Experimental study of thermo-convection performance of hybrid nanofluids of Al_2O_3-MWCNT/water in a differentially heated square cavity

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Highlights

• Using hybrid nanofluids yield enhanced in natural convection.
• Al2O3-MWCNT/water hybrid nanofluids prepared at different weight percentage.
• Natural convection of the hybrid nanofluids was experimentally examined.
• The influence of weight percent, ΔT, and *Ra* on *Nuav, hav* and *Qav* has been investigated.
• The arrangement for maximum heat transfer performance was investigated.

Abstract

Hybrid nanofluids as a new class of nanofluids known for their improved thermal and flow properties over single-particle nanofluids. However, experimental studies on the natural convection of hybrid nanofluids in enclosures are very scarce in the public domain. This paper investigates the natural convection of Al_2O_3−MWCNT/water nanofluids at various bi-nanoparticles' percent weights (Al_2O_3:MWCNT; 80:20, 60:40, 40:60, and 20:80) for 0.1 vol% in a square cavity. The Nu_{av}, h_{av}, *Ra* and Q_{av} at varying temperature gradients (20 °C–50 °C) were considered. The viscosity and thermal conductivity of the stable nanofluids and base fluid were experimentally measured at a temperature range of 20 °C–50 °C. The obtained experimental data for these properties were engaged in the study. The range of *Ra* considered in this work was 1.65×10^8–3.80×10^8. A direct relationship was noticed between *Ra* and Nu_{av}. Temperature gradient and percent weight of bi-nanoparticles in the nanofluids were observed to augment Nu_{av}, h_{av}, and Q_{av}. The hybrid nanofluid with 60:40 wt% of Al_2O_3 and MWCNT nanoparticles was identified to have the highest value for *Ra,* Nu_{av}, h_{av}, and Q_{av} at various temperature gradients. Furthermore, maximum enhancements of 16.2%, 20.5%, and 19.4% were recorded for Nu_{av}, h_{av}, and Q_{av}, respectively, at ΔT = 50 °C, in relation to the base fluid. The engagement of Al_2O_3−MWCNT/water nanofluids in a square cavity has shown improved natural convection performance. A new correlation as related to *Ra* and bi-nanoparticles ratio has been developed for predicting Nu_{av}. Results from this study further corroborate the advantage afforded by hybrid nanofluids over single-particle nanofluids.

Keywords: Hybrid nanofluids; Natural convection; Heat transfer; MWCNT; Al_2O_3, Square cavity

Nomenclature

X	percent weight of nanoparticles' type,%
M	mass of nanoparticles' type, g
C_p	specific heat capacity (at constant pressure), J/kg °C
T	temperature, °C
R	ratio of hybrid nanoparticles
$\dot{m}$	mass flow rate, kg/s
Q	heat transfer, W
g	gravitational acceleration, m^2/s
L	characteristic length of cavity, m
Ra	Rayleigh number
Nu	Nusselt number
h	average coefficient of heat transfer, W/m^2 °C
Pr	Prandtl number, $C_p\mu$/°C
B	dimensionless heat source length
Ha	Hartmann number
D	dimensionless heat source location
Q_p	heat generation parameter
Greek symbols	
κ	thermal conductivity, W/m °C
ρ	density of nanoparticles, kg/m^3
β	thermal expansion coefficient, 1/°C
φ	volume concentration
μ	viscosity, mPas
σ	electrical conductivity, μS/cm
Δ	change
ψ	phase deviation
ε	porosity of the medium
Subscript	
c	critical
av	average
hnf	hybrid nanofluid
bf	base fluid (water)
MWCNT	Multi-walled carbon nanotubes nanoparticles
Al_2O_3	Alumina nanoparticles
i	in
o	out
H	hot side
C	cold side

1. Introduction

Nano-sized materials have been employed in the field of heat and fluid transfer as advanced fluids with improved thermal and flow properties relative to conventional fluids. The suspension of nano-scaled materials into various conventional fluids to synthesize nanofluids have been researched and accepted to possess superior thermophysical properties relative to the existing traditional fluids. As the thermo-physical properties of nanofluids are augmented, the convective heat transfer performance of nanofluids is also enhanced. Subject to this, nanofluids have been investigated as thermal transport media in relevant fields of study and applied in heat exchangers, electronics and thermal transport systems as coolants. Natural convection as a thermal transport mechanism is extensively employed in different applications in which thermal cooling is primarily due to density difference of the working fluid engaged.

The wide application of natural convection in engineering discipline has been responsible for the use of nanofluids as better working fluids in relation to the traditional fluids. The application of natural convection includes heat exchangers, electronic cooling devices, nuclear energy, solar energy collectors and desalination, geophysics, electric ovens, and other industrial processes such as melting and solidification and lubrication. Khanafer et al. [1] pioneered the study of thermo-convection characteristics of nanofluids (Cu-water) in a square cavity using a numerical technique. Thereafter, numerous studies have been carried out on the natural convection of diverse nanofluids contained in several shapes (square, rectangular, trapezoidal, L, cylinder, complex, etc.) of enclosures and subjected to various thermal and boundary conditions using both numerical and experimental techniques [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. However, limited studies on the experiment-based free convection of nanofluids in enclosures of various configurations have been investigated relative to the numerical works published [3,9,[13], [14], [15], [16], [17], [18], [19], [20]].

Putra et al. [19] was the first to study the natural convection of nanofluids in an enclosure. They utilized distilled water-based Al_2O_3 and CuO nanofluids $(\varphi = 1 - 4\text{vol.}\%)$ filled into a differentially-heated horizontal cylinder with aspect ratios (ARs) of 0.5–1.5. Result revealed the attenuation of heat transfer for the nanofluids as a function of φ, AR, and nanoparticle density Ghodsinezhad et al. [16] experimentally examined the influence of different volume concentrations (0.05%–0.6%) of Al_2O_3/water nanofluid contained in a differentially heated rectangular enclosure on the natural convection heat transfer coefficient with *Ra* range of 3.49×10^8 to 1.05×10^9. The convective heat transfer coefficient was augmented by a maximum value of 15% obtained at 0.1 vol%, in comparison to the base fluid. Li et al. [21] utilized ZnO/deionized water-ethylene glycol (75:25, 85:15, and 95:5 vol%) nanofluid with φ = 5.25 wt% in a square cavity and demonstrated that heat transfer was attenuated for the nanofluids relative to deionized water-ethylene glycol. This observation was noticed to increase as the ethylene glycol quantity in the base fluid increased. Hu et al. [22] engaged deionized water-based TiO_2 (3.85 - 10.71 wt%) nanofluid in a vertical square and they noticed that heat transfer was attenuated relative to the deionized water. Kouloulias et al. [20] studied the natural convection of Al_2O_3/water (0.01–0.12 vol%) nanofluid in a square cavity and they also observed deterioration of heat transfer of the nanofluid in comparison to water.

