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Analysis of mixed convection flow in an inclined lid-driven enclosure with Buongiorno's nanofluid model

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ABSTRACT

The laminar mixed convection flow in an inclined lid-driven cavity filled with a nanofluid is investigated in the presence of internal heat generation. The two sidewalls of the enclosure are sinusoidally heated while the top and bottom walls are insulted. The Buongiorno's model that incorporates the effects of Brownian motion and thermophoresis is applied to describe the nanofluid behaviours. Parametrical studies are given on the regimes of the complex flow, temperature and concentration fields. The developed equations are nondimensionalized and then solved numerically by the newly developed wavelet-homotopy technique. Comparisons with previously studies in literature are presented and found to be in excellent agreement. The results of this work indicate that the Grashof number, the slipping parameters, the nanoparticles related parameters, the inclination, the boundary coefficients including amplitude ratios of temperature and concentration, as well as the phase deviation have significant effects on characteristics of the cavity flow.

1. Introduction

Mixed convection in fluid-filled square cavities is of great interest in the fields of science and engineering. Its applications include atmosphere flow [1], lakes and reservoirs [2], nuclear reactors [3], chemical equipment [4], lubrication grooves [5], solar collectors [6], solidification process [7] and float grass production [8]. Many studies have been done on various aspects of cavity flows and heat transfer. Among them, Torrance et al. [9] studied the combined effects of the lid driven wall and the buoyancy on the cavity flows. Iwatsu et al. [10] carried on a detailed studies on mixed convection in a driven cavity with a vertical temperature gradient. Aydim [11] examined the mechanisms of aiding and opposing mixed convection flows in a shear and buoyancy-driven cavity. Cheng and Liu [12] respectively considered the influences of the temperature gradient orientation and the inclination on the characteristics of mixed convection flow in a lid-driven square cavity. Waheed [13] examined the mixed convective flow and heat transfer in rectangular enclosures driven by a continuously moving horizontal plate. Other classical investigations involving various aspects of mixed convection cavity flows such as the inclination and non-uniform heated boundaries were given by Oztop and Dagtekin [14], Chattopadhyay et al. [15], Sharif [16], Basak et al. [17], Sivasankaran et al. [18].

Nanofluids are found to have great potentials for heat transfer enhancement become they have higher thermal conductivity and convective heat transfer coefficient than pure fluids. Nanofluids are expected to be used in contemporary engineering problems involving into solar collectors, polymerase chain reaction efficiency, electronic cooling system and radiators. Comprehensive literature reviews and books referring to behaviours of convective flow of nanofluids have been done by Das et al. [19], Yu et al. [20], Kakaç and Pramuanjaroenkij [21], Murshed et al. [22], Özerinç [23], Saidur *et al.* [24], Bejan [25]. Several mathematical models have been proposed for description of nanofluids' characteristics, such as the homogenous flow model [26], the dispersion model [27], the Buongiorno's model [28]. Among them, the Buongiorno's model are most plausible owing to its reasonable explanation on the slip mechanisms between the relative velocity of nanoparticles and base fluid.

Some investigations on nanofluid flow and heat transfer in various configurations of cavities have been conducted by Tiwari and Das [29], Chamkha et al. [30], Abu-Nada et al. [31], Talebi et al. [32], Esfe et al. [33], Sheikholeslami et al. [34–43] and Öztop et al. [44–47]. However, most of them are based on the homogenous flow models, which are incompatible with the experimental observation by Buongiorno [28] about the pure fluid correlations

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(such as Dittus-Boelter's) deviating from the heat transfer coefficient of nanofluid, or the comparison of analytical predictions and experimental results on a nanofluid flow in a uniformly heated tube by Maïga et al. [48].

It is worth mentioning that several researchers [49–53] have paid their attention to nanofluids flow in cavities using the Buongiorno's model [28]. However, many aspects of them are not yet investigated with this model, such as the combination influences of lid-driven directions, inclination, non-uniform temperature and nanoparticles distributions, and buoyancy.

In this paper, the mixed convection flow in an inclined cavity filled with nanofluids in the presence of nonuniform temperature and nanoparticle distributions are to be investigated. The Buongiorno's model will be applied to formulate the flow problem. The nondimensionalized governing equations are to be solved numerically by the newly developed wavelet-Galerkin homotopy technique [54]. Discussions about the effects of various parameters such as the Grashof number, the slipping parameters, the nanoparticles related parameters, the inclination, the boundary coefficients including amplitude ratios of temperature and concentration on behaviours of nanofluid flow in the cavity are to be performed.

2. Mathematical descriptions

A schematic diagram of a two-dimension inclined cavity filled by water-statured nanofluid with physical dimensions is illustrated in Fig. 1. The origin of the Cartesian coordinate system is located at the lower left corner, x-, y-axis are along the length and height of the cavity respectively, H is the square scale. The top and bottom lids of the cavity move with the constant velocity U_0 and λU_0, while the two sidewalls are kept stationary respectively. Here $\lambda = 0$ indicates that the bottom wall is stationary, $\lambda = \pm 1$ means that the bottom wall has the same velocity scale as the top one in coincidentally or inversely. The top and bottom walls are thermally isolated without concentration variation of nanoparticles, while the two sidewalls are sinusoidally heated and linearly distributed with nanoparticles volume fraction.

