of nanoparticles quite away from the respective region that result in declining the \( \psi \)-curves.

Figure 11 shows the effects on \( \theta, \phi, \psi \) due to gradual elevation of thermophoresis parameter \( (N_s) \). Gradually, for different increasing values of \( N_s \), the thermal, concentration, and density of motile microorganism BLs tend to be enhanced in both flow cases. These nanoparticles show a powerful impact of heat transport properties of Carreau
fluid. The thermophoretic force develops as a consequence of temperature gradient which in turn results in increasing the flow rate of the fluid away from plate, wedge, and stagnation point. The outcome of this rapid flow of the fluid is that as the $N_t$ parameter increases, the thermal boundary layer increases. The concentration increases as $N_t$ increases. Basically, the nanoparticles due to this thermophoresis force are activated and start moving from hot to cold surface that comes out with the consequence that increases the mass related thickness. So, rise in $N_t$ parameter upsurges the concentration curves of fluid flow. Figure 11 also highlights the graphical impacts of varying $N_t$ on profile $\psi$ that results in increasing the density of motile microorganism. All these figures indicate the effects for both shear thinning and thickening cases for plate, wedge, and stagnation point orderly.

4. Conclusion

In this paper, a numerical investigation on MHD Carreau nanofluid flow comprising gyrotactic microorganisms over a wedge/plate/stagnation point of the plate is performed under the influence of suction/injection, viscous dissipation, Brownian, and thermophoresis motion. The results are carried out by utilizing the bvp4c and RKF techniques. Impacts of salient flow parameters on velocity, temperature, nanoparticle concentration, and density of motile microorganism to control the fluid transport properties are discussed. Some important findings drawn from the present work are summarized as follows:

(i) The influence of Weissenberg number for various flow geometries upon Carreau nanofluid has an opposite behavior for shear thinning/shear thickening fluids on velocity, temperature, concentration, and motile microorganism distributions; i.e., as $W_e$ increases, velocity profile increases in shear thinning case but decreases in shear thickening case. But, for rising values of $W_e$, the thermal, concentration, and motile microorganism profiles depreciate for shear thinning case but quite reverse behavior is seen for shear thickening fluid.

(ii) A rise in suction/injection parameter $S$ leads to enhancing the fluid velocity but decreases the temperature, nanoparticle concentration, and density of motile microorganism of the fluid. Suction or injection can be used to control boundary layer flows as it helps to bring stability in the flow.

(iii) In both the shear thinning and thickening cases, the temperature increases with increasing $Ec$, $R$, $Nb$, and $Nt$.

(iv) The nanoparticle concentration and density of motile microorganism decrease in both the shear thinning and shear thickening cases, for increasing values of $Nb$, but reverse trend is observed for rising values of $Nt$.

(v) The shear thinning nanofluid has slightly higher rate of heat, mass, and motile microorganisms mass transfers than shear thickening fluid.

(vi) All the profiles except velocity field show decreasing behavior for higher values of magnetic field parameter.

(vii) Both profiles, i.e., nanoparticle concentration and density of motile microorganism profile, show decreasing trend for higher values of $Sc$ and $Pe$ in both flow situations ($n < 1$) and ($n > 1$).

(viii) Among all three flow geometries, i.e., plate, wedge, and stagnation point of a flat plate, for both shear thinning and shear thickening cases, the flow over a plate has lesser skin friction factor.

(ix) Both shear thinning and thickening nanofluid have a low rate of heat/mass and gyrotactic microorganisms mass transfer over plate among wedge and stagnation point flow.

(x) The bioconvection with nanoparticle interaction can be used in thermal transpiration for engineering and industrial processes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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