Using MWCNT/water and Al_2O_3/water nanofluids, Joshi and Pattamatta [18] experimentally investigated the natural convection heat transfer of these nanofluids in a square cavity. The work was conducted at *Ra* range of 7×10^5–1×10^7 and volume concentration ranges of 0.1–2% (Al_2O_3/water nanofluids) and 0.1–0.5% (MWCNT/water nanofluids). They showed that for both nanofluids, *Nu* was enhanced as *Ra* increased. Also, *Nu* was improved by 35% for MWCNT/water nanofluid at 0.1 vol% and *Ra* = 1×10^6, in relation to the base fluid. The highest augmentation of *Nu* for both types of nanofluids was observed at 0.1 vol%, with MWCNT/water nanofluid having a considerable improvement in *Nu* compared to Al_2O_3/water nanofluid, all in relation to the base fluid. Additionally, Garbadeen et al. [17] studied the heat transfer behavior of MWCNT/water nanofluid for a volume concentration range of 0–1% contained a square cavity and at *Ra* of 10^8. An optimum heat transfer augmentation of 45% was reported for the concentration of 0.1 vol%.

Solomon et al. [3] have studied the effect of ARs (1, 2, 4) of cavities on the heat transfer performance of Al_2O_3/water nanofluids. They showed that the coefficient of convective heat transfer and *Nu* were significantly related to the AR of the cavities. The maximum heat transfer for each AR of the cavity was observed to be a function of the volume concentration. For the square cavity (AR = 1), the maximum heat transfer and convective heat transfer coefficient were achieved at 0.1 vol%. Both the buoyancy and *Nu* were found to be strongly connected to *Ra*. Joshi and Pattamatta [23] examined the natural convection of Al_2O_3, MWCNT, and graphene/distilled water (0.1–0.5 vol%) nanofluids contained in a square enclosure. In comparison to distilled water, the maximum improvement in *Nu* for all the nanofluids was noticed for φ = 0.1 vol% with the MWCNT/distilled water nanofluid showing the highest value of 35%.

A recent study by Ilyas et al. [9] investigated the natural convection of MWCNT/thermal oil (0–1 wt%) nanofluid in a vertical rectangular cavity (AR = 4) and revealed the depreciation in *h* and *Nu* as φ increased. Sharifpur et al. [10] employed TiO_2-deionized water (0.05–0.8 vol%) nanofluid in a rectangular cavity to study the natural convection behavior. They reported optimum heat transfer enhancement of 8.2% at φ = 0.05 vol%. In addition, Choudhary et al. [24] engaged Al_2O_3/deionized water (0.01 and 0.1 vol%) nanofluid contained in a rectangular cavity having AR = 0.3–2.5 to examine the natural convection heat transfer performance. They observed that the natural convection performance depended on AR, *Ra*, and φ, with the maximum augmentation of 29.5% for 0.01 vol% (at $Ra = 7.89 \times 10^8$ and AR = 0.5).

The emergence of a new class of nanofluids (hybrid nanofluids) proven to possess better thermal and convective properties than the mono-particle nanofluids has spurred studies on the natural convection of hybrid nanofluids in cavities. The open literature has revealed that limited studies have been conducted on the natural convection heat transfer behavior of hybrid nanofluids in selected cavities [25], [26], [27], [28], [29], [30]. However, these existing works were noticed to be conducted using numerical techniques of which the experimentally performed studies were lacking. Ashorynejad and Shahriari [25] numerically studied the natural convection heat transfer characteristics of a hybrid nanofluid (water based Al_2O_3—Cu) filled into a waxy-walled open cavity under a uniform magnetic field. They showed that *Nu* was deteriorated with an increase in *Ha* and it was enhanced as *Ra* and φ increased. At $Ra = 10^5$, *Nu* was observed to be enhanced as φ and ψ increased. Maximum heat transfer improvement was achieved at *Ha* = 90 and the lowest at *Ha* = 30.

Rashad and Co-workers [29] used a numerical technique to examined the MHD natural convection of a water based hybrid nanofluid (Cu-Al_2O_3/water) inside a triangular cavity heated from the bottom wall. The result revealed that heat transfer rate was improved with an increase in *D* and *Ra*, and reduction in *B*, but it depreciated with the rise of Q_p and *Ha*. The influence of increasing φ was noticed to be pronounced when *Ra* was low, *Ha* was high and when *D* and *B* increased. No significant difference in heat transfer enhancement augmentation was noticed for the hybrid and single-particle nanofluids. Mehryan et al. [26] conducted a numerical study on the thermo-convection heat transfer behavior of the hybrid nanofluid in a porous square cavity. They demonstrated that at *Ra* of 10–100, φ of 0–2% and porosity (ε) of 0.3–0.9, the rate of heat transfer of Al_2O_3 and Cu nanofluids in the cavity was higher than that of hybrid nanofluid (Al_2O_3—Cu at 96.2%:3.8%). The Nu_{ave} was observed to decline with an increase in volume concentration for the studied porosity values except 0.9.

The above survey showed that experimental studies on the natural convection of hybrid nanofluids in various configurations of cavity are evidently scarce in the open literature. The identified gap has been filled by conducting experimental work on the natural convection heat transfer behavior of Al_2O_3-MWCNT/water nanofluids contained in a square cavity under varying temperature gradients. In this present work, different percent weights of Al_2O_3-MWCNT nanoparticles suspended in water to formulate hybrid nanofluids at 0.1 vol% have been examined in the cavity for their natural convection performance.

2. Materials and methods

2.1. Nanofluids formulation and characterization

The hybrid nanoparticles of γ-Al_2O_3 and MWCNT were utilized in this study. The γ-Al_2O_3 nanoparticles (20–30 nm diameter as specified by the manufacturer) was sourced from Nanostructured and Amorphous Materials Inc., Houston, Texas, USA and the MWCNT nanoparticles (lengths, inner and outer diameters of 10–30 μm, 3–5 nm and 10–20 nm, respectively) were purchased from MKnano Company, Ontario, Canada. The sodium dodecyl sulfate (≥ 98.5% purity) was used as a surfactant and bought from Sigma-Aldrich, Germany. A two-step procedure was engaged in the formulation of the hybrid nanofluids using Al_2O_3 and MWCNT nanoparticles at various percent weights (80:20, 60:40, 40:60 and 20:80) suspended in water. Appropriate weights of both types of nanoparticles depending on the percent weight and surfactant at 1% dispersion fraction were added to 1.4 l of water to obtained 0.1% volume concentration according to Eq. (1). The mixture was then homogenized using an ultrasonicator (Qsonica Q-700; 700 W and 20 KHz) with a 7 s pulse on 2 s pulse at an amplitude of 85% for a period of 2 h in a water bath (LAUDA ECO RE1225). The absorbance of the formulated hybrid nanofluids was determined using (UV–visible spectrophotometer; Jenway (model 7315)). Both the absorbance (for 20 h) and visual inspection (few weeks) were used to monitor the stability of the hybrid nanofluids [3]. In addition, the viscosity of the hybrid nanofluids was measured using vibro-viscometer (SV-10; A&D; Japan; ± 1% accuracy) at a temperature range of 20 °C–50 °C. The electrical conductivity was measured using electrical conductivity meter (EUTECH Instrument (CON700); ± 1% accuracy) for the hybrid nanofluids at the temperature range considered in this study.