$$\nabla \cdot \mathbf{V} = 0, \tag{1}$$

$$\rho_f \frac{D\mathbf{V}}{Dt} = -\nabla P + \mu \nabla^2 \mathbf{V} + (\rho_f - \rho_0)\mathbf{g}, \tag{2}$$

$$\rho_f c_f \frac{DT}{Dt} = \nabla \cdot k_f \nabla T + \rho_p c_p \left[D_B \nabla T \cdot \nabla C + \left(\frac{D_T}{T_0}\right) \nabla T \cdot \nabla T \right], \tag{3}$$

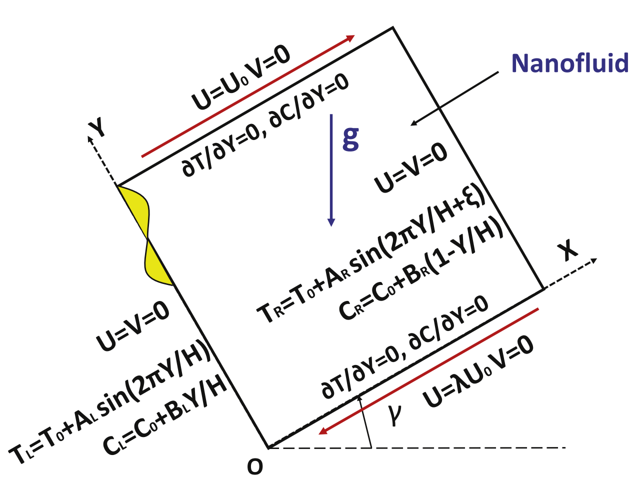

Fig. 1. Schematic diagram of the physical system.

$$\frac{DC}{Dt} = D_B \nabla^2 C + \left(\frac{D_T}{T_0}\right) \nabla^2 T, \tag{4}$$

where $\mathbf{V}$ is the velocity vector, P is the fluid pressure, T is the fluid temperature, C is the nanoparticle volume fraction, μ is the dynamic viscosity, $\mathbf{g}$ is the gravity vector, ρ is the density and c is the specific heat with the subscripts f denoting nanofluid and p denoting nanoparticles, k_f is the thermal conductivity, D_B is the Brownian diffusion coefficient, D_T is the thermophoretic diffusion coefficient, T_0 is the reference temperature, respectively.

It is known that Nield and Kuznetsov [55] once expressed the buoyancy term of Eq. (2) via the linear Boussinesq approximation in the following form

$$\rho_f - \rho_0 \approx (C - C_0)(\rho_p - \rho_{w0}) - (1 - C_0)\rho_{w0}\beta_T(T - T_0), \tag{5}$$

which is obtained using the correlations

$$\rho_f = \rho_p C + (1 - C)\rho_w, \quad \rho_0 = \rho_p C_0 + (1 - C_0)\rho_{w0}, \tag{6}$$

where the subscripts 0 denotes the reference value, w denotes the base fluid.

However, too many parameters are involved in their expression, it is not easy to distinguish the effects of various physical progresses. In stead, we suggest another model used in the boundary layer flow with chemical reaction [56], which is written as

$$\rho_f = \rho_0[1 - \beta_T(T - T_0) - \beta_C(C - C_0)]. \tag{7}$$

Here β_T, β_C are coefficients of thermal and concentration expansions and the subscript zero refers to a reference states, respectively. This expression is easier to show the individual effects of temperature and nanoparticle on the buoyancy.

Since the flow transients are always smooth, the steady mixed convection flow in a square cavity makes sense compared to the unsteady one. The governing Eqs. (1)–(4) for the steady case are written as follows,

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0, \tag{8}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{1}{\rho_f}\frac{\partial P}{\partial X} + \nu\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + \frac{\rho_0 - \rho_f}{\rho_f} g \sin\gamma, \tag{9}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{\rho_f}\frac{\partial P}{\partial Y} + \nu\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \frac{\rho_0 - \rho_f}{\rho_f} g \cos\gamma, \tag{10}$$

$$U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \alpha\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) + \tau D_B\left(\frac{\partial T}{\partial X}\frac{\partial C}{\partial X} + \frac{\partial T}{\partial Y}\frac{\partial C}{\partial Y}\right) + \tau\left(\frac{D_T}{T_0}\right)\left[\left(\frac{\partial T}{\partial X}\right)^2 + \left(\frac{\partial T}{\partial Y}\right)^2\right], \tag{11}$$

$$U\frac{\partial C}{\partial X} + V\frac{\partial C}{\partial Y} = D_B\left(\frac{\partial^2 C}{\partial X^2} + \frac{\partial^2 C}{\partial Y^2}\right) + \left(\frac{D_T}{T_0}\right)\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right), \tag{12}$$

where U, V are the velocity components in X, Y direction, ν is the kinetic viscosity, $\alpha = k_f/(\rho_f c_f)$ denotes the effective thermal diffusivity, $\tau = (\rho c)_p/(\rho c)_f$ is the heat capacity ratio. The corresponding boundary conditions to this problem are

$$\begin{aligned} &U = \lambda U_0, \quad V = 0, \quad \frac{\partial T}{\partial Y} = 0, \quad \frac{\partial C}{\partial Y} = 0, \quad \text{on} \quad Y = 0, \\ &U = U_0, \quad V = 0, \quad \frac{\partial T}{\partial Y} = 0, \quad \frac{\partial C}{\partial Y} = 0, \quad \text{on} \quad Y = H, \\ &U = 0, \quad V = 0, \quad T = T_L, \quad C = C_L, \quad \text{on} \quad X = 0, \\ &U = 0, \quad V = 0, \quad T = T_R, \quad C = C_R, \quad \text{on} \quad X = H. \end{aligned} \tag{13}$$