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Experimental and numerical study of natural convection in a square enclosure filled with nanofluid

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ABSTRACT

The coefficient of thermal conductivity and viscosity of Al_2O_3–water nanofluid is measured, and its heat transfer is experimentally investigated in a square enclosure. In addition, a 2D two-phase Lattice Boltzmann model considering interaction forces (gravity and buoyancy force, drag force, interaction potential force and Brownian force) between nanoparticles and base fluid is developed for natural convection of nanofluid, and is applied to simulate the flow and heat transfer of Al_2O_3–water nanofluid in the square enclosure by coupling the density distribution (D2Q9) and the temperature distribution with 4-speeds. In this paper, the effects of different nanoparticle volume fractions ($\varphi = 0.25\%$, $\varphi = 0.5\%$, $\varphi = 0.77\%$) and different Rayleigh numbers ($Ra = 30{,}855{,}746$ and $Ra = 63{,}943{,}592$ for $\varphi = 0.25\%$, $Ra = 38{,}801{,}494$ and $Ra = 67{,}175{,}834$ for $\varphi = 0.5\%$ and $Ra = 55{,}888{,}498$ and $Ra = 70{,}513{,}049$ for $\varphi = 0.77\%$) on heat transfer in the transition region are experimentally and numerically discussed. The numerical results have a good agreement with the experimental results. It is found that the heat transfer of nanofluid is more sensitive to the thermal conductivity than viscosity at low nanoparticle fractions and it is more sensitive to the viscosity than the thermal conductivity at high nanoparticle fractions. In addition, the forces between water and nanoparticles are analyzed, and the nanoparticle volume fraction distribution is investigated. It is found that the temperature difference driving force makes the greatest contribution to the nanoparticle volume fraction distribution, and nanoparticle volume fraction distribution is opposite to that of the water phase density distribution.

1. Introduction

Natural convection is applied in more and more fields, for example, in heat exchangers, cooling of electronics, crystal growth and so on. Due to the fact that nanofluid has a higher thermal conductivity compared to the base fluid such as pure water or oil, thus in order to enhance the heat transfer of natural convection, nanofluid is used as the medium instead of just the base fluid. Gradually, researchers began to experimentally and numerically investigate the natural convection of nanofluid.

Researchers have performed extensive experiments on the natural convection of nanofluid in recent years. Ho et al. [1] experimentally studied the natural convection heat transfer of a nanofluid in vertical square enclosures of different sizes, and the effects of nanoparticle volume fractions and Rayleigh numbers are investigated. Xuan et al. [2] experimentally studied the flow and heat transfer of Cu–water nanofluid in a tube, and obtained the conclusion that the nanofluid has a larger heat transfer coefficient than that of water and that the heat transfer feature of the nanofluid increases with nanoparticle volume fraction. Williams et al. [3] experimentally investigated the natural convection of alumina–water and zirconia–water nanofluids in horizontal tubes, and discussed the effects of velocity, temperature, heat flux and volume fraction. Ding et al. [4] experimentally studied the heat transfer of aqueous suspensions of multi-walled carbon nanotubes (CNT nanofluid) in a horizontal tube, and the effects of flow conditions, CNT concentration and the PH on the enhancement are discussed. Chang et al. [5] experimentally investigated the natural convection of alumina–water nanofluid in an enclosure at angles of inclination to the horizontal of 90°, 30°and 0°, and the effects of nanoparticle volume fractions, Rayleigh numbers and the angles are discussed. Usually, the natural convection of nanofluid with different volume fractions ($\varphi = 1$–5%) at different Rayleigh numbers ($Ra = 10^3$–10^5) is investigated. However, there are few studies on natural convection of Al_2O_3–water nanofluid in a square enclosure with a small volume fraction at high Rayleigh numbers. In this paper, the natural convection of nanofluid with different mass

