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Fluid Dynamics and Transport Phenomena

Optimization of natural convection heat transfer of Newtonian nanofluids in a cylindrical enclosure

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ABSTRACT

This study characterizes and optimizes natural convection heat transfer of two Newtonian Al_2O_3 and TiO_2/water nanofluids in a cylindrical enclosure. Nusselt number (*Nu*) of nanofluids in relation to Rayleigh number (*Ra*) for different concentrations of nanofluids is investigated at different configurations and orientations of the enclosure. Results show that adding nanoparticles to water has a negligible or even adverse influence upon natural convection heat transfer of water: only a slight increase in natural convection heat transfer of Al_2O_3/water is observed, while natural convection heat transfer for TiO_2/water nanofluid is inferior to that for the base fluid. Results also reveal that at low *Ra*, the likelihood of enhancement in natural convection heat transfer is more than at high *Ra*: at low *Ra*, inclination angle, aspect ratio of the enclosure and nanoparticle concentration influence natural convection heat transfer more pronouncedly than that in high *Ra*.

1. Introduction

During the past few years, the use of nanofluids as a conventional fluid to enhance heat transfer has attracted considerable attention. Improvement in forced convection regime of heat transfer has been widely proven by many researchers. However, it is still a hot debate among workers regarding the role of nanoparticles in natural convection heat transfer.

There are several researchers who employed numerical techniques to explore natural convection heat transfer of nanofluids in enclosures. The effect of nanoparticle shape on heat transfer enhancement by "dissolving" rod-like and spherical nanoparticles in water was numerically investigated by Kim *et al.* [1]. The increase in the convective heat transfer with rod-like particles is more than spherical particles. Khanafer *et al.* [2] developed a model to study heat transfer enhancement of Cu/water nanofluid in a two-dimensional enclosure. They employed the finite-volume approach along with the alternating direction implicit procedure to solve the transport equations numerically. They reported that heat transfer rate rises significantly as the volume fraction of nanoparticles increases in the base fluid. Jou *et al.* [3] employed Khanafer's model to study natural convection heat transfer in a rectangular enclosure utilizing finite difference approach. They observed that increasing the buoyancy parameter and nanoparticle volume fraction increases the average heat transfer coefficient. Polidori *et al.* [4] theoretically investigated the natural convection flow and heat transfer of Al_2O_3/water nanofluid over a vertical semi-infinite plate. Results showed that the heat transfer enhancement of nanofluids depends on both nanofluid effective thermal conductivity and the proposed viscosity model. Hwang *et al.* [5] applied Jang and Choi's model [6] to predict the effective thermal conductivity of Al_2O_3/water nanofluid in a rectangular cavity heated from below. They concluded that the ratio of heat transfer coefficient of nanofluid to that of base fluid is lessened as the size of nanoparticles increases. Ho *et al.* [7] aimed at identifying impacts of uncertainties of effective dynamic viscosity and thermal conductivity of nanofluid in natural convection heat transfer of a square enclosure. They concluded that the type of the viscosity model applied to calculate the viscosity of nanofluids has significant impact on heat transfer. Pakravan and Yaghoubi [8] simultaneously investigated the thermophoresis of nanoparticles and the Dufour effect on natural convection heat transfer of nanofluids. They reported that there is a decreasing linear relation between the heat transfer coefficients of nanofluids and the particle diameter as well as the volume fraction. Alloui *et al.* [9] carried out an analytical and numerical study of natural convection heat transfer in a shallow rectangular cavity filled with nanofluids. They reported that heat transfer of nanofluids reached a maximum that depends on the Rayleigh as well as nanoparticle volume fraction. Daungthongsuk and Wongwises [10] delved into the convective heat transfer coefficient of TiO_2/water in a double-tube counter flow heat exchanger. They studied the influence of physical properties

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of nanofluid over heat transfer of the exchanger and managed to develop mathematical models to predict the physical properties of the nanofluid. Effects of inclination angle on natural convection heat transfer and fluid flow of Cu/water nanofluid in a two-dimensional enclosure by solving the governing equations using finite-volume technique was studied numerically by Abu-Nada and Oztop [11]. They stated that the inclination angle of the enclosure can be an effective major parameter in natural convection heat transfer of the Cu/water nanofluid. In a study by Ghasemi and Aminossadati [12], the influence of Rayleigh number, inclination angle, and solid volume fraction upon natural convection heat transfer of a two-dimensional inclined enclosure filled with a CuO/water nanofluid was numerically studied. In this study, two opposite walls of the enclosure were insulated and the other two walls were kept at different temperatures. Results revealed that at a specific concentration of nano-particles and a specific inclination angle for the enclosure, natural convection heat transfer reached its maximum and the value of the maximum depended on the studied Rayleigh number.

Compared with extensive numerical and theoretical studies on natural convection heat transfer of nanofluids, limited experimental work has been conducted. In a pioneering work, Putra *et al.* [13] investigated natural convection heat transfer of Al_2O_3/water and Cu/water nanofluids through a horizontal cylinder, which was heated from one end and cooled from the other. They claimed that particle density, concentration, and the aspect ratio of the cylinder are effective parameters upon natural convection heat transfer. Wen and Ding [14] studied natural convection heat transfer of TiO_2/water nanofluid between two disks. Experimental results showed that as particle concentration was increased, the natural convection heat transfer coefficient was decreased, which was in contradiction to the initial expectation. Nnanna [15] carried out experimental studies of heat transfer behavior of a buoyancy-driven Al_2O_3/water nanofluid in a two dimensional rectangular cavity which its vertical walls were heated partially and the horizontal walls were isolated. They managed to develop an empirical correlation for Nusselt number as a function of the volume fraction of the nanoparticles and Rayleigh number. They claimed that the heat transfer rate can be enhanced even by a small volume fraction of nanoparticles.

