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Abstract

© 2020 John Wiley & Sons, Ltd. Nanofluid is divided in two major section, mono nanofluid (MN) and hybrid nanofluid (HN). MN is created when a solid nanoparticle disperses in a fluid, whereas HN has more than one solid nanomaterial. In this research, iron (III) oxide (Fe3O4) is MN, and Fe3O4 plus multiwalled carbon nanotube (MWCNT) is HN, whereas both are mixed and dispersed into the water basefluid. Thermal conductivity (TC) of Fe3O4/water and MWCNT/Fe3O4/water was measured after preparation and numerical model performed on the resulted data. After that, field emission scanning electron microscope (FESEM) was studied for microstructural observation of nanoparticles. MN and HN TC were studied at temperature ranges of 25 to 50°C and volume fractions of 0.2% to 1.0%. For MN and HN, thermal conductivity enhancement (TCE) of 32.76% and 33.23% was measured at 50°C temperature—1.0% volume fraction, individually. Different correlations have been calculated for numerical modeling, with R2 = 0.9. Deviation of 0.6007% and 0.6096% was calculated for given correlations for MN and HN individually. Deviation of 0.5862% and 0.6057% was calculated for trained models, for MN and HN individually. Thus, by adding MWCNT to Fe3O4-H2O nanofluid, TC is enhanced 0.47%, and this HN has agreeable heat transfer potential.

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Thermal conductivity enhancement of nanofluid by adding Multi-Walled Carbon Nano Tubes: Characterization and numerical modeling patterns

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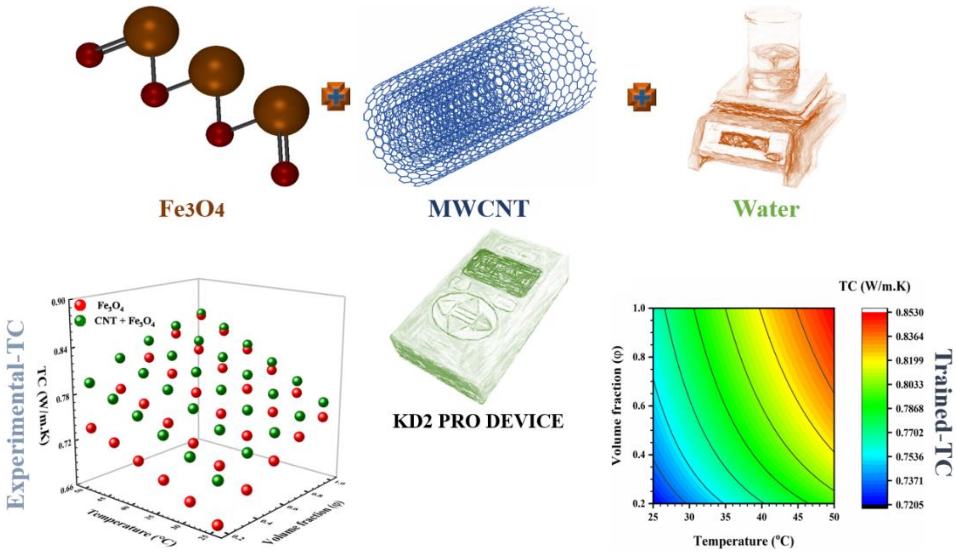
Abstract

Nanofluid is divided in two major section, Mono nanofluid (MN) and hybrid nanofluid (HN). MN is created when a solid nano-particle disperses in a fluid, while HN has more than one solid nanomaterial. In this research, Iron (III) Oxide (Fe_3O_4) is MN and Fe_3O_4 plus Multi-Walled Carbon Nanotube (MWCNT) is HN, while both are mixed and dispersed into the water basefluid. Thermal conductivity (TC) of Fe_3O_4/Water and MWCNT/Fe_3O_4/Water, were measured after preparation and numerical model performed on the resulted data. Then, X-ray diffraction analysis (XRD) and Energy dispersive X-ray analysis (EDX) were studied for Phase and structural analysis. After that, Field emission scanning electron microscope (FESEM) was studied for Microstructural-observation of nanoparticles. MN and HN TC were studied at temperature ranges of 25 to 50^{o}C and volume fractions of 0.2 to 1.0%. For MN and HN, Thermal conductivity enhancement (TCE) of 32.76% and 33.23%, was measured at 50^{o}C temperature - 1.0% volume fraction, individually. Different correlations have been calculated for numerical modeling, with R^2=0.9 and also, Artificial neural network (ANN) has been modeled with R^2=0.999. Deviation of 0.6007% and 0.6096%, were calculated for given correlations for MN and HN individually. Deviation of 0.5862% and 0.6057%, were calculated for trained models, for MN and HN individually. Thus, by adding MWCNT to Fe_3O_4-H_2O nanofluid, TC is enhanced 0.47% and this HN has agreeable heat transfer potential.

