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Natural convection of silica nanofluids in square and triangular enclosures: Theoretical and experimental study

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ABSTRACT

In this paper, the values of average Nusselt number and heat transfer coefficient ratio for natural convection of silica/water nanofluids in square and triangular cavities are estimated using theoretical correlations. The correlations that are used to calculate the heat transfer characteristics of enclosures are a function of thermophysical properties of nanofluids. Many studies demonstrated that using classic thermophysical models to determine the properties such as thermal conductivity, viscosity, and density sometimes may lead to substantial errors. To avoid such errors, it is helpful to determine the thermophysical properties through experiments. For this purpose, first SiO_2 nanoparticles with a diameter of 7 nm are suspended into water to prepare stable nanofluids. Next, thermal conductivity, viscosity, and density of nanofluids with volume fractions of 0.5%, 1%, and 2% are measured at a temperature range of 25–60 °C. Measured data are compared with the outcomes of theoretical models. The comparison of experimental data and classic models shows a considerable difference between the outputs particularly at high volume fractions of nanoparticles. Moreover, theoretical models predict a descending trend for variations of thermal conductivity ratio with temperature, but, on the contrary, experimental data unveil an ascending tendency. Finally, Nusselt number and heat transfer coefficient ratio for various cavities including square cavity in horizontal and inclined (angle of 45°) positions and the right triangular enclosure are predicted at Rayleigh numbers of 10^5 and 10^6. The findings indicate that even without having measured data of thermophysical properties, the average Nusselt number could be estimated with the same trend and maximum difference of 4.5%. However, the results of heat transfer coefficient ratio reveal the significant of using experimental data for properties to find the optimum working fluid for application in cavities since the theoretical models and experiment-based model may give different trends for heat transfer coefficient in enclosures.

1. Introduction

Natural convection in enclosures with various configurations and boundary conditions has numerous applications in industry and thermal equipment such as cooling of electrical devices, glass fabrication, furnaces, food and drying technologies, thermal energy storage tanks and so on. Therefore, optimization of such systems could be an aid to save energy [1–4]. Using a "nanofluid" instead of conventional working fluids such as water could be a solution to optimize the heat transfer processes in enclosures. In principle, nanofluids are mixtures of a liquid such as water, and solid particles usually with the size of 1–100 nm. Now, it is almost two decades that scholars attempt for the development of nanofluid applications in different thermal engineering systems such as solar collectors, nuclear reactors, car radiators and heat exchangers [5–8]. From 2003 to present, many studies have been carried out on the natural convection in enclosures filled with a nanofluid. Here, a brief review is made of the experimental and numerical studies. In 2003, for the first time, Khanafer et al. [9] paid attention to the free convection problem in a square cavity using Cu/water nanofluids with volume fractions by 20% and Grashof numbers ranging from 10^3 to 10^5. Their results indicated that particle loading results in a dramatic increase in average Nusselt number, especially at $Gr = 10^5$. They presented a correlation for the average Nusselt number in terms of volume fraction and Grashof number. Ho et al. [10] perused theoretically the effects

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Nomenclature

C_p	specific heat
g	gravitational acceleration
Gr	Grashof number
h	heat transfer coefficient
k	thermal conductivity
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Ra	Rayleigh number
t	time
T	temperature
u	velocity component in x-direction
v	velocity component in y-direction

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
μ	dynamic viscosity
ν	kinematic viscosity
ϕ	nanoparticle volumetric fraction
ρ	density

Subscripts

f	base fluid
n	nanofluid
p	nanoparticle

of different thermophysical models on the natural convection indexes of Al_2O_3/water nanofluids in a square cavity for Rayleigh numbers between 10^3 and 10^6, and volume fractions between 0% and 4% where the side walls were differentially heated. They found that with the increase of Rayleigh number, using appropriate models for thermophysical properties becomes imperative. Their results also indicated that with an increase in the volume fraction, the average Nusselt number augments. Santra et al. [11] numerically studied the natural convection in a partially heated square enclosure where the working fluid was Cu/water nanofluid with different volume concentrations ranging from 0.05% to 5%. For Rayleigh numbers between 10^4 and 10^7 and particles with the size of 100 nm, they revealed that at a given Rayleigh number, particle loading reduces heat transfer in the cavity.

