Research Article

Magneto-Burgers Nanofluid Stratified Flow with Swimming Motile Microorganisms and Dual Variables Conductivity Configured by a Stretching Cylinder/Plate

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1.Introduction

Numerous scholars are fascinated by nanofluids due to their larger thermophysical properties and uses in heavy industrial and engineering technologies. Nanofluids contain fictional features that make them extremely useful and have gained substantial interest owing to their huge variety of applications such as cooling factors in electrical devices, automobiles, industrial-grade engines, and factories to improve efficiency, save energy, and minimize emission levels.
Nanoﬂuids are also used as medicines and antibiotics in the biological sciences. Choi rendered the ﬁrst use of nanofluid in 1995 [1]. Buongiorno [2] suggested two key features, thermophoresis and Brownian motion, to advance the convection of nanofluids. The hybrid nanofluids in the various kinds of heat structure for speciﬁc boundary constraints and physical scrutinized by Humic [3]. The two-dimensional Darcy-Forchheimer nanofluid ﬂow over the curved stretching layer was analyzed by Hayat et al. [4]. Ellahi et al. [5] explored the role of the slip in the two-phase nanofluid ﬂow. The analysis of mixed convection ﬂow over a vertical sheet having hybrid nanoparticles with porous medium was observed by Waini et al. [6]. Ahmed et al. [7] addressed the entropy generation in magnetohydrodynamics Eyring–Powell nanoliquids ﬂow with the consequences of dissipation, nonlinear mixed convection, and Joule heating. Lahmar et al. [8] reported the ﬂow and heat transfer of a squeezing unsteady nanofluid between two parallel plates. First and second law study of aqueous (NF) including suspended Ag nanoadditives in two micro-channel heat sinks is analyzed by Yang et al. [9]. The steady nanofluid ﬂow over a permeable stretch/shrink cylinder was evaluated by Roşca et al. [10]. Khan et al. [11] explored the behaviour of magnetic dipole on non-Newtonian ﬂuid including nanoparticles. Abbas et al. [12] analyzed the characteristics of thermal conductivity on magnetized Carreau nanofluid. Abbas et al. [13] analyzed Wu’s slip impacts on the magnetohydrodynamic ﬂow of nanofluid with activation energy. Abbas et al. [14] discussed the thermal dependent viscosity on nanofluid with entropy generation. Abbas et al. [15] scrutinized the micropolar nanofluid with magnetic ﬁeld under three-dimensional ﬂows. There are many investigators who investigated the nanofluid behaviours [16–20].

The theory of heat and mass transfer in magnetohydrodynamic ﬂow has many applications in a wide range of industrial applications, including geophysics, magnetic material processing, crude oil puriﬁcation, and cooling rate control. The behaviour of energy equations under the Joule heating effect was discussed by Khan et al. [21]. The unstable ﬂow of viscous ﬂuid via magnetohydrodynamics was scrutinized by Ghalib et al. [22]. Khan et al. [23] premeditated 2-dimensional ﬂow over a stretched surface of a non-Newtonian liquid with entropy optimization. Mohamad et al. [24] studied mixed convection of unstable noncoaxial viscous ﬂuid rotational ﬂow past an accelerated vertical disk. The effect of binary chemical reactions and activation energy on 3rd-grade hydromagnetic nanofluid streams combined with convective boundary layers was evaluated by Hayat et al. [25]. Iskender et al. [26] analyzed the steady ﬂow of nanomaterials with melting heat phenomenon. Khedr et al. [27] explored the micropolar ﬂuid with the impact of the magnetic ﬁeld and heat source sink. Zaraki et al. [28] discussed the analysis of heat and mass transfer on nanomaterials liquid. Chamkha [29] analyzed the MHD ﬂow under a porous medium over a vertical plate. Chamkha and Khaled [30] explored the coupled thermal and mass transfer over a permeable surface. Reddy et al. [31] scrutinized the heat and solutal transfer in nanofluid past a disk embedded in a porous medium. Many researchers [32–35] discussed the nanofluid properties over a different surface.