Keywords: Thermal conductivity; Numerical modeling; Artificial Neural Network (ANN); MWCNT; Fe3O4; Water



Graphical Abstract

Nomenclature		Subscripts	
XRD	X-ray diffraction analysis	**bf**	Base Fluid
FESEM-EDX	field emission scanning electron microscope plus energy dispersive X-ray analysis	**nf**	Nanofluid
TC	Thermal Conductivity	**Exp**	Experimental
TCR	Thermal Conductivity Ratio	**pred**	Predicted
TCE	Thermal Conductivity Enhancement	**np**	Nanoparticle
MWCNT	Multi-Walled Carbon Nanotube	**r**	Ratio

1. Introduction

Recently, with their great potentialities in different technological fields such as heterogeneous catalysis, magnetic data storage and electrical devices, Carbon nanotubes (CNTs)-based magnetic nanocomposites have drawn considerable research interest. Cunha et al. and Teymourian et al., synthesized the MWCNTs functionalized with Fe3O4 and Fe3O4/MWCNT–COOH, for tissue engineering applications and for the low potential detection of NADH, respectively. As MRI contrasting agent, Wu et al. used the Fe3O4/MWCNT–COOH.

Sumio Iijima discovered Carbon nanotubes (CNTs) in 1991. CNT caused a revolution in different fields of nanotechnology: pharmacology, chemistry, environment, mechanic and electronics. Porous structures and facile surface functionalization are those physical properties which have made the application of the CNTs more attractive [1]. Many modification methods such as chemical, physical or both have been used for the homogeneous dispersion of CNTs in common solvents to improve their solubility. Wide surface of CNTs compared with its length scale in diameter, makes good position for the functionalization and adding different functional groups [2]. Multi-walled carbon nanotubes (MWCNTs) gain more attention compare to single walled carbon nanotubes (SWCNTs), due to their availability in large quantities and low production costs. One of the first CNT nanofluids studied by Choi et al. They reported 160% increase in TC of 1.0 vol.% MWNTs dispersed in synthetic poly(a-olefin) oil [3].

Magnetite (Fe3O4), particularly when it is in nano scale, has great significance in different fields. Thus, this material due to its characteristics, inspire researcher's new ideas [4]. Recently, considerable research has been focused on iron oxides, γ -Fe2O3 and Fe3O4 nanoparticles, which have attracted interest in the field of medical applications such as magnetic sensing, catalysis, high frequency applications, sensors, magneto-optics devices, microwave devices, cancer therapy and medical diagnostics, magnetic resonance imaging (MRI), photomagnetics, radio frequency hyperthermia, drug delivery systems (DDS), data storage, magnetic fluids, high-density digital recording disks and magnetic recording media such as audio and videotape. For such practical uses of magnetic nanoparticles, surface properties of the nanoparticles, magnetic properties and the particle size have great importance [5]. There are different ways to prepare Fe3O4 nanoparticles, such as high temperature decomposition of organic precursors, microemulsions, laser ablation, mechanical grinding and arc discharge [6]. These synthetic methods yield Fe3O4 nanoparticles with high crystallinity and narrow size distribution [7].

Recently, industries require fluids which can carry more heat in less time [8]. To improve the performance, energy consumption must be reduced [9]. Thus, fluids with faster heat transfer must be replaced with current fluids. One of these fluids are nanofluids (Introduced by Choi in 1995), which have attracted great concentration in recent years [10]. Nanofluids, are fluids with dispersed nano-size particles into basefluids such as Water, Oil and Ethylene Glycol [11]. Thermal conductivity increases or decrease if any nano-size particle dispersed into a fluid. After Choi, One-, two- and three- dimensional nanomaterials such as fibers, sheets and particles and also different basefluids investigated to realize the effect of each material on thermal conductivity enhancement. There are two types of Nanofluids, mono and hybrid [12]. Mono-nanofluid is prepared by dispersion of one nanoparticle in a fluid, but hybrid-nanofluid is composed of more than one solid particle. In fact, each nanoparticle has its own properties [13]. Thus, this is possible to make use of different nanoparticles properties at the same time. Nanofluids can be used in different industrial applications: systems of engine cooling, electronic device cooling, heating and cooling system for buildings [14].

Recently, Artificial neural network was used in transformers heat analysis. The ANN, as a new parameter to investigate in each research, can model the data in specific range of temperature or volume fraction, with more than 1000 data. This means the highly reduction in the experiment costs. The ANN can model complex patterns by using simple computations. Thus, in nanofluid study, ANN modeling can be useful.

The aim of this research is to investigate hybrid nanofluid's thermal conductivity. Thus, Multi-Walled Carbon Nanotube and Iron (III) Oxide nanoparticles dispersed in Water, and hybrid nanofluid (with composition of MWCNT 50% / Fe_3O_4 50%) was prepared at different volume fractions up to 1.0 %. After that, experiments done at different temperatures up to 50^oC (by hot-wire method). With using available data and curve fitting method, new correlations have been offered to calculate thermal conductivity of Iron (III) Oxide /Water MN and MWCNT/Iron (III) Oxide /Water HN in specified range of volume fraction and temperature [15]. Also, artificial neural network was modeled for both MN and HN to predict TC behavior in other volume fractions and temperatures.

2. Materials and Methods

2.1. Materials

For nano-size solid materials, Multi-Walled Carbon Nanotube and Iron (III) Oxide were used. Figure 1, shows the 3D-chemical structure of MWCNT and Fe_3O_4. MWCNT was purchased from nano-bazar, Inc with length of ~ 30 um, ID 5-10 nm and OD 10-20 nm with COOH content of 2.0 wt%. Fe_3O_4 was purchased from US Research Nanomaterials, Inc. Table 1, shows thermophysical properties of nanoparticles and basefluid. X-ray diffraction analysis was studied by D8ADVANCE Bruker X-ray diffractometer. Field emission scanning electron microscope images were taken by NOVA NanoSEM to observe sample morphology. Also, to certify XRD results, Energy dispersive X-ray analysis was used.

