Effect of thermal radiation on combined bioconvection in a horizontal channel filled by nanoliquid and gyrotactic microorganisms

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Abstract. The present study analyses the effects of thermal radiation and internal heat generation on fully developed combined bioconvection nanofluid in a horizontal channel containing gyrotactic microorganisms. The two walls of the channel are maintained at two different constant temperatures. The Brownian motion and thermophoresis are considered into account for nanofluid model. The similarity transformations are used to convert the existing partial differential equations into the non-linear ordinary differential equations with boundary conditions and solved analytically by homotopy analysis method (HAM). The causes on the temperature distribution, the nanoparticle volume fraction and density of microorganisms in the presence of physical parameters are discussed in brief. The thermal radiation and thermophoresis parameters diminish the heat transfer rate inside the channel.

Keywords: Nanofluid, Bioconvection, Microorganisms, Thermal Radiation, Chemical reaction, Horizontal channel.

1. Introduction
Nanofluid is a fluid with nano-scale particles such as metals, non-metals, oxides, carbides, which was initially coined by [1]. Adding such particles (below 0.01 by volume) into base fluid has improved the thermal conductivity of the base fluid. Buongiorno[2] showed that the Brownian diffusion and thermophoresis are important slip in nanofluids. Tao[3] examined the laminar fully developed combined bioconvection flow through parallel plate vertical channels. Hamadah and Wirtz [4] proved that the buoyancy force increases the quality of the heat transfer rate close to the high temperature wall and produces a flow to an opposite direction close to the fairly low temperature wall. The combined convection flow of a nanofluid passed in a vertical channel was investigated by Xu et al. [5]. Ahmed et al. [6] studied the effects caused by unreliability of thermal conductivity and dynamic viscosity of boundary layer nanofluid flow on a permeable stretching tube in the existence of heat generation or absorption.

Bioconvection is a occurrence of macroscopic convective flow of the fluid with respect to the density gradient generated by upward swimming microorganisms. The microorganisms are denser than water, they can swim towards the surface of the fluid, resulting the top layer becomes denser than the lower layer. Due to numerous applications in biological and bio-microsystems, the study of bioconvection is important and getting attention in this decade. The fully developed combined bioconvection flow through horizontal channel that contains nanoliquid which include gyrotactic microorganisms was discussed by Xu and Pop [7]. In the recent years, Kuznetsov [8, 9, 10] was done a sequence of investigation on the nanofluid based bioconvection with nanoparticles and
microorganisms. Also he found that the character of microorganisms in nanofluid is to develop its stability.

Recently, the researchers focused on the study of heat transfer and boundary layer flow of a nanofluid by taking the effect of radiation. There are many important applications of radiation effect in physical sciences and engineering. The radiation effect on unsteady 3D magnetohydrodynamics flow and heat transfer of a viscoelastic fluid along a stretching surface was studied by Eswaramoorthi et al. [11]. The effects of thermal radiation, cross diffusion on combined convection stagnation-point MHD flow through a vertical plate in a porous medium were analysed by Karthikeyan et al. [12]. Also, the effects of radiation and heat generation on a stagnation-point flow of MHD mixed convection with chemical reaction in a porous medium were examined by Nirajan et al. [13].

The aim of this paper is to analyse the effects of combined convective heat and mass transfer of nanoliquid with microorganisms between two horizontal parallel plates in the existence of internal heat generation and radiation. The present investigation is to continue the work carried out by Xu and Pop [7] to the occurrence of special effects such as internal heat generation and radiation on fully developed combined bioconvection flow through flat channel containing nanoliquid and microorganisms.

2. Mathematical Modelling

Consider the combined bio-convection of nanofluid in a horizontal channel of length $2L$ filled with gyrotactic microorganisms as shown in the figure 1. The axes $x$ and $y$ are along the horizontal and vertical directions of the channel respectively. Let the velocity of upper and lower walls are $u_1 = ax$. Let $T_1$ and $T_2$ are the constant temperatures of lower and upper walls. Suppose $N_1$ and $N_2$ are constant densities of the movable microorganisms. Let us consider on the upper wall, the nanoparticle volume fraction satisfies the passively controlled model, but on the lower wall, it is constant. The equations of continuity, momentum, heat energy, nanoliquid volume fraction and the microorganisms density are:

$$\nabla \cdot \mathbf{v} = 0,$$
$$\rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \mu \nabla^2 \mathbf{v},$$
$$\mathbf{v} \cdot \nabla T = \alpha \nabla^2 T + \tau \left[ D_B \nabla T \cdot \nabla C + \left( \frac{D_T}{T_0} \right) \nabla T \cdot \nabla T \right] + \frac{Q}{\rho c_p (T - T_0)} - \frac{1}{\rho c_p} \nabla q_r,$$
$$\Delta j = 0,$$

where $\mathbf{v} = (u, v)$ being the velocity components of nanoliquid in the Cartesian coordinates, $p$ and $T$ be the pressure and heat energy, $C$ represents the nanoparticle volume fraction, $\rho, \mu$ and $\alpha$ are respectively density, viscosity and thermal diffusivity of the nanoliquid, $Q$ represents the coefficient of internal heat generation and $c_p$ represents the specific heat.

![Figure 1. Physical configuration and co-ordinate systems.](image-url)
By Rosseland approximation, the radiative heat flux is given by \( q_T = -\frac{4\sigma_\ast \partial T^4}{3k^* \partial y} \) where \( \sigma_\ast \) be the Stefan-Boltzman constant, \( k^* \) is the coefficient of absorption. Suppose the temperature difference inside the flow is \( T^4 \), it can be expressed by using truncated Taylor’s series at \( T_0 \) as \( T^4 = 4T_0^3T - 3T_0^4 \). The ratio of the efficient heat energy measure of the nanoparticle to the basic liquid is represented by \( \tau = (\rho c_p)_P/(\rho c_p)_f \). \( D_b \) and \( D_t \) are called the two diffusion coefficients. The flux of microorganisms is \( J = N\nu + N\nu - D_n \nabla N \) with respect to the convection of fluid, self-motivated swimming, and scattering. Here \( N \) is the microorganisms motile density, the nanofluid cell swimming average directional velocity with the microorganisms diffusivity \( D_n \) is given by \( \hat{\nu} = (\hat{u}_1, \hat{v}_1) \) where \( \hat{u}_1 = (bW_c/C_0)C_x, \hat{v}_1 = (bW_c/C_0)C_y \), the chemotaxis constant is \( b \) and the maximum speed of swimming cell is \( W_c \).

For a horizontal 2D channel flow problem, equation (2) can be written by

\[
\begin{align*}
    u_1u_{1x} + v_1u_{1y} &= -\frac{1}{\rho_f}p_x + \nu(u_{1xx} + u_{1yy}), \\
    u_1v_{1x} + v_1v_{1y} &= -\frac{1}{\rho_f}p_x + \nu(v_{1xx} + v_{1yy}),
\end{align*}
\]

by using the following transformation, the previous equations are simplified

\[ \zeta = v_1x - u_1y = -\nabla^2 \psi \] where \( u_1 = \psi_x \) and \( v_1 = -\psi_y \).

From the above equations, the expanded governing equations (1)-(5) are given by

\[
\begin{align*}
    u_{ix} + v_{iy} &= 0, \\
    u_{i\zeta_x} + v_{i\zeta_y} &= \nu (\zeta_{xx} + \zeta_{yy}), \\
    u_{iT_x} + v_{iT_y} &= \alpha(T_{xx} + T_{yy}) - \frac{1}{\rho c_p} (q_{rx} + q_{ry}) + \frac{Q}{\rho c_p} (T - T_0) \\
    &+ \tau \left[ D_B \left( C_x T_x + C_y T_y \right) + \frac{D_T}{T_0} \left( (T_x^2 + (T_y^2) \right) \right], \\
    u_i C_x + v_i C_y &= D_B \left( C_{xx} + C_{yy} \right) + \frac{D_T}{T_0} \left( (T_{xx} + T_{yy} \right), \\
    u_i N_x + v_i N_y + (N\hat{\nu})_y &= D_n N_{yy}.
\end{align*}
\]

The conditions at wall and centre of the channel are as follows:

\[
\begin{align*}
    u_i = ax, \quad v_i = 0, \quad T = T_2, \quad D_B \frac{dC}{dy} + \frac{D_T}{T_0} \frac{dT}{dy} = 0, \quad N = N_2 & \quad \text{as} \quad y = L; \\
    u_{iy} = 0, \quad v_i = 0 & \quad \text{as} \quad y = 0; \quad u_i = ax, \quad v_i = 0, \quad T = T_1, \quad C = C_1, \quad N = N_1 & \quad \text{as} \quad y = -L.
\end{align*}
\]