Bioconvection induced by variations in density of motile microorganisms is efﬁciently coordinated in the ﬁelds of ecological classiﬁcations, biogas, and production. The existence of such microorganisms improves the main density of the liquid and produces a gradient of density by floating that contributes to bioconvection. This fascinating discovery ultimately leads to an unstable, low-density layer. For example, microorganisms are spontaneously driven and move in the liquids to the atmosphere, while nanoparticles are directed by thermophoresis and Brownian motion in the surface liquid. Adding motile microorganisms to dilute nanomaterials suspensions is tremendously helpful for improving mass transport. Microorganisms were usually categorized as gyrotactic and gravitational microorganisms based on the pulsating force of different forms. There are still some different and related properties of nanostructures and motile microorganisms. The bioconvective stagnation point movement of nanoliquid, like swimming microorganisms, through a nonlinear stretching surface, is viewed by Mondal and Pal [36]. The Carreau-Yasuda nanofluid bioconvective ﬂow in the appearance of microorganisms has been reported by Waqas et al. [37]. Two-dimensional generalized second-grade nanoliquid ﬂow pasta Riga plate is investigated by Waqas et al. [38]. Khan et al. [39] analyzed the rheology of nanofluid stress couples using activation energy, thermal radiation, porous material, and convective boundary conditions of the ﬁeld. The magnetized bioconvective movement of a nanofluid with microorganisms across a nonlinear inclined stretch sheet is intentional by Beg et al. [40]. Bhatti and Michaelides [41] inspect the activation energy of Arrhenius via the Riga plate for nanofluid thermobio-convection. Zadeh et al. [42] digitally observe the movement, heat, and mass transfer of nanofluids through a vertical stretch layer under the effect of motile microorganisms. Many researchers scrutinize the bioconvective aspects with nanofluids [43–48].

The main aspiration of the current inquiry is to evaluate the MHD ﬂow of Burgers nanofluid conﬁgured by a stretching cylinder/plate. The consequences of thermal radiation, motile microorganisms, and chemical reactions are also taken into account. The governing equations of the ﬂow problem are reduced by eminent shooting technique and cracked numerically with the bvp4c method via MATLAB commercial software. The effects of prominent parameters of the ﬂow equation against velocity concentration and temperature proﬁle are extracted numerically and graphically through graphs and tables. The considered problem may be helpful in industrial sectors. The current model is more useful in the ﬁeld of technology to improve the heat transfer rate of heat storage devices. The proposed model is useful in automobiles, industrial-grid engines, cancer treatment, medicine, biosciences, biotechnology, pharmaceutical science, mechanical engineering, nuclear reactor, cooling of devices, and electrical engineering, as well as in many more ﬁelds. Bioconvective model is more faithful in the biosensors, oil reﬁneries, drugs delivery, medicines, chemotherapy, and military sectors.
2. Mathematical Formulation

In this article, we analyzed the consequences of Burgers nanofluid with the impacts of thermal radiation and motile microorganisms past a stretching cylinder/plate. Burgers nanofluid flow model over an expanding cylinder/plate is constructed with the strength of uniform magnetic field $B = [B_0, 0, 0]$ which is vertical to the flow path. Also, the temperature and concentration at the surface of the cylinder are supposed to be $(T_w, C_w)$ each (see Figure 1).

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} &= 0, \\
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + \frac{\partial v}{\partial z} &= 0, \\
\frac{\partial r}{\partial t} + u \frac{\partial r}{\partial x} + \frac{\partial r}{\partial z} &= 0,
\end{align*}
\]

(1)
In expressions (3) and (5), the thermal diffusivity and solutal diffusivity are read as $k(T) = k_\infty [1 + \varepsilon_1 \left( \frac{(T - T_\infty)}{(T_f - T_\infty)} \right)]$ and $D(C) = D_\infty [1 + \varepsilon_2 \left( \frac{(C - C_\infty)}{(C_f - C_\infty)} \right)]$.

With boundary conditions

\[
\begin{align*}
\frac{\partial w}{\partial r} & = h_g(N_f - N), \quad \text{at } r = R, \\
\frac{\partial w}{\partial r} & = 0, \\
T & \rightarrow T_f, \\
C & \rightarrow C_f, \\
N & \rightarrow N_f, \quad \text{as } r \rightarrow \infty.
\end{align*}
\]

The following similarities are introduced for obtaining dimension system of the current problem:

\[
\begin{align*}
u &= \frac{R}{r} \sqrt{\frac{U_0}{l}}, \\
w &= \frac{U_0 z}{l} f'(\zeta), \\
\theta(\zeta) &= \frac{T - T_\infty}{T_f - T_\infty}, \\
\phi(\zeta) &= \frac{\frac{C - C_\infty}{C_f - C_\infty}}{N - N_\infty}, \quad \text{at } \zeta = 0, \\
\zeta &= \sqrt{\frac{U_0}{vl}} \left( r^2 - R^2 \right).
\end{align*}
\]