Table 1. Thermophysical Properties of Basefluid and Nanoparticles

Properties	**Water (Base fluid)**	**Iron (III) Oxide (Nanoparticle 50%)**	**Multi-Walled CNT (Nanoparticle 50%)**
Chemical formula	H_2O	Fe3O4; FeO.Fe2O3	C
Appearance	---	Lustrous black	Black
Purity (%)	Distilled water	97%	98%
Molar mass (g/mol)	18.0153	231.533	12.011
Density (gr/m^3)	0.998	5.2	2.6
Thermal conductivity (W/m·K)	~0.6 (@ 20°C)	**This paper**	

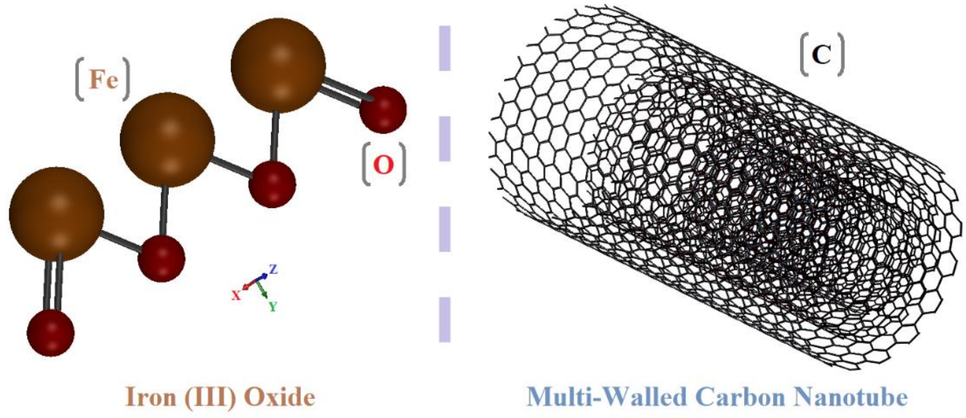


Figure 1. 3D-schematic form of Multi-Walled Carbon Nanotube (MWCNT) and Iron (III) Oxide (Fe_3O_4)

2.2. Nanofluid Preparation

In this research, mono and hybrid nanofluid prepared separately, to measure nanofluid's thermophysical properties. Fe_3O_4 as mono nanofluid, and Fe_3O_4 plus MWCNT (equal 50-50) as hybrid nanofluid, dispersed into water [16]. Various percentages of mono and hybrid nanofluid (0.2, 0.4, 0.6, 0.8 and 1.0 vol%) were prepared and then, pH meter, magnetic stirring and sonication were used to break agglomerations between nanoparticles to reach a stable suspension. To made and test this stable suspension, 120min magnetic stirring and 35min ultrasonic (400 W - 24 kHz), were done.

2.3. Thermal Conductivity Measurement

To measure thermo properties of mono and hybrid nanofluid, a KD2 Pro device (Decagon Devices, Inc., USA) was used. This device use hot-wire method with 5% error, and it needs to be calibrated with pure water. Mono and hybrid nanofluid containers placed at temp. bath and then, a single needle (stainless steel) sensor -KS.1- was inserted into containers, independently [17]. Thermal conductivity was measured 4-times, for each temperature (25, 30, 35, 40, 45 and 50^{o}C), independently [18].

Thermal conductivity ratio (TCR) and Thermal conductivity enhancement (TCE) are calculated by equations 1 and 2, respectively.

$$\text{Thermal conductivity ratio} = \frac{k_{nf}}{k_{bf}} \tag{01}$$

$$\text{Thermal conductivity enhancement } (\%) = \frac{k_{nf} - k_{bf}}{k_{bf}} * 100 \tag{02}$$

Where k is thermal conductivity (TC) of nanofluid. Also, "$_{bf}$" is basefluid and "$_{nf}$" is nanofluid.

3. Result and Discussion

3.1. Materials

3.1.1. Phase and Structural Analysis

XRD

Figure 2, displays the X-ray diffraction analysis of MWCNT–COOH and Fe_3O_4. An intense characteristic peak at (002) plane, 2θ = 26.04˚ with interlayer spacing (Via Bragg's law Cu Kα: 1.541˚ Å wavelength) of 3.418 Ǻ d-spacing is visible in the pattern [19]. Also, low-intensity peaks which indicates the crystalline structure of MWCNT are in (100), (004), and (110) planes, at 2θ = 42.64˚, 2θ = 53.18˚ and 2θ = 78.22˚ [20]. For the Fe_3O_4 [21] XRD pattern of the sample, shows identical to pure magnetite (96-900-5840) with Cubic Crystal system. As it can be seen, (220) plane at 2θ = 29.98˚, (311) plane at 2θ = 35.45˚ and with 2.52 Ǻ d-spacing, (400) plane at 2θ = 43.13˚ (422) plane at 2θ = 53.44˚ (511) plane at 2θ = 56.94˚ (440) plane at 2θ = 62.61˚ are the sample peaks.

