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Double-diffusive natural convective in a porous square enclosure filled with nanofluid

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ABSTRACT

In this work, effects of double-diffusive natural convection of Al_2O_3–water nanofluid on flow field and heat transfer in a porous square cavity are investigated. Homogeneous and two-component non-homogeneous of Buongiorno's model that includes the effects of Brownian motion and thermophoresis are utilized, while the Darcy model is used for the porous medium. The governing equations are discretized using the finite difference and control volume method. 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 difference between the hot and cold walls from 1 to 20 °C, bulk volume fraction of nanoparticles from 0 to 0.04, and porosity between 0.1 and 0.5. Both models suggest that by increasing the bulk volume fraction of nanoparticles heat transfer is reduced, but non-homogeneous model predicts a greater reduction compared to the homogeneous model. Also non-homogeneous model predicts reduced heat transfer with increased porosity.

1. Introduction

Nanofluids contain small quantity of nano-sized particles (usually less than 100 nm) that are suspended in a liquid. Researchers [1,2] have observed that nanofluids can have anomalously higher thermal conductivities than that of the base fluids even for low solid volume fraction of nanoparticles in a mixture, thus posing as a promising alternative for thermal applications. Although the higher conductivity is encouraging, it is by no means conclusive evidence of the cooling capabilities of such fluids and the sensitivity to the viscosity model and other seems to be undeniable and it plays a key role for heat transfer behavior.

Natural convection in pure fluids is driven only by density variations due to temperature gradient. However, Double-diffusive convection in nanofluids is an important fluid dynamics topic describing a form of convection driven by two different density gradients with different rates of diffusion [3]. These density variations may be caused by gradients in the volume fraction of the nanofluid or by temperature gradient.

One of the most common assumptions in studying the nanofluids behavior is that there aren't any gradients in the volume fraction. This assumption results in a homogeneous mixture of nanoparticles in the fluid. Many researchers used this assumption and they were not able to predict the decreasing behavior of Nusselt number with adding the nanoparticles volume fraction [4].

There are several mechanisms such as Brownian motion and thermophoresis that cause heterogeneity in suspensions. Brownian motion, named after Robert Brown, is the presumably random drifting of particles suspended in a fluid [5]. Temperature gradient can cause mass flux by a process called either thermophoresis or thermal diffusion and the Soret effect. This was first reported by Tyndall [6] in 1870. Concentration gradients can produce heat transfer known as diffusion-thermo, or Dufour effect, which is usually small and negligible [7]. Buongiorno [8] 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 mechanisms. Kuznetsov and Nield [9] 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. Pakravan and Yaghoubi [10] investigated effects of Brownian motion,

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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_T	thermophoresis coefficient, m^2/s K
g	gravitational acceleration, m/s^2
h	local heat transfer coefficient, W/m^2 K
J_P	particle flux vector, kg/m^2 s
K	permeability of the porous medium
k	thermal conductivity, W/m K
k_B	Boltzmann constant, J/K
L	length, m
n	normal vector
N_{BT}	ratio of Brownian and thermophoretic diffusivities
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Ra	Rayleigh number, defined by Eq. (27)
Re	Reynolds number
S_T	thermophoresis parameter
T	temperature, K
x, y	dimensional coordinates, m
X,Y	dimensionless coordinates

Greek symbols

α	fluid thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
ε	porosity
φ	nanoparticle volume fraction
Φ	normalized nanoparticle volumetric fraction
μ	dynamic viscosity, $N.s/m^2$
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, bed
B	Brownian
C	cold
eff	effective
f	fluid
fr	freezing point of the base liquid
H	hot, homogeneous
nf	nanofluid
p	Particle
s	solid
T	thermophoresis

Superscripts

-	average

thermophoresis and Dufour in natural convection heat transfer, analytically. They reported good agreement for Nusselt number by comparing their results with various experimental results. However they didn't study some effects such as double diffusive natural convection and change of properties due to presence of volume fraction gradient. Aminfar and Haghgoo [11] and Pakravan and Yaghoubi [12] investigated the effects of Brownian motion and thermophoresis on natural convection heat transfer of alumina–-water nanofluid in a square vertical cavity using the two-component model, numerically. They concluded that the use of single phase homogeneous method does not seem reasonable for modeling this class of natural convection. Haddad et al. [13] studied numerically, Cuo-water nanofluid Rayleigh-Bénard convection considering the role of Brownian and thermophoresis effects and made comparison with the case where both effects were neglected. They noticed higher heat transfer when Brownian and thermophoresis effects were considered. Ho et al. [14] investigated natural convection of Al_2O_3–water nanofluid in square enclosures of three different sizes, experimentally. 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 nanoparticle transport mechanisms which change the homogeneity of the volume fraction of nanoparticles in the domain are also important. In our previous numerical works [15,16] we utilized Buongiorno's nanofluid model that includes the effects of Brownian motion and thermophoresis to the case square enclosure (without porous matrix). We showed homogeneous model is not competent to predict the heat transfer features of nanofluids and our predictions were in better agreement with experimental results.

Natural convection flow in porous media, due to thermal buoyancy alone, has been widely studied (Combarnous and Bories, 1975) and well-documented in the literature (Cheng [17], 1978; Bejan [18], 1984) while only a few works have been devoted to double-diffusive natural convection in porous media. The problem of natural convection in a porous square enclosure studied by Osvair et al. [19]. This problem is further investigated in Beckermann et al. [20] and Basak et al. [21].

A first extension to the case of a natural convective in a porous medium saturated by a nanofluid, based on a model presented by Buongiorno [8] was made by Nield and Kuznetsov [22]. In their paper it was assumed that one could control the value of the nanoparticles volume fraction at the boundary in the same way as the temperature there could be controlled, but no indication was given of how this could be done in practice. Khan and Aziz [23] used the Buongiorno model [8] and similarity method to study the double-diffusive natural convection from a vertical plate to a porous medium saturated with a nanofluid. They showed the highest values of reduced Nusselt numbers are achieved in mono diffusion in a regular fluid and the lowest values occur with double diffusion in nanofluids. Nield and Kuznetsov [24] employing the Darcy model for the momentum equation, presented a similarity solution. They assumed the simplest possible boundary conditions, namely those in which both the temperature and the nanoparticles volume fraction are constant along the wall. They found that with increasing the thermophoresis parameter, Brownian motion parameter, Dufour parameter and with decreasing the buoyancy ratio, the reduced Nusselt number decreases. Yadav et al. [25] examined the effect of boundaries and constant internal heat source on the onset of Darcy-Brinkman convection in a nanofluid saturated porous layer heated uniformly from below and cooled from above. Kuznetsov and Nield [26] used the Buongiorno model [8] to study the double-diffusive natural convection from a vertical plate to a porous medium saturated with a nanofluid using similarity method. They revisited their previous model and extended it to the case when the zero nanoparticle flux is imposed on the boundary. They found that the reduced Nusselt number is almost independent of the Brownian motion parameter. Tham et al. [27] studied the problem of steady