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Original Research Paper

Numerical study of nanofluid thermo-bioconvection containing gravitactic microorganisms in porous media: Effect of vertical throughflow

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ABSTRACT

An analytical investigation of the onset of nanofluid thermo-bioconvection in a fluid saturated by porous media containing gravitactic and nanoparticles microorganisms subjected to a vertical throughflow is presented. The heat conservation equation is formulated by introducing the convective term of nanoparticle flux. The fluid is stimulated with modified Brinkman model, normal mode analysis and six-term Galerkin methods are used to solve the governing equations. The combined effects of vertical throughflow, nanoparticles, gravitactic microorganisms, and porosity have been taken into account. The effects of bioconvection Rayleigh number, bioconvection Péclet number, nanoparticle Rayleigh number, Péclet number, bioconvection Lewis number, and porosity on critical thermal Rayleigh number have been examined. The analysis leads that critical wave number is the function of bioconvection parameters, nanofluid parameters and throughflow parameters. It is also found that vertical throughflow disturbs the formation of bioconvection pattern which are necessary for the development of bioconvection.

1. Introduction

Wooding [1] was the first who introduced the concept of throughflow. By using the concept of critical Rayleigh number, Sutton [2] evaluated the vertical temperature gradient for a hydrothermal system. The effect of throughflow in packed beds and porous media is examined by [3,4]. Quoi and Kaloni [5] performed the nonlinear stability analysis using the energy method to study the combined effects of vertical throughflow and inclined temperature. They found that destabilization starts earlier for smaller values of the Péclet number. In other investigation, Chen [6] studied the convective instability in a superposed fluid with an effect of throughflow.

The impact of throughflow on bioconvection has many applications such as lithostatic pressure within the Earth's crust, mineralization in hydrothermal systems, and convection at the ocean crust [7–9]. Avramenko and Kuznetsov [10] studied the bioconvection containing gyrotactic microorganisms in the porous layer with vertical throughflow and found that vertical throughflow stabilizes the bioconvection. Patil and Rees [11] explored the combined effects of throughflow and local thermal nonequilibrium.

Bioconvection is a phenomenon that occurs when convective instability is induced by self-propelled up swimming microorganisms that are denser than cell fluid. Bioconvection has been used in water treatment plants, products like: ethanol, hydrogen gas, biofuel, fertilizers, biodiesel, and separation of vigorously swimming subpopulations and purification of cultures. Platt [13] introduced the term bioconvection and studied the moving polygonal patterns in dense cultures of Tetrahymena. Plesset and Winet [14] addressed the bioconvection in terms of Rayleigh-Taylor instability. In 1975, Childress et al. [15] were the first who proposed the extensive theory for bioconvection containing gravitactic microorganisms and also developed the mathematical model for gravitactic bioconvection. Pedley et al. [16] presented the theoretical bioconvective model for the gyrotactic microorganism. The growing volume of work devoted to experimental results, mathematical models, and mechanism of microorganisms is well documented by [17–21]. Kuznetsov and Ziang [22] found that critical value of permeability is approximately $4 \times 10^{-7} m^2$ and if critical value of permeability is smaller than $4 \times 10^{-7} m^2$, then no bioconvection develops. Kuznetsov and Avramenko [23] reported that spherical shape of microorganisms produces the more unstable disturbance. Bahoul et al. [24] numerically studied the linear stability of a bioconvection in a fluid layer. For slowly swimmers, the gravitactic

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Nomenclature

D_B	Brownian diffusion coefficient
D_m	diffusivity of microorganisms
D_T	thermophoresis diffusion coefficient
D_a	Darcy number
$\tilde{D}_a$	modified Darcy number
$\mathbf{g}$	gravity vector
H	dimensional layer depth
$\mathbf{j}$	flux of microorganisms
$\mathbf{k}$	vertically upward unit vector
k_m	effective thermal conductivity of porous media
κ	permeability of the porous media
L_b	bioconvection Lewis number
L_e	Lewis number
n	microorganism concentration
$\bar{n}$	average concentration of microorganisms
N_A	modified diffusivity ratio
N_B	particle density increment number
p	pressure
Q_v	Péclet number
Q_b	bioconvection Péclet number
R_a	thermal Rayleigh number
$\mathrm{R_b}$	bioconvection Rayleigh number
R_m	basic density Rayleigh number
R_n	nanoparticle Rayleigh number
t	time
T	temperature
T_c	reference temperature
$\mathbf{V}$	dimensionless Darcy velocity
W_0	vertical upward velocity
W_c	microorganisms velocity
(u, v, w)	Darcy velocity components
(x, y, z)	space co-ordinates