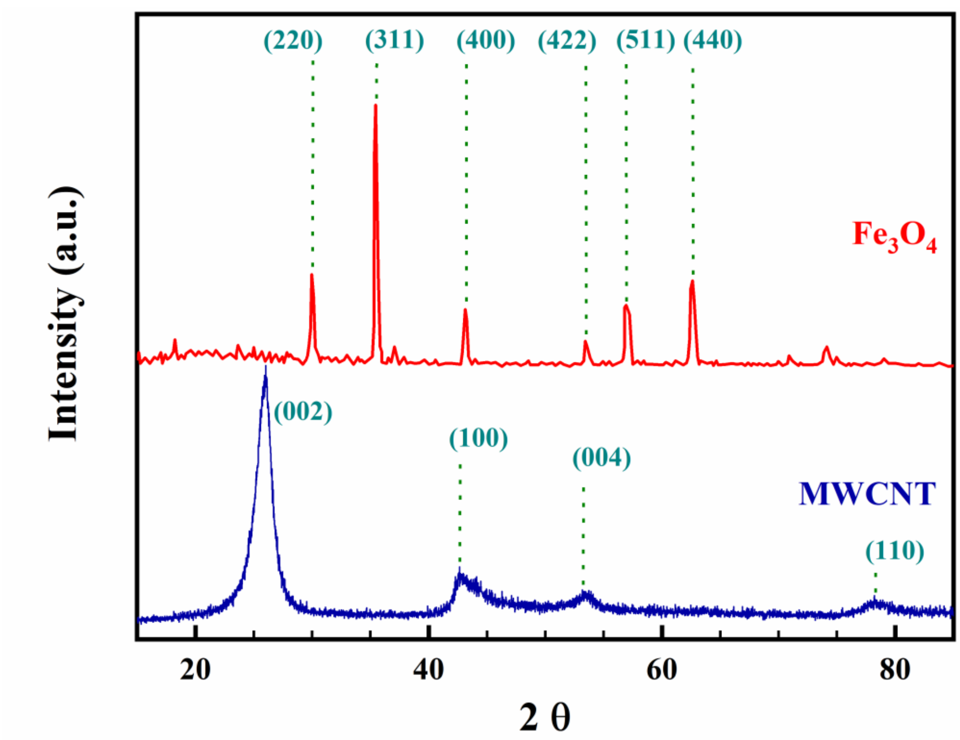


Figure 2. XRD of Multi-Walled Carbon Nanotube (MWCNT) and Iron (III) Oxide (Fe_3O_4)

3.1.2. Microstructural Observations

FESEM and EDX

Figure 3 shows Field emission scanning electron microscope image of MWCNT with the magnification scales of 3000 (left) and 500 nm. 0D nanomaterials are nanoparticles and in 1D nanomaterials, one dimension is outside the nanoscale. As it can be seen, MW Carbon Nanotubes has one-dimension structure as like as nanorods, and nanowires. From the figure, nanotubes have nanometer scale which is under 100 nm [22]. MWCNT has a rough surface structure due to the attachment of oxygenated functional groups on its surface after acid treatment [23] and a smooth surface with bundles of tangled tubes. The chemical compositions of MWCNT was verified by using Two-point Energy dispersive X-ray analysis [24]. Figure 4 and Table 2 show 2-point EDX of MWCNT. MWCNT had impurities, however after acid functionalization [25], these metal impurities were removed. MWCNT at point-A contains utmost 95.63 at.% Carbon, 2.63 at.% Oxygen and 1.74 at.% Nitrogen. MWCNT at point-B contains utmost 96.49 at.% Carbon, 2.87 at.% Oxygen and 0.64 at.% Nitrogen.

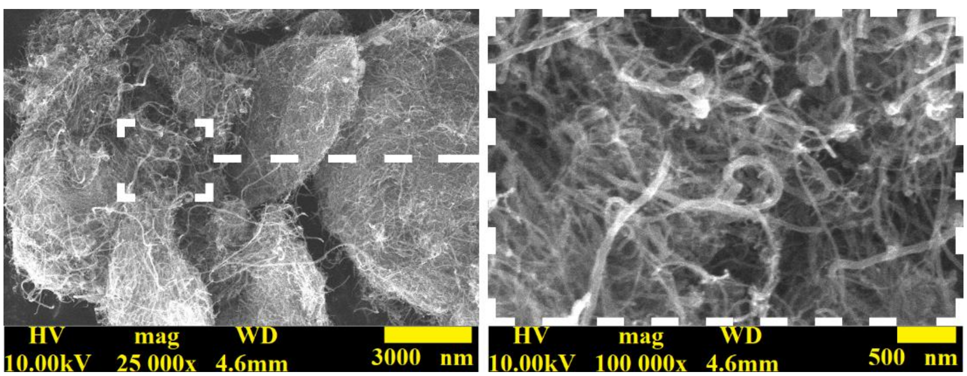


Figure 3. FESEM of Multi-Walled Carbon Nanotube (MWCNT)