It is noteworthy to mention that the volume concentration of 0.1% employed in this work is subject to the findings reported by previous studies. They showed that water-based Al_2O_3 and MWCNT nanofluids contained in square cavities attained a maximum enhancement of heat transfer at 0.1 vol% [3,[16], [17], [18]].

$$\varphi = \left(\frac{X_{Al_2O_3}\left(\frac{M}{\rho}\right)_{Al_2O_3} + X_{MWCNT}\left(\frac{M}{\rho}\right)_{MWCNT}}{X_{Al_2O_3}\left(\frac{M}{\rho}\right)_{Al_2O_3} + X_{MWCNT}\left(\frac{M}{\rho}\right)_{MWCNT} + \left(\frac{M}{\rho}\right)_{bf}} \right) \tag{1}$$

2.2. Description of experimental setup and procedure

A square cavity (96 mm × breadth 96 mm × height 105 mm) containing the hybrid nanofluids was engaged in the investigation of the thermo-convection heat transfer performance. The bottom and top walls of the cavity were thermally insulated whereas the opposite vertical walls were differentially heated. The cavity was well-insulated (2-cm with k = 0.033) to reduce heat loss to the surrounding. T-type thermocouples (Omega Engineering Inc., USA) were mounted at various points inside (walls (6) and spaces (11)) and outside (inlet (2) and outlet (4) pipes) the cavity. This was to determine different temperatures around the cavity (outside and inside) as the experiment proceeded. Prior to the commencement of this work, the thermocouples were calibrated between a temperature range of 5 °C–60 °C. For the insulated thermocouples outside the cavity, 3% heat was lost subject to the temperature difference between them and the environment.

Constant temperatures were maintained at the two differentially heated walls of the cavity using the isothermal shell and tube heat exchangers (counter-flow). Water at different constant temperatures (5 °C–55 °C) was circulated through the heat exchangers using programmable water baths (PR20R-30 Polyscience; −30 and 200 °C; 0.005 °C accuracy). The flow rates of the water circulating between the heat exchangers and the water baths were measured using flow meters (Burkert Type 8081; ±0.01% accuracy (full scale) +2% (measured value)) mounted at the inlets to the heat exchangers. The obtained data (flow rate and temperature) from the experiments were logged into the computer with the aid of a data logger (National Instrument; type SCXI-1303; 32 channels) and a LABVIEW software (2014 version). The experimental set up for this study is provided in Fig. 1.

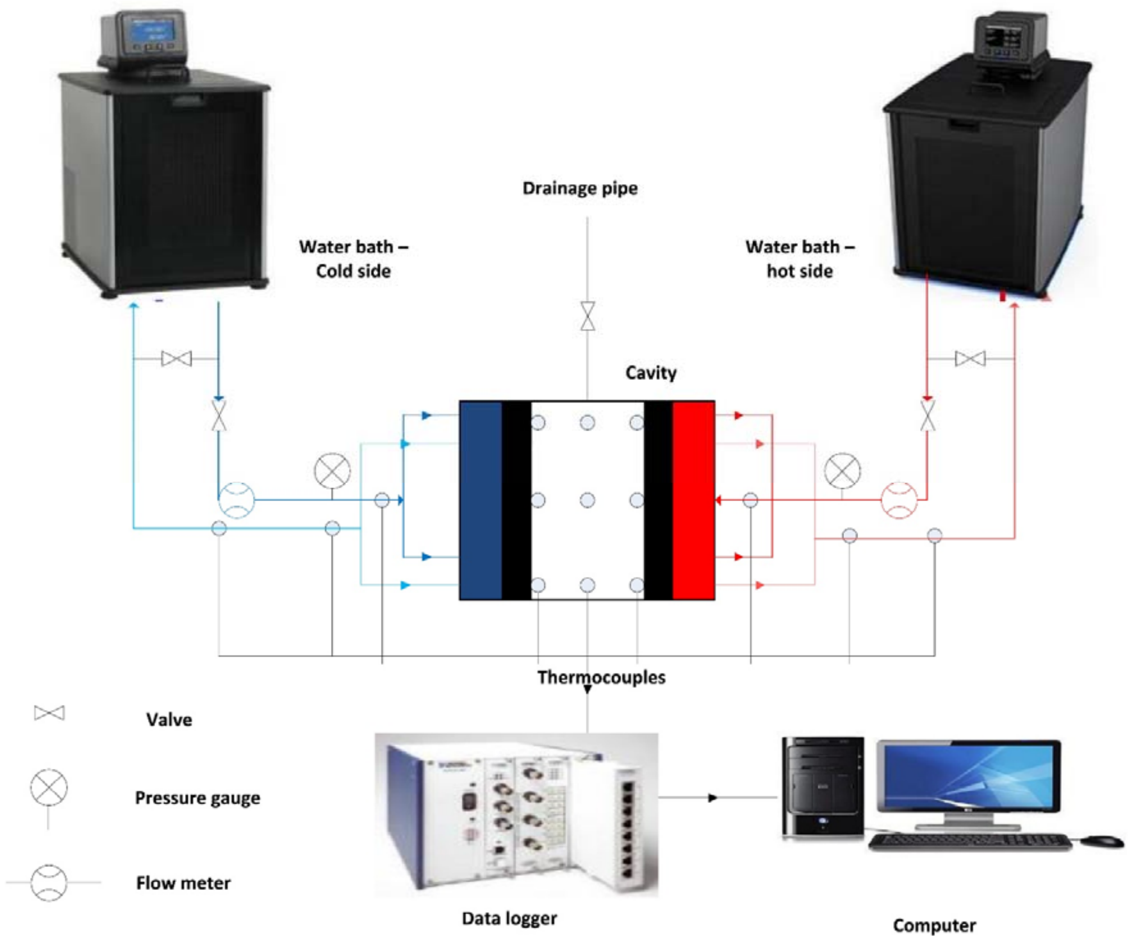

Fig. 1. Experimental setup of this study.

Samples of water and hybrid nanofluids were filled into the cavity. Four runs of experiments per sample were carried out at four different ΔT (20, 30, 40 and 50 °C) between the hot and cold walls of the differentially heated cavity. At each given ΔT, a thermal equilibrium was ensured in the cavity for the given sample contained in it. For the equality of the rate of heat extracted and added within the cavity subject to ΔT, a maximum value of 5% was maintained for each run of the experiment.

2.3. Data reduction

The obtained temperatures and flow rates along with the thermal properties of the nanofluids and base fluid were employed to estimate various key parameters (*Ra*, Nu_{av}, h_{av} Q_{av}, etc.) investigated in this study. Eq. (2) and Equations 3–5 were empirical and theoretical mixture correlations sourced from the literature [29] for the estimation of the density, thermal expansion coefficient, and specific heat of hybrid nanofluids, respectively. The thermophysical properties of water, MWCNT, and Al_2O_3 nanoparticles were provided in Table 1 while the experimentally obtained viscosity of the base fluid and hybrid nanofluids are given in Table 2.

