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Shahid Chamran
University of Ahvaz

Journal of Applied and Computational Mechanics



Research Paper

Effect of Chemical Reaction on Bioconvective Flow in Oxytactic Microorganisms Suspended Porous Cavity

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Received July 13 2019; Revised October 04 2019; Accepted for publication October 11 2019.

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& International Research Center for Mathematics & Mechanics of Complex Systems (M&MoCS)

Abstract. In this paper, the bioconvective flow in a porous square cavity containing oxytactic microorganism in the presence of chemical reaction is investigated. The bioconvection flow and heat transfer in porous media are formulated based on the Darcy model of Boussinesq approximation. The governing partial differential equations are solved using the Galerkin finite element method. The computational numerical results are exhibited by the streamlines, isotherms, isoconcentrations of oxygen, isoconcentrations of microorganisms, average Nusselt number, average Sherwood numbers of oxygen concentration and microorganisms. The effects of key parameters such as bioconvection Rayleigh number (Rb), chemical reaction parameter (Kr) and thermal Rayleigh number (Ra) are presented and analyzed. It can be deduced that the chemical reaction reduces the strength of isoconcentrations of both oxygen and microorganisms. It has been revealed that the chemical reaction has a greater effect on the swimming of the microorganisms, average Nusselt number, and average density number.

Keywords: Thermo-bioconvection, Oxytactic Microorganisms, Porous square cavity, Chemical reaction, Finite Element Method.

1. Introduction

Abundant investigations on convective heat transfer in porous media are ascribed to the enormous of applications, such as utilization and storage of thermal/geothermal energy, reservoirs of petroleum, devices of catalytic convertors, dispersion of underground pollutants, underground feeder cables, technology of porous ceramic burners, food industry, tertiary recovery, chemical reactors, chemical separations, moisture migration in stored grain, thermal cooling of electronic equipment, , heating of rooms, combustion, etc. The basic nature and the increased volume of work in this area are adequately archived in the books by Nield and Bejan[1], Ingham and Pop [2], Vafai[3], Pop and Ingham [4]. Natural convection in cavities of various geometries discovers a salient feature for engineering analysis. It has huge applications in engineering, such as solar applications, building applications, electronic industry, etc. Natural convection phenomena in the porous square cavity are investigated by Rahman et al.[5] and Balla et al. [6-8]. The latest development for microfluidic devices is heat transfer in porous media with bioconvection phenomena. Bioconvection refers to a macroscopic convective movement of fluid-induced by the swimming of motile microorganisms. Different types of microorganisms can be found, showing various swimming behaviours. Negatively geotactic microorganisms swim

opposite to gravity [9], and for gyrotactic microorganisms, the direction of swimming depends on the balance of gravitational and viscous torques [10-11]. Generally, oxytactic microorganisms swim towards the upper surface since the upper surface of any layer is opened to the atmosphere where the oxygen concentration is abundant. As microorganisms are heavier than water, the growth of their concentration at the upper surface generates the inverting instability, which leads to the formation of bioconvection. Hillesdon et al. [12] and Hillesdon and Pedley [13] developed the theoretical model of bioconvection in a suspension of oxytactic micro-organisms. Many authors studied the onset of thermo bioconvection in suspensions of oxytactic microorganisms [14-17]. Kuznetsov [18] presented a continuum model for thermo bioconvection of oxytactic micro-organisms in porous media and examined the mixed consequences of up swimming of bacteria and heat transfer below horizontal layer containing a fluid-saturated porous medium. Ahmed et al. [19] studied thermo-bioconvection in a homogeneous and isotropic porous medium saturated square enclosure containing oxytactic microorganisms. Anwarbeg et al. [20] employed a mathematical model for nano-bioconvection past an impermeable vertical porous flat wall filled with oxytactic microorganisms. Bioconvection finds an important place in bio-microsystems for the augmentation of mass transport and microfluidic devices such as micromixers with bacteria power [21]. One significant development of bioconvection in porous media is the technology of microbial enhanced oil recovery, applied to improve the life of matured oil reservoirs [22-24]. Balla et al. [25] examined the effect of bioconvection parameters in suspensions of oxytactic microorganisms present in the porous media. Kumar et al. [26] investigated the nanofluid flow containing gyrotactic microorganisms and second-order slip with convective conditions. Tlili et al. [27,28] studied the convective flow over the stretching sheet and horizontal circular cylinder. Alkanhal et al. [29] studied convective flow in a porous medium enclosed in a cavity.

Another situation that takes place in practice is a chemical reaction formed in the porous medium. The pivotal features arising in the modeling of a chemical reaction in a porous medium are elaborated by Nield and Bejan [1]. Anjalidevi and Kandasamy [30] investigated the chemical reaction of first-order, homogeneous with a constant rate on laminar flow past a horizontal plate. An appreciable attention is drawn to study the flow with chemical reaction because of its applications in hydrometallurgical industries, drying, evaporation, food processing, cooling towers. A good number of research works were documented in this area [31- 37]. The influence of first-order chemical reaction and variable surface heat flux past a flat plate in a porous medium is reported by Zhang et al. [38]. The effect of variable chemical reaction on three-dimensional incompressible nanofluid-flow over an exponentially-stretching sheet obeying convective boundary condition is investigated by Manoj et al. [39]. Makinde et al. [40] investigated numerically, chemically reacting and radiating unsteady mixed convection past a surface placed in a porous medium. Mahanthesh et al. [41] studied the effects of chemical reaction on three-dimensional flow over an exponentially stretching surface. Hayat et al. [42, 43] studied the constructive and destructive chemical reaction in the magneto-hydrodynamic flow of Jeffery liquid and Carreau fluid. Farooq et al. [44] investigated theoretically the effects of chemical reaction on convective flow.

The novelty and significance of this study is to combine the impacts of the chemical reaction and bioconvective flow in the square cavity. To the best of authors' knowledge, the present work is not studied to the extent that the effect of the chemical reaction of bioconvection in the presence of motile oxytactic microorganisms in a porous square cavity. The potential applications of this study are found in bio-microsystems, microbial enhanced oil recovery, etc. The current state of the art of this paper is to extend the work of Balla et al. [25] to the case of thermobioconvection in a suspension of oxytactic microorganisms in the presence of chemical reaction.