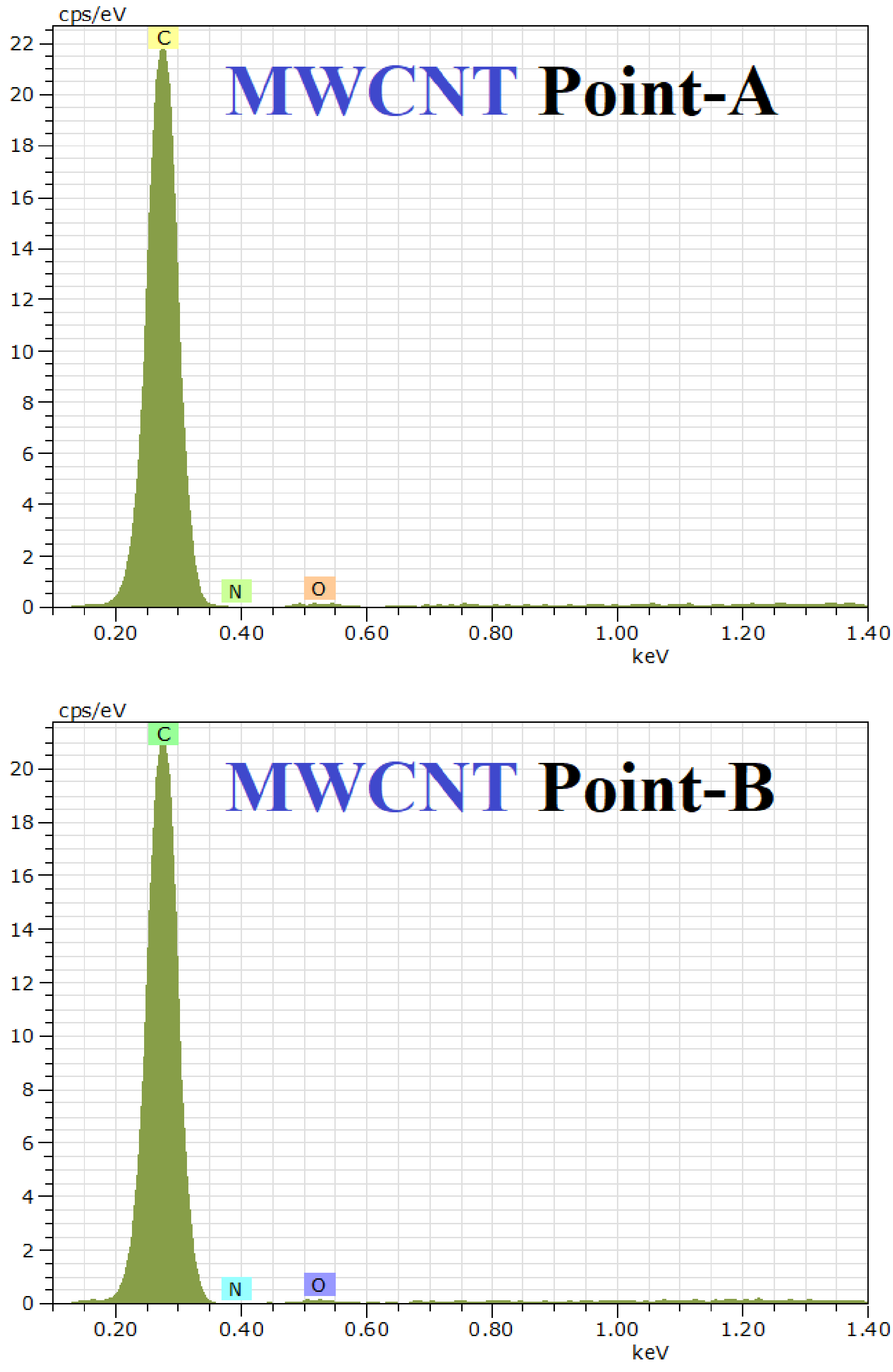


Figure 4. EDX 2-point of Multi-Walled Carbon Nanotube (MWCNT)

Table 2. EDX 2-point data for Multi-Walled Carbon Nanotube (MWCNT)

MWCNT – First Point				
El AN Series	unn. C	norm. C	Atom. C	Error (1 Sigma)
	[wt.%]	[wt.%]	[at.%]	[wt.%]
C	95.63	95.63	96.50	12.65
O	2.63	2.63	1.99	1.37
N	1.74	1.74	1.51	1.68
	100	100	100	
MWCNT – Second Point				
El AN Series	unn. C	norm. C	Atom. C	Error (1 Sigma)
	[wt.%]	[wt.%]	[at.%]	[wt.%]
C	96.49	96.49	97.28	13.09
O	2.87	2.87	2.17	1.56
N	0.64	0.64	0.55	1.09
	100	100	100	

3.2. Nanofluid Preparation

3.2.1. Thermal Conductivity

Validation

KD2-Pro device was calibrated with glycerin and maximum error of 0.47% was calculated, at T=45^{o}C. This error was acceptable based on KD2-Pro manufacturer manual [26]. After that, water (basefluid) thermal conductivity was measured. Then in Figure 5, the data obtained from ASHRAE handbook [27] for thermal conductivity compared with experimental data.

