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Effects of nanoparticles transport mechanisms on Al_2O_3–water nanofluid natural convection in a square enclosure

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In this numerical study, effects of nanoparticles transport in natural convection of Al_2O_3–water nanofluid on flow field and heat transfer in a square cavity have been investigated and comparisons between predictions of newly developed transport model and the homogeneous model have been made. In the transport model, transport mechanisms including Brownian and thermophoresis diffusions, which cause non-homogeneity, have been considered. The governing equations have been discretized using the control volume method. Variable properties of nanofluid have been assumed functions of temperature and volume fraction of nanoparticles. Since constant Rayleigh number could not be used, simulations have been performed for various physical conditions such as temperature differences between the hot and cold walls from 2 to 10 °C, bulk volume fractions of nanoparticles from 0 to 0.04 and nanoparticles sizes from 25 nm to 105 nm. Comparisons revealed better agreement with experimental results considering the transport model instead of the homogeneous model. Moreover, it was shown that Dufour effect on heat transfer is negligible. Both models suggested heat transfer reduction by increasing the bulk volume fraction of nanoparticles, but transport model predicted a greater reduction. Transport model predicted heat transfer decrease with increased nanoparticles size, but homogeneous model acted vice versa.

1. Introduction

Ultrahigh cooling performance is one of the most vital needs in many industrial technologies. However, inherently low thermal conductivity is a primary limitation in developing energy-efficient heat transfer fluids. Nanofluids are engineered by suspending nanoparticles with average sizes below 100 nm in traditional heat transfer fluids such as water, oil, and ethylene glycol. Several researches [1–23] have indicated that by adding nanoparticle with low volume fraction (1–5%), the thermal conductivity can be increased by about 20%. Although the higher conductivity is encouraging, it is by no means conclusive evidence of the cooling capabilities of such fluids. For that, it is necessary to have definitive proof of the performance of these fluids in convective environments.

Many experimental studies have been performed in the field of nanofluid natural convection. Putra et al. [4] studied natural convection of Al_2O_3–water and CuO–water in a horizontal cylinder, experimentally. They found that the Nusselt number decreases by increasing volume fraction of nanoparticles. Wen and Ding [5] investigated natural convection of TiO_2-water between two disks experimentally and obtained the same result as of Putra et al. [4]. Ho et al. [6] investigated the natural convection of Al_2O_3–water nanofluid in square enclosures of three different sizes, experimentally. They measured the thermophysical properties of the nanofluid as well. They explained the unusual increase or decrease of heat transfer cannot be explained solely based on relative changes in thermophysical properties of the nanofluid, and other factors such as transport mechanisms which change the homogeneity of the volume fraction of nanoparticles in the domain are also important.

Numerous analytical and numerical models have been presented for nanofluids convective heat transfer, which can be divided into homogeneous, non-homogeneous and dispersion models. In the homogeneous model, nanofluid is assumed as a usual fluid; thus, all traditional equations of mass, momentum and energy are used considering effective constant properties of the nanofluid. On the other hand, in the non-homogeneous model, it is assumed that nanoparticles transport due to relative velocity between nanoparticles and the base fluid. Nanoparticles transport may lead to non-homogeneity in nanofluid. In the dispersion model, the relative velocity between nanoparticles and the base

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Nomenclature

c_p	specific heat capacity, J/kg.K
C_s	non-continuum constant
d	diameter, m
D_B	Brownian coefficient, m^2/s
D_D	Dufour coefficient, W/m
D_T	thermophoresis coefficient, m^2/s.K
g	gravitational acceleration, m/s^2
h	local heat transfer coefficient, W/m^2.K
h_C	local heat transfer coefficient due to temperature gradient, W/m^2.K
J_P	particle flux vector, kg/m^2.s
J_h	heat flux vector, W/m^2
k	thermal conductivity, W/m.K
k_B	Boltzmann constant, J/K
Kn	Knudsen number
L	length, m
n	normal vector
N_{BT}	ratio of Brownian and thermophoretic diffusivities
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
R	gas constant, J/kg.K
Ra	Rayleigh number
Re	Reynolds number
S_T	thermophoresis parameter
T	temperature, K
u, v	dimensional x and y-components of velocity, m s^{-1}
U, V	dimensionless velocities
x, y	dimensional coordinates, m
X, Y	dimensionless coordinates