2. Mathematical Formulation

A two-dimensional bioconvective flow in a porous square cavity filled by oxytactic microorganisms with chemical reaction is considered. Assume that the left and right walls of the square cavity whose side is L being maintained at the temperatures T_H and T_C respectively such that $T_H > T_C$. It is also assumed that the top and bottom walls of the cavity are adiabatic. The vector of gravity g works in the opposite direction to the y -axis. The suspension containing oxytactic microorganisms is based on the mathematical model of Hillesdon and Pedley [13]. The suspension is supposed to be dilute and inertia terms are ignored due to the very slow motion of bioconvective flow [10]. Considering the Boussinesq approximation, the steady-state governing equations can be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\frac{\mu}{K} u = -\frac{\partial p}{\partial x} \quad (2)$$

$$\frac{\mu}{K} v = -\frac{\partial p}{\partial y} - [\gamma \Delta \rho n - \rho_f \beta (T - T_C)] g \quad (3)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_c \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) - \delta n - kr(C - C_{\min}) \quad (5)$$

$$\frac{\partial}{\partial x} \left[un + \tilde{u}n - D_n \frac{\partial n}{\partial x} \right] + \frac{\partial}{\partial y} \left[vn + \tilde{v}n - D_n \frac{\partial n}{\partial y} \right] = 0 \quad (6)$$

Here u and v are components of velocity in x and y -directions, p is the excess pressure above hydrostatic, β is the coefficient of volumetric expansion of water at constant pressure, μ is the dynamic viscosity of the suspension, ρ_f is the density of the fluid, $\Delta\rho = \rho_{\text{cell}} - \rho_f$ is the difference between densities of cell and fluid, γ is the average volume of a microorganism, K is the permeability of the porous medium, T is the temperature of fluid, α_m is the effective thermal diffusivity of the porous medium, kr is the dimensional chemical reaction, C is the oxygen concentration, $\Delta C = C_0 - C_{\min}$ where C_0 is the concentration of oxygen at free surface, and $C_{\min}$ is the minimum concentration of oxygen required for microorganisms to be active. The parameter n is the number density of motile microorganisms, $-\delta n$ describes the consumption of oxygen by the microorganism. The terms $\tilde{u}$ and $\tilde{v}$ are given by

$$\tilde{v} = \left(\frac{bW_c}{\Delta C} \right) \frac{\partial C}{\partial y} \quad (7)$$

and

$$\tilde{u} = \left(\frac{bW_c}{\Delta C} \right) \frac{\partial C}{\partial x} \quad (8)$$

where b is the chemotaxis constant and W_c is the maximum cell swimming speed. Using the following dimensionless variables

$$X = \frac{x}{L}, Y = \frac{y}{L}, \Psi = \frac{\psi}{\alpha_m}, \theta = \frac{T - T_c}{\Delta T}, \phi = \frac{C - C_{\min}}{\Delta C}, N = \frac{n}{n_0} \quad (9)$$

where n_0 is the average density of the microorganism. Utilising dimensional stream function ψ , which is given by $u = \partial\psi / \partial y$ and $v = -\partial\psi / \partial x$, the following non-dimensionalised partial differential equations have resulted.

$$\frac{\partial^2 \Psi}{\partial X^2} + \frac{\partial^2 \Psi}{\partial Y^2} = -Ra \left(\frac{\partial \theta}{\partial X} - Rb \frac{\partial N}{\partial X} \right) \quad (10)$$

$$\frac{\partial \Psi}{\partial Y} \frac{\partial \theta}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial \theta}{\partial Y} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \quad (11)$$

$$\frac{\partial \Psi}{\partial Y} \frac{\partial \phi}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial \phi}{\partial Y} = \frac{1}{Le} \left(\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2} \right) - \frac{\sigma}{Le} N - Kr\phi \quad (12)$$

$$Le\chi \left(\frac{\partial \Psi}{\partial Y} \frac{\partial N}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial N}{\partial Y} \right) + Pe \left[\frac{\partial}{\partial X} \left(N \frac{\partial \phi}{\partial X} \right) + \frac{\partial}{\partial Y} \left(N \frac{\partial \phi}{\partial Y} \right) \right] = \frac{\partial^2 N}{\partial X^2} + \frac{\partial^2 N}{\partial Y^2} \quad (13)$$

where the parameters of bioconvection Rayleigh number Rb , Rayleigh number of porous medium Ra , Peclet number Pe , Lewis number Le , dimensionless chemical reaction Kr and constant σ are defined as

$$Ra = \frac{gK\beta\Delta TL}{\nu\alpha_m}, Le = \frac{\alpha_m}{D_c}, Rb = \frac{\gamma\Delta\rho n_0}{\rho_f\beta\Delta T}, \chi = \frac{D_c}{D_n}, Pe = \frac{bW_c}{D_n}, \sigma = \frac{\delta n_0 L^2}{D_c \Delta C}, \quad (14)$$

$$Kr = \frac{L^2 kr}{\alpha_m} \quad (15)$$

The dimensionless boundary conditions of Equations (13)-(15) are given by

$$\Psi = 0, \theta = 1, \phi = 1, N = 1 \text{ at } X = 0 \quad (16)$$

$$\Psi = 0, \theta = 0, \phi = 1, N = 1 \text{ at } X = 1$$

$$\Psi = 0, \frac{\partial \theta}{\partial Y} = 0, \phi = 1, PeN \frac{\partial \phi}{\partial Y} = \frac{\partial N}{\partial Y} \text{ at } Y = 0$$

$$\Psi = 0, \frac{\partial \theta}{\partial Y} = 0, \frac{\partial \phi}{\partial Y} = 0, \frac{\partial N}{\partial Y} = 0 \text{ at } Y = 1$$

The local Nusselt number Nu_Y , local Sherwood number Sh_Y , local density number of motile microorganisms Nn_Y on the vertical walls, average Nusselt number Nu_{avg} , average Sherwood number of oxygen concentration Sh_{avg} and average Sherwood number of microorganisms Nn_{avg} are given by

$$Nu_Y = -\left(\frac{\partial \theta}{\partial X}\right)_{X=0,1}, Sh_Y = -\left(\frac{\partial \phi}{\partial X}\right)_{X=0,1}, Nn_Y = -\left(\frac{\partial n}{\partial X}\right)_{X=0,1} \quad (17)$$

$$Nu_{avg} = \int_0^1 Nu_Y dY, Sh_{avg} = \int_0^1 Sh_Y dY, Nn_{avg} = \int_0^1 Nn_Y dY \quad (18)$$

3. Method of Solution

The finite element method of Galerkin's weighted residual approach is employed to solve the system of non-dimensionalised partial differential eq. (10)-(15) with associated boundary conditions (16). In this scheme, suitable trial solutions are deputed and residuals are collected. The product of residuals and weight functions is integrated over each element and assumed to be zero [45-47].

We write the approximate solutions of Ψ, θ, ϕ, N by

$$\Psi = \sum_{i=1}^3 \Psi_i \xi_i; \quad \theta = \sum_{i=1}^3 \theta_i \xi_i; \quad \phi = \sum_{i=1}^3 \phi_i \xi_i; \quad N = \sum_{i=1}^3 N_i \xi_i \quad (19)$$

where ξ_i are the linear interpolation functions for a triangular element. The model of Galerkin finite element method for a typical element Ω_e is given by

$$\begin{bmatrix} [K^{11}] & [K^{12}] & [K^{13}] & [K^{14}] \\ [K^{21}] & [K^{22}] & [K^{23}] & [K^{24}] \\ [K^{31}] & [K^{32}] & [K^{33}] & [K^{34}] \\ [K^{41}] & [K^{42}] & [K^{43}] & [K^{44}] \end{bmatrix} \begin{bmatrix} \{\Psi\} \\ \{\theta\} \\ \{\phi\} \\ \{N\} \end{bmatrix} = \begin{bmatrix} \{F^1\} \\ \{F^2\} \\ \{F^3\} \\ \{F^4\} \end{bmatrix} \quad (20a)$$

where

$$K^{11} = \iint_{\Omega_e} \left[\frac{\partial \xi_j}{\partial X} \frac{\partial \xi_i}{\partial X} + \frac{\partial \xi_j}{\partial Y} \frac{\partial \xi_i}{\partial Y} \right] dXdY \quad (20b)$$