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Nomenclature

a	radius of nanoparticle (m)
A	Hamaker constant
B_α	adjustable coefficient
c	reference lattice velocity
c_s	lattice sound velocity
c_p	specific heat capacity (J/kg · K)
$\boldsymbol{e}_\alpha$	lattice velocity vector
f_α^σ	density distribution function
$f_\alpha^{\sigma eq}$	local equilibrium density distribution function
$\boldsymbol{F}_\alpha^{\sigma'}$	dimensionless external force in direction of lattice velocity
$\boldsymbol{F}_\alpha^\sigma$	dimensionless total interparticle interaction forces
$\boldsymbol{F}_H$	dimensionless gravity and buoyancy force
$\boldsymbol{F}_D$	dimensionless drag force
$\boldsymbol{F}_A$	dimensionless interaction potential force
$\boldsymbol{F}_S$	dimensionless buoyancy force due to temperature difference
$\boldsymbol{g}$	dimensionless gravitational acceleration
$\boldsymbol{G}$	dimensionless effective external force
G_i	Gaussian random number
$\boldsymbol{h}_{\alpha\beta}$	convective heat transfer coefficient (W/(m^2 K))
H	dimensionless characteristic length of the square cavity
k	thermal conductivity coefficient (W m^{-1} K^{-1})
k_B	Boltzmann constant
L_{cc}	center-to-center distance between particles (m)
Ma	Mach number
m^σ	mass of a single nanoparticle (kg)
n_i	number of the particles within the adjacent lattice i
Nu	Nusselt number
Pr	Prandtl number
$\boldsymbol{r}$	position vector
Ra	Rayleigh number
t	time (s)
T_α^σ	temperature distribution function
$T_\alpha^{\sigma eq}$	local equilibrium temperature distribution function
T	dimensionless temperature
T_0	dimensionless average temperature ($T_0 = (T_H + T_C)/2$)
T_H	dimensionless hot temperature
T_C	dimensionless cold temperature
$\boldsymbol{u}^\sigma$	dimensionless macro-velocity
u_c	dimensionless characteristic velocity of natural convection
V_A	dimensionless interaction potential
V	volume of a single lattice (m^3)
w_α	weight coefficient
x, y	dimensionless coordinates

Greek symbols

β^σ	thermal expansion coefficient (K^{-1})
ρ^σ	density (kg/m^3)
ν	kinematic viscosity (m^2 s^{-1})
η	dynamic viscosity (Pa s)
χ	thermal diffusion coefficient (m^2 s^{-1})
γ	surface tension (N/m)
φ	nanoparticle volume fraction
δ_x	lattice step
δ_t	time step t
σ	components (σ = 1, 2, water and nanoparticles)
τ_f	dimensionless collision-relaxation time for the flow field
τ_T	dimensionless collision-relaxation time for the temperature field
ΔT	dimensionless temperature difference ($\Delta T = T_H - T_C$)
$\Delta\rho'$	dimensionless mass density difference between nanoparticles and base fluid
Δu	dimensionless velocity difference between nanoparticles and base fluid
$\Phi_{\alpha\beta}$	dimensionless energy exchange between nanoparticles and base fluid
$Error_1$	maximal relative error of velocities between two adjacent time layers
$Error_2$	maximal relative error of temperatures between two adjacent time layers

Subscripts

α	lattice velocity direction
avg	average
C	cold
nf	nanofluid
H	hot
w	base fluid
p	nanoparticle

fractions (wt% = 1%, wt% = 2% and wt% = 3%, which are equivalent to the volume fractions: $\varphi = 0.25\%$, $\varphi = 0.5\%$, $\varphi = 0.77\%$) in a square enclosure at different Rayleigh numbers (Ra = 30,855,746 and Ra = 63,943,592) is investigated.

Computational fluid dynamics (CFD) is becoming more accessible to graduate engineers for research and development in industries [6]. With the development of nanotechnology, nanofluid has been widely used in the enhancement of heat transfer and different models are applied to simulate this kind of problems [7–11]. In order to investigate the mechanisms and the microscopic details of natural convection, several research groups began to use various numerical methods to simulate the natural convection characteristics of nanofluids [12–16]. Among these methods, the Lattice Boltzmann method is a new way to investigate natural convection of nanofluid. The method has many merits, for example, the algorithm is simple, the boundary conditions are easily dealt with, and the transform between macroscopical equations and microscopic equations is easily achieved. Hence, the Lattice Boltzmann method is widely applied in the study of natural convection [17–19].

Barrios et al. [20] proposed a Lattice Boltzmann model and numerically investigated the natural convection in a square enclosure with a partially heated left wall. Peng et al. [21] proposed a simple Lattice Boltzmann model without gradient term, which is easily applied, on the assumption that there is no thermal diffusion. He et al. [22] developed a new Lattice Boltzmann model, which introduced an energy density distribution function to simulate the temperature field, and the simulation result has good agreement with the benchmark solution. Nemati et al. [23] simulated the natural convection of lid driven flow in a square filled with nanofluid, and the effects of nanoparticle fraction and Reynolds number on heat transfer were discussed. Kefayati et al. [24,25] simulated natural convection in an open cavity with magnetic field, a cavity with sinusoidal temperature distribution, and also turbulent natural convection. Sheikholeslami et al. [26,27] took the simulations of natural convection considering different kind of nanoparticles, the effects of magnetic field, and various figures of enclosures. Dixit et al. [28] simulated the natural convection in a square cavity at high Rayleigh number by a thermal Boltzmann method based on the BGK model, which used the