Experimental Investigation into Natural Convection of Zinc Oxide/Water Nanofluids in a Square Cavity

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ABSTRACT

The public domain is inundated with discrepancies in numerical and experimental findings on the natural convection heat transfer performance of nanofluids in a cavity. This paper presents the experimental investigation of the natural convection of deionized water (DIW)-based zinc oxide (ZnO) nanofluid in a rectangular cavity. The ZnO nanoparticles (20 nm) were dispersed in DIW to formulate nanofluids at various volume concentrations (0.10, 0.18, 0.36, 0.50 and 1.0 vol.%). The spectrophotometer and zeta potential were used to verify the stability of ZnO/DIW nanofluid at various temperatures and concentrations. ZnO/DIW nanofluids and DIW were charged into a rectangular cavity with the opposite vertical walls under varying temperature differences. The natural convection of ZnO/DIW nanofluid was performed at Rayleigh number range of 7.45×10^7 and 9.20×10^8. Zeta potential values revealed stable nanofluids with no sedimentation of nanoparticles observed within 24 h. At 0.10 vol.% and temperature difference of 32 °C, the ZnO/DIW nanofluid was observed to enhance the heat transfer coefficient by 9.14% relative to DIW. Further increase in volume concentration resulted in the attenuation of heat transfer. Additionally, the Nusselt number and heat transfer rate were augmented by 8.42% and 6.75% at 0.10 vol.%, respectively.

Introduction

The last century witnessed many researchers involved in industrial and electronic cooling processes paying remarkable attention to various techniques of thermal transport. An increase in the coefficient of heat transfer was observed to lead to an increase in the efficiency of power output. The innovation started by improving the thermal conductivity of conventional fluids through the dispersion of nanoparticles (1 to 100 nm) of metals, metal oxides or nanotubes to make nanofluids [1]. The low thermal conductivity associated with conventional fluid was augmented by dispersing nanoparticles with a considerably higher thermal conductivity into it. This led to the engineering of a new class of heat transfer medium with higher thermal conductivity and improved convective heat transfer. To achieve thermal and cost-efficient traditional heat transfer fluids, nanofluids are generally accepted as a suitable alternative to meeting the present cooling demand posed by the state of technological advancement in various areas of application e.g. building air conditioning, electronic cooling, automobiles, industries, solar collector, nuclear reactor cooling, and chemical processes [2].

The complexity of nanofluid systems has led to the disparity of results among researchers concerning its heat transfer efficiency. In convective heat transfer, the coefficient of heat transfer depended on the viscosity and thermal conductivity of the nanofluid. The temperature, volume concentration, and particle size considerably affect the viscosity of nanofluids [3]. There is a need to investigate which nanofluids improved or attenuated the coefficient of heat transfer. With natural convection cooling, the design of components and devices could be minimized in addition to the cost, noise, and pollution. However, natural convection is known to have a lower coefficient of heat transfer relative to other thermal transport techniques. The number of numerical studies that have been conducted on the natural convection of nanofluid is far higher than the experimental ones. Table 1 summarizes the numerical and experimental

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Nomenclature

A	area, m^2
Ag	silver
Al_2O_3	aluminium oxide
c_p	specific heat, J/(kgK)
Cu	copper
CuO	copper oxide
DIW	deionized water
EG	ethylene glycol
g	acceleration due to gravity, m/s^2
h	heat transfer coefficient, $W/(m^2.K)$
k	thermal conductivity, W/(m.K)
L_c	characteristic length of cavity, m
$\dot{m}$	mass flow rate, kg/s
MWCNT	multi-walled carbon nanotube
Nu	Nusselt number
PG	propylene glycol
$\dot{Q}$	heat transfer rate, W
Ra	Rayleigh number
T	temperature, °C
T_{ave}	average temperature in the cavity or average temperatures of the hot and cold walls, °C
T_C	temperature of the cold wall in the cavity, °C
TEM	transmission electron microscopy
T_H	temperature of the hot wall in the cavity, °C
T_{in}	temperatures at the inlet of the heat exchanger, °C
TiO_2	titanium oxide
T_{out}	temperatures at the outlet of the heat exchanger, °C
wt	weight, kg
x	distance along the cavity from hot wall, m
ZnO	zinc oxide
ZP	zeta potential, mV

Greek symbols

β	volumetric coefficient of thermal expansion, 1/K
φ	volume concentration of nanofluid, vol.%
θ	non-dimensional temperature
μ	dynamic viscosity, kg/m.s
ρ	density, kg/m^3
δ	non-dimensional distance of the cavity

Subscripts

bf	base fluid
eff	effective
nf	nanofluid
np	nanoparticle

studies of natural nanofluid convection in a differentially heated rectangular enclosure [4–14].

Khanafer et al. [4] numerically examined the natural convection heat transfer in a rectangular enclosure containing a Cu/water nanofluid. The heat transfer of Cu/water nanofluid was improved by 25% at 0.2 vol.%. On the contrary, Putra et al. [5] experimentally reported attenuation of the natural convection heat transfer rate of water-based Al_2O_3 and CuO nanofluids contained in a cylindrical cavity. Hwang et al. [6] used a theoretical technique to study the natural convection of water-based Al_2O_3 nanofluid inside a rectangular cavity and compared their findings with that of Putra et al. [5]. Heat transfer was improved with a reduction in the size of the nanoparticles or as temperature and φ increased. This was observed to be contrary to the result of attenuation reported by Putra et al. [5]. Experimentally, Wen and Ding [7] studied the natural convection of TiO_2/water nanofluid inside a horizontal cylinder. The heat transfer coefficient of TiO_2/water attenuated relative to water with an increase in φ with a maximum value of 30% at 2.5 wt.%.

To understand the effect of Brownian motion, Ludwig–Soret effect, and sedimentation on the natural convection of water-based Al_2O_3 nanofluid filled into a rectangular enclosure, Ho et al. [13] used both numerical and experimental techniques. They demonstrated that both methods enhanced Nu of Al_2O_3/water nanofluids compared to water and it augmented with an increase in φ. An increase in *Ra* was noticed to enhance Nu. The influence of sedimentation was more significant than those of Brownian motion and Ludwig–Soret effect. Using an experimental method, Ho et al. [8] examined the natural convection of water-based Al_2O_3 nanofluid inside three dissimilar square cavities. Their result showed that heat transfer was augmented at $\varphi = 0.10$ and 0.30 vol.% for all the cavities, which increased with an increase in cavity size. At $\varphi = 0.10$ vol.%, the highest heat transfer enhancement of 18% was attained using the largest cavity. This occurred due to the dominance of viscosity in the coefficient of heat transfer model.