$$K^{12} = -Ra \iint_{\Omega_e} \left[\xi_j \frac{\partial \xi_i}{\partial X} \right] dXdY; \quad K^{14} = RaRb \iint_{\Omega_e} \left[\xi_j \frac{\partial \xi_i}{\partial X} \right] dXdY \quad (20c)$$

$$F^1 = 0; K^{21} = 0; K^{31} = 0; K^{34} = 0; F^2 = 0 \quad (20d)$$

$$K^{22} = \iint_{\Omega_e} \left[\xi_j \frac{\partial \bar{\Psi}}{\partial Y} \frac{\partial \xi_i}{\partial X} - \xi_j \frac{\partial \bar{\Psi}}{\partial X} \frac{\partial \xi_i}{\partial Y} + \frac{\partial \xi_j}{\partial X} \frac{\partial \xi_i}{\partial X} + \frac{\partial \xi_j}{\partial Y} \frac{\partial \xi_i}{\partial Y} \right] dXdY \quad (20e)$$

$$K^{23} = 0; K^{32} = 0 \quad (20f)$$

$$K^{33} = \iint_{\Omega_e} \left[\frac{\partial \bar{\Psi}}{\partial Y} \xi_j \frac{\partial \xi_i}{\partial X} - \frac{\partial \bar{\Psi}}{\partial X} \xi_j \frac{\partial \xi_i}{\partial Y} + \frac{1}{Le} \left(\frac{\partial \xi_j}{\partial X} \frac{\partial \xi_i}{\partial X} + \frac{\partial \xi_j}{\partial Y} \frac{\partial \xi_i}{\partial Y} \right) + Kr \xi_j \xi_i \right] dXdY \quad (20g)$$

$$K^{34} = \iint_{\Omega_c} \frac{\sigma}{Le} \xi_j \xi_i dXdY \quad (20h)$$

$$F^3 = 0 \quad ; K^{41} = 0 \quad ; K^{42} = 0 \quad ; K^{43} = 0 \quad ; F^4 = 0 \quad (20i)$$

$$K^{44} = \iint_{\Omega_c} \left[Le \chi \left(\frac{\partial \bar{\Psi}}{\partial Y} \xi_j \frac{\partial \xi_i}{\partial X} - \frac{\partial \bar{\Psi}}{\partial X} \xi_j \frac{\partial \xi_i}{\partial Y} \right) + Pe \xi_j \xi_i \left(\frac{\partial^2 \bar{\phi}}{\partial X^2} + \frac{\partial^2 \bar{\phi}}{\partial Y^2} \right) + \left(\frac{\partial \xi_j}{\partial X} \frac{\partial \xi_i}{\partial X} + \frac{\partial \xi_j}{\partial Y} \frac{\partial \xi_i}{\partial Y} \right) \right] dXdY \quad (20j)$$

where

$$\bar{\Psi} = \sum_{j=1}^3 \bar{\Psi}_j \xi_j \quad ; \quad \bar{\theta} = \sum_{j=1}^3 \bar{\theta}_j \xi_j \quad ; \quad \bar{\phi} = \sum_{j=1}^3 \bar{\phi}_j \xi_j \quad (20k)$$

The convergence scheme of solutions is set when the relative error for each variable between two successive iterations is observed below the convergence criterion such that $|\varphi^{n+1} - \varphi^n| \leq 10^{-5}$, where n is the number of iterations and φ stands for Ψ , θ , ϕ and N . In order to choose the grid size, the grid independency test is executed for the grids 21×21 , 41×41 , 61×61 , 81×81 and 91×91 . The grid independence test reveals that a grid mesh of size 81×81 is tolerable to study the bioconvection phenomena correctly. The present model has been validated in the absence of chemical reaction and microorganisms. A comparison of present results with the works of Manole and Lage [48], Baytas and Pop [49], Revnic et al. [50] and Sheremet and Pop [51], made evident that the present results are in good agreement with the available results, as shown in Table 1.

Table 1. Comparison of the Nusselt numbers at the hot wall.

	Ra=10	Ra=100	Ra=1000
Manole and Lage [48]	-	3.118	13.637
Baytas and Pop [49]	1.079	3.16	14.06
Revnic et al. [50]	-	-	13.664
Sheremet and Pop [51]	1.079	3.115	13.667
Present results	1.08	3.129	13.7353

4. Results and Discussion

The numerical computations have been carried out for the investigation of the boundary value problem Eq. (10) - (14), for the following ranges of parameters: Rayleigh number ($Ra = 1 - 150$), bioconvection Rayleigh number ($Rb = 2 - 50$), chemical reaction parameter ($Kr = 1 - 20$), Lewis number ($Le = 0.01 - 1$) and Peclet number ($Pe = 0 - 1$). The range of each of the parameters is chosen owing to its significant effect on the physical problem.

4.1 Effect of Rayleigh number on streamlines

Figure 1 illustrates the effect of Rayleigh number Ra on streamlines, isotherms, oxygen isoconcentrations, and microorganisms isoconcentrations. The streamlines form a single cell occupying the entire cavity with anticlockwise rotation when $Ra = 10$. As Ra increases, the flow strength enhances and single-cell splits into two cells when $Ra = 150$, which are extended in opposite directions. The absolute values of streamlines increase with Ra .

4.2 Effect of Rayleigh number on isotherms

The isotherms are parallel to the heated walls when $Ra = 10$. As Ra increases, the isotherms are stratified horizontally at the center of the cavity indicating the convection mode of heat transfer. The heat transfer is high for higher values of Ra .

4.3 Effect of Rayleigh number on isoconcentrations of oxygen and microorganisms

It is observed that gradients of oxygen concentration and microorganisms concentration are more at the left, bottom and right walls of the cavity. Due to this reason less density is observed at the center of the cavity. A semi vortex is formed in the isoconcentrations of oxygen. As the Rayleigh number increased the vortex shifts towards the hot wall. It is also observed that a vortex is formed in the isoconcentrations of microorganisms indicating the low density of microorganisms at the center. As the Rayleigh number increased most of the low-density region is moved to the cold wall which characterizes the effect of oxytactic bacteria. The profiles of isoconcentrations of oxygen and microorganisms are pronounced by increasing the Rayleigh number. A vortex is formed in the isoconcentrations of oxygen and microorganisms which indicate the higher density of oxygen and motile organisms at centre of the cavity. The absolute values of isoconcentrations of oxygen and microorganisms increase with the increase in Ra .