By using the successive similarity transformations \( \psi(x, y) = axf_i(\eta), \quad \eta = \frac{y}{L}, \quad \theta(\eta) = \frac{T - T_0}{T_2 - T_0}, \quad \phi(\eta) = \frac{C - C_0}{C_0}, \quad S(\eta) = \frac{N}{N_2} \) in Eqs. (6)-(10), continuity equation (6) is obviously true and the simplified form of other equations are given by

\[
\begin{align*}
    f_1'' + Re(f_1 f_1'' - f_1 f_1') &= 0, \\
    \left[ 1 + \frac{4}{3} Rd \right] \theta'' + (RePr) f_1 \theta' + Nb \theta' \phi + Nt(\theta')^2 + S\theta &= 0,
\end{align*}
\]
\[ \phi' + \frac{Nt}{Nb} \theta' + (\text{ReSc}_{b}) f_{1} \phi' = 0, \] (13)

\[ s' - Pe_{b}(\phi s' + s \phi') + (\text{ReSc}_{b}) f_{1} s' = 0, \] (14)

along with the following conditions at boundary

\[ f_{1} = 0, \quad f_{1}' = 1, \quad \theta = 1, \quad Nb \phi + Nt \theta = 0, \quad s = 1 \] as \( \eta = +1; \)

\[ f_{1} = 0, \quad f_{1}' = 0 \] as \( \eta = 0; \)

\[ f_{1} = 0, \quad f_{1}' = 1, \quad \theta = \delta_{s}, \quad \phi = \delta_{s}, \quad s = \delta_{s} \] as \( \eta = -1. \)

The dimensionless numbers are given by

\[ Re = \frac{a L^{2}}{\nu}, \quad Pr = \frac{\nu}{\alpha}, \quad Nb = \frac{d D_{b} C_{0}}{\alpha}, \quad Nt = \frac{1}{\alpha} \left( \frac{D_{b}}{T_{0}} \right) T_{2} - T_{0}, \quad Sc_{b} = \frac{\nu}{D_{b}}, \quad Pe_{b} = \frac{b W_{c}}{D_{n}}, \quad Sc_{n} = \frac{\nu}{D_{n}}, \]

\[ S = \frac{QL}{k}, \quad Rd = \frac{4c T_{0}^{3}}{k^{*}k}, \quad \delta_{s} = \frac{T_{1} - T_{0}}{T_{2} - T_{0}}, \quad \delta_{s} = \frac{C_{1} - C_{0}}{C_{0}}, \quad \delta_{s} = \frac{N_{1}}{N_{2}}, \]

here \( Re \) -Reynolds number, \( Pr \) -Prandtl number, \( Nb \) -Brownian motion parameter, \( Nt \) -Thermophoresis parameter, \( Sc_{b} \) - Schmidt number for Brownian motion coefficient, \( Pe_{b} \) -Peclet number, \( Sc_{n} \) -Schmidt number for microorganisms density, \( S \) -Heat generation/absorption parameter, \( Rd \) -Thermal radiation parameter and \( \delta_{s}, \delta_{s}, \delta_{s} \) are constants.

In convection flow problems, it is very important to aware the quantity of heat transfer inbetween the solid wall and the liquid. The definition of the local Nusselt number is given by

\[ Nu = \frac{q_{w}x}{k(T_{2} - T_{0})}, \quad q_{w} = -k \left( \frac{\partial T}{\partial y} \right)_{y=0} - \frac{4\sigma^{\star}}{3k^{*}} \left( \frac{\partial T^{4}}{\partial y^{4}} \right)_{y=0} \] be the heat flux.

From the above equation, the dimensionless form of the Nusselt number of this model is

\[ Nu = \left[ 1 + \frac{4}{3} Rd \right] \theta'(0). \]

3. Results and analysis

The set of non-linear differential equations (11)-(14) are evaluated by using HAM technique subject to the values of parameters \( h_{l} = h_{g} = -1.5, \quad h_{l} = -0.2, \quad h_{g} = -0.5. \) The fixed values of other parameters are taken as \( Pr = Sc = Pe_{b} = 1, \quad \delta_{s} = \delta_{s} = 0.5, \quad \delta_{s} = 1. \) Also the range of parameter are taken by \(-0.5 \leq S \leq 0.5 \) for heat generation/absorption parameter, \(-15 \leq Re \leq 15 \) for Reynolds number, \( 0 \leq Rd \leq 13 \) for thermal radiation parameter in addition to other parameter.

