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Experimental investigation on cavity flow natural convection of Al_2O_3–water nanofluids☆

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ABSTRACT

Thermo-physical properties of nanofluids have attracted the attention of researchers more than the heat transfer characteristic of nanofluids. On the other hand, contradictory results were reported on the thermal-fluid behaviour of nanofluids numerically and experimentally in the open literature. In addition to that, experimental natural convection has been investigated less than others. In this paper, characteristic and stability of Al_2O_3–water nanofluid ($d = 30$ nm) has been analyzed by using Malvern Zetasizer, Zeta potential, and UV–visible spectroscopy. The natural convection of Al_2O_3–water nanofluids (formulated with single-step method) was experimentally studied in detail for volume fractions of 0, 0.05, 0.1, 0.2, 0.4 and 0.6% in a rectangular cavity, heated differentially on two opposite vertical walls for Rayleigh number (Ra) range 3.49×10^8 to 1.05×10^9. The viscosity of the Al_2O_3–water nanofluids are also measured experimentally in a temperature range between 15 °C and 50 °C and effect of temperature and volume fraction on viscosity have investigated. Detailed study on the influence of nanoparticle concentration on natural convection heat transfer coefficient was performed. It was found that increasing concentration of nanoparticles improves heat transfer coefficient up to an optimum value of 15% enhancement, at 0.1% volume fraction, then further increasing of concentration of the nanoparticles deteriorates natural convection heat transfer coefficient. This research also supports the idea of "for nanofluids with thermal conductivity more than the base fluids, there may exist an optimum concentration which maximizes the heat transfer in an exact condition as natural convection, laminar forced convection or turbulence forced convection".

1. Introduction

Natural convection application in confined volume is widespread in engineering application. Cooling of electronic equipment, solar collectors, ventilation and cooling of buildings, aeronautics, transportation, cooling of a nuclear reactor, pharmaceutics and food industry are some application of natural convection in confined volume [1]. Natural convection has inherently low heat transfer coefficient, therefore, investigations of how to increase heat transfer coefficient of natural convection should be considered. To enhance heat transfer performance of a system there are two methods, one way is new design, such as geometry optimization, which is not applicable for a miniaturized system such as Micro-Electro-Mechanical-Systems (MEMS), an alternative way is scaling up of heat transfer capacity by using new heat transfer fluids. Nanofluids are the centre of attention as a high potential heat transfer medium. They are dilute engineered colloidal suspension of nanometer size (d < 100 nm) metal, non-metal, metal oxide, carbides and carbon nanotubes in conventional heat transfer fluids [2]. Brownian motion, nanolayer, nanocluster, thermophoresis and ballistic nature of heat transfer are possible mechanisms of heat transport in nanofluids [3]. Many researchers have investigated laminar and turbulent convection heat transfer of nanofluids [4]. Heyhat et al. [5] experimentally studied turbulent convection heat transfer of Al_2O_3–water nanofluid. They find 23% enhancement in heat transfer coefficient with 2% volume fraction of Al_2O_3 nanoparticles. Zeinali et al. [6] studied experimentally laminar forced convection with Al_2O_3–water (d = 20 nm) and CuO–water (d = 50–60 nm) nanofluids. The improvement of heat transfer by increasing the nanofluid concentration is reported. Sonawane et al. [7] studied the performance of concentric heat exchanger by using Al_2O_3–water nanofluids, and they report an enhancement in the performance of the heat exchanger. However, it is reported no or small heat transfer improvement of water as a base fluid with applying different metal oxide nanoparticles (mass concentration of 3% to 45%) by Haghighi et al. [8].

A few researchers have investigated on natural convection heat transfer of nanofluids. Most studies on natural convection with nanofluids are a numerical simulation with two approaches, single-phase model and two-phase model. Contradictory results of nanoparticle concentration effect on heat transfer were shown through different studies. Khanafer et al. [9] numerically investigated natural convection

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Nomenclature

Ar	Aspect ratio
AWG	American wire gage
C_p	Specific heat, J/kg K
d	Nanoparticle diameter, m
F_n	Thermo-physical properties ratio
g	Gravitational acceleration, m^2/s
H	Height, m
h	Average heat transfer coefficient, W/m^2K
h_D	Hydraulic diameter, m
k	Thermal conductivity, W/m K
L	Depth, m
m	Mass flow rate, kg/S
n	Exponent value Eq. (3)
Nu	Nusselt number
$\overline{Nu}$	Average Nusselt number
Pr	Prandtl number, $C_p\mu/k$
$\bar{q}$	Average heat transfer rate, W
Q	Heat transfer, J
Ra	Rayleigh number
s	Distance from the hot heat exchanger surface
T	Temperature, °C
W	Width, m
wt	Mass fraction
ΔT	Temperature difference, °C
Greek symbols	
α	Ultrasonic energy density, KJ/ml
β	Thermal expansion coefficient,1/K
ρ	Density, kg/m^3
μ	Dynamic viscosity, Pa s
θ	Dimensionless temperature
δ	Dimensionless distance
φ	Volume fraction
Subscript	
P	Nanoparticle
bf	Based fluids
nf	Nanofluids