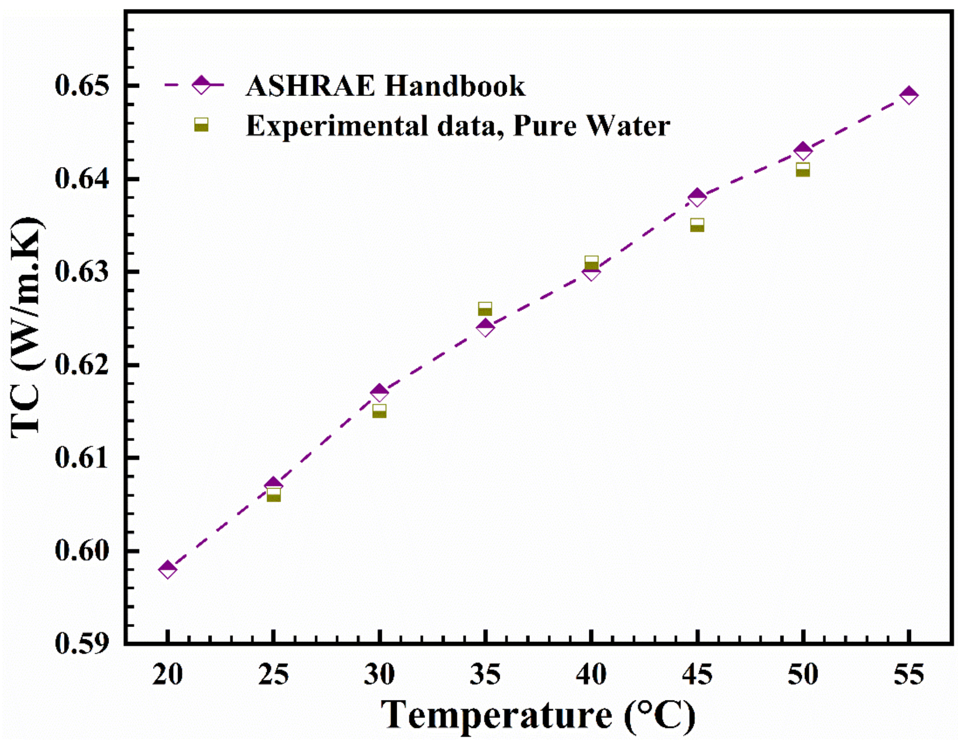


Figure 5. Pure water validation – Experimental results and ASHRAE handbook [27]

Volume Fraction and Temperature Effect

For Fe_3O_4 mono nanofluid (MN)

Thermal conductivity of Fe_3O_4/H_2O MN was measured at volume fraction ranges of 0.2 to 1.0% and temperature ranges of 25 to 50^oC [28]. Temperature and volume fraction factors in thermal conductivity, were considered for this MN [29]. Figure 6 displays MN thermal conductivity by volume fraction in various temperatures while Figure 7 shows thermal conductivity by temperature in different volume fractions. It is obvious that, thermal conductivity was raised with increasement in temperature and volume fraction. Results pointed out that the trend for temperature and volume fraction is not similar [30]. It means that in higher volume fractions, temperature has more effect, For instance:

For MN 0.2 Vol%, Thermal conductivity raised 0.071W/m.k (0.666 to 0.737 from 25^oC to 50^oC);

For MN 1.0 Vol%, Thermal conductivity raised 0.108W/m.k (0.743 to 0.851 from 25^oC to 50^oC);

Which means when volume fraction increased about 5.0 times, Thermal conductivity raised about 1.52 times.