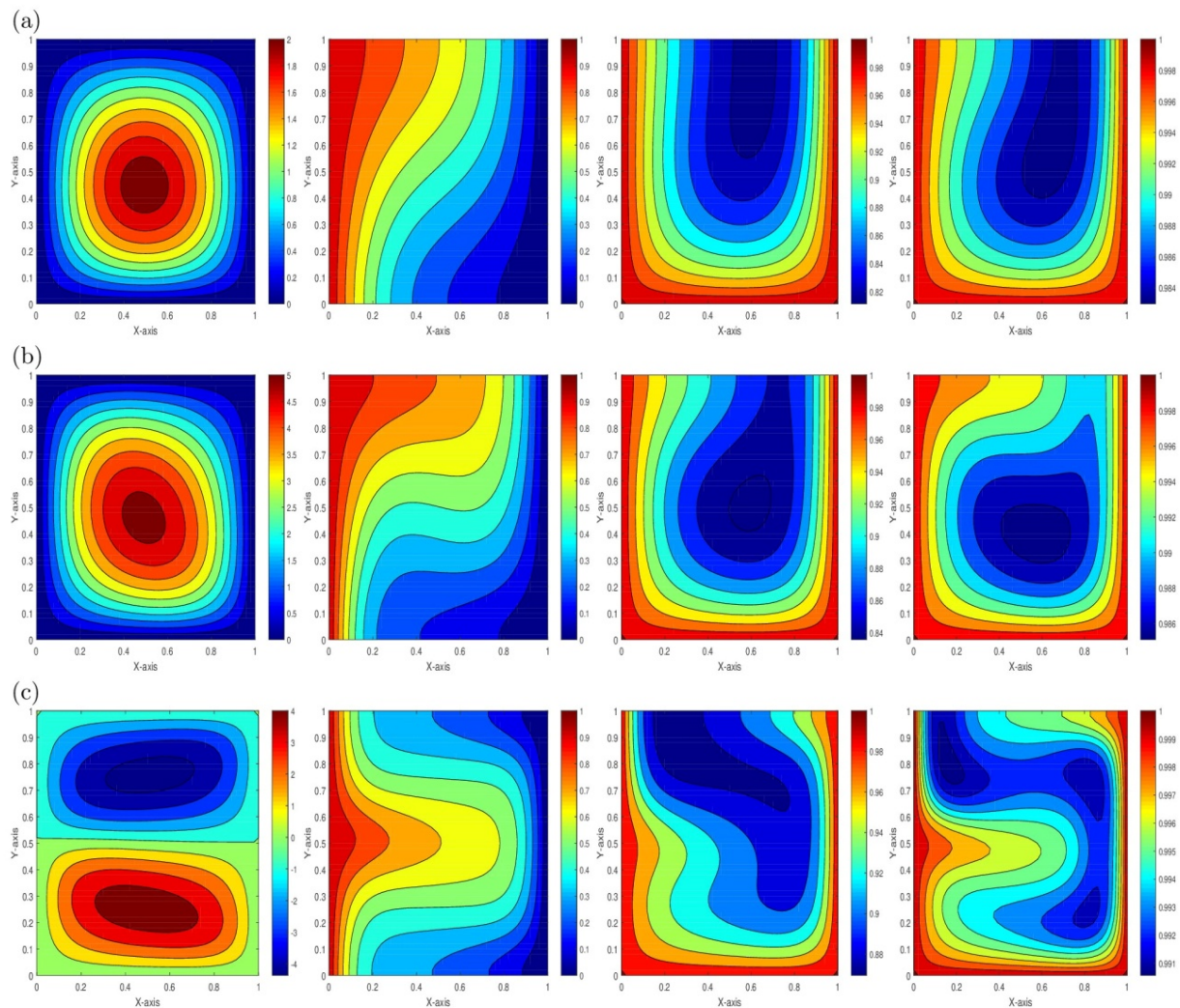


Fig. 1. Streamlines, Isotherms, oxygen isoconcentrations and microorganisms isoconcentrations for (a) $Ra=50$ (b) $Ra=100$ (c) $Ra=150$ and $Rb=10$, $Pe=0.1$, $Kr=5$, $Le=1$.

4.4 Effect of chemical reaction on streamlines

The effect of chemical reaction parameters on the streamlines, isotherms, and isoconcentrations of oxygen and microorganisms is shown in Fig. 2. Enhancement in Kr strongly pronounces the flow strength of streamlines. A vortex is formed at the center of the cavity it moves towards the bottom wall and flow gradient increases at the wall. As the chemical reaction increases to $Kr=10$, reverse flow at the top wall has occurred.

4.5 Effect of chemical reaction on isotherms

A significant effect of the chemical reaction is found on isotherms. When the chemical reaction is low the heat transfer to the top of the cold wall is high. The heat transfer shifts to the centre of the cavity, for the higher values of a chemical reaction due to the reverse swimming of microorganisms to the top of the cold wall.

4.6 Effect of chemical reaction on isoconcentrations of oxygen and microorganisms

Because of the boundary conditions, there is density flux of both oxygen and microorganisms near the left, bottom and right walls. The low-density region of oxygen shifts towards the bottom wall and the open end of semi vortex moves to hot wall. A vortex indicating low-density region of oxytactic bacteria is formed at the center of the cavity. The growth in chemical reaction weakens the bonding among the oxygen particles, So the values of isoconcentration decrease. Due to the increased chemical reaction between the species microorganisms move to the hot wall creating a low-density region near the bottom of cold wall. Physically, the reverse flow of oxytactic bacteria moves the open end of semi vortex to hot wall. The isoconcentration field of oxygen is strongly diminished by chemical reaction. As a result the isoconcentration field of microorganisms is also diminished.