\[
\begin{align*}
& (1 + 2\lambda \zeta)^2 \gamma_1 \left( 2 f f' f'' - f^3 f'' \right) - (1 + 2\lambda \zeta)\lambda \gamma_1 f^2 f'' \\
& - (1 + 2\lambda \zeta)^2 \gamma_2 \left( 3 f^2 (f'')^2 + 2 f (f')^2 f'' - f^3 f'' \right) \\
& - 4\lambda \gamma_3 f'' f''' + (1 + 2\lambda \zeta) \gamma_2 \left( 3 f^2 (f'')^2 + f^3 f'' \right) \\
& + (1 + 2\lambda \zeta)^2 \gamma_3 \left( (f'')^2 - f f'' \right) - 4\lambda \gamma_3 (1 + 2\lambda \zeta)^2 f f'' \\
& + (1 + 2\lambda \zeta)^3 f'' + (1 + 2\lambda \zeta)^2 \left( 2 f'' + f f'' - (f')^2 \right) \\
& + (1 + 2\lambda \zeta)^2 \lambda \theta f f'' - (1 + 2\lambda \zeta)^2 \lambda \theta f' \\
& \cdot \left[ -A + \gamma_1 f f'' - \gamma_1 f f'' + f' \right] \\
& + S(\theta - N r f - N c \gamma) \sin \frac{\delta}{2} = 0,
\end{align*}
\]

\[
\begin{align*}
\frac{\partial \theta'}{\partial \zeta} & = \frac{\epsilon_1 \theta''}{1 + \theta(\theta'' - 1)} \theta' \left( 1 + 2\lambda \zeta \right) \\
& + \epsilon_3 \theta'' + \epsilon_2 \theta' + Pr \theta' \lambda f + Pr Nb \theta' \left( 1 + 2\lambda \zeta \right) + Pr N t \theta' \left( 1 + 2\lambda \zeta \right) = 0, \\
\frac{\partial \phi'}{\partial \zeta} & = \frac{\epsilon_2 \phi''}{1 + 2\lambda \zeta} \phi' \left( 1 + 2\lambda \zeta \right) + \epsilon_2 \phi' + 2 \phi' + Le Pr f \phi' \\
& + (1 + 2\lambda \zeta) \left( \frac{N_t}{N_b} \right) \phi' + 2\lambda \left( \frac{N_t}{N_b} \right) \phi' - Pr Le \sigma^* \\
& \cdot (1 + \delta \theta') \exp \left( \frac{-E}{(1 + \delta \theta')} \right) \phi = 0,
\end{align*}
\]

\[
\begin{align*}
& (1 + 2\lambda \zeta) \chi'' + 2\lambda \chi' + Le f \chi' - Pe [\phi'' (\chi + \delta_1) + \chi' \phi'] = 0,
\end{align*}
\]
\[ f = 0, \\
\frac{df}{dz} = 1, \\
\frac{d\theta}{dz} = -\alpha_1 (1 - \theta(\zeta)), \\
\frac{d\phi}{dz} = -\alpha_2 (1 - \phi(\zeta)), \\
\frac{d\chi}{dz} = -\alpha_3 (1 - \chi(\zeta)), \quad \text{at } \zeta = 0, \\
\frac{df}{dz} \rightarrow A, \\
\frac{d\theta}{dz} \rightarrow 0, \\
\frac{d\phi}{dz} \rightarrow 0, \\
\frac{d\chi}{dz} \rightarrow 0, \quad \text{as } \zeta \rightarrow \infty. \quad (12) \]

We have that velocity ratio parameter is \( A = (U_{oc}/U_0) \), \( U_{oc} \) denotes the velocity of free stream, \( U_0 \) stands for stretching velocity, \( S \) denotes mixed convection parameter, \( Nr \) stands for buoyancy ratio parameter, \( Nc \) stands for bioconvection Rayleigh number, \( \alpha \) is the curvature parameter, \( \gamma_1 \) and \( \gamma_3 \) are Deborah numbers, Burgers fluid parameter is represented by \( \gamma_2 \), \( M \) is the magnetic parameter, \( Pr \) denotes Prandtl number, Lewis number is denoted by \( Lb \), \( Pe \) is Peclet number, microorganisms Biot number, which are given as follows:

\[
S = \frac{t^2 \beta^{**} \omega_f (1 - C_{co})(T_f - T_0)}{zU_0^2 M_f}, \\
Nr = \frac{(\rho_p - \rho_f)(C_f - C_0)}{(1 - C_{co})(T_f - T_0)}, \\
Nc = \frac{\gamma^* (\rho_m - \rho_f)(N_f - N_0)}{(1 - C_{co})(T_f - T_0){\beta^{**}}}, \\
\lambda = \frac{1}{R} \sqrt{\frac{\nu}{U_0}}, \\
\gamma_1 = \beta \frac{U_0}{T}, \\
\gamma_3 = \beta \frac{U_0}{T}, \\
\gamma_2 = \beta \frac{U_0}{T} \frac{M}{(\rho_f U_0)^2} \left(1 + \frac{1}{2} \ln \frac{U_0^2}{\rho_f} \right)^{1/2}, \\
Le = \frac{\alpha_1}{D_B}, \\
Pr = \frac{\nu}{\alpha_1}, \\
\theta_w = \frac{T_f}{T_{co}}.
\]