Abu-Nada et al. [12] examined the effects of using different models for thermal conductivity and viscosity as well as the aspect ratio on the natural convection of two nanofluids including Al_2O_3/water and CuO/water in a rectangular cavity where the range of Rayleigh number is between 10^3 and 10^6, and nanofluid concentration changes from 0% to 9%. They found that in the case of the square enclosure and Al_2O_3/water nanofluids, the average Nusselt number is maximized at high Rayleigh numbers when nanofluid concentration reaches 5% while particle loading at low Rayleigh numbers leads to a little increase in Nusselt number. For CuO/water nanofluid, adding nanoparticles to the base fluid results in a decrease of Nusselt number at high Rayleigh numbers whereas at low Rayleigh numbers the changes in concentration have no visible effect on the Nusselt number. Their results also elucidated that more accuracy should be employed in the selection of suitable viscosity models compared to thermal conductivity models. Ho et al. [13] experimentally investigated the natural convection of water-based nanofluids containing alumina with concentrations less than 4% in three square cavities with different sizes. Their results unfold that the heat transfer could be enhanced up to 18% by using nanofluids at very low concentrations (much less than 0.1%) while the heat transfer rate is reduced at high concentrations compared to water.

Kahveci [14] presented a numerical solution of natural convection of five different nanofluids including Cu/water, Ag/water, CuO/water, Al_2O_3/water, and TiO_2/water with volume fractions up to 20% in an inclined cavity with variable slopes between 0° and 90°. He reported that using nanofluids enhances the heat transfer from 21% to 138% depends on the Rayleigh number and inclination angle. The maximum enhancement was associated with Ag (silver) nanoparticles that have the highest thermal conductivity compared to other particles. Jahanshahi et al. [15] studied the natural convection of silica/water nanofluids in a square cavity with differentially heated side walls for Rayleigh numbers between 10^5 and 10^7 and concentrations not higher than 4%. They used two sets of data for thermal conductivity. The first set of data obtained from Hamilton model and the second set of data was obtained from their experiments. They found that using experiment-based data for thermal conductivity shows an ascending trend for the average Nusselt number with concentration while the theoretical-based data present an opposite trend. Corcione [16] in a theoretical study of natural convection of nanofluids in rectangular cavities demonstrated that the nanofluid flow is similar to single-phase flows, and, consequently the same correlations may be used for the problems involved with nanofluid. The study showed that there is an optimal concentration in which the heat transfer rate reaches the maximum point.

Abouali and Ahmadi [17] theoretically showed that just by using available correlations, which are functions of thermophysical properties, the average Nusselt number and heat transfer coefficient due to free convection in enclosures with various shapes could be predicted with high accuracy and there is no need for time-consuming numerical simulations. In the investigation, they assumed that the nanofluid is a homogenous mixture, and there is no slip between particles and the liquid's molecules. Their results verified for two types of water-based suspensions including Al_2O_3 and CuO nanofluids.

Rezaiguia et al. [18] dealt with the natural convection of Cu/water nanofluids in an isosceles triangular cavity where a heat source was utilized for heating the bottom side. The variable parameters in the study were Rayleigh number (between 10^4 and 10^6), heat source length, nanofluid concentration (between 0% and 6%), and slope of the cavity. They disclosed that particle loading was an effective way for cooling of the cavity. They found that at high Rayleigh numbers, the effects of inclination angle on the fluid flow and heat transfer characteristics are pronounced. Rashidi et al. [19] examined the natural convection of Al_2O_3/water nanofluids with volume fractions up to 9% in a square cavity where Rayleigh number changes from 10^3 to 10^6. Nine different profiles of heat flux were applied to the bottom of the cavity where the total amount of heat flux for all cases was the same. They presented the optimal heat flux profile for the cavity by which the average Nusselt number is maximized. In an interesting work, Cho [20] conducted a numerical study to find the average Nusselt number and total entropy generation due to natural convection of Al_2O_3/water nanofluid in a wavy-shaped cavity. The author pointed out that using nanofluid will decrease the entropy generation, and, on the contrary, the heat transfer rate in the enclosure rises. Hu et al. [21] employed a two-phase Lattice Boltzmann to simulate the natural convection of Al_2O_3/water nanofluids with volume