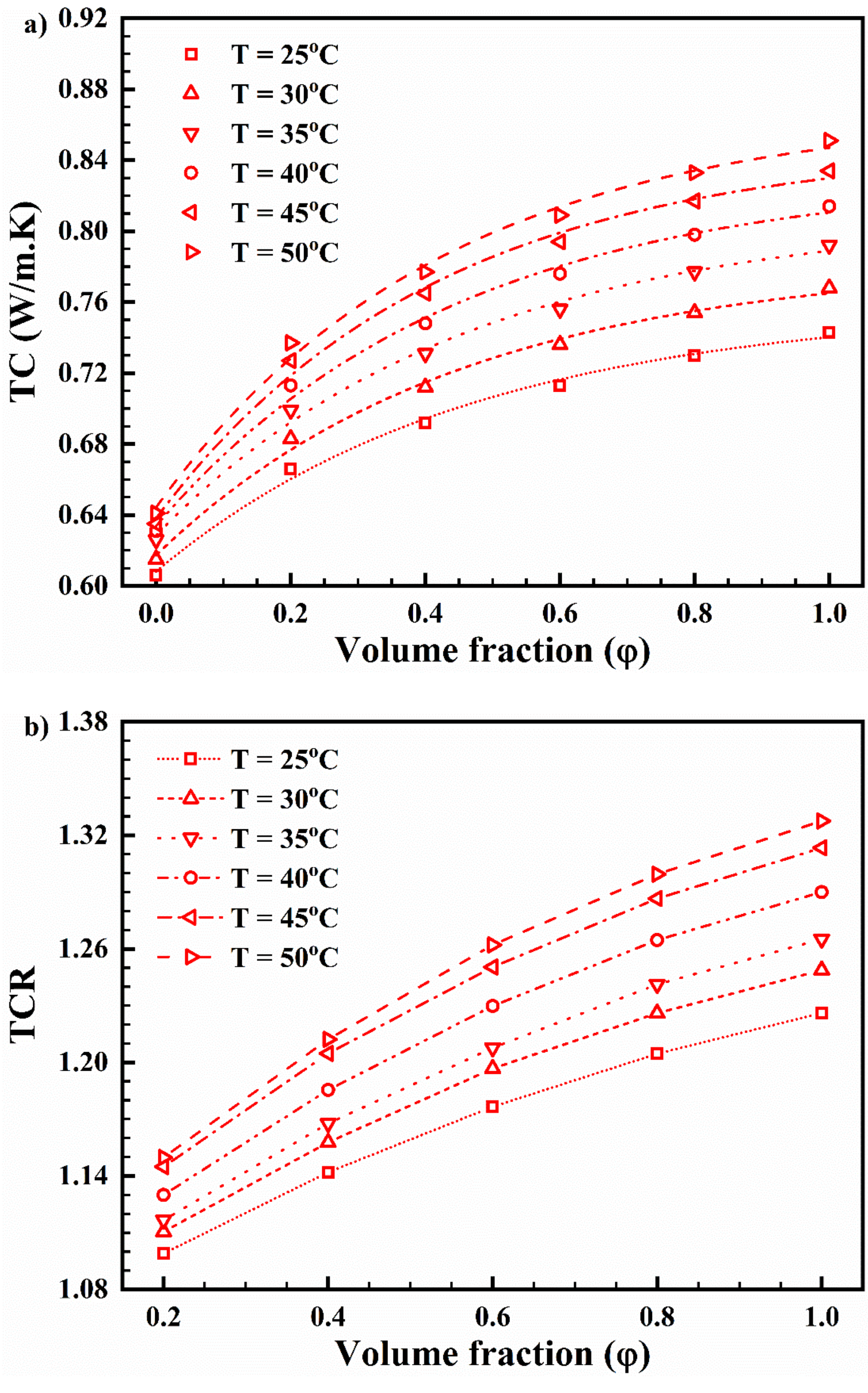


Figure 6. Changes in (a) Thermal conductivity and (b) Thermal conductivity ratio – by volume fraction at different temperatures

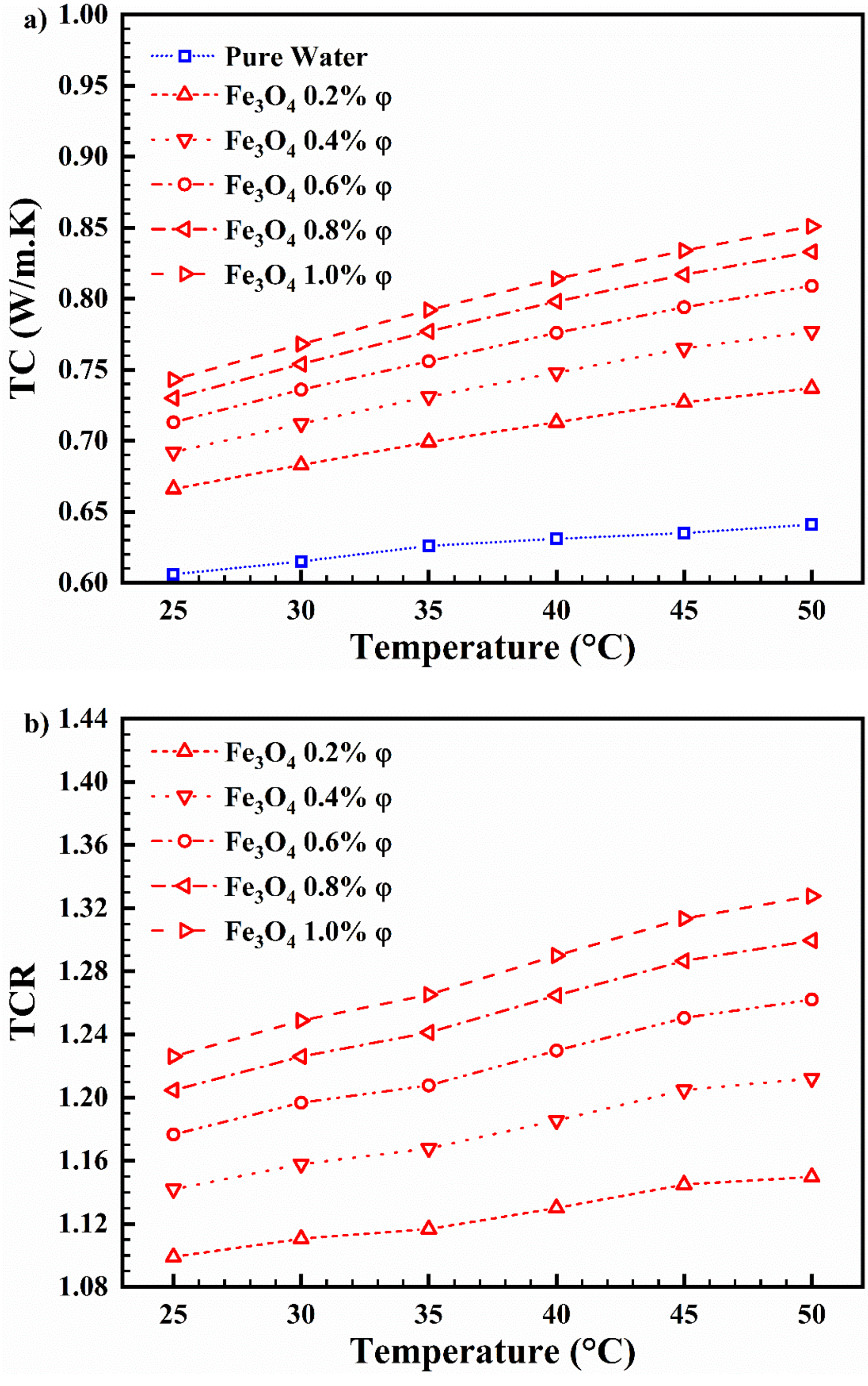


Figure 7. Changes in (a) Thermal conductivity and (b) Thermal conductivity ratio - by temperature at different volume fractions

For CNT/Fe_3O_4 Hybrid nanofluid (HN)

