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Natural convection of Al_2O_3-water nanofluid in an inclined cavity using Buongiorno's two-phase model

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ABSTRACT

In the present study, natural convection of Al_2O_3–water nanofluid and nano-particles local distribution inside a tilted square enclosure has been investigated using non-homogenous two-phase Buongiorno's model. The left and right vertical walls of cavity are kept at constant temperatures T_h and T_c, respectively, while the other walls are thermally insulated. Using the finite volume method and the SIMPLE algorithm, the governing equations have been discretized. Simulations have been carried out for different inclination angle ($0^\circ \le \theta \le 60^\circ$), Rayleigh number ($10^2 \le Ra \le 10^6$) as well as particle average volume fraction (φ) ranging from 0.01 to 0.04. Results show that at low Rayleigh numbers regardless of particle volume fraction, with increasing the inclination angle the average Nusselt number (Nu_{Ave}) and heat transfer enhancement percentage remains almost constant. On the other hand, for high Rayleigh numbers Nu_{Ave} rises and then reduces with inclination angle whereas, heat transfer enhancement percent continuously increases with increasing inclination angle. It is also observed that for all inclination angles and at low Rayleigh numbers, the particle distribution is fairly non-uniform while, at high Ra numbers particles have nearly uniform distribution.

1. Introduction

Because of wide applications of the natural convection, it becomes one of the major topics of research in the last two centuries. These applications occur in industrial and technological applications such as crystal growth, electronic cooling, oil extraction, solar collectors and etc.

Researchers and engineers are extensively seeking to find new ways to respond to industrial demands in the area of advanced thermal sciences. Maxwell's idea of suspension metallic millimeter- or micrometer-sized particles to enhance the thermal conductivity of fluid is well-known [1]. However, such particles cannot be used in micro-systems and micro-devices because of serious problems such as abrasion and clogging. However, modern nanotechnology provides great opportunities to produce materials with the average size of 100 nm or less. These particles can be well-dispersed in conventional heat transfer fluids such as water, ethylene-glycol (EG), and oil to produce a new kind of heat transfer fluid called nanofluids [2]. Miniaturization and thermal management of engineering systems strongly depend on the thermal behavior improvement of working fluids. Nanofluids, as a novel heat transfer fluids, can play an important role in improving the thermal efficiency of engineering devices such as heat exchangers and cooling systems. Thus, numerous investigations have been dedicated to estimate nanofluid thermal properties such as thermal conductivity and viscosity. Results showed that the thermal conductivity of nanofluids, in general, is higher than that of the conventional fluids that are currently used in different thermal devices. Several authors have measured thermal conductivity of nanofluids with different nanoparticle concentrations, mean diameters, materials, and different base fluids. All findings confirm that thermal conductivity of nanofluid is superior to that of base fluid. For example, the thermal conductivity of Al_2O_3/water and TiO_2/water nanofluids with 4.3 vol% is approximately 32% and 11% higher than that of the base liquid, respectively [3].

From numerical point of view, there are two different methods for simulation of flow and heat transfer of nanofluids, namely single-phase and two-phase. In single phase models, it is assumed that the fluid and particles are in thermal equilibrium and move with the same velocity [4,5]. In fact, the effect of particles existence is considered only in effective properties of nanofluids. However, experimental studies show that the validity of the single-phase

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model for nanofluids is somewhat questionable [6]. However, in the two phase models, effect of Brownian motion, thermophoresis and other interactions between carrier fluid and nano-particles are taken into account [7,8]. Homogenous model is one of the single-phase models in which effective properties of nanofluid is applied in the continuity, momentum and energy equations. Therefore, more complex and nonhomogeneous methods such as two-phase mixture models were successfully developed and employed in order to consider slip velocity between the base fluid and particles [9–16].

Buongiorno [9] developed a non-homogeneous equilibrium model by considering the effect of the Brownian, diffusion and thermophoresis. He reported the seven slip mechanisms in nanofluids: inertia, Brownian, diffusion, thermophoresis, diffusiophoresis, Magnus effect, fluid drainage and gravitational settling and concluded that in the absence of turbulence, the Brownian and thermophoresis are the most important effects. In the recent years, a number of investigations have been conducted based on the transport equations derived by Buongiorno. For example, Corcione et al. [10] reported natural convection of nanofluids inside a differentially heated cavity using Buongiorno's model and concluded that the two phase mixture method is more accurate than the single-phase model. A similar study has been conducted by Pakravan and Yaghoubi [12] and Sheikhzadeh et al. [13] to investigate the effects of Brownian diffusion and thermophoresis. Tzou [17,18] investigated the Benárd instability of a quiescent nanofluid between two parallel walls. A numerical study was presented by Garoosi et al. [19] using Buongiorno's model. They analyzed natural and mixed convection heat transfer of a nanofluid (Al_2O_3-water) in a laterally heated square cavity. They observed that at low Rayleigh and high Richardson numbers, the particle distribution is fairly non-uniform while at high Rayleigh and low Richardson numbers particle distribution remains almost uniform for free and mixed convection cases, respectively. For more information see the recent published review papers about single-phase and two-phase treatments of convective heat transfer enhancement with nanofluids [20–22].

