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Double diffusion natural convection in a square cavity filled with nanofluid

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ABSTRACT

Double diffusive natural convection of nanofluid is commonly found in renewable energy engineering. However, nowadays our understanding on its fundamental characteristics is still limited. Especially, three crucial questions on its fundament have not been answered yet: (1) its performance not only in laminar regimes but also beyond laminar regimes, (2) the influence of the ratio of buoyancy forces on heat and mass transfer, (3) the correlation among the dimonsionless quantities which describe the features of this kind of convection. The present work tries to reveal the characteristics of double diffusive natural convection of nanofluid over a wide range, from laminar regimes to turbulent regimes, with the aid of numerical experiments. It is observed that the behavior of nanofluid in the laminar regimes is different from that in the turbulent regimes. Some conclusions presented in previous literature for laminar double diffusive of nanofluid may be invalid in its turbulent counterpart. The effect of the ratio of buoyancy forces on heat and mass transfer of nanofluid possesses some similarities with the pure base fluid as well as some obvious differences. Especially, a power-like correlation among the Nusselt number, Sherwood number, Rayleigh number, ratio of buoyancy forces and nanoparticle volume fraction has been extracted for the first time through our numerical experiments.

1. Introduction

Nanofluid is a mixture of base fluid (e.g. water) and nanometer-sized particles. The suspending nanoparticles, typically made of metals, oxides, carbides, or carbon nanotubes, can significantly enhance the thermal conductivity of base fluid [1]. Consequently, as a promising new generation of coolant, nanofluid has a great potential adopted in many important applications such as microelectronics, domestic refrigerator and aircrafts. One can refer to Refs. [2–5] for the latest progress in this field.

Compared with the available numerous studies on the characteristics of heat transfer of nanofluid induced by thermal buoyancy [4], the exploration taking effects of compositional buoyancy into account is quite limited, although compositional buoyancy exists and plays an important role in many industrial applications utilizing nanofluid, such as solar energy industry [6]. Esfahani and Bordbar [7] perhaps are some of the pioneers on this topic. In Ref. [7], they investigated laminar double-diffusive natural convection heat transfer enhancement in a square enclosure filled with various nanofluids by numerical simulation. The influences of the nanoparticle volume fraction, Rayleigh and Lewis number on the Nusselt and Sherwood number were discussed. Later, Parvin et al. [8] numerically analyzed the flow and natural convection patterns of water–Al_2O_3 nanofluid in a partially heated enclosure. In their study, the nanoparticle volume fraction varies from 0 to 0.2 with the Rayleigh number up to 10^6. Through their work, it is very clear that the distributions of isotherms and iso-concentrations depend closely on the position of active walls of the cavity. Recently, laminar double diffusive convection in a solar collector using water–CuO nanofluid was modelled in Ref. [9]. The cross section of the solar collector is triangular. The authors revealed the incident angle of the solar collector influenced the performance of heat and mass transfer of nanofluid significantly. The above publications all focus on the behavior of double diffusive convection of nanofluid confined by a closed container. The double diffusive convection in a nanofluid layer was firstly reported by Nield and Kuznetsov [10,11]. They discussed the onset and thickness of such layer through analytical study. In succession, the same authors extended their discussion to a porous medium saturated by nanofluid [12]. More recently, Beg and Tripathi [13] conducted a

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theoretical study on double diffusive convection in nanofluid through a deformable channel. Through the work, the authors tried to deepen our understanding on the usability of nanofluid in physiological areas. About buoyant flow of nanofluid in a cavity, some interesting work also has been published. For example, in Ref. [14] the influence of inclination angles of cavity on fluid flow has been reported and Ho et al. [15] investigated the Ludwig–Soret effect in nanofluid enclosed by a cavity.

Through the above literature survey it is clear that at least three fundamental questions on double diffusive convection of nanofluid are not answered yet: firstly, the characteristics of double diffusive convection of nanofluid beyond laminar regimes; secondly, the influence of the ratio of buoyancy forces on heat and mass transfer; and thirdly, the correlation among the Nusselt/Sherwood number, Rayleigh number and nanoparticle volume fraction under double diffusive natural convection. The goal of this paper is to answer these three critical questions with the aid of a comprehensive numerical experiment. What should be pointed out is that a two-dimensional investigated domain is adopted in the present work while turbulence is an inherently three-dimensional phenomenon, so further work is required in the future to validate the reliability of the present research for real applications.