$$\frac{k_{hnf}}{k_{bf}} = ((k_{Al_2O_3}X_{Al_2O_3} + k_{MWCNT}X_{MWCNT}) + 2k_{bf} +2\left(\varphi_{Al_2O_3}k_{Al_2O_3}X_{Al_2O_3} + \varphi_{MWCNT}k_{MWCNT}X_{MWCNT}\right) - 2\varphi_{hnp}k_{bf}) \times ((k_{Al_2O_3}X_{Al_2O_3} + k_{MWCNT}X_{MWCNT}) + 2k_{bf} - (\varphi_{Al_2O_3}k_{Al_2O_3}X_{Al_2O_3} + \varphi_{MWCNT}k_{MWCNT}X_{MWCNT}) + \varphi_{hnp}k_{bf})^{-1} \quad (2)$$

$$\rho_{hnf} = \varphi_{MWCNT}\rho_{MWCNT} + \varphi_{Al_2O_3}\rho_{Al_2O_3} + (1 - \varphi_{hnf})\rho_{bf} \quad (3)$$

$$(\rho\beta)_{hnf} = \varphi_{MWCNT}(\rho\beta)_{MWCNT} + \varphi_{Al_2O_3}(\rho\beta)_{Al_2O_3} + (1 - \varphi_{hnf})(\rho\beta)_{bf} \quad (4)$$

$$(\rho C_p)_{hnf} = \varphi_{MWCNT}(\rho C_p)_{MWCNT} + \varphi_{Al_2O_3}(\rho C_p)_{Al_2O_3} + (1 - \varphi_{hnf})(\rho C_p)_{bf} \quad (5)$$

Table 1. Thermophysical properties of studied materials.

Properties	Water	MWCNT	Al_2O_3
Density (kg/m^3)	997	2100	3970
Thermal conductivity (W/mK)	0.613	2000	40
Heat capacity (J/kgK)	4179	710	765
Thermal expansion coefficient (1/K)	2.1×10^{-4}	2.1×10^{-5}	
Particle size (nm)	–	lengths, inner and outer diameters of 10–30, 3–5 and 10–20.	20 - 30

Table 2. Viscosity of base fluid and hybrid nanofluids at different percent weights.

Temperature	Viscosity (hybrid nanofluids; percent weights)				Viscosity (base fluid)
	80:20	60:40	40:60	20:80	
15	1.27	1.27	1.25	1.23	1.13
25	1.07	1.06	1.04	1.02	0.92
35	0.94	0.93	0.92	0.90	0.78
45	0.82	0.81	0.80	0.79	0.67

The heat transferred within the cavity subject to the differential heating of its vertical walls was expressed using Eq. (6).

$$Q = \dot{m}C_p\Delta T \quad (6)$$

The *h, Ra* and *Nu* of the natural convection of the hybrid nanofluids and water in the cavity were expressed and estimated with Eqs. (7)-(9).

$$h = \frac{Q}{A(T_h - T_c)} \quad (7)$$

$$Ra = \frac{g\beta(T_H - T_C)(\rho)^2(C_p)L_c{}^3}{(\mu)(\kappa)} \quad (8)$$

$$Nu = \frac{(h)L_c}{\kappa_{eff}} \quad (9)$$

2.4. Validation and uncertainty analysis

To validate the obtained experimental result (water) for this study, the models proposed by Berkovsky and Polevikov model [3], Leong et al. [31] and Cioni et al. [16] were employed. These models are expressed in Eqs. (10) [31], 11 [16] and 12 [3].

$$Nu = 0.08461 \times Ra^{0.3125} \quad \left(10^4 < Ra < 10^8\right) \quad (10)$$

$$Nu = 0.145 \times Ra^{0.292} \quad \left(3.7x10^8 \leq Ra \leq 7x10^9\right) \quad (11)$$

$$Nu = 0.18 \times (Pr\,/\,(0.2 + Pr)\,Ra)^{0.29} \quad \left(Pr \leq 10^5;\ Ra \leq 10^{10};\ 1 \leq H/L \leq 10\right) \quad (12)$$

Where

$$Pr = \frac{\mu C_p}{k}$$

To show the reliability of the obtained data, the uncertainty analysis was carried out. The primary sources of errors were the measurements taken for the temperatures and flow rates. Eqs. (13)–15 were used in estimating the uncertainty related to *Q, Nu,* and *h*, respectively.

$$\delta Q = \left(\left(\frac{\partial Q}{\partial \dot{m}}\delta \dot{m}\right)^2 + \left(\frac{\partial Q}{\partial C_{p_{bf}}}\delta C_{p_{bf}}\right)^2 + \left(\frac{\partial Q}{\partial T_H}\delta T_H\right)^2 + \left(\frac{\partial Q}{\partial T_C}\delta T_C\right)^2\right)^{\frac{1}{2}} \quad (13)$$

$$\delta h = \left(\left(\frac{\partial h}{\partial Q}\delta Q\right)^2 + \left(\frac{\partial h}{\partial A}\delta A\right)^2 + \left(\frac{\partial h}{\partial T_H}\delta T_H\right)^2 + \left(\frac{\partial h}{\partial T_C}\delta T_C\right)^2\right)^{\frac{1}{2}} \quad (14)$$

$$\delta Nu = \left(\left(\frac{\partial\, Nu}{\partial h}\delta h\right)^2 + \left(\frac{\partial Q}{\partial L_c}\delta L_c\right)^2 + \left(\frac{\partial Q}{\partial k_{eff}}\delta k_{eff}\right)^2\right)^{\frac{1}{2}} \quad (15)$$

Maximum uncertainties of 8.47%, 2.12%, and 1.85% were calculated for *Q, Nu,* and *h*, respectively, using the applicable Equations.

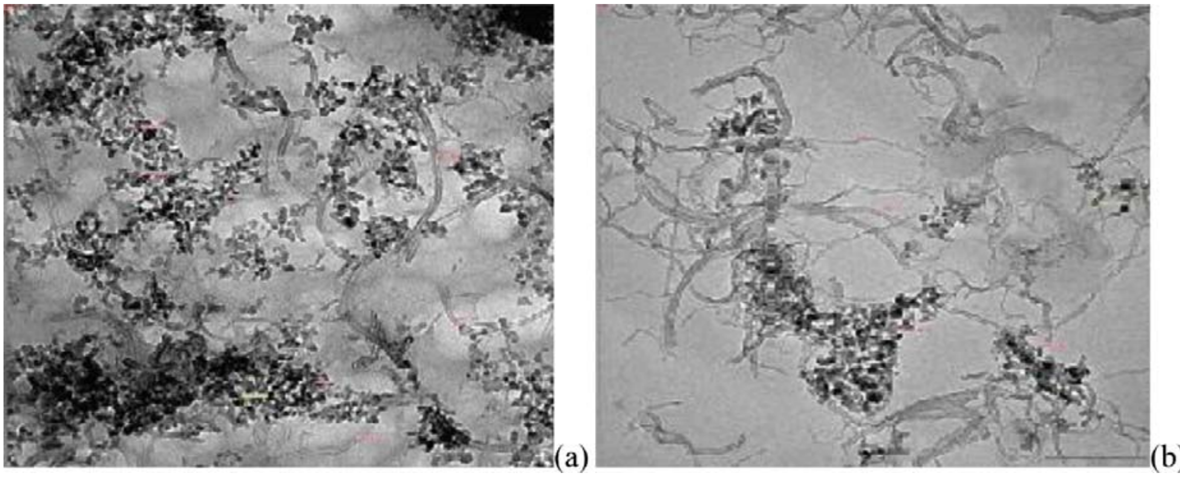

Fig. 2. TEM pictures showing (a) Al_2O_3-MWCNT (80%:20%)/water and (b) Al_2O_3-MWCNT (20%:80%)/water nanofluids.