Greek symbol

α	Wave number
α_c	critical wave number
β_T	volumetric thermal expansion coefficient
$\Delta\rho = \rho_{cell} - \rho_f$	difference between cell density and a fluid density
μ	viscosity
$\tilde{\mu}$	effective viscosity
θ	average volume of microorganisms
ϕ	nanoparticles volume fraction
ρ_p	density of nanoparticles
ρ_f	density of the base fluid
$(\rho c)_p$	heat capacity for the nanoparticles
$(\rho c)_f$	heat capacity for the fluid
$(\rho c)_m$	effective heat capacity for the porous media

Subscript

b	Basic state
c	Upper boundary
h	Lower boundary

Superscript

$*$	dimensional variable
$'$	perturbed state

bioconvection is similar to Bénard convection, while for faster swimmers, this phenomenon is quantitatively and qualitatively different from Bénard convection [25]. Kuznetsov [26] found the correlation between two Rayleigh number, bioconvection Rayleigh number, and traditional Rayleigh number.

Due to a vast range of applications, nanofluids are widely used in cooling, micro heat pipes, microchannel heat sinks, microreactors, cancer therapy, sterilization of medical suspensions, process industries, polymer coatings, aerospace tribology, microfluid delivery devices etc [27,28]. Buongiorno [29] was perhaps the first who proposed a model, which predicts the behavior of nanoparticles. Using the Buongiorno model, Tzou [30] and Nield and Kuznetsov [31,32] investigated the thermal Rayleigh instability of nanofluid and found that nanoparticles enhance the thermal conductivity of the fluid. Nield and Kuznetsov [33] also examined the effect of throughflow on instability in nanofluid saturated by porous medium. In 2013, Baehr and Stephan [34] gave the concept of physically realistic boundary conditions and proposed zero nanoparticle flux on the boundaries. Incorporating the suggestions made by [34], Nield and Kuznetsov [35,36] revised their work [31,33] by considering the more realistic boundary conditions. Double diffusive mixed convection in a porous cavity is analytically studied by Sheremet et al. [37]. Sheremet et al. [38] also examined the natural convection of a nanofluid in a wavy-walled porous cavity and they found that local heat source has an efficient influence of the heat transfer rate. Recently, Saini and Sharma [39] studied the thermal instability in Rivlin-Erickson Elastico-Viscous nanofluid with the effect of throughflow and found that throughflow stabilizes the system.

Kuznetsov [40,41] extended the work of [31,32] for the suspension containing both gyrotactic microorganisms and nanoparticles. He observed that adding the microorganisms to a nanofluid increases the stability of a suspension. Later, Sheremet and Pop [42] extended the work of [26] to the case of bioconvection in a square porous cavity filled by microorganisms. Nanofluid with bioconvection may find useful applications in different biomicrosystems, such as inflammatory responses, chip-size microdevices for assessing nanoparticle toxicity, toxic of the lung to silica nanoparticles, enzyme biosensors, mass transport enhancement, and mixing [43,44].

In the present paper, we study the effect of vertical throughflow on nanofluid thermo-bioconvection using the modified mass flux condition. Our attention is mainly focused on the dependence of various parameters such as nanofluid parameters, bioconvection parameters, and throughflow parameters on thermal Rayleigh number and wave number. Also, this work has some relevance to highly efficient microbial fuel cells utilizing Bacillus licheniformis, bioconvection nanotechnological devices, and bioconvection in motile thermophilic microorganisms.

2. Problem formulation

We consider a plane horizontal porous layer with thickness H, saturated by nanofluid with gravitactic microorganisms confined between the planes $Z^* = 0$ and $Z^* = H$ (see Fig. 1). It is assumed that the nanoparticles suspended in the base fluid are stable [45], and the concentration of nanoparticles is than 1% (since the larger concentration of nanoparticles would suppress bioconvection instability [2]). The base fluid is water so that microorganisms can stay alive in it. Nanoparticles do not affect the velocity and direction of gravitactic microorganisms. It is assumed that motion of microorganism's can be split into random and directional components [15]. Nanofluid is assumed to be Newtonian, laminar, and

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