\[
Rd = \frac{16 \sigma T_{co}^3}{3 k k^*}, \\
Nt = \frac{\tau D_f (T_f - T_{co})}{\nu T_{co}}, \\
Nb = \frac{\tau D_B (C_f - C_{co})}{\nu}, \\
\sigma^* = \frac{\lambda k r^2}{U_0}, \\
\delta = \frac{T_f - T_0}{T_{co}}, \\
E = \frac{E_m}{D_m}, \\
Lb = \frac{\nu}{D_m}, \\
Pe = \frac{bW_c}{D_m}, \\
\delta_1 = \frac{N_{co}}{N_f - N_0}, \\
\alpha_1 = \frac{h_f}{k} \frac{\sqrt{\nu}}{U_0}, \\
\alpha_2 = \frac{h_g}{D_B} \frac{\sqrt{\nu}}{U_0}, \\
\alpha_3 = \frac{h_g}{D_m} \frac{\sqrt{\nu}}{U_0}.
\]

The physical quantities of interest are defined as follows:

\[
\begin{align*}
\text{Nu}_z &= \frac{2q_m}{k (T_w - T_{co})}, \\
\text{Sh}_z &= \frac{2j_m}{D_B (C_w - C_{co})}, \\
\text{Sn}_z &= \frac{2q_m}{D_m (N_w - N_{co})}, \\
q_m &= -k \frac{\partial T}{\partial r} \bigg|_{r=R} - 16 \sigma T_{co}^3 \frac{\partial T}{\partial r} \bigg|_{r=R}, \\
j_m &= -D_B \frac{\partial C}{\partial r} \bigg|_{r=R}, \\
q_m &= -D_m \frac{\partial N}{\partial r} \bigg|_{r=R}, \\
\text{Nu}_z \text{Re}^{-(1/2)} &= \left( 1 + \frac{4}{3} \left( R_d (1 + (\theta_w - 1)\theta(0)) \right) \right)^3 \theta' (0), \\
\text{Sh}_z \text{Re}^{-(1/2)} &= -\phi' (0), \\
\text{Sn}_z \text{Re}^{-(1/2)} &= -\chi' (0).
\end{align*}
\]
3. Numerical Scheme

The numerical limitations of the dimensionless flow system (8)–(11), along with boundary restriction (12), are tackled numerically. As established equations are highly nonlinear, it is difficult to get an accurate solution. Therefore, we use a famous numerical scheme through bvp4c via MATLAB computational software. So, we have to renovate the higher-order BVP to 1st-order IVP.

Let

\begin{align*}
  f &= h_1, \\
  f' &= h_2, \\
  f'' &= h_3, \\
  f''' &= h_4, \\
  f'''' &= h_5', \\
  \theta &= h_5, \\
  \theta' &= h_6, \\
  \theta'' &= h_6', \\
  \phi &= h_7, \\
  \phi' &= h_8, \\
  \phi'' &= h_8', \\
  \chi &= h_9, \\
  \chi' &= h_{10}, \\
  \chi'' &= h_{10}', \\
  h_4' &= (1 + 2\lambda\zeta)^2 y_1 \left[ 2h_1 h_2 h_3 - h_3^2 h_4 \right] - (1 + 2\lambda\zeta)\lambda y_1 h_1^2 h_3 - \\
  & \quad \cdot (1 + 2\lambda\zeta)^2 y_2 \left[ 3h_1^2 (h_3)^2 + 2h_1 (h_2)^2 h_3 \right] - 4\lambda^2 y_2 h_1 h_3 \\
  & \quad + (1 + 2\lambda\zeta)\lambda y_2 \left[ 3h_1^2 h_2 h_3 + h_1^2 h_4 \right] + (1 + 2\lambda\zeta)^3 y_3 (h_3)^2 \\
  & \quad - 4\lambda y_3 (1 + 2\lambda\zeta)^2 h_1 h_4 + (1 + 2\lambda\zeta)^3 h_4 + (1 + 2\lambda\zeta)^2 \left[ 2h_3 + h_1 h_3 - (h_2)^2 \right] \\
  & \quad + (1 + 2\lambda\zeta)^2 A^2 - (1 + 2\lambda\zeta)^2 M^2 \left[ A + y_2 h_1 h_4 - y_1 h_1 h_3 + h_2 \right] - S (h_5 - N_r h_7 - N_c h_9) \sin (\delta/2) \\
  & \quad \left( 1 + 2\lambda\zeta \right)^3 y_3 h_1 - (1 + 2\lambda\zeta)^2 y_2 h_1 \right) \\
  h_6' &= \frac{-Pr h_6 h_1 - \epsilon_1 h_5^2 - Pr N_b h_6 (1 + 2\lambda\zeta) - Pr N_t h_6' (1 + 2\lambda\zeta)}{\left[ \left[ Rd (1 + h_5 (\theta - 1)) \right] \left( 1 + 2\lambda\zeta \right) + \epsilon_1 h_5 \right]^2}, \\
  & \quad - 2\lambda h_8 - Le Pr h_1 h_8 - (1 + 2\lambda\zeta) (N_t/N_b) h_6' - 2\lambda (N_t/N_b) h_6 \\
  h_8' &= \frac{Pr Le \sigma^2 (1 + \delta h_5)^6 \exp (-E/(1 + \delta h_5)) h_7 - \epsilon_3 h_8^2}{(1 + 2\lambda\zeta) + \epsilon_2 h_7},
\end{align*}
\[ h_{10}' = \frac{-2\lambda h_{10} - Lbh_{10} + Pe[h_{9}'(h_{9} + \delta_{1}) + h_{10}h_{8}]}{(1 + 2\lambda \zeta)} \]