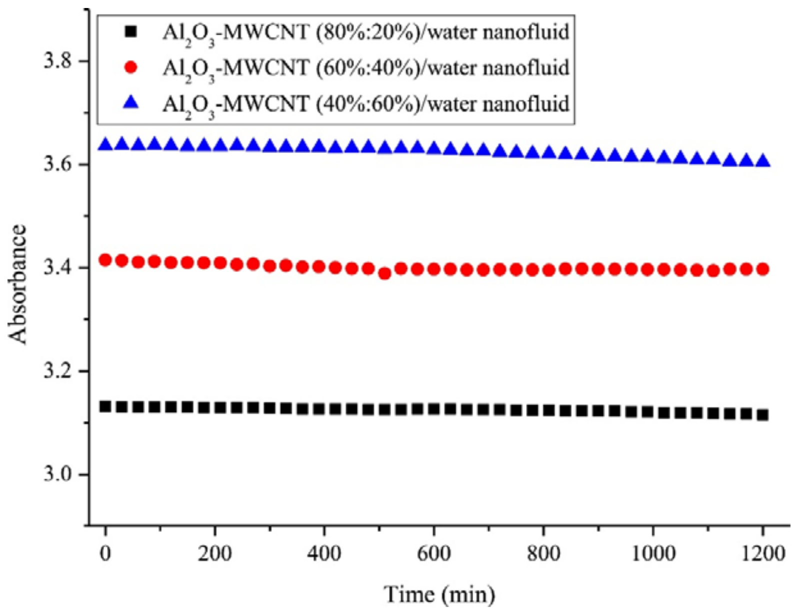

Fig. 3. Stability of hybrid nanofluids monitored via UV-visible spectrophotometer.

3. Results and discussion

3.1. Morphology and stability of hybrid nanofluids

The particle size and morphology of Al_2O_3-MWCNT/water nanofluids for 80:20 and 20:80 percent weights were monitored using TEM. The TEM images for the hybrid nanofluids are presented in Fig. 2. Both nanoparticles (Al_2O_3; spherical-shaped and MWCNT; cylindrical-shaped) were identified and noticed to be well suspended in the base fluid (Figs. 2a and b). The Al_2O_3 nanoparticles have a size range of 15.42 nm–49.87 nm and observed to be attached to the surface of the MWCNT nanoparticles (size ranging from 5.63 nm to 16.98 nm). From Fig. 3, the stability of the hybrid nanofluids for nanoparticles' percent weights of 80:20, 60:40 and 40:60 (Al_2O_3:MWCNT) has been checked by measuring the absorbance using a UV-visible spectrophotometer. For 20 h duration, relatively constant values of absorbance were observed for the hybrid nanofluids, which indicate their stability within this time frame. The absorbance diminished with an increase in the MWCNT nanoparticles proportion (reduction in alumina nanoparticles quantity) for the hybrid nanofluids (Fig. 3). The Al_2O_3−MWCNT (40:60)/water nanofluid was noticed to have the best stability of the three. The wavelength range of 291–301 nm was determined for the nanofluids of which wavelength of 225 nm has been reported for water-based Al_2O_3 nanofluids [16]. The increase in the wavelength could be attributed to the hybridization of the nanofluids through the addition of MWCNT nanoparticles in various proportions. After two months of bi-weekly observation, the hybrid nanofluids were observed to be visually stable.

3.2. Viscosity and electrical conductivity of hybrid nanofluids

Fig. 4 illustrates how the measured effective viscosity of the hybrid nanofluids relates to temperature rise for different percent weights of the hybrid nanoparticles. The effective viscosity of the various hybrid nanofluids was augmented with a rise in the proportions of MWCNT nanoparticles (with a corresponding reduction in Al_2O_3 nanoparticles) suspended into the base fluid. The effective viscosity of the nanofluids was noticed to diminish with a temperature rise. This observation agrees with the literature regarding the relationship between viscosity and temperature [32], [33], [34]. Relative to the base fluid, a maximum augmentation of 24.56% was achieved for Al_2O_3-MWCNT (80%:20%)/water nanofluid at 0.1 vol% and 55 °C. The absence of an existing model to predict the obtained experimental data as a function of nanoparticles' percent weights (R) and temperature in the literature has led to proposing a new correlation. The proposed correlation is articulated in Eq. (16).(16)

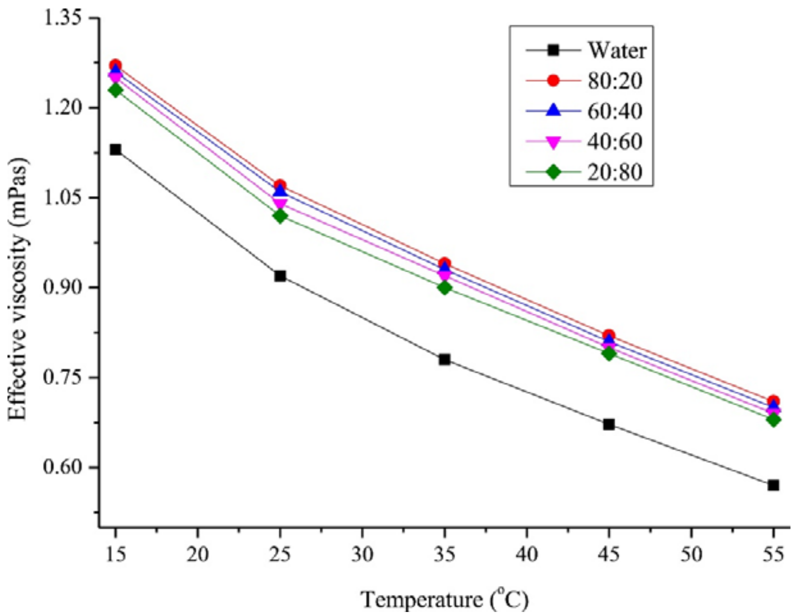

Fig. 4. Effective viscosity of hybrid nanofluids against temperature.

An illustration of the effective electrical conductivity of the hybrid nanofluid as a function of temperature is presented in Fig. 5. It can be observed that the effective electrical conductivity increases with a temperature rise. Generally, the dispersion of hybrid nanoparticles into water was noticed to significantly enhance the effective electrical conductivity of water. This is because Al_2O_3 and MWCNT nanoparticles possess higher electrical conductivity values than water. In comparison to water, the electrical conductivity of the hybrid nanofluids was enhanced by 134.12%–255.34% for the temperatures considered. The Al_2O_3−MWCNT (80%:20%)/water nanofluid was noticed to yield the highest values (1127–1265 μS/cm) of electrical conductivity at the various temperatures studied (Fig. 5). Using the measured data of electrical conductivity for the hybrid nanofluids, a correlation was developed. Eq. (17) expresses the electrical conductivity of Al_2O_3−MWCNT/water nanofluid as a function of percent weight (*R*) of hybrid nanoparticles and temperature.

$$\sigma_{hnf} = 1112.882 - 94.9343R + 3.323T \left(R^2 = 95.61\%\right) \tag{17}$$