Sheremet et al. [23,24] investigated the nanofluid flow and heat transfer in porous cavities using Buongiorno's model. In another work, Sheremet and Pop [25] employed Buongiorno's model to analyze the mixed convection of nanofluid in a lid-driven cavity. The effects of important parameters such as Reynolds, Grashof, Prandtl and Lewis numbers on flow pattern and heat transfer were explored.

Laminar natural convection of nanofluids has been extensively studied in the differentially heated enclosures. But very few works have been performed concerning inclined enclosures. Some researchers have used single-phase or homogenous models to study heat transfer and fluid flow in nanofluids in inclined geometries [26–30]. It was found that in a differentially heated inclined enclosure, the heat transfer rate increases as the inclination angle increases up to an optimum inclination angle (45° for $Ra = 10^4$, 30° for $Ra = 10^5$ and 10^6), beyond which the heat transfer rate decreases [27,29,30]. Aminossadati and Ghasemi [25] studied heat transfer characteristics in an inclined square cavity with and without a central solid block. The inclination had no effect on heat transfer rate at low Rayleigh numbers. On the other hand, at high Rayleigh numbers, with a central block, inclination enhanced heat transfer rate. Recently, Ahmed et al. [31] used the two-phase lattice Boltzmann method (LBM) for the simulation of natural convection in inclined square cavity filled with Al_2O_3-water. Their results showed that thermophoresis has a considerable effect on heat transfer augmentation in laminar natural convection and the optimal inclination angle depends on e Ra number.

This research intends to explore the nano-particles local distribution and the rate of heat transfer of natural convection in an inclined cavity using Buongiorno's model. The effects of Rayleigh number ($10^2 \le Ra \le 10^6$), volume fraction ($0 \le \varphi_{Ave} \le 0.04$) and inclination angle ($0^\circ \le \theta \le 60^\circ$) are investigated. To the best of our knowledge, this study is the first one which used two-phase (inhomogeneous) Buongiorno's model to investigate the effect of inclination angle on nano particle distribution and natural convection of Al_2O_3-water nanofluid in a square cavity.

2. Mathematical modeling

2.1. Problem statement

The schematic of considered problem in the present investigation is shown in Fig. 1. A two-dimensional square cavity with an inclination angle (θ) and height of H is filled with Al_2O_3 -water nanofluid. The top and bottom walls are thermally insulated whereas two vertical walls are at constant but different temperatures T_h and T_c, respectively. As shown, the gravity force acts in the vertical direction.

2.2. Governing equations and boundary conditions

The flow is assumed to be 2D, steady, incompressible and laminar. Nanoparticles are assumed to have uniform shape and size and in thermal equilibrium with the base fluid. The density variation with the temperature in body force term is considered to be linear based on the Boussinesq's model. Moreover, dissipation and pressure work are ignored in the present study. Under the above assumptions the governing equations of continuity, momentum, energy and volume fraction are as follows [9]:

Continuity equation:

$$\nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

Momentum equation:

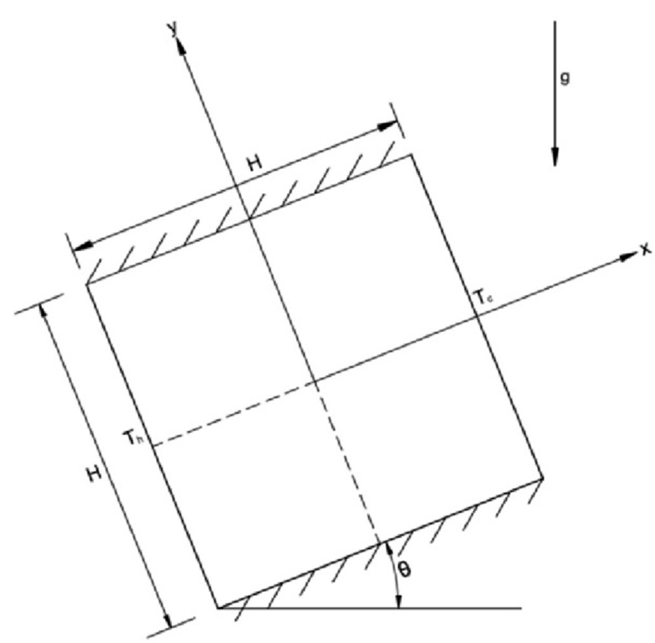

Fig. 1. Geometry of an inclined cavity.