\[ h_{1} = 0, \]
\[ h_{2} = 1, \]
\[ h_{c} = -\alpha_{1}(1 - h_{9}(\zeta)), \]
\[ h_{b} = -\alpha_{2}(1 - h_{9}(\zeta)), \]
\[ h_{10} = -\alpha_{3}(1 - h_{9}(\zeta)), \quad \text{at } \zeta \]
\[ h_{2} \to A, \]
\[ h_{3} \to 0, \]
\[ h_{5} \to 0, \]
\[ h_{7} \to 0, \]
\[ h_{9} \to 0, \quad \text{as } \zeta \to \infty. \quad (15) \]

4. Results and Discussion

Salient features of mixed convection parameter \( S \) versus the velocity of fluid \( f' \) are illustrated in Figure 2. It is viewed that the velocity field \( f' \) is enlarged for rising values of mixed convection parameter for both values \( (\lambda = 0 \& 0.3) \). Figure 3 reflects the consequence of the buoyancy ratio parameter \( N_{b} \) against the velocity profile \( f' \). The buoyancy ratio parameter reduced the velocity of Burgers nanofluid \( f' \) for both values \( (\lambda = 0 \& 0.3) \). Figure 4 displays the valuation in the velocity profile \( f' \) for bioconvection Rayleigh number \( N_{b} \). It is scrutinized through the figure that the mounting magnitude of bioconvection Rayleigh number decays the velocity distribution for both cases \( (\lambda = 0 \& 0.3) \). The behaviour of Burgers fluid parameter \( \gamma_{2} \) against the velocity field \( f' \) is clarified in Figure 5. Here velocity field \( f' \) reduced as the escalating value of the Burgers fluid parameter for both values \( (\lambda = 0 \& 0.3) \). Figure 6 elucidates the effect of Deborah numbers \( \gamma_{3} \) versus the velocity field \( f' \). It is noticed that the velocity of fluid \( f' \) is increased by increasing values of Deborah numbers for both cases \( (\lambda = 0 \& 0.3) \). Physically Deborah numbers \( \gamma_{3} \) depend upon retardation to time. As a result improvement in retardation times the Deborah number increase. The acceleration is induced in the flow of fluid and velocity field is boosted up. The influence of the magnetic parameter \( M \) versus the velocity field \( f' \) is explicated in Figure 7. It is to be observed that velocity of fluid \( f' \) decays by enhancing the variation in magnetic parameter for both cases \( (\lambda = 0 \& 0.3) \). Consequently, the Lorentz forces are introduced via a larger magnetic parameter, so the flow of fluid reduces.