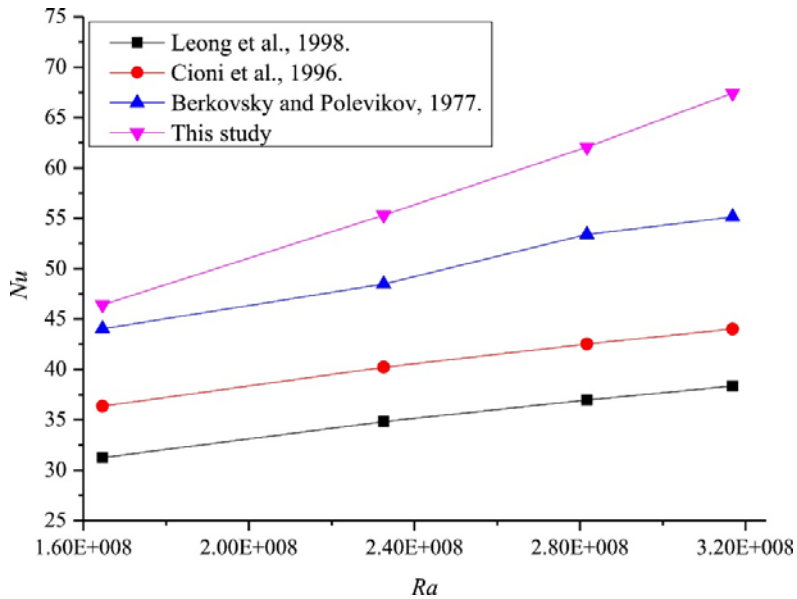

Fig. 5. Comparison of various correlations for predicting Nusselt number as a function of Rayleigh number.

3.3. Cavity validation

The performance of the square cavity engaged in this work was validated using the base fluid, water. Numerical models previously reported in the literature were used to validate the obtained experimental data of *Nu* [3,16,31]. Fig. 5 illustrates the *Nu* plotted against *Ra* for water using the developed models and the experimental data derived from this study. From Fig. 5, it can be noticed that all the correlations underestimated the *Nu* experimentally obtained in this work. The *Ra* range (10^4 < Ra< 10^8) for the model proposed by Leong et al. [31] was lower than the values (1.65×10^8 < Ra < 3.80×10^8) recorded in this study while that of Cioni et al. [16] was higher (3.7×10^8 < Ra < 7×10^9). Although the *Ra* range obtained in this work is within the range (Ra ≤ 10^{10}) of the Berkovsky and Polevikov model [3], however, the *Nu* values reported in this study were higher than that of this model. This result agrees with a previous study in which experimentally-obtained *Nu* for water in a square cavity was higher than that evaluated via Berkovsky and Polevikov model [3]. However, a previous study has reported a lower *Nu* (experimental) for water in a square cavity than the *Nu* estimated using Berkovsky and Polevikov model [3].

3.4. Heat transfer behavior of hybrid nanofluids

The performance of different percent weights of Al_2O_3-MWCNT/water nanofluid at 0.1 vol% in a square cavity under natural convection condition has been investigated for the h_{av}, Nu_{av}, and Q_{av}. The *Ra* as a function of the hybrid nanofluid with different percent weights of the hybrid nanoparticles under various ΔT is presented in Fig. 6. An increase in the ΔT was generally observed to increase the *Ra* for all the samples (water and hybrid nanofluids). At each ΔT, the nanofluids were noticed to have higher *Ra* values than that of the base fluid. The suspension of the hybrid nanoparticles into the base fluid at different proportions was seen to cause a rise in the *Ra* because of the change in the fluid properties and composition. The hybrid nanofluid with 60:40 percent weight of Al_2O_3:MWCNT was noticed to have the highest *Ra* value followed by those of 80:20, 40:60, and 20:80, for each ΔT. With the ΔT (20 °C–50 °C) considered in this work, the *Ra* range obtained was $1.65 \times 10^8 < Ra < 3.17 \times 10^8$ and $1.76 \times 10^8 < Ra < 3.80 \times 10^8$ for water and nanofluids, respectively.

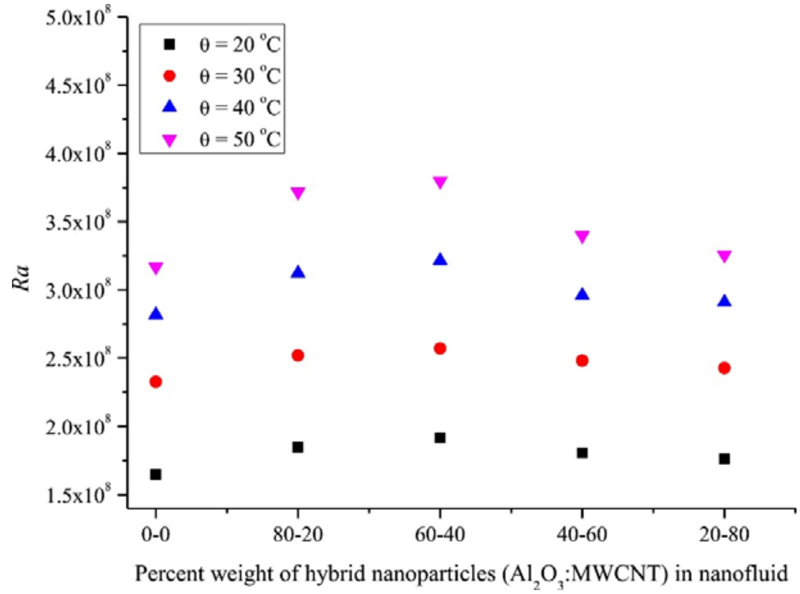

Fig. 6. Rayleigh number against hybrid nanofluid at different temperature gradients.

The experimentally obtained Nu_{av} values for the samples (water and nanofluids) examined in this study at different ΔT are shown in Fig. 7. It is apparent that the Nu_{av} for all the hybrid nanofluids is higher than the Nu_{av} for the base fluid, and this parameter is noticed to enhance with an increase of ΔT. On the engagement of the hybrid nanofluid, the Nu_{av} augmented for Al_2O_3-MWCNT (80:20)/water nanofluid in relation to the base fluid, which improved further when the MWCNT nanoparticles' proportion was increased to 40 wt% while the Al_2O_3 nanoparticles' reduced to 60 wt%. Thereafter, the Nu_{av} deteriorated for the Al_2O_3-MWCNT/water nanofluids with further reduction (Al_2O_3) and increment (MWCNT) of nanoparticles. Thus, the Nu_{av} of the base fluid improved on the use of hybrid nanofluids with the maximum value occurring for Al_2O_3-MWCNT (60:40)/water nanofluid. At ΔT = 50 °C, the Nu_{av} was enhanced by 13.3%, 16.2%, 12.2% and 10.2% for the hybrid nanofluids with percent weights of 80:20, 60:40, 40:60 and 20:80, respectively, in relation to the base fluid. These values are slightly lower than the earlier published enhancements of Nu_{av} by 11.8% and 17.2% for the same Al_2O_3-MWCNT/water nanofluid type but at percent weights of 95:5 and 90:10, respectively [35]. The correlations utilized in the previous work for estimating the thermal properties were observed to be inadequate and thus, overestimated the properties which consequently caused the high augmentation of Nu_{av} earlier reported.