Minea and Lorenzini [15] numerically investigated the natural convection behavior of water-based ZnO in a rectangular cavity uniform heat flux applied at the side and top. They reported enhancement of the coefficient of heat transfer by 1.33% − 10.27%, and −0.2% − 11.41% for exposing the side and top to uniform heat flux, respectively, with an increase in φ. Öğüt [10] investigated the natural convection of five water-based nanofluids (TiO_2, Al_2O_3, CuO, Ag and Cu) in an inclined square cavity. Heat transfer improvement was observed as both φ and Ra increased. The influence of changing the inclined angle of the cavity showed that the highest heat transfer rate was attained at an inclined angle of 30° and it attenuated at 90°. Ag/water nanofluid has the highest heat transfer rate of the nanofluids studied.

Joshi and Pattamatta [16] experimentally studied the natural convection of water-based MWCNT,

Table 1. Summarizes previous research for natural convection of nanofluid in a rectangular cavity.

Author	Nanofluid (φ)	Particle size	Ra	Method	Heat transfer enhancement
Khanafer et al. [4]	Cu/water $(0-20$ vol.%)	10 nm	10^3-10^6	Numerical	Improved
Putra et al. [5]	Water-based Al_2O_3 and CuO $(1-4$ vol.%)	131.2 nm 87 nm	10^6-10^8	Experimental	Deteriorated
Hwang et al. [6]	Al_2O_3/water $(0-5$ vol.%)	10,152,050 nm	10^6-10^7	Numerical	Improved
Wen and Ding [7]	TiO_2/water $(0-0.57$ vol.%)	Not specified	$5.0\times10^3-3.5\times10^4$	Experimental	Deteriorated
Ho et al. [8]	Al_2O_3/water $(0-4$ vol.%)	Not specified	10^3-10^6	Numerical	Improve and deteriorated
Abu-Nada and Chamkhab [9]	CuO/EG-water $(0-6$ vol.%)	29 nm	10^3-10^5	Numerical	Improve and deteriorate
Öğüt [10]	Water-based Cu, CuO, Al_2O_3, Ag, and TiO_2 $(8-20$ vol.%)	Not specified	10^4-10^6	Numerical	Improved and then deteriorated
Ho et al. [11]	Al_2O_3-water $0.1-4$ vol.%	33 nm	$6.21\times10^5-10^8$	Experimental	Improved and then deteriorated
Hu et al. [12]	TiO_2-water 3.8, 7.4, and 10.7 wt%	10 nm	$4\times10^4-2.4\times10^8$	Experimental and numerical	Improved
Ho et al. [13]	Al_2O_3-water $0-4$ vol.%	33 nm	$6.21\times10^5-2.56\times10^8$	Experimental and numerical	Improved
Hu et al. [14]	Al_2O_3- water $0-0.77$ vol.%	30 nm	$3.0\times10^7-7\times10^7$	Experimental and numerical	Improved and then deteriorated

graphene, and Al_2O_3 nanofluids in a square cavity. At $\varphi = 0.1$ vol.% and the range studied, Nu was observed to be enhanced for water-based MWCNT and Al_2O_3 nanofluids. Enhancements of 35%, 20%, and 5% were reported for water-based MWCNT, graphene, and Al_2O_3 nanofluids, respectively, relative to the water. Joshi and Pattamatta [17] experimentally studied the natural convection of MWCNT/water and Al_2O_3/water nanofluids in a square cavity. The result revealed that Nu of MWCNT/water nanofluid was higher than that of Al_2O_3/water nanofluid. Improvements of 35% and 11% at 0.1 vol.% and 0.3 vol.%, respectively, were observed for MWCNT/water nanofluid. Garbadden et al. [18] experimentally showed that the natural convection heat transfer of MWCNT/water in a square cavity was enhanced at $\varphi = 0.1$ vol.% after which attenuation was noticed with an increase in φ. Maximum heat transfer improvement of 45% was reported.

Hu et al. [12] examined the natural convection in a square cavity containing TiO_2/water nanofluid using numerical and experimental methods. They demonstrated using both methods that natural convection of nanofluid was susceptible to the enhancement of viscosity than that of thermal conductivity. Water was noticed to be a better heat transfer medium than TiO_2/water nanofluid at low Ra. After experimental and numerical investigation, Hu et al. [14] published Nu enhancement of 2% for Al_2O_3/water nanofluid in a square cavity at Ra of 6×10^7 and $\varphi = 0.25$ vol.%. However, at $\varphi = 0.77$ vol.%, Nu attenuated by 4% relative to water. Ghodsinezhad et al. [19] experimentally examined natural convection in a rectangular cavity containing Al_2O_3/water nanofluid. The result revealed that the heat transfer coefficient was improved for $\varphi = 0.05-0.10$ vol.% in comparison to the water. An increase in φ led to the depreciation of the coeffiecient of heat transfer. At $\varphi = 0.1$ vol.%, the optimum heat transfer coefficient of 15% was achieved.

Sharifpur et al. [20] experimentally examined the natural convection characteristics of TiO_2/water nanofluid inside a rectangular cavity. The result showed that Nu and $\dot{Q}$ were augmented with $\varphi \leq 0.2$ vol.% and they deteriorated when $\varphi > 0.2$ vol.%, relative to water. At $\varphi = 0.05$ vol.% and temperature gradient $(\Delta T) = 50\,^\circ C$, the maximum improvement of $\dot{Q}$ was 8.2%. Recently, Ilyas et al. [21] studied natural convection in a vertical rectangular cavity containing MWCNT/thermal oil nanofluid. They revealed the deterioration of the average heat transfer coefficient and Nu as φ increased. In comparison to the thermal oil, 21.3% and 35.7% attenuation of average heat transfer coefficient and Nu was noticed, respectively, at $\varphi = 1.0$ wt.%. High viscosity (62%) was attributed to the attenuation noticed. Solomon et al. [22] examined natural convection in a rectangular cavity with varying aspect ratios (1, 2, and 4) containing Al_2O_3/water nanofluid. They demonstrated that the heat transfer coefficient and Nu were related to φ, temperature difference, and aspect ratio. Maximum heat transfer was noticed for $\varphi = 0.1$, 0.2, and 0.3 vol.% in the cavities with aspect ratios of 1, 2, and 4, respectively, at $\Delta T = 50\,^\circ C$.