Figure 8 expounded the inspiration of Deborah numbers \( \gamma_{1} \) on the velocity of the fluid \( f' \). It is perceived that the velocity of fluid \( f' \) diminishes by enhancement in the magnitude of Deborah numbers for both cases of plate and cylinder \( (\lambda = 0 \& 0.3) \). Deborah number is the ratio of relaxation to observation times; thus, relaxation time rises with increment in Deborah number, and as a result confrontation in liquid motion swells which leads to reducing the flow of fluid. Prominent attribution of temperature ratio parameter \( \theta_{w} \) versus temperature distribution \( \theta \) is shown in Figure 9. The temperature field \( \theta \) is enlarged for a larger magnitude of fluid temperature ratio parameter \( \theta_{w} \) for both plate and cylinder \( (\lambda = 0 \& 0.3) \). The temperature ratio parameter improves the thermal state of liquid; therefore, the temperature field is improved. Figure 10 is deliberating the outcome of thermophoresis parameter \( N_{t} \) for the temperature concentration profile \( \theta \). It is pragmatic that augmentation in \( N_{t} \) boosted the temperature profile \( \theta \) for both values \( (\lambda = 0 \& 0.3) \). Figure 11 shows the variations in temperature profile \( \theta \) for swelling values of the Prandtl number \( Pr \). It is regarded through drafts that the growing variations of Prandtl number \( Pr \) fall off the temperature field \( \theta \) for both cases \( (\lambda = 0 \& 0.3) \). Physically the escalating value of Prandtl number causes a reduction in thermal diffusivity. Hence, the temperature field falls. Figure 12 is apprehended to examine the behaviour of thermal conductivity \( \varepsilon_{1} \) against temperature distribution \( \theta \). It is detected that the swelling variation of the thermal conductivity causes an upsurge in the temperature field \( \theta \). The impact of thermal stratification Biot number \( \alpha_{1} \) against temperature distribution \( \theta \) is accomplished in Figure 13. From the figure, it is initiated that the enhancing values of thermal stratification Biot number improved the temperature distribution for both plate and cylinder \( (\lambda = 0 \& 0.3) \).

Figure 14 illuminates the significance of the Prandtl number \( Pr \) for the concentration field \( \phi \). The increasing valuation of the Prandtl number reduces the concentration field \( \phi \). Figure 15 is captured to perceive the nature of thermophoresis parameter \( N_{t} \) against the volumetric concentration field \( \phi \). The approximation in the thermophoresis parameter results in a boost in the volumetric concentration of nanoparticles \( \phi \). Physically the solid particles transfer from hot section to cold region due to developed
\[ \gamma^2 = 0.1, 0.4, 0.8, 1.2 \]

\[ \zeta \]

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]

**Figure 2:** Disparity of \( S \) via \( f' \).

\[ M = 0.1, 0.4, 0.8, 1.2 \]

\[ \zeta \]

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]

**Figure 3:** Disparity of \( N_c \) via \( f' \).

\[ S = 0.1, 0.5, 1.0, 1.5 \]

\[ \zeta \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]

**Figure 5:** Disparity of \( \gamma_3 \) via \( f' \).

\[ \gamma_3 = 0.1, 0.4, 0.8, 1.2 \]

\[ \zeta \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]

**Figure 6:** Disparity of \( \gamma_3 \) via \( f' \).

\[ \gamma_3 = 0.1, 0.4, 0.8, 1.2 \]

\[ \zeta \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]

**Figure 7:** Disparity of \( M \) via \( f' \).

\[ N_c = 0.1, 0.4, 0.8, 1.2 \]

\[ \zeta \]

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]

**Figure 4:** Disparity of \( N_c \) via \( f' \).

\[ Nr = 0.1, 0.4, 0.8, 1.2 \]

\[ \zeta \]

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \]

\[ f' \]

\[ \lambda = 0.0 \text{ for plate} \]
\[ \lambda = 0.3 \text{ for cylinder} \]
\( \lambda = 0.0 \) for plate
\( \lambda = 0.3 \) for cylinder

Pr = 2.0, 3.0, 4.0, 5.0

\( \gamma_1 = 0.1, 0.4, 0.8, 1.2 \)

Figure 8: Disparity of \( \gamma_1 \) via \( f' \).

\( \theta_w = 1.5, 1.6, 1.7, 1.8 \)

Figure 9: Disparity of \( \theta_w \) via \( \theta \).

\( N_t = 0.1, 0.8, 1.6, 2.2 \)

Figure 10: Disparity of \( N_t \) via \( \theta \).

\( \alpha_1 = 0.1, 0.2, 0.3, 0.4 \)