Figure 2 shows the effect of temperature profile \( \theta(\eta) \) for various values of \( Rd \) in the absence of \( S \) and \( Re = \pm 5. \) In the region of the upper wall, the temperature of the fluid induces slowly for the positive \( Re \) values by increasing of \( Rd, \) where as it decreases accordingly for the negative \( Re \) values when increasing \( Rd \) values. But in the lower wall, the temperature profile is gradually enhancing for the negative \( Re \) values while it reduces sequentially for the positive \( Re \) values with increasing \( Rd. \) In figure 3, the effect of the thermophoresis parameter \( Nt \) on \( \theta(\eta) \) for \( Re = \pm 5 \) with \( S = \pm 0.5 \) is analysed. It is found that the temperature induces on increasing \( Nt \) with \( S = +0.5 \) for both the values of \( Re. \) But, it reduces on increasing the thermophoresis parameter with \( S = -0.5. \)

Figures 4(a) and 4(b) display the influence of radiation on temperature profile in the presence of heat generation (\( S = +1 \)) and heat absorption parameter (\( S = -1 \)) with \( Re = \pm 10. \) For \( S = -1, \theta(\eta) \)
increases gradually with different \( Rd \). In figure 4(a). For \( S = +1 \), \( \theta(\eta) \) reacts totally in the opposite manner, that is, it decreases for both \( Re \) values in figure 4(b). Comparing figure 2 and figure 4, the temperature distribution reacts in a different manner on increasing the thermal radiation parameter in the presence of internal heat generation. Further scrutinising these profiles, positive values of \( Re \) pronounced more on temperature than the negative values of \( Re \). Obviously, the effect of internal heat generation on temperature is reversed in the case of internal heat absorption case.

**Figure 2.** The temperature for different entries of \( Rd \) with \( Nu = Nt = S = 0 \).

**Figure 3.** The temperature for various entries of \( Nt \) with \( Re = \pm 5, S = \pm 0.5, Rd = 10 \).

**Figure 4.** The temperature for different entries of radiation parameter with \( Re = \pm 10 \) at (a) \( S = -1 \) and (b) \( S = +1 \).

**Figure 5.** The temperature for different entries of \( S \) with (a) \( Rd = 0 \) and (b) \( Rd = 10 \).
The effect of internal heat generation without radiation \((Rd = 0)\) and with radiation \((Rd = 10)\) on the temperature is plotted in figures 5(a) and 5(b), respectively. It is found that the increase of \(S\) induces the growing of \(\theta(\eta)\) for all values of \(Re\) in the channel in the absence of radiation in figure 5(a). The temperature near the lower wall is high for \(Re = +10\). However the temperature near the upper wall is high for \(Re = -10\) case for all values of \(S\) in figure 5(b). The effect of temperature profile range shown in figure 5(a) is lower than that of in figure 5(b) due to thermal radiation. That is, thermal radiation induces the increment on temperature inside the channel.

In figures 6(a) and 6(b), the effects of internal heat generation parameter on \(\phi(\eta)\) for the constant values of \(Re\) in the horizontal channel with/without radiation are discussed. It is seen from figure 6(a) that \(\phi(\eta)\) enlarges continuously as \(S\) increases for the negative values of \(Re\) whereas it reduces consecutively for the positive \(Re\) values with increasing of \(S\). This effect is made without thermal radiation. The influence of radiation on \(\phi(\eta)\), is analysed in figure 6(b). The profile of nanoparticle volume fraction grows up in the entire channel as \(S\) evolves for the positive and negative values of \(Re\). Comparing these two figures, it is evidenced that the impact of thermal radiation on nanoparticle volume fraction is clearly visible in figure 6(b).

![Figure 6](image1.png)

**Figure 6.** The nanoparticle concentration for various entries of \(S\) with (a) \(Rd = 0\) and (b) \(Rd = 10\).

It is also observed in figure 7 that the nanoparticle volume fraction \(\phi(\eta)\) is almost constant close to the lower wall of the channel when changing the values of \(Rd\) for \(Re = -15\). When \(Re = +15\), \(\phi(\eta)\) is constant for a given values of radiation parameter near the walls of the channel, but, it drastically changes in the middle of the channel. Figure 8 shows that the profile of \(\phi(\eta)\) goes against the increase of \(Nt\) with internal heat generation \(S = +0.5\) case where as it enhances gradually with increase of \(Nt\) for the internal heat absorption (\(S = -0.5\)) case in the channel along with thermal radiation. As shown in figure 9, the growing of \(Nb\) leads to increase \(\phi(\eta)\) for the positive and negative values of \(S\) in the presence of radiation.