Experimental studies on the natural convection heat transfer of nanofluids are rare. Hence, the objective of this work is to experimentally investigate the effects of two common nanoparticles on the natural convection heat transfer of water in a cylindrical enclosure. This study will clarify whether or not nanoparticle has a positive consequence on natural convection heat transfer. The influence of the geometry and configuration of the cylindrical enclosure on natural convection heat transfer is also studied for better understanding of the natural convection heat transfer of nanofluids.

2. Material and Methods

2.1. Test samples

γ-Al_2O_3 and TiO_2 nanoparticles (Nanostructured & Amorphous Materials Inc., USA) were dispersed into the de-ionized water for nanofluids preparation. Five nanofluids samples were prepared with different volume concentrations of nanoparticles (0.1%, 0.2%, 0.5%, 1% and 1.5%). The dispersion of nanoparticle into the water occurred by means of a mechanical mixer operated at 200 $r\cdot min^{-1}$. Afterwards, the mixture was located into an ultrasonic vibration apparatus for 240 min for better dispersion of nanoparticles into the base fluid. The behaviors of prepared samples (AL_2O_3/water [13] and TiO_2/water [16]) were highly Newtonian. The stability of the prepared nanofluids was frequently checked during experiments. Calculation of the density (by weighing a specific volume of each sample) of all the samples before and after each test (the difference was below 0.1%) showed that the samples were quite stable and no sedimentation of nanoparticles was observed throughout the experiment.

2.2. Description of experimental apparatus

Experimental setup is designed based on the work of Putra *et al.* [13]. Five distinct sections (test cell, data acquisition, power, PC, thermostatic bath) of the experimental setup are shown in Fig. 1.

Test cell is a vertical cylindrical enclosure with a diameter of 80 mm and a height of 250 mm that is made from PTFE (polytetra-fluoro-ethylene). The cylindrical enclosure was fully insulated for having a minimum heat loss during experiments so as to get results of better accuracy in the case of natural convection. The test cell was uniformly heated from bottom side by a heating system, which consisted of an aluminum circular plate and an electrical heater. The heater was located between the aluminum plate and a thick PTFE circular plate in order to provide constant heat flux. The PTFE plate is also an insulation. The upper cover of the cylindrical enclosure was mobile and could be moved along the cylinder for adjusting the height of the test cell. This makes it possible for us to investigate the effect of aspect ratio on natural convection heat transfer. Experimental setup also includes a thermostatic bath which provides and circulates cooling water to the upper cover of the chamber to adjust the upper surface temperature constant at 10 °C. Heat fluxes were provided by a DC power supply and the power changed by setting the voltage of the heater. The experimental section also has a PC and data acquisition system to gather, process, and record data from our experiments. Detailed description of the cylindrical enclosure is shown in Fig. 2.

Surface temperatures at the top and bottom plates of cylindrical enclosure were measured by virtue of six K-type thermocouples (three at each surface, accuracy of measurements: 0.1 °C). Surface temperature which was used in our calculations was the average of three temperatures measured by thermocouples. The inlet and the outlet temperatures of the water of the cooling chamber were also measured by thermocouples. A data acquisition system record measurements of thermocouples and sent them to a computer. Prepared samples (nanofluids) were cautiously added to the enclosure (test section) so that no air bubbles formed and interrupted experiments.

Experiments were all performed on days with exactly the same weather conditions (relative humidity and average temperature). They were repeatable within each series of tests on those days. Tests were also recorded and obtained at steady-state conditions in test cells (for heat transfer as indicated by a constant water outlet temperature value) that allowed good repeatability. Experiments were repeated three times. Results presented were the average of measurements in these three disparate tests. The uncertainty of tests was calculated from a combination of the experiment repetition error and the precision error of the thermocouples.

To investigate the performance of the setup apparatus, a benchmark experimentation was carried out with pure distilled water. At this stage, the variation of *Nu* (Nusselt number) in relation to *Ra* (Raleigh number) was experimentally verified at 0°, 30°, 45°, 60° and 90° inclination angles of the enclosure. At each specific inclination angle, *Ra* was increased by changing the heating power. By doing this, the temperature of the hot surface was changed, whereas the temperature of the cold surface was remained at a fixed value, the temperature difference in *Ra* and consequently *Ra* was varied. Note that other variables in *Ra* remained pretty constant during the experiment. Results for all inclination angles revealed that by increasing *Ra*, firstly, *Nu* increased dramatically and then showed a much less intensification from itself (Fig. 3).

This observation is in agreement with the result of all previous studies. For instance, Putra *et al.* [13] carried out an experiment to investigate natural convection heat transfer of pure water by exploring the relationship of *Nu* with *Ra*. Results in their study demonstrated that at first *Nu* increased significantly with *Ra*, then its trend became milder