Greek symbols

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

Subscripts

0	reference
b	bulk or overall
B	Brownian
C	cold
D	Dufour
f	fluid
fr	freezing point of the base liquid
H	hot, homogeneous
nf	nanofluid
p	Particle
T	thermophoresis, transport

Superscripts

$\bar{}$	average

fluid is treated as perturbation in the energy equation, which enhances turbulence and increases the convective heat transfer.

Homogeneous model has been used by many researchers. Khanafer et al. [7] studied Cu–water nanofluid convection in a two-dimensional rectangular enclosure. They reported an augmentation in heat transfer with increasing volume fraction of nanoparticles at any given Grashof number. Jou and Tzeng [8] and Oztop and Abu-Nada [9] showed similar results. Abu-Nada et al. [10] studied natural convection in horizontal annuli and showed that heat transfer is enhanced by using nanofluids. Abu-Nada et al. [11] studied Al_2O_3–water nanofluid convection in an enclosure using variable properties. With increasing volume fraction of Al_2O_3, they reported decrease in average Nusselt number at high Rayleigh numbers and increase in that at low Rayleigh numbers. Sheikhzadeh et al. [12] investigated numerically the buoyancy-driven fluid flow and heat transfer of Cu–water nanofluid in a square cavity with partially active side walls. They reported that the heat transfer rate increases with increasing the volume fraction of nanoparticles.

There are several mechanisms such as Brownian motion and thermophoresis nanoparticles transport in suspensions. Brownian motion, named after Robert Brown, is the presumably random drifting of particles suspended in a fluid [13]. Temperature gradient can cause mass flux by a process known as thermophoresis or thermal diffusion or the Soret effect. This was first reported by John Tyndall [14] in 1870. Concentration gradients can produce heat transfer known as diffusion-thermo, or Dufour effect. Dufour effect is usually small and negligible [15]. Buongiorno [16] introduced seven transport mechanisms which cause relative velocity between nanoparticles and fluid. By comparing the diffusion time scale of transport mechanisms he showed that the Brownian motion and thermophoresis are the two most important transport mechanisms. He theoretically investigated the unusual Nusselt number increase for force convection in a duct and related this heat transfer enhancement to reduction of viscosity due to nanoparticle transport within the boundary layer. He also assumed that energy transfer by nanoparticle dispersion was negligible; hence he did not study Dufour effect. Hwang et al. [17] investigated theoretically and experimentally laminar force convective heat transfer characteristics of Al_2O_3–water nanofluids with low volume fractions in a circular tube. Based on their experimental results, the Darcy friction factor of nanofluid had a good agreement with theoretical results for the single-phase flow model. Based on scale analysis, they showed that the flattened velocity profile due to particle transport is a possible mechanism of the convective heat transfer enhancement, which cannot be explained by increase in thermal conductivity of nanofluids alone. However, without physical explanation, they did not consider the effect of convection in nanoparticle transport equation. Kuznetsov and Nield [18] studied natural convective boundary-layer flow of a nanofluid past a vertical plate, analytically. By using similarity solution, they showed that the Brownian motion and thermophoresis decreases the Nusselt number. They assumed the volume fraction of nanoparticles at wall is constant, whereas physically zero particle flux at the wall will happen. This unrealistic boundary condition was also used in a similar geometry by Rana and Bhargava [19]. Pakravan and Yaghoubi [20] investigated effects of Brownian motion, thermophoresis and Dufour in natural convection heat transfer, analytically. They showed that Dufour effect reduces the total heat transfer compared with single-phase model predictions. They reported good agreement for Nusselt number by comparing their results with various experimental results. They did not study some effects such as double diffusive natural convection and change of properties due to presence of volume fraction gradient. Aminfar and Haghgoo [21] investigated effects of Brownian motion and