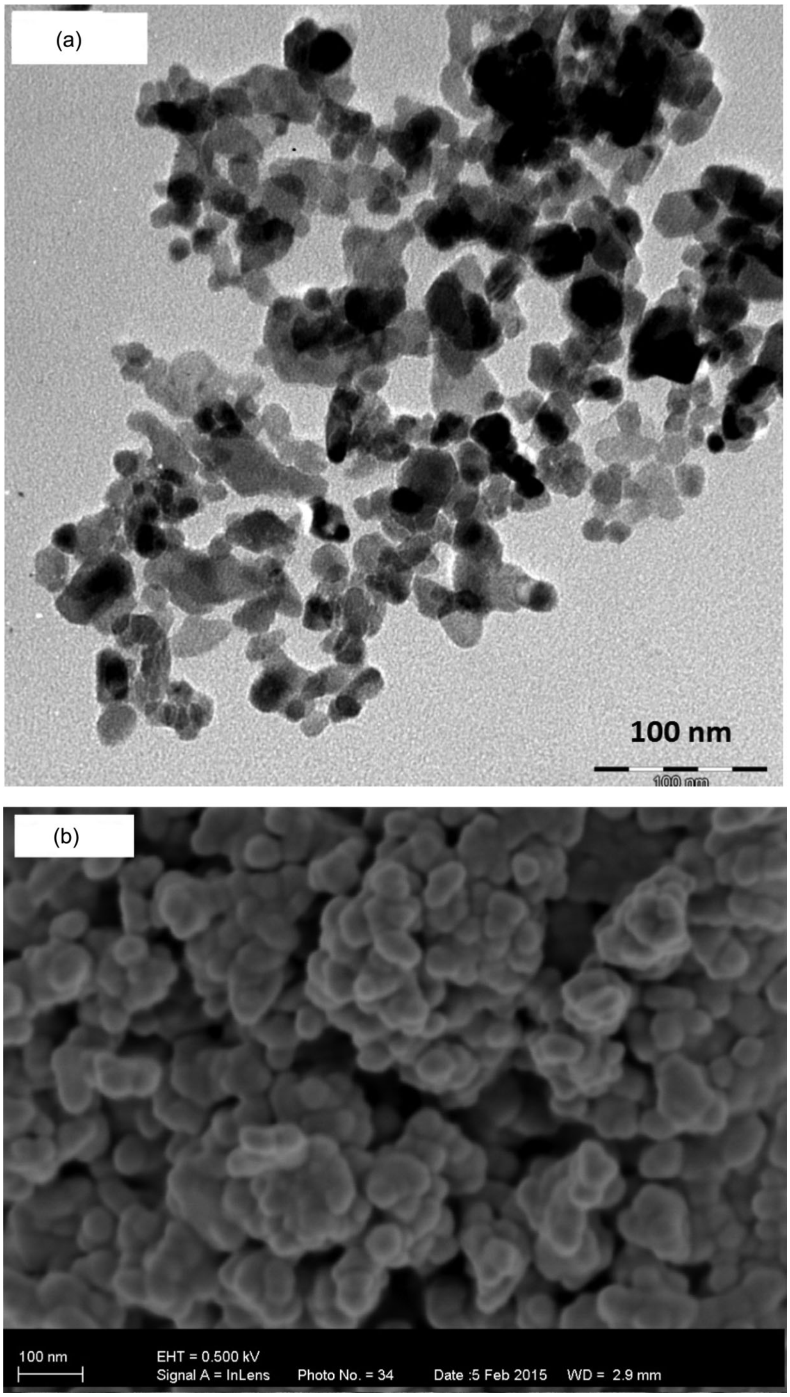

Figure 1. Transmission electron microscopy image of ZnO nanoparticles (a); and scanning electron microscopy image of dry powder of ZnO particles (b).

Esfe et al. [23] numerically studied the influence φ and aspect ratio on the natural convection of water-based MWCNT nanofluid inside a T-shaped cavity. They found an improvement of Nu as φ increased for the nanofluid in comparison to water. Increasing aspect ratio of the enclosure led to the deterioration of Nu. However, Snoussi et al. [24] reported deterioration of Nu with an increase in φ, when the natural convection in a cubical cavity containing Ag/water and Al_2O_3/water nanofluids was examined numerically. Using a numerical method, Minea and El-Maghlany [25] investigated the natural convection characteristics in a square cavity containing ionic fluid-based Al_2O_3 nanofluid. They noticed that the increased suspension of Al_2O_3 nanoparticles in the ionic fluid caused the attenuation of Nu.

Recently, Torki and Etesami [26] experimentally investigated the effect of cavity inclination and φ on

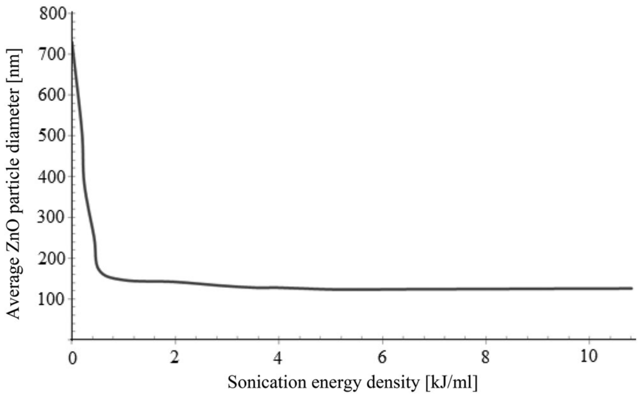

Figure 2. The effect of the sonication energy density of average aggregation size on ZnO-water nanofluid.

the natural convection behavior of water-based SiO_2 nanofluid in a rectangular cavity. They noticed optimum heat transfer at 0.01 vol.% relative to water after which deterioration was observed. Increasing the cavity inclination angle was noticed to deteriorate heat transfer. Giwa et al. [27] experimentally studied the natural convection in a square enclosure with Al_2O_3-MWCNT/water nanofluid at $\varphi = 0.10$ vol.%. The result showed an enhancement of heat transfer as the ratio of MWCNT nanoparticles increased in the hybrid nanofluid as compared to water. Maximum improvements of 19.4% and 9.8% were attained for the Nu and heat transfer coefficient, respectively.