Figure 13: Disparity of \( \alpha_1 \) via \( \theta \).
thermophoresis valuation. Outstanding features of the Brownian motion parameter $Nb$ for the concentration field $\phi$ are sketched in Figure 16. Concentration field $\phi$ dwindles by raising the magnitude of the Brownian motion parameter for both values ($\lambda = 0 & 0.3$). Physically Brownian motion controls the diffusion of the solid particles in the system away from the boundary. Hence, improvement of Brownian motion parameter results in a decline of concentration field. Figure 17 explicates the consequences of Lewis number $Le$ for the concentration field of nanoparticles $\phi$. By the escalation of Lewis number $Le$, the concentration field $\phi$ diminishes. Figure 18 illuminates the significance of solutal conductivity $\varepsilon_2$ against the concentration field $\phi$ of nanoparticles. It proposed that the concentration field of nanoparticles increased by the positive valuation of solutal conductivity for both values ($\lambda = 0 & 0.3$). Figure 19 describes the consequence of activation energy $E$ versus the concentration profile of nanoparticles $\phi$. It is anticipated that the concentration field of nanoparticles is amplified by the growing values of activation energy for both cases ($\lambda = 0 & 0.3$). The upshot of solutal Biot number $\alpha_2$ on the concentration field $\phi$ of nanomaterials is portrayed in Figure 20. It is estimated that the enhancing values of activation energy augmented the concentration field of nanoparticles for both cases ($\lambda = 0 & 0.3$). Figure 21 designates the conclusion of bioconvection Lewis number $Lb$ against microorganism’s concentration field $\chi$. It is inspected that the microorganism’s field $\chi$ is deteriorated for higher
Figure 18: Disparity of $\varepsilon_2$ via $\phi$.

Figure 19: Disparity of $E$ via $\phi$.

Figure 20: Disparity of $\alpha_2$ via $\phi$.

Figure 21: Disparity of $Pe$ via $\chi$.

Figure 22: Disparity of $\alpha_3$ via $\chi$.

Figure 23: Disparity of $Lb$ via $\chi$. 
Table 1: Comparison table for variation of \(-f''(0)\) for distinct values of \(M\) in special case when \(N_t = N_b = Pe = Lb = \lambda = 0\).

| \(M\)  | Shehzad et al. [49] | Hayat et al. [50] | Khan et al. [51] | Present study |
|-------|-------------------|-------------------|-----------------|--------------|
| 0.0   | 1.00000           | 1.00000           | 1.00000         | 1.00000      |
| 0.2   | 1.01980           | 1.01980           | 1.019801        | 1.019807     |
| 0.5   | 1.11803           | 1.11803           | 1.118029        | 1.118030     |
| 0.8   | 1.28063           | 1.28063           | 1.280633        | 1.280634     |
| 1.0   | 1.41421           | 1.41421           | 1.414221        | 1.414222     |
| 1.2   | 1.56205           | 1.56205           | 1.562048        | 1.562048     |
| 1.5   | 1.80303           | 1.80303           | 1.803044        | 1.803045     |

Table 2: Numerical result of local skin friction \(-f''(0)\) Versus \(M, S, Nr, Nc, \gamma_3, \gamma_1,\) and \(\gamma_2\).

| Parameters | \(-f''(0)\) \(\lambda = 0.0\) | \(-f''(0)\) \(\lambda = 0.3\) |
|-----------|-------------------------------|-------------------------------|
| \(M\)     | \(S\) | \(Nr\) | \(Nc\) | \(\gamma_3\) | \(\gamma_1\) | \(\gamma_2\) | \(\lambda = 0.0\) | \(\lambda = 0.3\) |
| 0.1       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.8241     | 0.9838       |
| 0.6       | 1.0  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.9643     | 1.0833       |
| 1.2       | 2.0  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 1.0966     | 1.1837       |
| 0.5       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.8493     | 0.8561       |
| 1.0       | 2.0  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 1.1015     | 1.4637       |
| 0.5       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 1.6714     | 1.7179       |
| 0.5       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.8958     | 0.8690       |
| 1.0       | 2.0  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.9104     | 0.9829       |
| 0.5       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.8548     | 0.9739       |
| 0.5       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.9101     | 1.0339       |
| 1.0       | 2.0  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 1.1151     | 1.2150       |
| 0.5       | 0.2  | 0.1   | 0.1   | 0.3      | 0.1      | 1.0      | 0.9172     | 1.0407       |

Table 3: Numerical results of \(-\theta'(0)\) corresponding to \(M, S, Nc, Nr, Nt, NbPr, Rd, \lambda_1,\) and \(Le\).

| \(M\)  | \(S\) | \(Nc\) | \(Nr\) | \(Nt\) | \(Nb\) | \(Pr\) | \(Rd\) | \(\alpha_1\) | \(Le\) | \(-\theta'(0)\) \(\lambda = 0.0\) | \(-\theta'(0)\) \(\lambda = 0.3\) |
|-------|-------|-------|-------|-------|-------|-------|-------|-------------|-------|-------------------------------|-------------------------------|
| 0.1   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1827                         | 0.1772                        |
| 0.6   | 1.0   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1788                         | 0.1746                        |
| 1.2   | 2.0   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1754                         | 0.1721                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1840                         | 0.1758                        |
| 1.6   | 1.0   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1882                         | 0.1767                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1828                         | 0.1769                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1848                         | 0.1759                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1732                         | 0.1754                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1619                         | 0.1747                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1814                         | 0.1767                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1765                         | 0.1707                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1703                         | 0.1632                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1802                         | 0.1760                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1771                         | 0.1723                        |
| 0.5   | 0.2   | 0.1   | 0.1   | 0.3   | 0.2   | 1.2   | 0.8   | 0.3         | 2.0  | 0.1735                         | 0.1681                        |
values of bioconvection Lewis number for both plate and cylinder ($\lambda = 0.0 \& 0.3$).