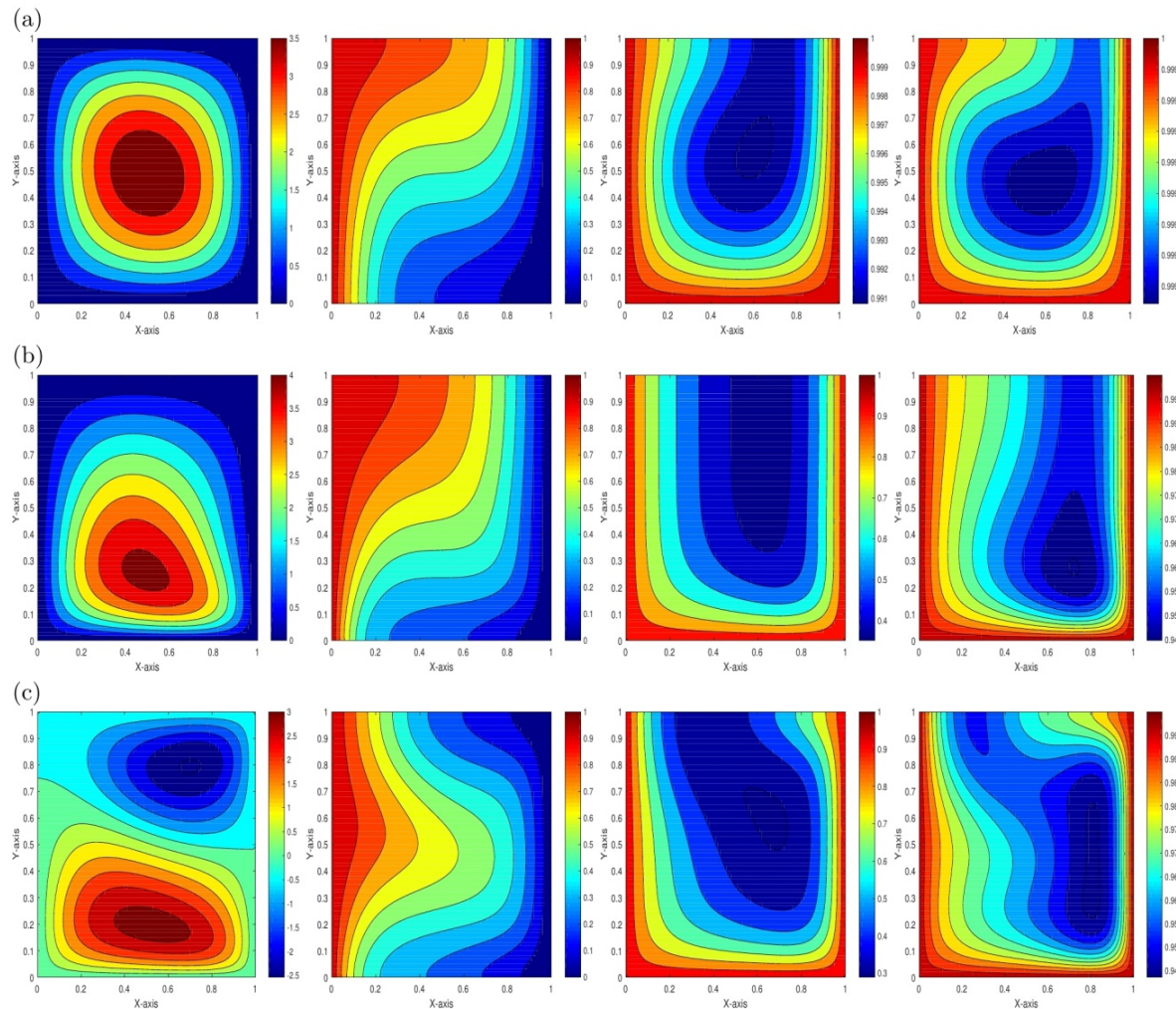


Fig. 2. Streamlines, Isotherms, oxygen isoconcentrations and microorganisms isoconcentrations for (a) $Kr=1$ (b) $Kr=5$ (c) $Kr=15$ and $Ra=70$, $Rb=10$, $Pe=0.1$, $Le=1$.

4.7 Effect of chemical reaction on average Nusselt number, average Sherwood numbers of oxygen concentration and microorganisms

Figure 3 shows the effect of chemical reaction versus Lewis number on average Nusselt number and Sherwood numbers. It is observed that the Nusselt number increases with an increase in Kr . This effect is pronounced with the increase in Le . The reverse phenomenon is observed in the case of the average Sherwood number of oxygen concentration. This is due to the dominance of swimming of oxytactic bacteria. The average Sherwood number of microorganisms reduces with chemical reaction parameter. The reduction is dominant when the Lewis number is high.

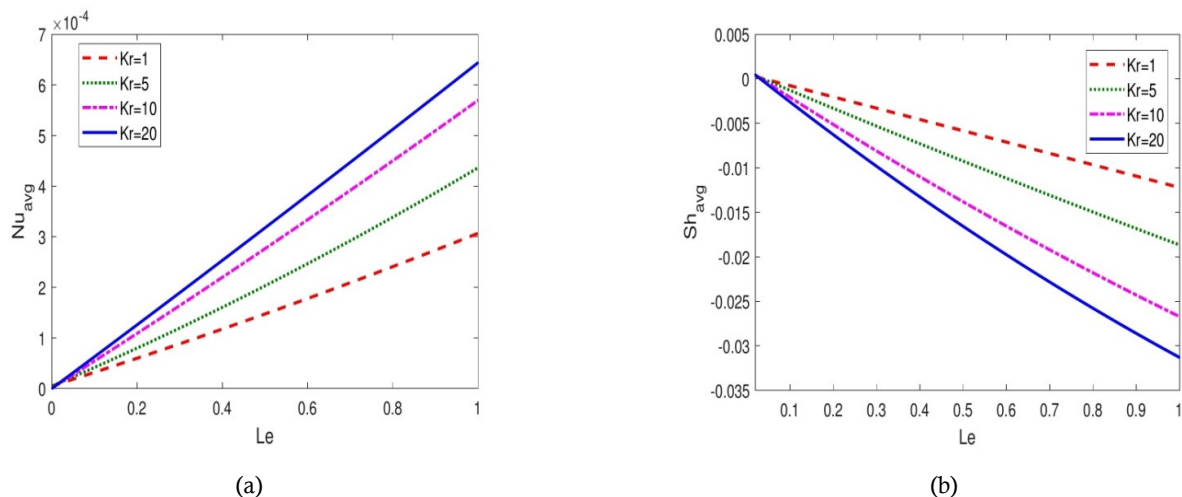
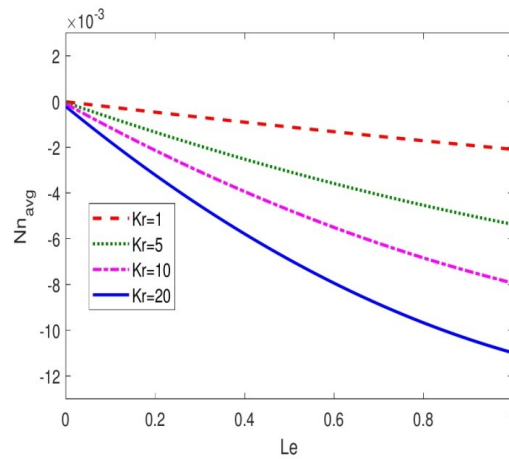
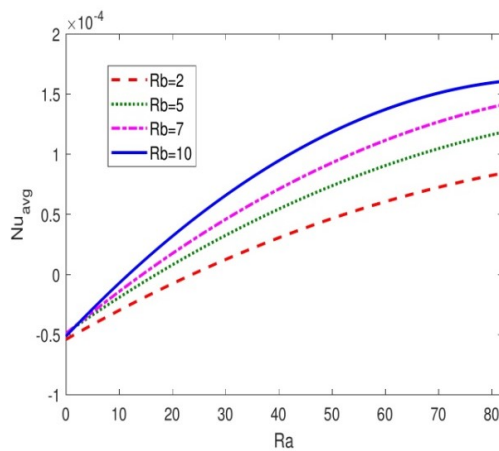


Fig. 3. Effect of chemical reaction parameter versus Peclet number (a) on average Nusselt number (b) average Sherwood number (c) average density number of microorganisms

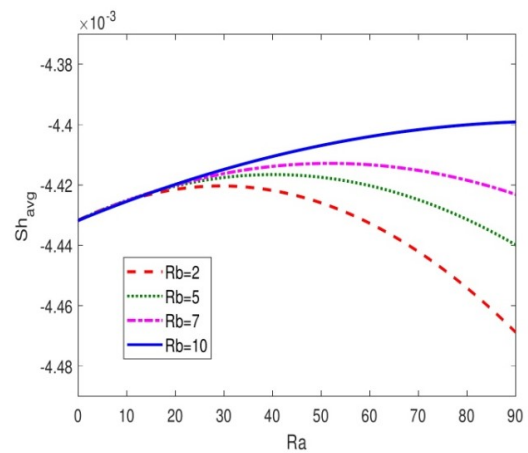


(c)

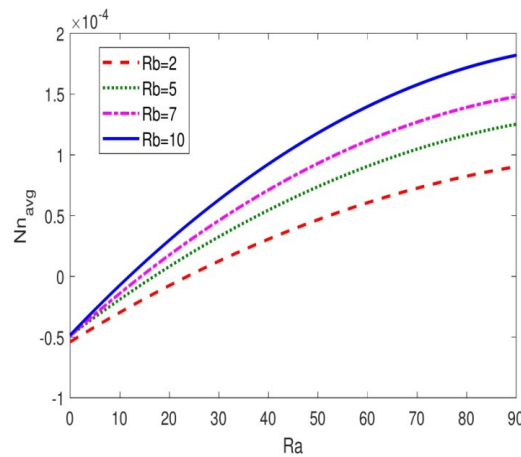
Fig. 3. Continued.