This survey revealed the inconsistency of results for the natural convection of various nanofluids in various cavities using both experimental and numerical techniques. There is a need to carry out more experimental investigations further to improve knowledge on the performance of nanofluids in cavities. Moreover, there is a scarcity of studies on the natural convection in a cavity containing ZnO/water nanofluid in the public domain. Therefore, this study aimed to experimentally study the natural convection heat transfer of ZnO/water nanofluids in a differentially heated rectangular cavity. Since the natural convection heat transfer of nanofluids was sensitive to viscosity, this study also measured the viscosity of ZnO/water nanofluid experimentally.

Method

Formulation of nanofluids

ZnO nanoparticles (20 nm) were purchased from Nanostructured & Amorphous Materials, Inc., USA. De-ionised water (DIW) was bought from Merck in South Africa and was used to formulate the nanofluid. The nanoparticles were suspended in the DIW to obtain a homogeneous fluid using Qsonica (Q-700; 700 W and 20 kHz) with 5 s active pulse and 2 s idle pulse. The transmission electron microscopy (TEM) was carried out to observe the morphology and size of the ZnO nanoparticles. The TEM image of ZnO nanoparticles revealed spherical shapes for ZnO nanoparticles with a nanosize range of $18-23$ nm which was around the value (20 nm) specified by the manufacturer (see Figure 1a). The scanning electron microscopy was used to detect the structure of the suspended ZnO nanoparticles in the DIW as presented in Figure 1b.

Table 2. Effect of different concentration on zeta potential of ZnO-water nanofluid.

Concentration (φ)	ZP [mV] (absolute value)	pH
0.006 vol.%	34	9
0.06 vol.%	42	10.3
0.12 vol.%	47	10.55

Using a two-step method, the nanofluids were formulated, and different surfactants were used to make them stable. The tetramethylammonium hydroxide pentahydrate purchased from Sigma-Aldrich (USA) was noticed to formulate a stable nanofluid. The quantity of the surfactant added to the nanofluid was 0.8 of the ZnO nanoparticles. An ultrasonicator (Q-700, Qsonica) with 20 kHz and 700 W was used to disperse and break down the nanoparticles' aggregation. Sharifpur et al. [28] found that 3 kJ/ml of sonication energy density was appropriate to minimize the average aggregation size of ZnO/DIW nanofluid. It can be observed that the average aggregation size of the nanofluid was reduced through sonication as a function of sonication energy density (Figure 2).

The stability and suspension of nanofluids were verified by zeta potential measurement using a Malvern Zetasizer Nano ZS (UK). The problem with stability can be expected at pH values between 4 and 7.5 when absolute zeta potential is below 30 mV. All concentrations showed more than an absolute value of 30 mV at a pH value greater than 9 (see Table 2). The colloids with zeta potentials greater than an absolute of 30 mV were considered as stable solutions at a pH greater than 7.5. The stability of a ZnO/DIW nanofluid with a 0.06 vol.% concentration was also examined at various temperatures by measuring zeta potential value (see Figure 3). As the temperature of the ZnO/DIW nanofluid increased, the absolute value of the zeta potential decreased. This means that the ZnO/DIW nanofluid showed better stability at a low temperature. The nanofluid stability was also examined using a spectrophotometer (Jenway 7315) with an accuracy of ±2 nm for wavelength and a standard

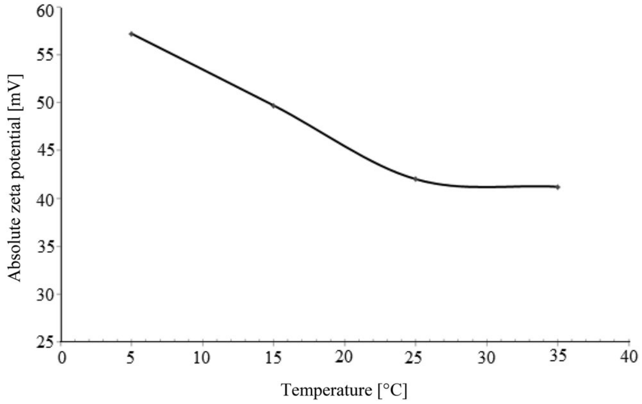

Figure 3. The influence of temperature on the zeta potential value of ZnO/water nanofluid with 0.06 vol.%.

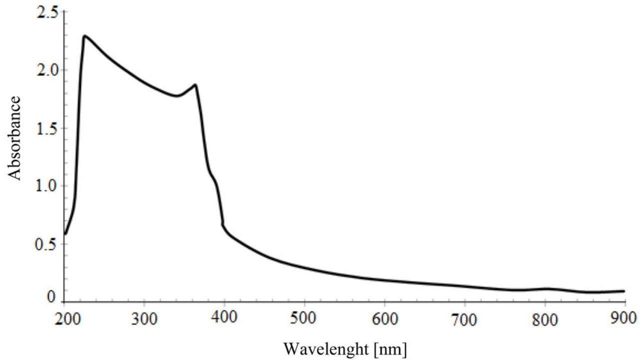

Figure 4. Absorbance of 0.0018 vol.% ZnO-water nanofluid versus wavelength.

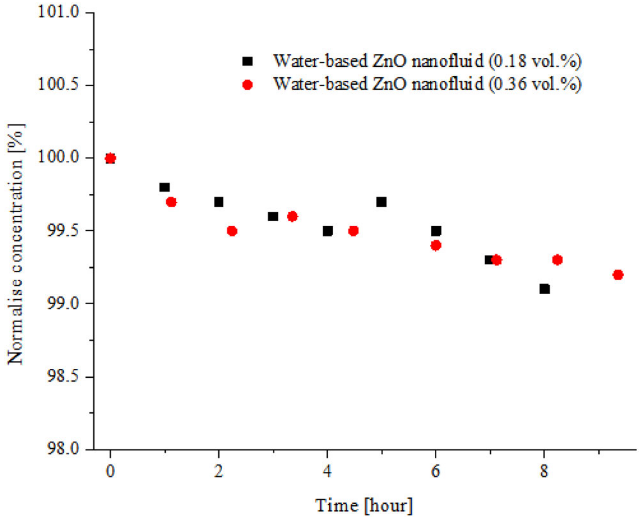

Figure 5. The effect of time on the concentration of water-based ZnO nanofluids.

deviation of ±0.01 absorbance at 1.0 absorbance. This method can estimate the colloidal concentration at a certain time as the sedimentation of nanoparticles increased. The peak absorbance of 2.293 with a sample of 0.0018 vol.% of ZnO/DIW nanofluid occurred at a wavelength of 230 nm (see Figure 4).

