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Heat transfer transitions of natural convection flows in a differentially heated square enclosure filled with nanofluids

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ABSTRACT

Numerical investigations are carried out for steady natural convection of $Al_2O_3 - H_2O$ nanofluids having temperature-dependent properties inside a differentially heated square enclosure by using Buongiorno's two-phase mixture model, where Brownian diffusion and thermophoresis are regarded as the primary slip mechanisms between solid and liquid phases. Influence of the Rayleigh number on the heat transfer behavior with increasing nanoparticle volume fraction to 6%, are systematically investigated for various physical conditions, including averaged temperature, temperature difference and nanoparticle diameter. There are three scenarios in general, except the type 1 (heat transfer rate enhances continuously) and the type 3 (optimum volume fraction exists) mentioned in previous references, the transition between these types, namely, type 2 (heat transfer rate becomes constant) is detected. By increasing the Rayleigh number, the heat transfer behavior of rising volume fraction experiences transition from type 1, type 2 and then to type 3 in sequence, and the transition is valid for low *Ra* only. The corresponding critical Rayleigh number is found to increase in pace with the rise of averaged temperature and temperature difference, but is found to decrease with the growth of the nanoparticle diameter. Finally, one correlation equation for reproducing the critical Rayleigh number with averaged temperature ranging from 300 K to 320 K is presented.

1. Introduction

Buoyancy induced convection in an enclosure is commonly adopted by many thermal engineering designers, e.g., heat exchangers, nuclear reactors and electronic packaging. However, the inherently low thermal conductivity of conventional coolants is a primary limitation in enhancing heat transfer. To overcome this drawback, utilizing nanofluids (suspending nano-sized particles into a base liquid) is a promising solution, whose effective thermal conductivity is known to be higher than that of the corresponding pure base liquid. Therefore, many studies have been performed in the field of nanofluids heat transfer [1,2].

The accuracy of nanofluids simulations rely on the suitable predictions of the effective physical properties, especially the effective thermal conductivity and dynamic viscosity of nanofluids [3]. The effective thermal conductivity is often predicted by traditional mean-field theories [4,5], which seem to be appropriate at room temperature and the temperature effect need to be included. Moreover, the famous theories developed by Einstein [6] and Brinkman [7] for predicting effective dynamic viscosity are found to obtain underestimated values by some experiments [8,9]. Therefore, some remedy models were proposed to obtain the effective thermal conductivity [10–14,17] and dynamic viscosity [15–17]. In particular, Corcione [17] provided the empirical correlations for predicting these two physical properties based on a high number of available experimental data in the literature, and the effects of nanoparticle diameter, volume fraction and temperature are included.

Another key factor which influences the accuracy of nanofluids simulations is the mathematical model of nanofluids, i.e., single-phase model or two-phase model. The typical approach used to study the heat transfer performance of nanofluids is based on the single-phase model [18–24], in which the solid and liquid phases are assumed to be in thermal equilibrium and no relative motion arises between them. The governing equations of nanofluids are developed from that of pure fluids by simply substituting the physical properties with corresponding effective properties, which are assumed to be constant in most studies. However, the validity of the single-phase assumption has been questioned by experimental studies [25], and the effect of particle migration should be further considered. Therefore, the so-called two-phase model was developed [26–32], where the slip velocity between the solid particles and base fluid is taken into account. Buongiorno [26] considered seven slip mechanisms and concluded that Brownian diffusion

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Nomenclature

c_p	specific heat capacity, J/kg K
d	diameter, m
D_B	Brownian coefficient, m^2/s
D_T	thermophoresis coefficient, m^2/s K
$\boldsymbol{g}$	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
k_b	Boltzmann constant, J/K
L	height of the cavity, m
N_{BT}	ratio of Brownian and thermophoretic diffusivities
Nu	Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
Sc	Schmidt number
T	temperature, K
u, v	velocity components in x and y directions, m/s
U, V	dimensionless velocities
x, y	Cartesian coordinates, m
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
φ	nanoparticle volume fraction
Φ	normalized nanoparticle volumetric fraction
μ	dynamic viscosity, kg/m s
ρ	density, kg/m^3
θ	dimensionless temperature
ν	kinematic viscosity, m^2/s

Subscripts

avg	average
C	cold
f	base fluid
H	hot
nf	nanofluids
p	nanoparticle

and thermophoresis are the most important nanoparticle/base-fluid slip mechanisms. Corcione et al. [27], Sheikhzadeh et al. [28] and Esfandiary et al. [30] investigated the natural convection of nanofluids inside a differentially heated enclosure using Buongiorno's model, and found that the two-phase model is more accuracy than the single-phase model.

