International Journal of Heat and Mass Transfer 73 (2014) 231–238

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A comparative experimental study on the natural convection heat transfer of different metal oxide nanopowders suspended in turbine oil inside an inclined cavity

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ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form 30 January 2014
Accepted 30 January 2014
Available online 4 March 2014

Keywords:
Natural convection
Inclination angle
Nanofluids
Experimental study

ABSTRACT

An experimental study is conducted to investigate the effects of inclination angle on the natural convection of nanofluids inside a cubic cavity with the side size of 10 cm. One of the surfaces of the cavity is kept in cold temperature and another one (opposite side) in hot temperature while the other four surfaces are insulated. The mixtures of three different types of nanoparticles including Al_2O_3, TiO_2, and CuO within turbine oil (TO) are used as the heat transfer fluid. The heat transfer in the cavity is investigated in three inclination angles with respect to the horizontal position including 0°, 45° and 90° where the weight fractions of nanoparticles are 0.2%, 0.5%, and 0.8%. The Nusselt number results are presented for the three types of nanofluids, and different angles of inclination, Rayleigh number, and weight fraction of nanoparticles. The results reveal that the turbine oil has the highest Nusselt number in any inclination angle of the cavity compared to the nanofluids. Also, it is found that at the inclination angle of 90°, and the weight fraction 0.2%, the application of TiO_2 particles results in the maximum Nusselt number while for weight fraction of 0.8%, the maximum Nusselt number is associated with the CuO nanopowders.

1. Introduction

Natural convection flow in enclosures is one of the classic problems that is important due to its application in many thermal engineering devices such as solar collectors, energy storage systems, electronic devices, and so on. Recent developments in the field of nanofluids as an advanced type of liquids with surprising properties have led to a renewed interest in the study of natural convection in enclosures where a nanofluid is the working fluid. The satisfactory effects of using nanofluids on the heat transfer enhancement are proven in many applications such as solar cells, solar collectors, nuclear reactors, automobiles, microchannels, electronic devices, phase change materials, and so on [1,2].

Here, some studies on the natural convection in cavities using nanofluids are reviewed briefly. First, the numerical works are reviewed. Ho et al. [3] in a numerical work investigated the effects of using different models to calculate the viscosity and thermal conductivity on the natural convection heat transfer inside a square cavity. The bottom and top walls were insulated while one of the side walls was assumed cold and another one hot. They used alumina/water nanofluids as the working fluid where the volume concentrations do not exceed 4%. They concluded that using different thermophysical models may lead to the estimations in an opposite trend for the Nusselt number especially in high solid volume fractions. Abu-Nada and Oztop [4] examined numerically the effects of inclination angle (between 0° and 120°) of a square cavity filled with Cu/water nanofluid (volume fractions upto 10%) on the heat transfer. The boundary conditions in this work were similar to the boundary conditions considered by Ho et al. [3]. Öğüt [5] simulated the natural convection of five different water based nanofluids (volume fractions upto 20%) containing Cu, Ag, CuO, Al_2O_3, and TiO_2 nanoparticles in a cavity where one of the side walls was heated using a heater mounted on the wall. The cavity angle was varied between 0° and 90°. They indicated that with increasing the concentration, the heat transfer rate increases. This increase was more considerable for the particles with higher thermal conductivity (i.e. Ag and Cu). In a similar work to the study of

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.01.071
0017-9310/

Nomenclature

A	heat transfer area
c_p	specific heat (kJ/kg K)
d_p	diameter of the alumina particles (nm)
g	gravitational acceleration (m/s^2)
$\bar{h}$	surface-averaged heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
l	length of cavity (m)
Nu_{nf}	average Nusselt number
q''	surface-averaged heat flux from the hot wall (W/m^2)
Pr_{nf}	Prandtl number
Ra_{nf}	Rayleigh number
T	temperature (C)

Greek symbols

α	thermal diffusivity (m^2/s)
β	volumetric thermal expansion coefficient (1/K)
μ	dynamic viscosity (kg/m s)
ρ	density (g/cm^3)

Subscripts

bf	base fluid
c	cold wall
h	hot wall
m	mean value
nf	nanofluid
p	nanoparticles

Ho et al. [3], Abu-Nada et al. [6] investigated the effects of uncertainties in thermophysical properties on the heat transfer of Al_2O_3–water and CuO–water nanofluids (volume fractions upto 9%) in the cavity. They concluded that the average Nusselt number has a higher sensitivity to viscosity compared to thermal conductivity at high Rayleigh numbers, hence, a suitable viscosity model should be selected for such conditions.