In figure 10, \(s(\eta)\) increases when radiation increases for both positive and negative \(Re\) values under the internal heat generation \(S = +1.\) Figures 11(a) and 11(b) exhibit that the effect of \(s(\eta)\) for various entries of \(S\) in the absence/presence of thermal radiation. \(s(\eta)\) decreases rapidly as the values of \(S\) increases for positive values of \(Re\) (figure 11(a)) in the entire channel. But for the negative values of \(Re\), \(s(\eta)\) goes opposite to the grows of \(S\) in the lower portion of the channel whereas as it enhances with increase of \(S\) in upper portion of the channel. But, the profile of \(s(\eta)\) in figure 11(b) is completely opposite to the above with respect to the values of \(Re\). The increase of \(S\) leads to
decrease $s(\eta)$ when $Re = -10$. While in the lower portion of the channel, $s(\eta)$ decreases as $S$ evolves, but in the upper channel $s(\eta)$ grows up as $S$ enlarge for $Re = +10$. Figure 12 and figure 13 deals the same effect of $s(\eta)$ with respect to $Nb$ and $Nt$ with positive and negative heat generation/absorption parameter ($S$). $s(\eta)$ decreases near the lower channel as $Nb$ and $Nt$ enlarges, but in the upper channel, it enhances rapidly as $Nb$ and $Nt$ are increasing.

**Figure 7.** The nanoparticle volume fraction for different entries of $Rd$ with $Re = \pm 15$ and $S = +1$.

**Figure 8.** The nanoparticle volume fraction for different entries of $Nt$ with $Re = \pm 5$, $S = \pm 0.5$ and $Rd = 10$.

**Figure 9.** The nanoparticle concentration for various entries of $Nb$ including $Re = \pm 10$, $S = \pm 0.1$, $Rd = 0$.

**Figure 10.** The microorganisms density for all entries of $Rd$ with $S = 1$, $Re = \pm 15$.

Figure 14 presents the effects of $Nt$ and $Rd$ on the Nusselt number ($Nu$) as the function of $Re$ and $S$. In figure 14(a), $Nu$ goes down as $Nt$ increases. At $Re = 0$, $Nu$ gets constant for all values of $Nt$ and it is equal to -0.25, after that $Nu$ enhances gradually as $Nt$ enlarge in the absence of $Rd$ and $S$. In figure 14(b), $Nu$ have the same effect in the presence of $Rd$ and it gets constant (-1.91667) at $Re = 0$ for all values of $Nt$. Figure 14(c) shows the Nusselt number values diminish on increasing of $Rd$ for fixed values of $Nb$, $Nt$ and $S$. In figure 14(d), $Nu$ is a function of $S$ and it decreases on increasing $Rd$ for $Nb=0.1$, $Nt=0.1$ and $Re = 5$. 
Figure 11. The microorganisms density for different entries of $S$ with $Re = \pm 10$ at (a) $Rd = 0$ and (b) $Rd = 10$.

Figure 12. The microorganisms density for different entries of $Nb$ with $S = \pm 0.1$, $Rd = 10$, $Re = 15$.

Figure 13. The microorganisms density for different entries of $Nt$ with $S = \pm 0.1$, $Rd = 10$, $Re = 10$.

4. Conclusion
A two-dimensional combined bioconvection flow of nanofluid with movable microorganisms in a horizontal channel is investigated in the presence of $S$ and $Rd$. By considering similarity transformations and dimensionless numbers, the basic governing equations are simplified by nonlinear ODE with boundary conditions. They are solved by using HAM. The thermal radiation parameter, internal heat generation parameter, Brownian motion parameter, thermophoresis parameter and Reynolds number are used to analyse the effects on temperature, nanoparticle volume fraction, microorganisms density, and heat transfer rate.

- For increasing values of $Rd$, the temperature decreases in the presence of $S$ whereas it increases in the absence of $S$.
- The increasing values of thermophoresis parameter induces the temperature distribution when $S > 0$ and it diminishes when $S < 0$.
- The temperature distribution enhances with heat generation/absorption regardless of $Rd$.
- The internal heat generation/absorption affects the nanoparticle volume fraction for the raising values of $Nt$. 
The density of motile microorganisms increases on raising the values of thermal radiation, thermophoresis and Brownian motion parameters.

The Nusselt number enhances with the values of thermophoresis parameter and internal heat generation parameter. But the Nusselt number decreases for the increasing radiation values.

![Graph](image)

Figure 14. Variation of the Nusselt number as a function of $Re$ and $S$.

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