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Natural convection of nanoparticle–water mixture near its density inversion in a rectangular enclosure☆

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ABSTRACT

Natural convection of mixture of nanoparticles and water near its density maximum in a rectangular enclosure is studied numerically. A non-Boussinesq homogenous model is used in mathematical formulations of governing equations. The finite volume method is used to solve the governing equations. The results are presented graphically in the form of streamlines, isotherms and velocity vectors and are discussed for various nanoparticle volume fractions. It is observed that flow and temperature field is affected significantly in the presence of nanoparticles. The average heat transfer rate considering a non-Boussinesq temperature-dependent density (inversion of density) is lower than considering a Boussinesq temperature-dependent density. The average Nusselt number increases with an increase of nanoparticle volume fraction. It is observed that the density inversion of water leaves strong effects on fluid flow and heat transfer due to the formation of bi-cellular structure. The properties of nanoparticles also affect the fluid flow and heat transfer.

1. Introduction

The augmentation of convective heat transfer cooling is frequently encountered in various engineering applications such as energy storage system, electronic cooling, solar energy collectors, heating and cooling of buildings and etc. Due to these applications, in recent years, the natural convection in fluid-filled enclosures has attended by many researchers in different conditions. Because of poor thermal properties of the working fluid, a better medium is needed to enhance the heat transfer characteristics and provide an optimal design in these problems.

One of the new techniques to improve the heat transfer characteristics is using the nano-scale particles in the pure fluid. Nanofluids, the suspension of nanoparticles in a base-fluid, exhibit superior heat transfer properties of the fluid and consequently enhance the heat transfer characteristics in comparison with conventional heat transfer fluids. An innovative technique, which uses a mixture of nanoparticles and the based fluid, was first reported by Choi [1] in order to develop advanced heat transfer fluids with substantially higher conductivities. Khanafer et al. [2] numerically investigated the buoyancy-driven convection in a two-dimensional enclosure filled with nanofluids. They found that the heat transfer across the enclosure increases with the volumetric fraction of the copper nanoparticles in water for different Grashof numbers. Abu-Nada et al. [3] investigated the influences of nanoparticles on the natural convection heat transfer enhancement in horizontal annuli with nanofluids containing various nanoparticles. They reported an enhancement of heat transfer in horizontal annuli. Shahi et al. [4] studied entropy generation due to natural convection of a nanofluid that consists of water and Cu in a cavity with a protruded heat source has been. They investigated the effect of Rayleigh number, solid concentration and heat source location on entropy generation. Mahmoudi et al. [5] investigated the conjugated heat transfer in a thick walled cavity filled with copper–water nanofluid. They found that an increase in the average Nusselt number was found with the solid concentration for the whole range of Rayleigh number. In addition, their results showed that the position of the divider and the ambient convective heat transfer coefficient have a considerable effect on the heat transfer enhancement. Aminossadati and Ghasemi [6] numerically studied the homogenous and Newtonian natural convection of water–CuO nanofluid in a two-dimensional square cavity with two pairs of heat source–sink covering the entire length of the bottom wall of the cavity. The results showed that regardless of the position of the pairs of source–sink, the heat transfer rate increases with an increase of the Rayleigh number and the solid volume fraction. Talebi et al. [7] executed a numerical investigation of laminar mixed convection flow of copper–water nanofluid in a square lid-driven cavity. In the present study, the top and bottom horizontal walls are insulated while the vertical walls are maintained at constant but different temperatures. It was found that at the fixed Reynolds number, the solid concentration affects on the flow pattern and thermal behavior particularly for a higher Rayleigh number. Transient natural convection heat transfer of aqueous nanofluids in a differentially heated square cavity is investigated numerically by Yu et al. [8]. The time-averaged Nusselt numbers were presented in terms of volume fraction of nanoparticles. It was shown that at constant

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Rayleigh numbers, the time-averaged Nusselt number is lowered with increasing volume fraction of nanoparticles. A review of the unique features of nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, thermophoresis and in addition, the outline of the recent research in experimental and theoretical studies on forced and free convective heat transfer in nanofluids, their thermo-physical properties and their applications is performed by Godson et al. [9].

Natural convection of water around its density maximum is complicated. Some reports on this can be found in literature. The inversion of water (base fluid) density affected the fluid flow and heat transfer within the enclosure [10–16].