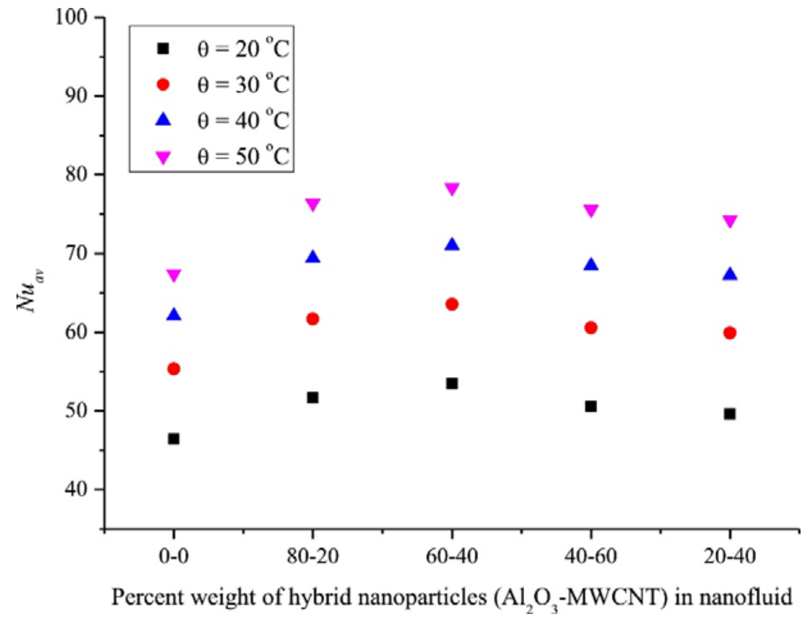

Fig. 7. Average Nusselt number against hybrid nanofluid at different temperature gradients.

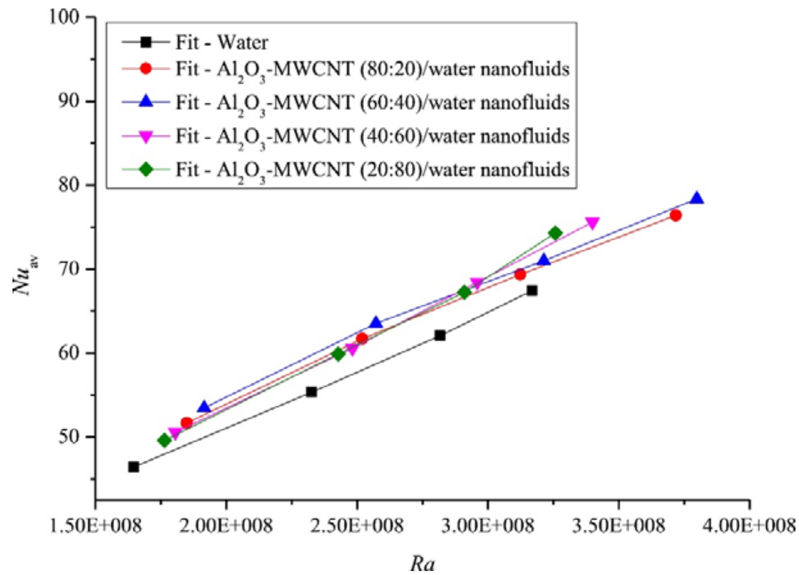

Fig. 8. Nusselt number against Rayleigh number at different percent weight of hybrid nanoparticles in nanofluids.

In addition, a linear relationship was observed between Nu_{av} and *Ra* for each of the studied sample (Fig. 8). It depicts that the Nu_{av} was enhanced as the *Ra* increased. This can be explained that as the buoyancy increased for the samples, heat transfer was also improved, which agrees with earlier studies in the literature [3,16,18]. The Al_2O_3−MWCNT/water nanofluid with 60:40 percent weight of the nanoparticles recorded the highest Nu_{av} and *Ra* (Fig. 8). The experimentally derived data for Nu_{av} and *Ra* and percent weight ratios (*R*) of the hybrid nanoparticles were utilized to develop a model. The existing models for estimating the Nu_{av} of nanofluids' performance in cavities are mainly functions of *Ra* and φ, which are inappropriate for this present study [16,36,37]. As expressed in Eq. (18), the Nu_{av} of the hybrid nanofluids can be predicted from *Ra* and *R* with high accuracy (coefficient of correlation and determination of 0.988 and 0.994, respectively).

$$Nu = 6.47 \times 10^{-4}(Ra)^{0.5928}(R)^{0.00169} \tag{18}$$

The proposed correlation can estimate the experimental data with a margin of deviation of −2.43% to 3.58%, root mean square error of 1.079, and average percent error of 0.011%. Fig. 9 demonstrates the relationship between the predicted and experimental data for Nu_{av}. An illustration of h_{av} in relation to the studied samples of water and hybrid nanofluids at various ΔT is provided in Fig. 10. The h_{av} was noticed to enhance with the rise in ΔT and the engagement of nanofluids. It is obvious from Fig. 10 that the h_{av} of the Al_2O_3−MWCNT/water nanofluids increased to a peak as the percent weights of the hybrid nanoparticles contained in the nanofluids changed from 80:20 to 60:40 (Al_2O_3:MWCNT) and then diminished progressively to the least h_{av} for percent weight of 20:80. At ΔT = 50 °C, the h_{av} of the Al_2O_3-MWCNT/water nanofluids was augmented by 17.6%, 20.5%, 15.7% and 12.5% for 80:20, 60:40, 40:60, and 20:80 percent weights of the bi-nanoparticles, respectively, in comparison with the base fluid. It is pertinent to mention that previous studies have reported 15% [16] and 18% [38] augmentation of h_{av} for Al_2O_3/water nanofluids, however, enhancement of 45% [17] was reported for MWCNT/water nanofluid filled into a square cavity. With the obtained result for h_{av} enhancements in this present study, it is sufficing to state that the employment of hybrid nanofluids (Al_2O_3-MWCNT/water) provided an improved h_{av} in comparison to single-particle nanofluids. The observed augmentation of h_{av} in this study can be explained by the synergetic effect afforded by hybridizing MWCNT and Al_2O_3 nanoparticles. A comparison of the obtained enhancements for h_{av} in this work to an earlier report of 12.7% and 19.4% improvements of h_{av} for Al_2O_3-MWCNT/water nanofluids at 95:5 and 90:10 percent weights, respectively, shows a case of overestimation of the thermophysical and convective properties as a result of the models and correlations used in their estimation as previously discussed.