2. Investigated domain and boundary conditions

In this work, double diffusive natural convection in a square cavity [7,16] is adopted as it is a good research prototype to reply the above questions. The investigated domain and boundary conditions are illustrated by Fig. 1. The dimensionless length of each side of the square cavity is unity. The dimensionless temperature and concentration on the hot wall and cold wall read $T_h = 0.5,\ Y_h = 0.5$ and $T_c = -0.5,\ Y_c = -0.5$, respectively. The top and bottom walls of the investigated domain are adiabatic. The gravity g is downward. The investigated domain and boundary conditions are identical to that in Ref. [16] where one can find the more detailed description on this investigated domain.

3. Governing equations

For nanofluid simulation, generally there are two ways: single phase and two-phase modelling [17]. In the former approach it is assumed that the suspending nanoparticles are in thermal equilibrium with the base fluid and there is no velocity slip between the solid particles and base fluid. Therefore the solid–liquid mixture can be treated as a kind of Newtonian fluid. However, in the latter, the discrete phase and continuum phase are described in a Lagrangian and a Eulerian scheme, respectively. Although it is physical sound over broader ranges than single phase approach, two-phase modelling suffers from a higher requirement on computational resources. If the solid volume fraction is small enough, single phase simplification can provide acceptable predictions for the heat transfer and hydrodynamic properties of nanofluid with cheaper computational cost. Consequently, single phase approach is popularly utilized for simulating double-diffusive natural convection of nanofluid [7–9]. The present study is also based on this approach.

To date there have been three categories of numerical methods to investigate flows beyond laminar regimes: Reynolds averaged Navier–Stokes equations (RANS), large eddy simulation (LES) and direct numerical simulation (DNS). Among them, LES is much cheaper than DNS regarding computational cost and can capture more turbulence details than RANS. As a result, in the present work LES is employed to numerically analyze double diffusive convection of nanofluid.

With the aid of the normalizing process introduced in Ref. [16], the corresponding dimensionless governing equations in the LES framework read [7,16]

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\nabla p + v_e \Delta \vec{u} - RaPr(T - NY)\frac{\vec{g}}{|\vec{g}|} \tag{2}$$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \alpha_e \Delta T \tag{3}$$

$$\frac{\partial Y}{\partial t} + \vec{u} \cdot \nabla Y = D_e \Delta Y \tag{4}$$

where v_e, α_e and D_e are the effective viscosity, thermal and solutal diffusivity, respectively. p is the pressure, T is the temperature and Y is the concentration. $\vec{u} = (u, v)$ is the velocity vector. The gravity $\vec{g}$ downward. N is the ratio of buoyancy forces, Ra is the Rayleigh number and Pr is the Prandtl number.

In the single phase approach for nanofluid simulation, the influences of addition of nanoparticles into base fluid are reflected by the change of viscosity and thermal conductivity of fluid [17,18]. Nowadays there are a number of models to predict these fundamental physical properties of nanofluid [17] and it has been found that the numerical results depend closely on the adopted models [18]. Even for laminar flow, the trends of numerical predictions may be completely inverse as a result of different models of viscosity and thermal conductivity used in simulation [18]. Unfortunately, until now there is still no consensus on this issue [17]. To avoid the uncertainties, the physical properties of

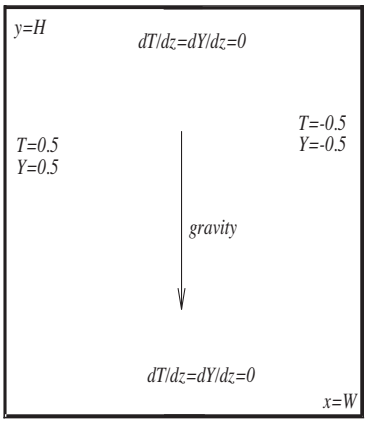

Fig. 1. Configuration of the computational domain and boundary conditions.

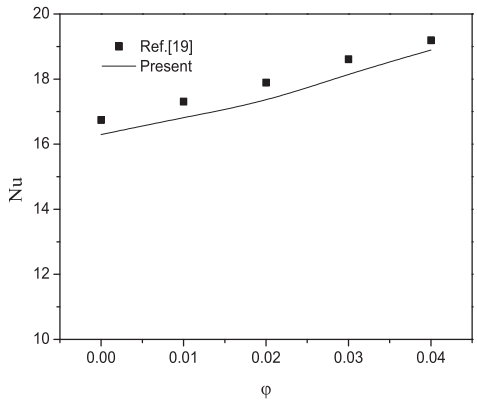

Fig. 2. Comparison of the Nusselt number for various nanoparticle volume fraction when $Ra = 10^7$.