The absorbance of a nanofluid varied with the changing concentration of the sample due to the sedimentation of nanoparticles in the base fluids. The normalized concentration indicated that the concentration percentages changed from the initial concentration of the nanofluid, which was obtained over 9 h (see Figure 5). This indicated that no sedimentation occurred during the experiment period.

Experimental setup

Figure 6 shows the simplified schematic diagram of the experimental setup for testing the natural convection of ZnO/DIW nanofluids while the picture of the experimental set up is presented in Figure 7. The rectangular cavity has two differentially heated vertical walls at opposite sides with heights and widths of 96 mm and 120 mm, respectively. The distance between the two walls, as a characteristic length, was 102 mm. Counterflow shell and tube heat exchangers with a hydraulic diameter (10.7 mm) have been designed and manufactured with copper to serve as a heat source and a heat sink. The rest of the cavity was built with polycarbonate, which has a thermal conductivity of 0.19 to 0.22 W/m.K at 23 °C. To minimize ambient heat loss, the test cell was covered with a big wooden box and gaps were filled with polystyrene insulation materials (insulation = 20 cm with k = 0.034 W/m.K).

Two thermal baths (Polyscience PR20R-30 (USA)) with accuracies of 0.005 °C were separately connected to each heat exchanger. These thermal baths supply a constant heat source and heat sink for the hot and cold walls, respectively. The heat exchangers' performance was examined in an air-filled cavity, which resulted in a deviation of 0.5 °C at various spots on the surface of the heat exchangers. Two Burkert 8081 ultrasonic flow meters (Germany) with an accuracy of ±0.01% of full-scale flow rate +2% (measured value) were installed to measure the flow rate of the water that circulates from the thermal baths to the heat exchangers. The temperature was measured with Type-T Omega Engineering thermocouples (USA) with part number TT-T-30-SLE (ROHS). These thermocouples have an accuracy of 0.02 °C after calibration. Temperatures and flow rates were collected by data acquisition using SCXI-1303, an isothermal terminal block from National Instruments (USA) which used LabVIEW software.

For each set of experiments, 8200 samples were measured at a frequency of 2 Hz. After 60 min, the temperature of the nanofluid inside the cavity was stabilized with a deviation of less than 1% of the average

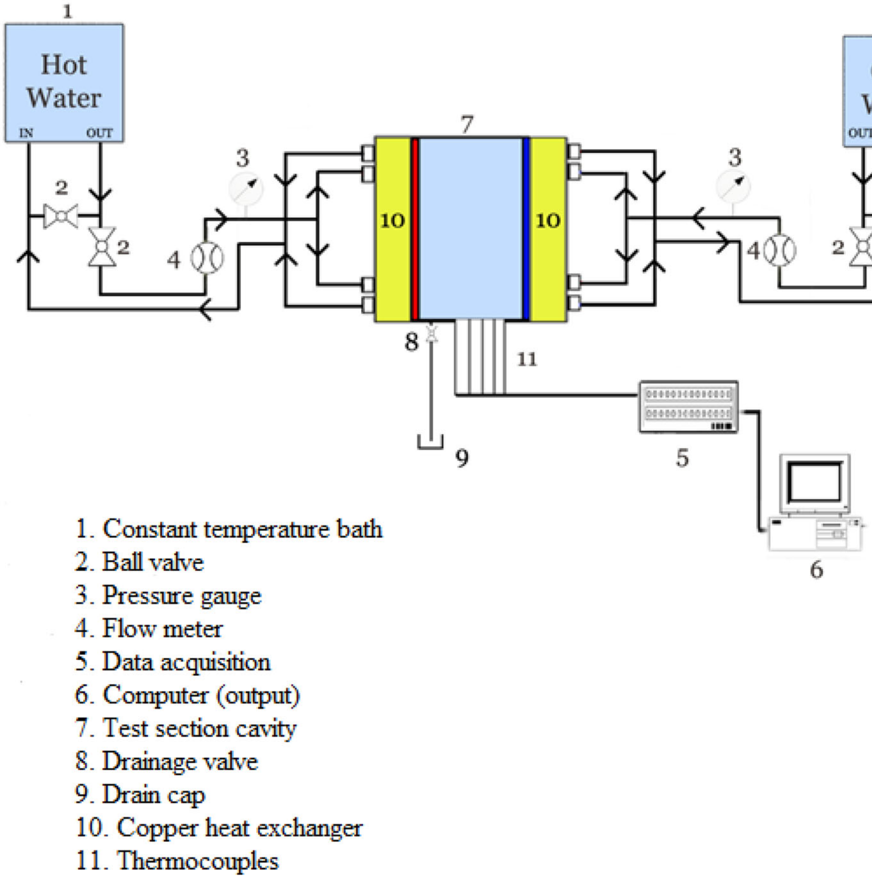

Figure 6. A schematic diagram of the experimental setup.

Figure 7. Pictorial representation of the experimental set up.

temperature of 30 °C. Therefore, the last 1000 samples were used for the results.

Experimental procedure

Figure 8 shows the arrangement of the thermocouples (inside and around the cavity) used in this study for the natural convection of ZnO/water nanofluid in a rectangular cavity. To obtain the temperatures at the hot and cold walls and within the cavity, the averages of the measured temperatures (using the thermocouples) were estimated. Heat transfer occurred through the enclosure due to the two different surface temperatures at the vertical walls.

$$T_{ave} = \frac{(T_H + T_C)}{2} \tag{1}$$

The thermo-physical properties (c_p, k, ρ, and β) were calculated based on the average temperatures of the hot and cold walls as follows:

$$c_{p,nf} = (1-\varphi)c_{p,bf} + c_{p,np} \tag{2}$$

The subscripts *bf* and *np* refer to the base fluid and nanoparticle, respectively, while c_p is the specific heat capacity and φ is the volume concentration of the nanoparticles.

