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Mixed convection flow in a channel with slip in a porous medium saturated with a nanofluid containing both nanoparticles and microorganisms

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ABSTRACT

The fully developed mixed convection channel flow in a porous medium saturated with a nanofluid in suspension of nanoparticles and microorganisms driven by its upper moving stripy wall is investigated. By a set of similarity variables, we reduce the governing equations of the conservation of total mass, momentum, thermal energy, nanoparticle volume fraction and microorganisms to four coupled nonlinear ordinary differential equations. The accurate solutions are obtained analytically. Besides, effects of physical parameters on important physical quantities are examined and discussed in detail. The transport mechanism of heat and mass due to the permeability, the slip parameter, the thermophoresis and Brownian diffusions, as well as the bioconvection diffusion is presented. As far as we know, the channel flow of a nanofluid with accelerating wall(s) is not yet considered before. Hence this investigation is original and new. It is expected that the current analysis can be applied in the petroleum engineering where nanoparticles and microorganisms play a role on exploitation efficiency enhancement and energy conservation.

1. Introduction

Flow driven in a channel has many important applications in many fields of industrial processes including power generation, chemical processes and heating or cooling processes and so on. At early stage, researchers mainly focuses on the purely fluid flow in channels. Many different cases including porous walls, accelerating or moving walls, expanding and contracting walls were considered, typical studies have been done by Berman [1], Morduchow [2], Terrill [3], Shrestha [4], Robinson [5], Skalak and Wang [6], Brady [7], Watson et al. [8], Cox and King [9], Dauenhauer and Majdalani [10], Xu et al. [11]. Later, researchers paid their attention to study convection heat transfer problems in a channel. Various configurations have been attacked, such as isothermal wall, linear temperature distributions or constant heat flux on the wall, some investigations can be found in Jagadeesan [12], Soundalgekar and Haldavnekar [13], Jana [14], Rao and Krishna [15], Raju and Rao [16], Pop et al. [17], Rao et al. [18], Seth and Singh [19], Seth et al. [20].

Since Choi [21] proposed the concept of nanofluids, several mathematical models have been established such as the homogenous flow model [21], the dispersion model [22] and the Buongiorno's model [23]. Several researchers made extension of the channel flow and heat transfer from Newtonian fluids to nanofluids. For example, Mohamad [24] putted forward to explain the magic of heat transfer enhancement by adding a few percentages of nanoparticles to the working pure fluid. Huminic and Huminic [25] summarized a list of published work on the heat transfer and fluid flow characteristics in curved tubes using conventional fluids and nanofluids as working fluids. Mohamad [24] putted forward to explain the magic of heat transfer enhancement by adding a few percentages of nanoparticles to the working pure fluid. Huminic and Huminic [25] summarized a list of published work on the heat transfer and fluid flow characteristics in curved tubes using conventional fluids and nanofluids as working fluids. Sheikholeslami et al. [26] considered a MHD flow of a nanofluid in a semi-porous channel. Raza et al. [27] analyzed a MHD flow and heat transfer of Cu-water nanofluid in a porous channel driven by stretching walls. Khan et al. [28–30] studied the effects of a magnetic field on nanofluid in mixed convection flow with constant wall temperature. You et al. [31] presented an analysis on

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Nomenclature

b	chemotaxis constant [m]
C	nanoparticle volumetric fraction [–]
C_w	nanoparticles volume fraction [–]
ΔC	nanoparticle volume fraction on the lower wall and at far field, $\Delta C = C_1 - C_0$ [–]
D_B	Brownian diffusion coefficient [m^2 s^{-1}]
D_n	diffusivity of microorganisms [m^2 s^{-1}]
D_T	thermophoretic diffusion coefficient [m^2 s^{-1}]
$\mathbf{j}$	flux of microorganisms, $\mathbf{j} = N\mathbf{v} + N\tilde{\mathbf{v}} - D_n\nabla N$ [kg m^2 s^{-1}]
K	permeability of the porous medium [m d^{-1}]
K_1	permeability parameter [–]
k_m	effective thermal conductivity of the porous medium [m^2 s^{-1}]
Le	Lewis number [–]
N	density motile of microorganisms [–]
N_B	Brownian motion coefficient [–]
N_T	thermophoresis parameter [–]
N_w	concentration of the motile microorganisms [–]
p	pressure [Pa]
Pe_b	bioconvection Péclet number [–]
Pr	Prandtl number [–]
q_{mw}	wall mass flux [kg m^{-2} s^{-1}]
q_{nw}	wall motile microorganisms flux [kg m^{-2} s^{-1}]
q_{Tw}	wall heat flux [W m^{-2}]
Re	Reynolds number, $Re = aH^2/\nu_m$ [–]
s_1	slip length [m]
S_1	slip parameter [–]
Sc	Schmidt number [–]
T	temperature [K]
T_w	wall distributions of the temperature[K]
u, v	velocity components along x and y respectively [m s^{-1}]
u_w	wall stretching velocity, $u_w = ax$, [m s^{-1}]
U_R	average velocity of channel flow, $U_R = aH$[m s^{-1}]
$\mathbf{v}$	flow velocity [m s^{-1}]
$\tilde{\mathbf{v}}$	velocity vector relating to the cell swimming in nanofluids, $\tilde{\mathbf{v}} = (bW_c/\nabla C)\Delta C$ [m s^{-1}]
W_c	maximum cell swimming speed [m s^{-1}].