(a)



(b)



(c)

Fig. 4. Effect of bioconvection Rayleigh number versus Rayleigh number (a) on average Nusselt number (b) average Sherwood number (c) average density number of microorganisms

4.8 Effect of bioconvection Rayleigh number on average Nusselt number, average Sherwood numbers of oxygen concentration and microorganisms

The effect of bioconvection Rayleigh number versus the thermal Rayleigh number is presented in Fig. 4. It is observed that the Rayleigh number increases the average Nusselt number. The effect is augmented for higher values of bioconvection Rayleigh number. The average Sherwood number of oxygen concentration increases with Rb. Thermal Rayleigh number also increases the Sherwood number of oxygen concentration. But higher values of Ra decrease the Sherwood number of concentration. The nature of average Sherwood number of microorganisms is the same as that of Nusselt number for any Rayleigh number and bioconvection Rayleigh number.

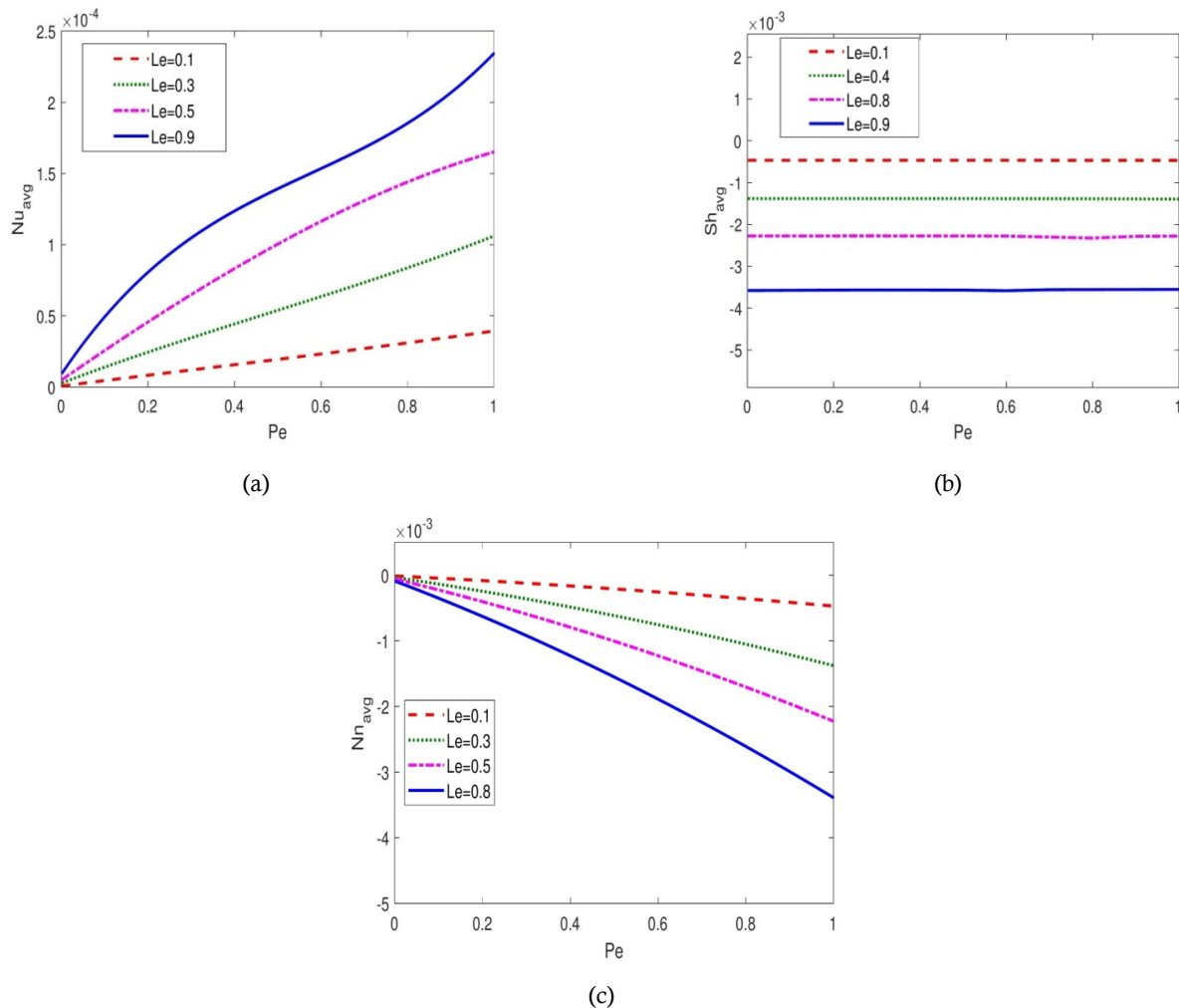


Fig. 5. Effect of Peclet number versus Lewis number (a) on average Nusselt number (b) average Sherwood number (c) average density number of microorganisms

4.9 Effect of Peclet number on average Nusselt number, average Sherwood numbers of oxygen concentration and microorganisms

Figure 5 shows the effect of Peclet number versus Lewis number on average Nusselt number and Sherwood numbers. From the figure, it is evident that the average Nusselt number is enhanced with the increase in Peclet number and Lewis number. The influence of the Peclet number is low for the high Lewis number. Lewis number decreases the average Sherwood number of oxygen concentration. The effect of the Peclet number is not significant on Sherwood number of oxygen concentration. The nature of average Sherwood number of microorganisms is opposite to that of average Nusselt number.

5. Conclusions

In this paper, bioconvection in a square cavity containing a suspension of oxytactic microorganisms in the presence of chemical reaction was investigated. The basic partial differential equations were transformed into non-dimensional form and solved using the finite element method. The streamlines, isotherms, isoconcentrations of oxygen and microorganisms and Nusselt number were calculated and presented graphically. The main conclusions could be summarized as:

- The flow strength is pronounced with Rayleigh number. Larger values of Rayleigh number form reverse swim patterns of microorganisms. Rayleigh number increases the fields of isoconcentrations of both oxygen and microorganisms. Isotherms are affected by the increase in Rayleigh number.
- Chemical reaction increases the flow cell and causes the splitting of the cell. Temperature distribution patterns are also affected by chemical reaction. Chemical reaction reduces the strength of isoconcentrations of both oxygen and microorganisms. The chemical reaction shows a greater effect on the swimming of the microorganisms.
- The average Nusselt number is increased with Peclet number, Rayleigh number, bioconvection Rayleigh number, and chemical reaction parameter but decreased with Lewis number.

- The average density number of oxytactic microorganisms increased with Rayleigh number and bioconvection Rayleigh number but decreased with chemical reaction parameter, Lewis number, and Peclet number.