The ρ and β of the nanofluids were calculated as follows:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \rho_{np}\varphi \tag{3}$$

$$(\beta\rho)_{nf} = (1-\varphi)(\beta\rho)_{bf} + \varphi(\beta\rho)_{np} \tag{4}$$

$$k_{nf} = k_{bf}\left[\frac{k_{np} + 2k_{bf} - 2\varphi(k_{bf} - k_{np})}{k_{np} + 2k_{bf} + \varphi(k_{bf} - k_{np})}\right] \tag{5}$$

whereρ is the density,β is the thermal expansion coefficient, and k is the thermal conductivity. The

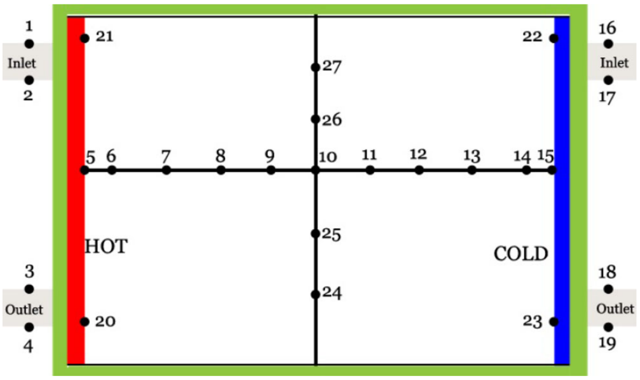

Figure 8. A schematic representation of thermocouples' arrangement in and around the cavity.

measured temperatures for the cavity in addition to the thermophysical properties were used to estimate $\dot{Q}$, Nu, heat transfer coefficient, and Ra as expressed in Equations (6 – 9). The heat transfer rate of the heat exchanger (hot) was estimated as follows:

$$\dot{Q}_H = \dot{m}_H c_p (T_{in} - T_{out}) \tag{6}$$

Where T_{in} and T_{out} are the temperatures at the inlet and outlet of the heat exchanger, respectively. A 5% deviation was noticed in the heat balance between the heat source and sink. This showed a slight loss of heat to the surroundings. The heat transfer by radiation was accounted to be insignificant. The coefficient of heat transfer of ZnO/DIW nanofluid was evaluated as follows:

$$h_{nf} = \frac{\dot{Q}}{A(T_H - T_C)} \tag{7}$$

A is the surface area of the heated wall. The dimensionless Nu was estimated using the coefficient of heat transfer (see Equation 6), which represented the ratio of convective heat transfer to conductive heat transfer.

$$Nu_{nf} = \frac{h_{nf} L_c}{k_{nf}} \tag{8}$$

The dimensionless Ra is calculated as follows:

$$Ra_{nf} = \frac{g \beta_{nf} \rho_{nf}{}^2 L_c{}^3 (T_H - T_C)}{\mu_{nf} k_{nf}} \tag{9}$$

To know how reliable the obtained data could be, the uncertainty analysis was conducted. It was observed that the main sources of errors were due to the measurements of the temperatures and flow rates. Using Equations (10 – 12), the uncertainty of *Q*, *Nu*, and *h*, respectively, were evaluated.

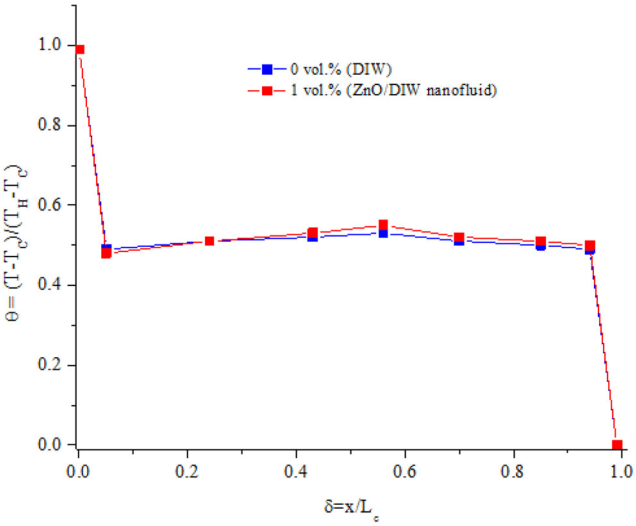

Figure 9. The non-dimensional temperature versus non-dimensional distance in the cavity.

$$\delta Q = \left(\left(\frac{\partial Q}{\partial \dot{m}} \delta \dot{m} \right)^2 + \left(\frac{\partial Q}{\partial C_{p_{bf}}} \delta c_{p_{bf}} \right)^2 + \left(\frac{\partial Q}{\partial T_{in}} \delta T_{in} \right)^2 + \left(\frac{\partial Q}{\partial T_o} \delta T_{out} \right)^2 \right)^{\frac{1}{2}} \tag{10}$$

$$\delta h = \left(\left(\frac{\partial h}{\partial Q} \delta Q \right)^2 + \left(\frac{\partial h}{\partial A} \delta A \right)^2 + \left(\frac{\partial h}{\partial T_H} \delta T_H \right)^2 + \left(\frac{\partial h}{\partial T_C} \delta T_C \right)^2 \right)^{\frac{1}{2}} \tag{11}$$

$$\delta Nu = \left(\left(\frac{\partial Nu}{\partial h} \delta h \right)^2 + \left(\frac{\partial Q}{\partial L_c} \delta L_c \right)^2 + \left(\frac{\partial Q}{\partial k_{eff}} \delta k_{eff} \right)^2 + \left(\frac{\partial Q}{\partial T_C} \delta T_C \right)^2 \right)^{\frac{1}{2}} \tag{12}$$

The SV-10 viscometer (A&D Instruments (Japan); with accuracy of ±3%) was used to determine the viscosity of ZnO/DIW nanofluid was at different φ between 10 and 60 °C. The test sample casing of the viscometer was connected to a water bath that maintained the test sample at the predetermined temperature. The calibration of the viscometer preceded the measurement of the viscosity of both water and ZnO-water nanofluid samples. To check the accuracy of the viscometer, the viscosity of water was measured from 10 to 60 °C. The obtained viscosities were compared with those provided in the literature [29] for water. The measured values were observed to agree well those of the literature with a deviation of 1.87%.