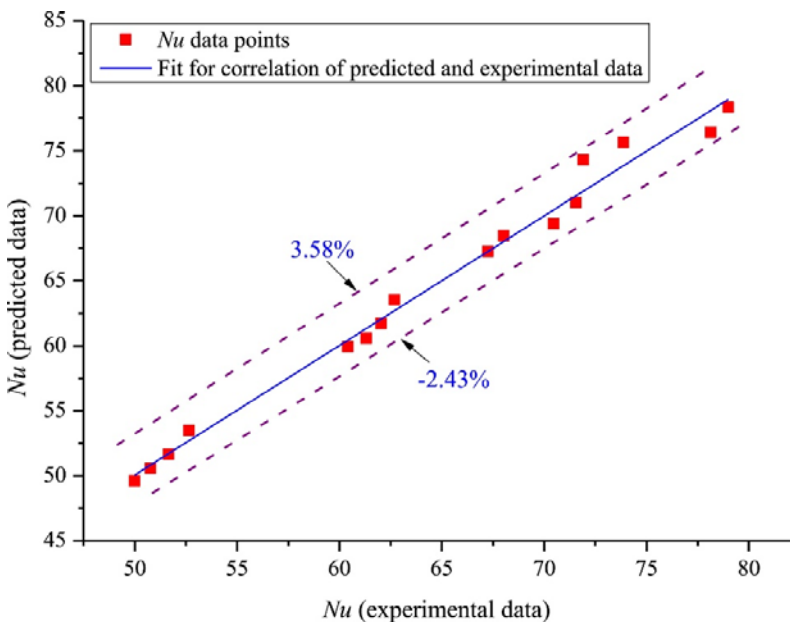

Fig. 9. Relationship between predicted and experimental Nusselt number for hybrid nanofluids in a square cavity.

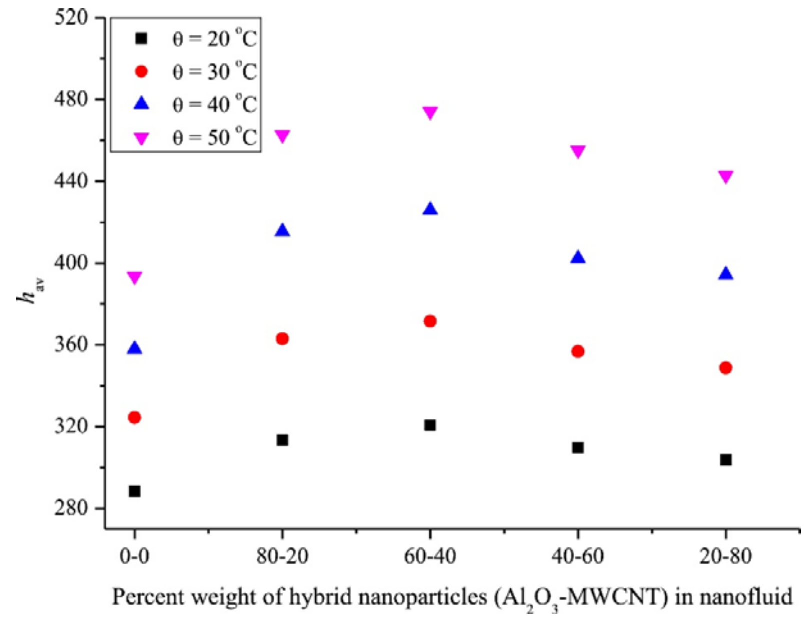

Fig. 10. Average convective heat transfer coefficient against hybrid nanofluid at different temperature gradients.

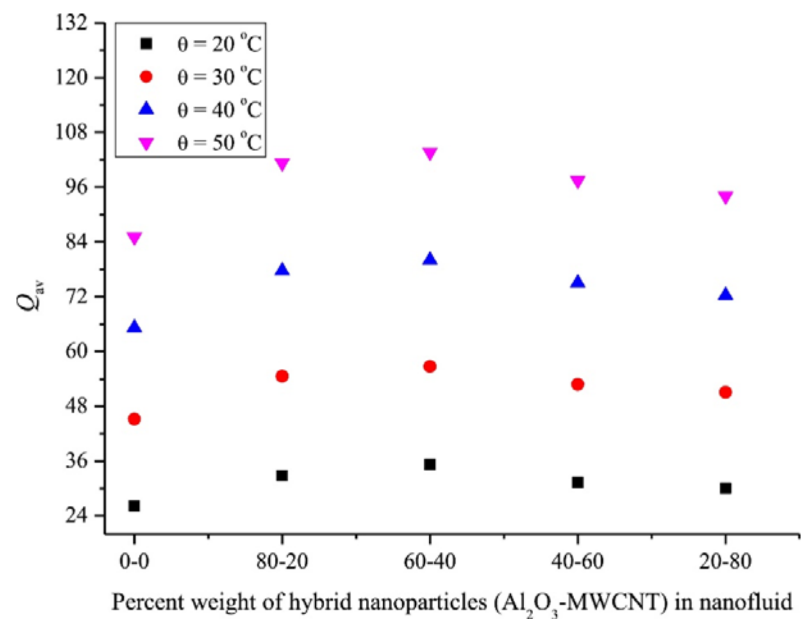

Fig. 11. Average heat transfer against hybrid nanofluid at different temperature gradients.

The quantities of heat transferred by the studied samples across the cavity due to varying ΔT are illustrated in Fig. 11. An identical pattern as earlier reported for *Ra*, Nu_{av}, and h_{av} was observed for Q_{av}. It is evident that the enhancement of Q_{av} is a function of the percent weights of the nanoparticles in the hybrid nanofluid and ΔT. Expectedly, more heat was transferred by the hybrid nanofluids than the base fluid due to the enhancement of the thermal properties of the base fluid by the suspension of the bi-nanoparticles. Fig. 11 shows that increasing the percent weight of MWCNT nanoparticles (leading to a reduction in Al_2O_3 nanoparticles' ratio) from 80:20 to 60:40 in the nanofluids was found to augment Q_{av}, which later diminished as the MWCNT nanoparticles' percent weight was further increased to 20:80. Apparently, Al_2O_3-MWCNT (60:40)/water nanofluid has the highest value of Q_{av} (105.13 W) at

ΔT = 50 °C with 19.4% enhancement in comparison to the base fluid. The Q_{av} of other hybrid nanofluids was augmented by 16.6% (Al_2O_3−MWCNT (80:20)), 11.5% (Al_2O_3-MWCNT (40:60)), and 7.2% (Al_2O_3-MWCNT (20:80)) at ΔT = 50 °C, relative to the base fluid.

4. Conclusions

A study of Al_2O_3-MWCNT/water nanofluids at various nanoparticles' percent weights for 0.1 vol% in a square cavity has been carried out. The range of Ra considered in this work was 1.65×10^8–3.80×10^8. It was noticed that the Nu_{av} enhanced with an increase in Ra. Nu_{av}, h_{av}, and Q_{av} were noticed to augment with the rise in ΔT and percent weights of bi-nanoparticles in the nanofluids. Hybrid nanofluid with 60:40 percent weight of Al_2O_3:MWCNT nanoparticles was observed to have the highest value for Ra, Nu_{av}, h_{av}, and Q_{av} at each ΔT. In addition, maximum enhancements of 16.2%, 20.5%, and 19.4% were achieved for Nu_{av}, h_{av}, and Q_{av} at ΔT = 50 °C, in comparison to the base fluid. The engagement of hybrid nanofluids was noticed to improve the thermal and flow properties of the base fluid which consequently enhanced the natural convection behavior of this new class of nanofluids in a square cavity. The results from this study further demonstrated the benefit offered by utilizing hybrid nanofluids over mono-particle nanofluids in heat transfer studies. It is worth stressing that the employment of appropriate experimentally derived correlations or experimental data for estimating thermo-physical properties is vital to an experimental study on thermo-convection heat transfer of a hybrid nanofluid in cavities.

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