The numerical outcomes of the skin friction coefficient, local Nusselt number, local Sherwood number, and local density number of motile microorganisms against developed parameters are captured through Tables 1–5. In Table 1, we accomplished the comparison. From Table 2, the local skin friction coefficient succeeds with $M$ while reducing for $S$. In
Table 5: The numerical results of $-\chi'(0)$ for $M$, $S$, $N_r$, $N_c$, $\gamma_3$, $Pe$, $L_b$, and $\alpha_3$.

| $M$ | $S$ | $N_r$ | $N_c$ | $\gamma_3$ | $Pe$ | $L_b$ | $\alpha_3$ | $\lambda = 0.0$ | $\lambda = 0.3$ |
|-----|-----|-------|-------|------------|------|-------|------------|---------------|---------------|
| 0.1 | 0.2 | 0.1   | 0.1   | 0.3        | 0.1  | 1.0   | 0.3        | 0.2036        | 0.1997        |
| 0.6 | 1.0 | 0.1   | 0.3   | 0.1        | 1.0  | 0.3   |            | 0.2001        | 0.1975        |
| 1.2 | 2.0 | 0.2   | 0.1   | 0.3        | 1.0  | 0.3   |            | 0.1977        | 0.1937        |
| 0.5 | 0.2 | 0.1   | 0.3   | 0.1        | 1.0  | 0.3   |            | 0.2014        | 0.1918        |
| 0.5 | 1.0 | 0.2   | 0.1   | 0.3        | 2.0  | 0.1   |            | 0.1977        | 0.1848        |
| 0.5 | 2.0 | 0.2   | 0.3   | 0.1        | 1.0  | 0.3   |            | 0.1815        | 0.1837        |
| 0.2 | 0.1 | 0.3   | 0.1   | 0.3        | 1.0  | 0.3   |            | 0.2039        | 0.1930        |
| 0.1 | 0.6 | 0.1   | 0.3   | 1.2        | 1.0  | 0.3   |            | 0.2027        | 0.1916        |
| 0.2 | 0.2 | 0.1   | 0.3   | 0.1        | 1.0  | 0.3   |            | 0.2013        | 0.1997        |
| 0.1 | 1.0 | 0.2   | 0.3   | 1.2        | 1.0  | 0.3   |            | 0.2048        | 0.2929        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2043        | 0.1812        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2034        | 0.1889        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2009        | 0.1975        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2015        | 0.1952        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2023        | 0.1931        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2027        | 0.1994        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2137        | 0.2109        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2252        | 0.2227        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2084        | 0.2055        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2271        | 0.2251        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.2395        | 0.2382        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.8600        | 0.0817        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.3032        | 0.2993        |
| 0.2 | 0.2 | 0.1   | 0.3   | 1.2        | 2.0  | 0.1   |            | 0.4047        | 0.2993        |

Table 3, it can be noticed that the local Nusselt number turns down for a larger amount $R_d$. From Table 4, it is scrutinized that the local Sherwood number boosted up with various values of $\alpha_2$. The rescaled density number of motile microorganisms is diminishing function of $\gamma_3$, which is shown in Table 5.

As a significance, from these tables, we are assured that the recent results are very accurate.

5. Concluding Remarks

The thermal and solutal conductivity phenomena for magneto-Burgers nanofluid with swimming motile microorganisms were established. The eminent shooting method is employed to crack the flow problems of magneto-Burgers nanofluid via bvp4c solver in computational software MATLAB. The main outcomes are highlighted as follows:

(i) It is scrutinized that the velocity of magneto-Burgers nanofluid signifies reducing trend for higher buoyancy ratio parameter, Burgers fluid parameter, and bioconvection Rayleigh number.

(ii) An improvement in the mixed convection parameter and Deborah numbers enhances velocity field.

(iii) Temperature distribution declines with a larger Prandtl number, while an inverse trend is shown for thermal Biot number.

(iv) An increment in the variations of solutal conductivity and activation energy enhances the volumetric concentration of nanoparticles.

(v) The rescaled microorganism’s field exaggerates with microorganisms Biot number while it dwindles for Peclet number and bioconvection Lewis number.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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