Natural convection of water near its density maximum in rectangular enclosure is investigated by Tong [10]. Ishikawa et al. [11] studied numerically the natural convection with density inversion of water in a cavity. They made a correlation between average Nusselt number and the parameters involved in the study. Therefore, the consideration of influence of nonlinear temperature dependent fluid density in enclosure in the presence of nanoparticles is necessary. The literature survey indicates that the density inversion of base fluid in nanofluid mixtures has not been considered yet. Osorio et al. [12] studied the natural convection of water in an inclined square cavity at temperatures near its maximum density using the spectral elements method. Anwar Hossain and Rees [13] considered the unsteady laminar natural convection flow of water subject to density inversion in a rectangular cavity formed by isothermal vertical walls with internal heat generation. The effects of both heat generation and variations in the aspect ratio on the streamlines, isotherms and the rate of heat transfer from the walls of the enclosure are presented. Michalek et al. [14] investigate and compare the performance of four different numerical methods: finite differences, finite volume, finite elements and mesh-free diffuse approximation method and defined a numerical benchmark solution to study the steady-state natural convection in a differentially heated cavity for temperatures in a vicinity of the freezing point. Kandaswamy et al. [15] studied numerically the transient natural convection of cold water around its density maximum in a square cavity. Nine different positions of the active zones were considered. It was found that the average Nusselt number behaves non-linearly as a function of Grashof number and the heat transfer rate was decreased in the density maximum regions. Oztop et al. [16] numerically performed an analysis of natural convection in right-angle triangular enclosure filled with saturated cold water which has a density maximum around of 3.98 °C. Non-Boussinesq and Darcy models were used in mathematical formulations of governing equations. It was observed that heat transfer decreases with the effects of density inversion and it decreases with increasing of aspect ratio.

The present work aims to numerically study the effects of density inversion of water on natural convection of nanoparticle–water mixture in a rectangular enclosure. Effects of changes in nanoparticles volume fraction on natural convection heat are presented through local and average Nusselt numbers. Results are provided for the selected range of and nanoparticle volume fraction ($\phi = 0, 0.01, 0.05, 0.08$). Also, streamlines, isotherms and their corresponding velocity and temperature profiles at the midline of enclosure are plotted to supply useful information about the influence of nanoparticle dispersion and the density inversion on flow and heat transfer distribution.

2. Mathematical formulation

Consider a two-dimensional cavity with vertical wall of height $H = 38$ mm and width $W = 38$ mm as shown in Fig. 1. The inner space of the cavity is filled with the nanofluid. It was assumed that the flow is steady, Newtonian and incompressible and that the base fluid and nanoparticles are in thermal equilibrium and no slip occurs between them. Thermo-physical properties of the Nanofluid are assumed to be constant except for the density variation which is simulated both by a forth order polynomial and the approximated Boussinesq model (see Eq. (6)).

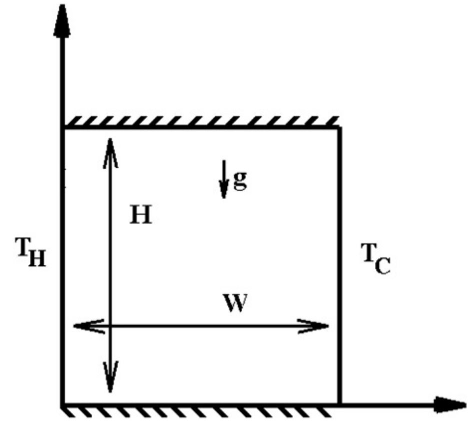

Fig. 1. Schematic for the physical model.

The thermo-physical properties of the base fluid and nanoparticle which were used for simulation are given in Table 1. The upper and lower walls of the cavity are horizontal and kept adiabatic. Vertical walls are kept isothermal. The wall at the right side is cold ($T = T_C$) and at the left side is hot ($T = T_H$). The gravity acceleration g acts vertically downwards. No slip boundary condition is applied for velocity components at both horizontal and vertical walls.

2.1. Heat and fluid flow analysis

It is also assumed that the base fluid and the nanoparticles are in thermodynamic equilibrium and that they flow at the same velocity. Under the assumption of constant thermal properties, the basic equations describing the steady flow driven by natural convection consist of conservation of mass, momentum and energy, and are given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{nf,0}}\left(-\frac{\partial p}{\partial x} + \mu_{nf}\nabla^2 u\right) \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}\left(-\frac{\partial p}{\partial y} + \mu_{nf}\nabla^2 v + (\rho\beta)_{nf} g (T - T_{ref})\right)_y \tag{3}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf,0}}\left(-\frac{\partial p}{\partial y} + \mu_{nf}\nabla^2 v - g\left(\rho_{nf}(T) - \rho_{nf,0}\right)\right)$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\partial}{\partial x}\left[\frac{\left(k_{nf,0} + k_d\right)}{\rho_{nf,0} C_{p,nf}}\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{\left(k_{nf,0} + k_d\right)}{\rho_{nf,0} C_{p,nf}}\frac{\partial T}{\partial y}\right] \tag{4}$$

Table 1
Thermo-physical properties of the Cu nanoparticles and base fluid (water).

Physical property	Cu Nanoparticle	Base fluid (water) at 0 °C
ρ[kg/m^3]	8954	999.8
μ[Pa.s]	–	0.0017888
c_p[J/kg K]	383	4212.0
k[W/m K]	400	0.566
Pr	–	13.31
d_p[m]	10^{-9}	–
β[1/K]	1.67×10^{-5}	6.73335×10^{-5}