Author Contributions

C.S. Balla planned the scheme and initiated the project; R. Alluguvelli developed the mathematical modeling and examined the theory validation; K. Naikoti developed the numerical code and performed computations. O.D. Makinde analyzed the numerical results and validated with empirical results. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The authors received no financial support for the research, authorship and publication of this article.

Nomenclature

b	Chemotaxis constant, m	Nn_{avg}	Average Sherwood number of microorganisms
α_m	Effective thermal diffusivity of the porous medium, m^2 / s	p	Excess pressure above hydrostatic
β	Volumetric thermal expansion coefficient of water at constant pressure, K^{-1}	Pe	Peclet number
C	Concentration of oxygen	ϕ	Dimensionless oxygen concentration
C_{min}	Minimum concentration of oxygen required for microorganisms to be active	ρ	Density of cell, Kg / m^3
C_0	Concentration at free surface	ρ_f	Fluid density, Kg / m^3
D_c	Diffusivity of oxygen, m^2 / s	Ra	Rayleigh number of porous medium
D_n	Diffusivity of microorganisms, m^2 / s	Rb	Bioconvection Rayleigh number
g	Acceleration due to gravity, m / s^2	ψ	Stream function, m^2 / s
V	Average volume of a microorganism	Ψ	Dimensionless stream function
K	Permeability of the porous medium	Sh_Y	Local Sherwood number of oxygen concentration
kr	Chemical reaction parameter	Sh_{avg}	Average Sherwood number of oxygen concentration
Kr	Dimensionless chemical reaction parameter	σ	Electric conductivity, S / m
L	Length of porous cavity, m	T	Temperature, K
Le	Lewis number	T_H	Temperature at hot wall, K
μ	Dynamic viscosity of the suspension, $(N.s) / m^2$	T_C	Temperature at cold wall, K
ν	Kinematic viscosity, m^2 / s	θ	Dimensionless temperature
n	Number density of motile microorganisms	u, v	Velocity components in x, y -directions, m / s
n_0	Average density of the microorganism	W_C	Maximum cell swimming speed
N	Dimensionless number density of microorganisms	χ	Constant
Nu_Y	Local Nusselt number	x, y	Cartesian coordinates, m
Nu_{avg}	Average Nusselt number	X, Y	Dimensionless coordinates
Nn_Y	Local Sherwood number of microorganisms		

References

- [1] Nield, D. A., Bejan, A., *Convection in Porous Media*, 4th edn., Springer, New York, 2013.
- [2] Ingham, D.B., Pop, I., *Transport Phenomena in Porous Media*, Vol. III., Elsevier, Oxford, 2005.
- [3] Vafai, K., *Handbook of Porous Media*, 2nd edition, Taylor and Francis, New York, 2005.
- [4] Pop, I., Ingham, D.B., *Convective Heat Transfer: Mathematical and Computational Modeling of Viscous Fluids and Porous Media*, Pergamon, Oxford, 2001.

- [5] Rahman, M.M., Pop, I., Saghir, M.Z., Steady free convection flow within a tilted nanofluid saturated porous cavity in the presence of a sloping magnetic field energized by an exothermic chemical reaction administered by Arrhenius kinetics, *International Journal of Heat and Mass Transfer*, 129, 2019, 198–211
- [6] Balla C.S., Haritha, C., Kishan, N., Magnetohydrodynamic convection in a porous square cavity filled by a nanofluid with viscous dissipation effects, *Proceedings of the Institution of Mechanical Engineers, Part E: J Process Mechanical Engineering*, 233(3), 2019, 474–488.
- [7] Balla, C.S., Kishan, N., Chamkha, A.J., Soret and Dufour effects on MHD natural convective heat and solute transfer in fluid-saturated porous cavity, *Journal of Porous Media*, 19(8), 2016, 669–686.
- [8] Balla C.S., Kishan, N., Haritha, C., Convection in Nanofluid-Filled Porous Cavity with Heat Absorption/Generation and Radiation, *Journal of Thermophysics and Heat Transfer*, 31(3), 2016, 549–562.
- [9] S. Childress, S., Levandowsky, M., Spiegel, E.A., Pattern formation in a suspension of swimming microorganisms-equations and stability theory, *Journal of Fluid Mechanics*, 69, 1975, 591–61.
- [10] Pedley, T.J., Hill, N.A., Kessler, J.O., The growth of bioconvection patterns in a uniform suspension of gyrotactic microorganisms, *Journal of Fluid Mechanics*, 195, 1988, 223–237.
- [11] Hill, N.A., Pedley, T.J., Kessler, J.O., Growth of bioconvection patterns in a suspension of gyrotactic microorganisms in a layer of finite depth, *Journal of Fluid Mechanics*, 208, 1989, 509–543.
- [12] Hillesdon, A.J., Pedley, T.J., Kessler, J.O., The development of concentration gradients in a suspension of chemotactic bacteria Bull, *Mathematical Biology*, 57, 1995, 299–344.
- [13] Hillesdon, A.J., Pedley, T.J., Bioconvection in suspensions of oxytactic bacteria: linear theory, *Journal of Fluid Mechanics*, 324, 1996, 223–259.
- [14] Makinde, O.D., Animasaun, I.L., Bioconvection in MHD nanofluid flow with nonlinear thermal radiation and quartic autocatalysis chemical reaction past an upper surface of a paraboloid of revolution, *International Journal of Thermal Sciences*, 109, 2016, 159–171.
- [15] Makinde, O.D., Animasaun, I.L., Thermophoresis and Brownian motion effects on MHD bioconvection of nanofluid with nonlinear thermal radiation and quartic chemical reaction past an upper horizontal surface of a paraboloid of revolution, *Journal of Molecular Liquids*, 221, 2016, 733–743.
- [16] Mutuku, W.N., Makinde, O.D., Hydromagnetic bioconvection of nanofluid over a permeable vertical plate due to gyrotactic microorganisms, *Computers and Fluids*, 95, 2014, 88–97.
- [17] Sheremet, M.A., Pop, I., Thermo bioconvection in a square porous cavity filled by oxytactic microorganisms, *Transport Porous Media*, 103, 2014, 191–205.
- [18] Kuznetsov, A.V., The onset of thermo-bioconvection in a shallow fluid-saturated porous layer heated from below in a suspension of oxytactic microorganisms, *European Journal of Mechanics B/Fluids*, 25, 2006, 223–233
- [19] Ahmed, S.E., Oztop, H.F., Mansour, M.A., Abu-Hamdeh, N., MHD Mixed Thermo-Bioconvection in Porous Cavity Filled by Oxytactic Microorganisms, *Thermal Science*, 22(6B), 2018, 2711–2721
- [20] Anwar Beg, O., Prasad, V.R., Vasu, B., Numerical Study Of Mixed Bioconvection in Porous Media Saturated with Nanofluid Containing Oxytactic Microorganisms, *Journal of Mechanics in Medicine and Biology*, 13(4), 2013, 1350067.
- [21] Tham, L., Nazar, R., Pop, I., Mixed convection flow over a solid sphere embedded in a porous medium filled by a nanofluid containing gyrotactic microorganisms, *International Journal of Heat and Mass Transfer*, 62, 2013, 647–660.
- [22] Khan, W.A., Makinde, O.D., Khan, Z.H., MHD boundary layer flow of a nanofluid containing gyrotactic microorganisms past a vertical plate with Navier slip, *International Journal of Heat and Mass Transfer*, 74, 2014, 285–291.
- [23] Khan, W.A., Makinde, O.D., MHD nanofluid bioconvection due to gyrotactic microorganisms over a convectively heat stretching sheet, *International Journal of Thermal Sciences*, 81, 2014, 118–124.
- [24] Saranya, S., Radha, K.V., Review of nano biopolymers for controlled drug delivery, *Polymer-Plastics Technology and Materials*, 53, 2014, 1636–1646.
- [25] Balla, C.S., Haritha, C., Kishan, N., Rashad, A.M., Bioconvection in nanofluid-saturated porous square cavity containing oxytactic microorganisms, *International Journal of Numerical Methods for Heat & Fluid Flow*, 29(4), 2019, 1448–1465.
- [26] Kumar, P.B.S., Gireesha, B.J., Mahanthesh, B., Chamkha, A.J., Thermal analysis of nanofluid flow containing gyrotactic microorganisms in bioconvection and second-order slip with convective condition, *Journal of Thermal Analysis and Calorimetry*, 136(5), 2019, 1947–1957.
- [27] Tlili, I., Khan, W.A., Ramadan, K., Entropy Generation Due to MHD Stagnation Point Flow of a Nanofluid on a Stretching Surface in the Presence of Radiation, *Journal of Nanofluids*, 7(5), 2018, 879–890.
- [28] Tlili, I., Khan, W.A., Ramadan, K., MHD Flow of Nanofluid Flow Across Horizontal Circular Cylinder: Steady Forced Convection, *Journal of Nanofluids*, 8(1), 2019, 179–186.
- [29] Tawfeeq A.A., Sheikholeslami, M., Usman, M., Haq, R.U., Shafee, Saad Al-Ahmadi, A., Tlili, I., Thermal management of MHD nanofluid within the porous medium enclosed in a wavy shaped cavity with square obstacle in the presence of radiation heat source, *International Journal of Heat and Mass Transfer*, 139, 2019, 87–94.
- [30] Anjalidevi, S.P., Kandasamy, R., Effect of chemical reaction, heat and mass transfer on laminar flow along a semi-infinite horizontal plate, *Heat and Mass Transfer*, 35, 1999, 465–472
- [31] Patil, P.M., Kulkarni, P.S., Effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation, *International Journal of Thermal Sciences*, 47, 2008, 1043–1054.
- [32] Das, K., Influence of chemical reaction and viscous dissipation on MHD mixed convection flow, *Journal of*