of ultrafine copper particles and water. Brinkman model [10] and Wasp model [11] were used for viscosity and thermal conductivity, respectively. For any given Grashof number boosting volume fraction improves the heat transfer rate. Ögüt [12] numerically scrutinized heat transfer of nanofluids (Cu, CuO, Al_2O_3 and TiO_2 in water) using constant heat flux in an inclined cavity. The nanofluids heat transfer escalates with increasing nanoparticle concentration. In contrary, Abu-Neda [13] numerically examined the influence of applying different thermal conductivity and viscosity models from Chon et al. [14], and Nguyen et al. [15], respectively, on heat transfer coefficient. He observed the effect of Rayleigh number (*Ra*) and concentration of Al_2O_3–water nanofluid on natural convection heat transfer. Enhancement of *Nu* by increasing volume fraction at $Ra = 10^3$ is reported, however, for $Ra \geq 10^4$ average *Nu* deteriorates with scaling up of the ultrafine particles concentration. The effect of alumina nanoparticle size distribution on augmentation or mitigation of heat transfer in a cavity was examined numerically by Lin and Violi [16]. Their results show on one hand; for smaller nanoparticles there is an increase in the heat transfer coefficient by adding nanoparticles (8% enhancement at $\varphi = 1$ vol% where $d = 5$ nm). On the other hand, for big nanoparticles, there is mitigation in the heat transfer coefficient by adding nanoparticles (26% mitigation at $\varphi = 1\%$ with d = 250 nm). Effect of using different viscosity and thermal conductivity models in 2D numerical simulation of a square enclosure filled with Al_2O_3–water nanofluid was analysed at [17]. Ho et al. [17] show that the prediction of nanofluids heat transfer is more sensitive to the selected viscosity model than the thermal conductivity model.

Buongiorno [18] points out that thermophoresis and Brownian diffusion are the most important slip mechanism in two-phase mixture of nanofluids, which is used for two-phase nanofluids simulation. Haddad et al. [19] scrutinise the effect of thermophoresis and Brownian motion on CuO–water nanofluid in natural convection using finite element method. They conclude that both thermophoresis and Brownian diffusion improve heat transfer rate at any volume fraction. Nevertheless, by neglecting the effect of thermophoresis and Brownian motion, the natural convection heat transfer declines with an increase in particle concentration.

Segni and Bennacer [20] numerically examined the effect of heterogeneous mixture model on the prediction of nanofluid natural convection. They indicate improvement in *Nu* with increasing nanoparticle concentration up to 5% (for alumina particles) then deterioration of the *Nu* for further boosting nanoparticle concentration. They also report the same trend for TiO_2 and Cu nanoparticles. However, they revealed that using homogeneous mixture model predicts a systematic decline of *Nu* with increasing nanoparticle concentration. He et al. [21] conducted a numerical investigation on alumina nanofluid in a square cavity. They observe a constant decrease in *Nu* with adding alumina nanoparticles. Sheikhzadeh et al. [22] compared novel transport model and homogeneous model, to predict the effect of nanoparticle concentration on natural convection heat transfer of Al_2O_3–water nanofluid. A reduction in natural convection heat transfer by adding nanoparticles for both models is reported. However, their results showed the transport model predicts greater reduction for nanofluids and it also showed better agreement with reported experimental results of Ho et al. [23]. Alumina water nanofluids ($\varphi = 1$ to 4% and *Ra* between $Ra = 7 \times 10^6$ and 7×10^7) in horizontal cylinder were investigated numerically by Meng and Li [24]. The natural convection heat transfer coefficient decreases with increasing alumina concentration.

Contradictory results on numerical investigation of natural convection in an enclosure and lack of enough experimental works, lead towards more experimental investigations. Relatively, a few experimental investigations are available in the literature due to the difficulty of measurement of effective parameters. Putra et al. [25] examined the effect of nanoparticle concentration on natural convection heat transfer coefficient. Natural convection in a horizontal cylinder heated from one side and cooled from another side was investigated. Al_2O_3 (d = 131.3 nm) and CuO (d = 87.3 nm) were suspended in distilled water. To break down aggregation of particles (50 ml volume) 4 h of sonication was used. They assumed that sonication time is enough to prevent sedimentation during the experiment and visual observation method was used to ensure the stability of the nanofluids. Systematic deterioration of heat transfer with increasing concentration of nanoparticles ($\varphi = 1$ to 4%) is reported. However, to ensure the stability of nanofluids, which needs to be examined accurately, scientific method should be applied such as UV–visible spectroscopy method or by measuring Zeta potential.

Natural convection of TiO_2–water (nominal diameter size claimed by the manufacturer was 30–40 nm) in a disc-shape enclosure for 0.19, 0.36 and 0.57% volume fraction was investigated experimentally by Wen and Ding [26]. Stable nanofluid was formulated at pH = 3 with measured ZP = +45 mV at 0.024% volume fraction. However, such level of acidity of the solution increases corrosion rate, therefore, restricts its industrial application. To reduce average aggregation size of the ultrafine particles high-shear homogenizer was used. They observed that the mean size of aggregation reduced from 193 nm to 170 nm for zero to 50 min of applying high-shear homogenizer. However, a small amount of sedimentation was reported in the study. Experimental average *Nu* for only water was found to be between two