Focusing on the thermal performance of bouncy induced flows, the Rayleigh number (Ra) is an important factor where the heat transfer is known to increase in tandem with the increase of Ra. For nanofluids flow, the volume fraction of nanoparticles is another critical parameter on heat transfer analysis. Khanafer et al. [18] presented that increasing volume fraction of nanoparticles, which up to 20%, would results in a continuous improvement in heat transfer at any given Rayleigh number. This heat transfer enhancement by increasing the particles loading were also presented in some relative works [33–35]. On the other hand, Sheikhzadeh et al. [28] and Esfandiary et al. [30] demonstrated that slip mechanisms have caused decreasing heat transfer with increasing the bulk volume fraction. In fact, some experiments [36] detected the existence of an optimal particle loading for maximum heat transfer, i.e., increasing volume fraction beyond the optimum value becomes negative effect on heat transfer, and similar results were observed by numerical simulation [27]. Garoosi et al. [29] further indicated that the heat transfer rate increases continuously with the augmentation of nanoparticle volume fraction at low Rayleigh number, while the optimal particle loading for maximum heat transfer can be detected for higher Rayleigh number. However, there were relatively less attention regarding the heat transfer transitions between the mentioned types.

In the present study, numerical investigations are carried out for steady natural convection of $Al_2O_3 - H_2O$ nanofluids having temperature-dependent properties inside a side-heated square enclosure by using Buongiorno's two-phase mixture model, where the slip mechanisms of Brownian diffusion and thermophoresis are considered. With the increasing of nanoparticle volume fraction, both thermal conductivity and viscosity of the fluid enhance, resulting the heat transfer might increase or decrease by the combination of these two effects. Consequently, the previous works indicated the heat transfer enhances with the increase of volume fraction at low Rayleigh number, while the optimum volume fraction with maximin heat transfer exists for higher Rayleigh number. However, the heat transfer transitions between the mentioned types were not studied extensively. Therefore, the main purpose here is to investigate the influence of various physical conditions, including averaged temperature, temperature difference and nanoparticle diameter, on the heat transfer behavior with increasing volume fraction (0–6%) at different Rayleigh numbers. Finally, the heat transfer transitions are systematically reported and the variations of the critical Rayleigh numbers at different physical conditions are addressed.

2. Numerical method

The schematic configuration of the system considered in the present study is shown in Fig. 1. Two vertical walls are cooled and heated at specified temperatures (T_C) and (T_H), respectively, and the other walls are adiabatic. The thermal convection flow is assumed to be two-dimensional, incompressible and laminar. The nanofluid is consisted of base fluid (water) and nanoparticles

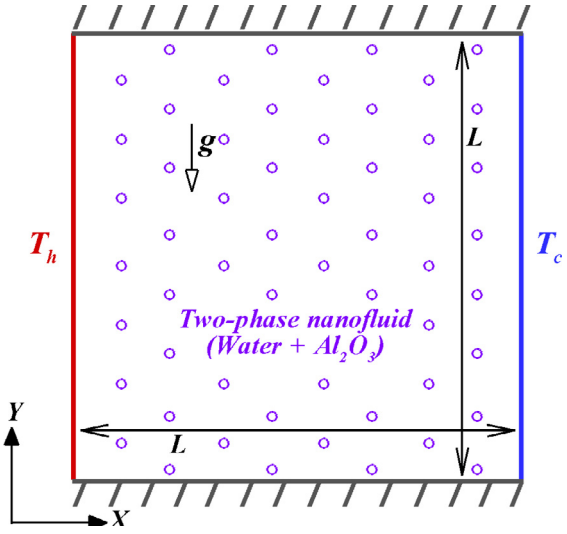

Fig. 1. Computational domain and boundary conditions.