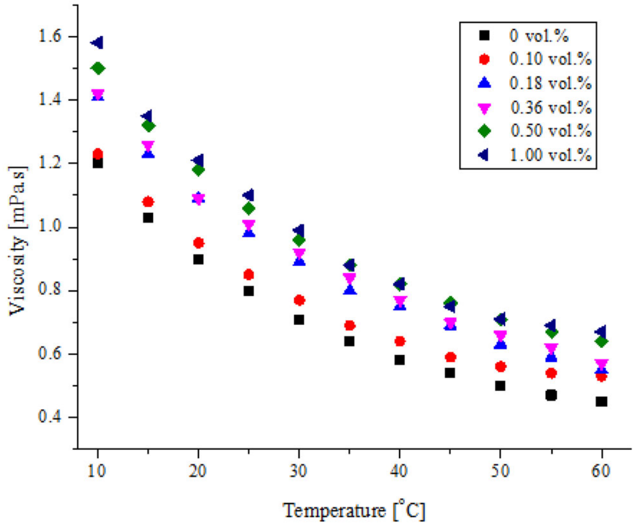

Figure 10. The effect of volume fraction and temperature on the viscosity of ZnO/DIW nanofluid.

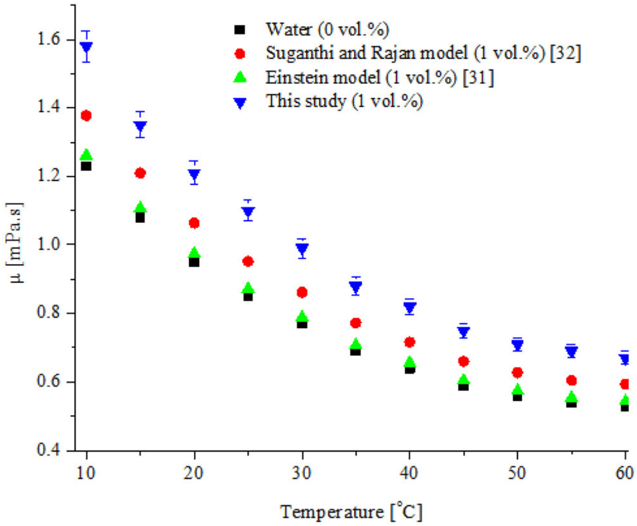

Figure 11. The viscosity of a ZnO/DIW nanofluid with theoretical and experimental measurements.

Results and discussion

Figure 9 presents a plot of the non-dimensional distance (δ) of the cavity against the non-dimensional temperature (θ) distribution inside the cavity. The temperatures observed at the mid-point were slightly higher than the average of the cold and hot walls as a result of the slight heat loss at the walls of the cavity. In Figure 10, the viscosity of ZnO/DIW nanofluid as related to a rise in temperature for different φ is provided. The viscosity of ZnO/DIW nanofluid at $\varphi = 0-1.0$ vol.% was measured for temperatures of 10 and 60 °C. Expectedly, the viscosity was observed to enhance as φ increased. At 20 °C, the viscosity of ZnO/DIW nanofluid at $\varphi = 1.0$ vol.% was found to be significantly higher (24%) than the viscosity of DIW. As the temperature rose, the viscosity of ZnO/DIW nanofluid, and was noticed to be consistent with the literature [30]. Furthermore, the differences in the viscosity of ZnO/DIW nanofluid at different φ were higher at a low temperature relative to those at a high temperature.

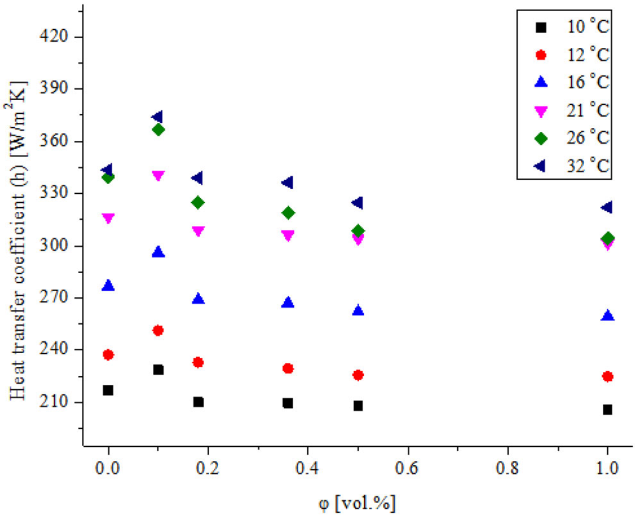

Figure 12. The effect of φ on heat transfer coefficient at various temperature differences.

The Einstein viscosity model [31] (see Equation (13)) predicted values 20% lower than that obtained experimentally at 20 °C and $\varphi = 1.0$ vol.%. Similarly, Brinkman's model [31] (see Equation (14)) predicted viscosity values close to those estimated using Einstein's model. Suganthi and Rajan [32] (see Equation (15)) proposed an empirical correlation for estimating the viscosity of ZnO/DIW nanofluid for $\varphi = 0.25-2.0$ vol.%. From Figure 11, it can be seen that the experimental data for ZnO/DIW nanofluid at $\varphi = 1.0$ vol.% were higher than those proposed by Suganthi and Rajan [32]. This showed that the Suganthi and Rajan model underestimated the experimental data of ZnO/DIW nanofluid viscosity because the model was proposed as a function of φ whereas the obtained viscosity data for this present study was dependent on temperature and φ. The uncertainty related to the measurement of the viscosity of ZnO/DIW nanoflids was 2.85%.

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi) \tag{13}$$

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\varphi)^{2.5}} \tag{14}$$

$$\mu_{nf} = \mu_{bf}(1 + 11.97\varphi) \tag{15}$$

The natural convection of ZnO/DIW nanofluid at $\varphi = 0.10-1.0$ vol.% in a rectangular was performed

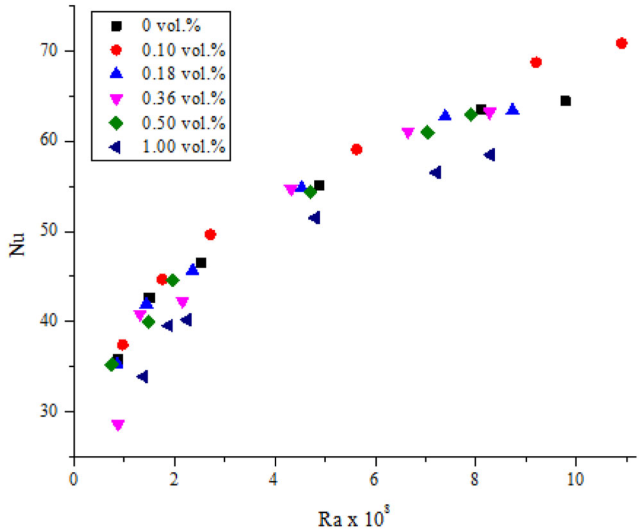

Figure 13. The effect of Ra on Nu at different φ.