Ghasemi and Aminossadati [7] analysed numerically the flow of Cu, Al_2O_3 and TiO_2 nanoparticles suspended in water in a cavity where the top and bottom walls are insulated, right wall is kept cold and the left wall is subjected to a periodic heat flux. They found that using Cu and TiO_2 (volume fractions upto 20%) leads to the maximum and minimum heat removal from the heat source, respectively. Shahi et al. [8] considered the flow of Cu/water nanofluid (volume fractions upto 5%) in a square cavity where the bottom wall is subjected a constant heat flux, while the cooling of the cavity is conducted by entering a nanofluid flow from the left wall and exiting from the right wall. They concluded that an increase in the volume fraction increases the average Nusselt number in the cavity. Lin and Violi [9] simulated the effects of particle size on the natural convection flow of Al_2O_3/water nanofluid (volume fraction upto 5%) in a cavity. Their results indicated that by decreasing the nanoparticle size from 250 nm to 5 nm, the heat transfer rate increases.

Kahveci [10] conducted a work similar to Ref. [5], with this difference that the cavity can rotate from 0° to 90°. The author revealed that with the increase of the Rayleigh number, the inclination angle in which the maximum heat transfer rate occurs, changes from 45° to 30°. He also found that using Ag nanopartilces results in the maximum heat transfer rate, while the heat transfer rate is minimum for TiO_2 nanoparticles. Corcione [11] obtained the optimum particle loading for the nanofluid flow in a cavity with different aspect ratios. The author concluded that with the decrease of nanoparticle size, the level of optimal volume fraction increases. Mahmoudi et al. [12] studied the mixed convection flow of Cu/water nanofluid in a cavity where four different configurations were considered based on the inlet and outlet flow. In another work, Mahmoudi et al. [13] solved the natural convection problem where the thickness of the left wall is considered.

The interested readers can refer to other numerical works are as follows. The effects of temperature dependent models on the natural convection were considered by Abu-Nada [14], the natural convection of nanofluids in a cavity using the lattice Boltzmann method was studied by Lee and Yang [15], investigation of thermophoresis and Brownian motion effects on natural convection by Haddad et al. [16], double-diffusive natural convection of nanofluid was studied by Parvin et al. [17], heatline analysis of nanofluid flow in natural convection has been conducted by Basak and Chamkhah [18], the effect of nanoparticle shape was investigated by Ooi and Popov [19], free convection in a complicated cavity was studied by Nasrin and Alim [20], and finally the free convection in a cavity filled with nanofluids was considered by Garoosi et al. [21] where several pairs of coolers and heaters were installed inside the cavity. A comprehensive review on the natural convection of nanofluids in cavities with different structures is performed by Haddad et al. [22].

However, also some experimental works on the natural convection of nanofluids in cavities are observed in the literature.

Wen and Ding [23] during an experimental work on the natural convection of TiO_2/water nanofluid between two parallel disks, concluded that using nanofluids leads to the decrease of the heat transfer rate in the enclosure. They used the nanofluids at low volume concentrations (not more than 0.57%). Nnanna [24] tested Al_2O_3–water nanofluids with volume fractions upto 8% in a partially heated cavity. It was found that using nanofluids with concentrations upto 2% results in the increase in the heat transfer rate while for volume fractions greater than 2%, due the unfavorable effects of viscosity the heat transfer rate decreases. Li and Peterson [25] sought for the possible reasons behind the heat transfer detraction due to using Al_2O_3/water nanofluids (volume fractions upto 6%) in a vertical cylindrical cavity. In separate experiments, they could find that the Brownian motion and thermophoresis phenomena affect the heat transfer rate. In a nice work, Ho et al. [26] examined the natural convection of Al_2O_3/water nanofluid (volume fractions upto 4%) in the vertical cavities with three different aspect ratios. They concluded that increasing the particle loading (more than about 1%) leads to the decrease of the average Nusselt number especially at lower Rayleigh numbers.

As it is seen, although extensive numerical studies have been performed on the natural convection in a cavity using nanofluids, but there has been little experimental works in this field. This is due to the difficulties in the experimental study of such flows. Also, in most of the studies the base fluids were water or ethylene glycol.

The present work aims to provide a comprehensive investigation on the effects of using three different turbine oil (TO) based nanofluids including Al_2O_3, TiO_2, and CuO nanoparticles in a cubic cavity. After preparing the suspensions of nanofluids, the effects of the inclination angle, Rayleigh number, and volume fraction of nanoparticles on the Nusselt number are investigated. Utilizing three different types of nanoparticles let to find out the effects of thermal conductivity, heat capacity, density and thermal expansion of nanoparticles on the heat transfer rate.