Mechanical Science and Technology, 28, 2014, 1881-1885.

- [33] Seddeek, M.A., Darwish, A.A., Abdelmeguid, M.S., Effects of chemical reaction and variable viscosity on hydromagnetic mixed convection heat and mass transfer for Hiemenz flow through porous media with radiation, *Communications in Nonlinear Science and Numerical Simulation*, 12, 2007, 195–213
- [34] Postelnicu, A., Influence of chemical reaction on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects, *Heat Mass Transfer*, 43, 2007, 595–602
- [35] Balla, C.S., Kishan, N., Radiation effects on unsteady MHD convective heat and mass transfer past a vertical plate with chemical reaction and viscous dissipation, *Alexandria Engineering Journal*, 2015, 54: 661-671.
- [36] Reddy, C.S., Kishan, N., Balla, C.S., MHD boundary layer flow and heat transfer of a nanofluid over a shrinking sheet with mass suction and chemical reaction, *Journal of Nanofluids*, 4, 2015, 518-527.
- [37] Balla, C.S., Haritha, C., Kishan, N., MHD double-diffusive convection in fluid-saturated inclined porous cavity with thermal radiation and chemical reaction, *Journal of Chemical Technology and Metallurgy*, 53(3), 2018, 518-536.
- [38] Zhang, C., Zheng, L., Zhang, X., Chen, G., MHD flow and radiation heat transfer of nanofluids in porous media with variable surface heat flux and chemical reaction, *Applied Mathematical Modelling*, 39, 2015, 165–181.
- [39] Manoj, K.N., Shaw, S., Makinde, O.D., Chemically reacting and radiating nanofluid flow past an exponentially stretching sheet in a porous medium, *Indian Journal of Pure & Applied Physics*, 56(10), 2018, 773-786.
- [40] Makinde, O.D., Egunjobi, A.S., Shuungula, O., Neossi-Nguetchue, S.N., Hydromagnetic chemically reacting and radiating unsteady mixed convection Blasius flow past surface flat in a porous medium, *International Journal of Computing Science and Mathematics*, 9(6), 2018, 525-538.
- [41] Mahanthesh, B., Mabood, F., Gireesha, B.J., Gorla, R.S.R., Effects of chemical reaction and partial slip on the three-dimensional flow of a nanofluid impinging on an exponentially stretching surface, *The European Physical Journal Plus*, 2017, 132(3), 113.
- [42] Hayat, T., Waqas, M., Khan, M.I., Alsaedi, A., Impacts of constructive and destructive chemical reactions in magnetohydrodynamic (MHD) flow of Jeffrey liquid due to nonlinear radially stretched surface, *Journal of Molecular Liquids*, 2017, 225, 302-310.
- [43] Hayat, T., Qayyum, S., Waqa, M., Ahmed, B., Influence of thermal radiation and chemical reaction in mixed convection stagnation point flow of Carreau fluid, *Results in Physics*, 2017, 7, 4058-4064.
- [44] Farooq, S., Khan, M.I., Hayat, T., Waqas, M., Alsaedi, A., Theoretical investigation of peristalsis transport in flow of hyperbolic tangent fluid with slip effects and chemical reaction, *Journal of Molecular Liquids*, 2019, 285, 314-322.
- [45] Balla, C.S., Kishan, N., Finite element analysis of magnetohydrodynamic transient free convection flow of nanofluid over a vertical cone with thermal radiation, *Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanomaterials, Nanoengineering, and Nanosystems*, 230(3), 2016, 161-173.
- [46] Balla, C.S., Kishan, N., Finite element analysis of fully developed unsteady MHD convection flow in a vertical rectangular duct with viscous dissipation and heat source/sink, *Journal of Applied Science and Engineering*, 18(2), 2015, 143-152.
- [47] Balla, C.S., Kishan, N., Finite element analysis of natural convective heat transfer in a porous square cavity filled with nanofluids in the presence of thermal radiation, *Journal of Physics: Conference Series*, 662, 2015, 012017.
- [48] Manole, D.M., Lage, J.M., Numerical benchmark results for natural convection in a porous medium cavity, *Heat and Mass Transfer Porous Media, ASME Conference*, 105, 1992, 44-59.
- [49] Baytas, A.C., Pop, I., Free convection in oblique enclosures filled with a porous medium, *International Journal of Heat and Mass Transfer*, 42, 1999, 1047-1057.
- [50] Revnic, C., Grosan, T., Pop, I., Ingham, D.B., Free convection in a square cavity filled with a bidisperse porous medium, *International Journal of Thermal Sciences*, 48, 2009, 1876-1883.
- [51] Sheremet, M.A., Pop, I., Thermo bioconvection in a square porous cavity filled by oxytactic microorganisms, *Transport Porous Media*, 103, 2014, 191-205.

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