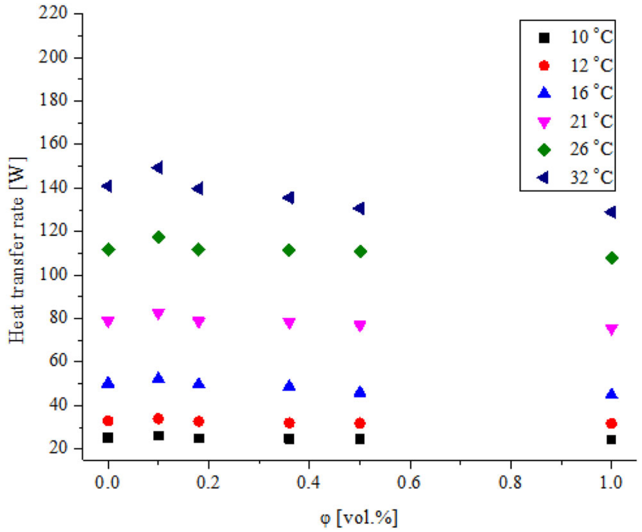

Figure 14. The effect of φ on heat transfer rate at various temperature differences.

with Ra ranging $7.45 \times 10^7 - 9.20 \times 10^8$. The average heat transfer coefficient was measured for different φ of ZnO/DIW nanofluid at various temperature differences ranging between 10 and 32 °C (see Figure 12). Initially, the natural convection heat transfer coefficient of ZnO/DIW was enhanced. Subsequently, it attenuated with an increase in the volume concentrations. The natural convection heat transfer coefficient was enhanced for 0.10 vol.% while deterioration was observed with an increase in the volume concentration beyond 0.10 vol.%, relative to the DIW. An enhancement of 9.14% was achieved for 0.10 vol.% at the temperature difference of 32 °C. The result showed an optimum φ where the heat transfer coefficient of ZnO/DIW nanofluid was enhanced.

The effect of Ra on Nu for different volume concentrations is presented in Figure 13. Expectedly, the Nu increased as the Ra increased, but the Nu was only enhanced for 0.10 vol.% in comparison with that of DIW. The enhancement of Nu was more pronounced at higher Ra. Increasing the volume concentration from 0.18 vol.% – 1.0 vol.% revealed the deterioration of Nu. Figure 14 shows the effect of volume concentrations of ZnO/DIW nanofluid on $\dot{Q}$ of the same. At 0.10 vol.% and 32 °C, enhancement of $\dot{Q}$ was observed compared to DIW while attenuation was observed at other volume concentrations of ZnO/DIW nanofluid. Additionally, the Nu and $\dot{Q}$ were augmented by 8.42% and 6.75% for 0.10 vol.%, respectively, in relation to DIW. Hence, the addition of ZnO nanoparticles to DIW enhanced Nu, coefficient of heat transfer and $\dot{Q}$ at 0.1 vol.% which has the lowest viscosity of the ZnO/DIW nanofluid samples. It can be inferred that buoyancy was augmented at a lower viscosity leading to an increase in $\dot{Q}$.

Suganthi and Rajan [32] showed heat transfer and coefficient of heat transfer enhancements of 4.24% and 25.6% at 2.0 vol.% when the natural convection of ZnO/PG nanofluid was investigated in a cylindrical cavity. Ho et al. [8] reported 18% enhancement of the coefficient of heat transfer for Al_2O_3/DIW nanofluid at 0.10 vol.% in a rectangular cavity. Similarly, using Al_2O_3/DIW nanofluid, Ghodsinezhad et al. [19] published optimum augmentation of 15% for the coefficient of heat transfer of Al_2O_3/DIW nanofluid in a rectangular fluid. Garbadeen et al. [18] and Sharifpur et al. [20] achieved heat transfer enhancement of 45% and 8% at 0.10 vol.% and 0.05 vol.% for MWCNT/DIW and TiO_2/DIW nanofluids in rectangular cavities, respectively. Furthermore, Giwa et al. [27] showed 12.7% – 19.4%, 11.8% – 17.2%, 7.2% – 9.8% for the coefficient of heat transfer, Nu and $\dot{Q}$, respectively, for Al_2O_3-MWCNT/DIW nanofluid at 0.10 vol.% in a rectangular cavity. It can be observed that the result of this present study was well within the ranges of values reported in previous studies for other nanofluids in different cavities.

To examine the reliability of experimental data, a relative uncertainty analysis was performed. The main sources of error were via the measurement of temperature, flow rate, and cavity size. Uncertainty of $\dot{Q}$, heat transfer coefficient and Nu for this study were 2.93%, 3.06%, and 3.05%, respectively.

Conclusions

The natural convection heat transfer of ZnO/DIW nanofluid in a rectangular cavity at various φ (0.10, 0.18, 0.36, 0.5, and 1.0 vol.%) was performed at Ra of 7.45×10^7 and 9.20×10^8. The stability of ZnO/DIW nanofluid was verified using a spectrophotometer and Malvern Zetasizer. With an absolute zeta potential of 57.2 mV, the ZnO/DIW nanofluid at 0.06 vol.% was noticed to be very stable. At a low temperature, the ZnO/DIW nanofluid was observed to have better stability. The measured viscosity of 1.0 vol.% ZnO-DIW nanofluid was noticed to be 20% higher than those of the classical models (Einstein and Brinkman models). For the first time, the natural convection heat transfer of ZnO/DIW in a rectangular cavity was experimentally performed. The findings showed that ZnO/DIW improved the natural convection heat transfer at 0.10 vol.%. The natural convection of nanofluid deteriorated when φ increased beyond 0.10 vol.%. It was observed that by changing the thermo-physical properties of DIW via suspension of ZnO nanoparticles in the DIW, natural convection heat transfer was augmented at $\varphi = 0.10$ vol.%.

Disclosure statement

No potential conflict of interest was reported by the authors.

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