Greek symbols

α_m	thermal diffusivity of the porous medium, $\alpha_m = k_m/(\rho c)_f$ [m^{-2} s^{-1}]
ϵ	porosity [–]
μ	viscosity of the fluid [kg m^{-1} s^{-1}]
μ_m	effective viscosity of the porous medium [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ν_m	kinematic viscosity of porous medium, $\nu_m = \nu/\epsilon$ [m^2 s^{-1}]
ρ_f	fluid density [kg m^{-3}]
$(\rho c)_f$	heat capacity of the fluid [J kg^{-1} K^{-1}]
$(\rho c)_p$	heat capacity of the nanoparticle material [J kg^{-1} K^{-1}]
σ	pressure constant [–]
τ	nanofluid heat capacity ratio, $\tau = \epsilon(\rho c)_p/(\rho c)_f$ [–]

fully developed opposing mixed convection flow in an inclined channel filled with a nanofluid. Xu and Pop [32] studied a laminar mixed convection flow in a horizontal channel filled by a nanofluid in suspension of both nanoparticles and gyrotactic microorganisms. Recently, Uddin et al. [33–35] studied the bio-nanofluid containing gyrotactic microorganisms under different conditions. Rashidi et al. [36] compared the single- and two-phase modeling approaches for forced convection flow of a nanofluid.

Many aspects of bio-convection flow problems in suspensions of small solid particles were investigated by several researchers such as Kuznetsov and Avramenko [37], Geng and Kuznetsov [38,39], Kuznetsov and Geng [40], and Kuznetsov [41]. Recently, Kuznetsov [42–44] analyzed a bio-convection flow that both nanoparticles and microorganisms are suspended. His found that the stability of nanofluids can be improved when appropriate gyrotactic microorganisms are added. He further found that suspensions of small microorganisms could exhibit a macroscopic motion in the fluid induced by upswimming or the motion of microorganisms. Currently, thermo-bioconvection has great potentials in practical applications such as exploitation of oil and gas from sedimentary basins [45] and microbial enhanced oil recovery [46,47].

The aim of the present study is to investigate a fully developed mixed convection flow in a porous medium saturated with a nanofluid containing both nanoparticles and small microorganisms between two paralleled horizontal flat plates driven by its upper stretching stripy wall. The Buongiorno's model [23] is applied for formulation of flow problem. Particularly, the slip boundary condition is imposed on the upper stretching wall of the channel, which makes this work different from previous studies. A set of coupled nonlinear equations with linear boundary conditions are obtained via similarity reductions, Accurate solutions are given. Besides, the influences of various governing parameters on important physically quantities such as the skin friction, the Nusselt number, the Sherwood number, as well as the fluxes of motile microorganisms are graphically presented and discussed. The inherent physical transport mechanisms are given. As far as we know, this problem is never considered before so that the results are new and original.

2. Basic equations

Consider a fully developed mixed convection flow of a porous medium in suspension of nanoparticles and microorganisms driven by its upper moving stripy wall between two paralleled horizontal plates separated by a distance $2H$. As shown in Fig. 1, the Cartesian coordinate system is chosen with the x-axis being along the channel walls and the y-axis being orthogonal to the channel walls. The upper wall has tiny stripes and is stretched by a velocity $u_w = ax$, while the lower wall is flat and keeps stationary. The distributions of temperature, nanoparticles fraction and the microorganisms on both walls are all constant. It should be noted that the

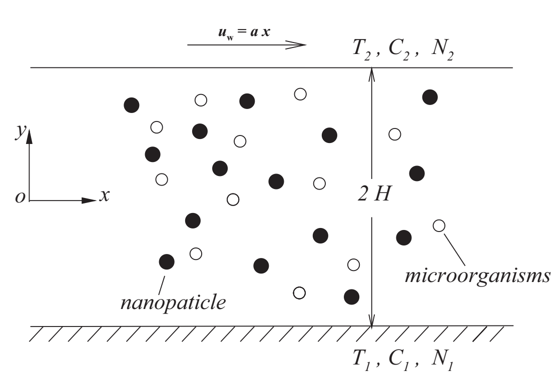

Fig. 1. Physical sketch.