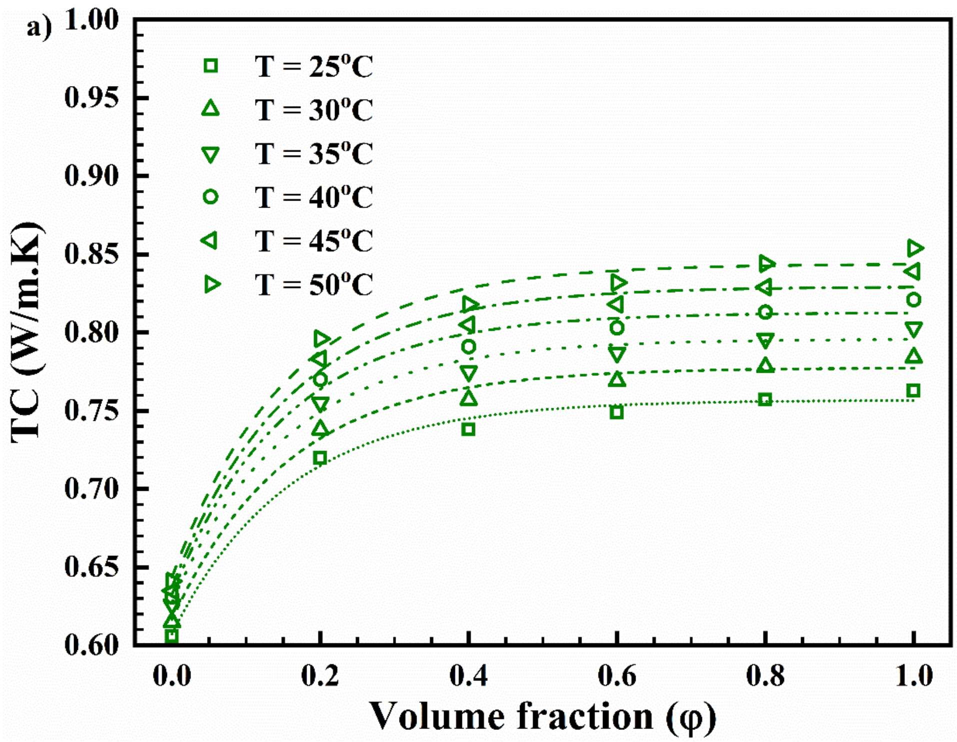
After that by adding MWCNT, thermal conductivity of MWCNT/Fe_3O_4/H_2O HN was measured at volume fraction ranges of 0.2 to 1.0% and temperature ranges of 25 to 50°C. Temperature and volume fraction factors in thermal conductivity, were considered for this HN [31]. Figure 8 displays HN thermal conductivity by volume fraction in various temperatures while Figure 9 shows thermal conductivity by temperature in different volume fractions. It is obvious that, thermal conductivity raised with increasement in temperature and volume fraction [32]. Results pointed out that the trend for temperature and volume fraction is not similar. It means that in higher volume fractions, temperature has more effect, For instance:

For HN 0.2 Vol%, Thermal conductivity raised 0.076W/m.k (0.72 to 0.796 from 25°C to 50°C);

For HN 1.0 Vol%, Thermal conductivity raised 0.091W/m.k (0.763 to 0.854 from 25°C to 50°C);

Which means when volume fraction increased about 5.0 times, Thermal conductivity raised about 1.197 times.

Figure 10, compare thermal conductivity of MN and HN by both volume fraction and temperature in three- dimensional status.



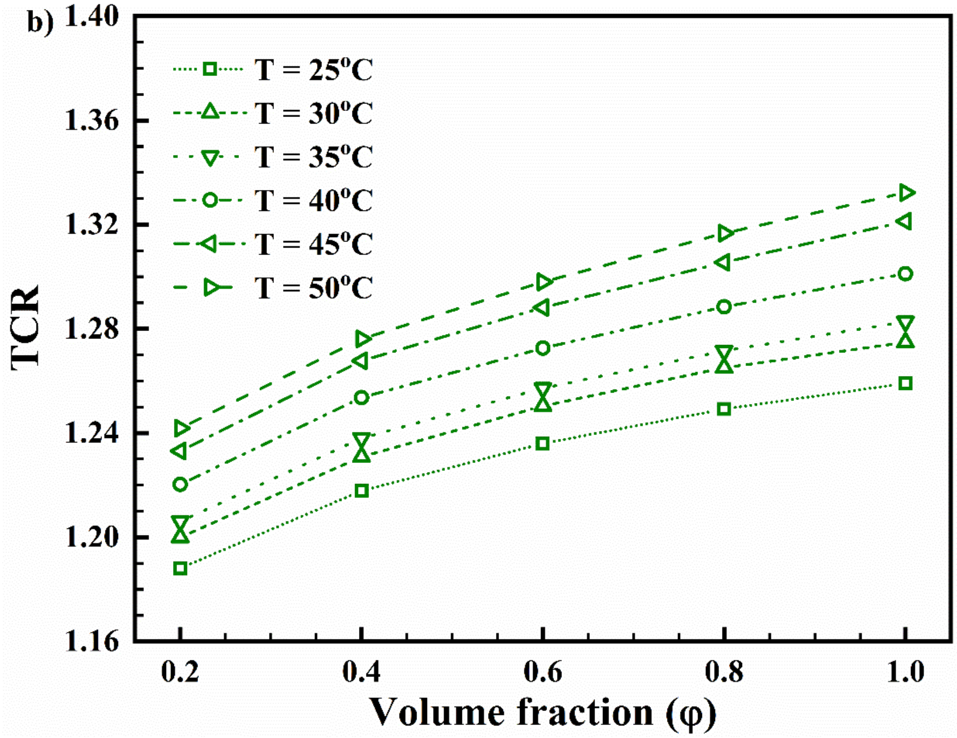
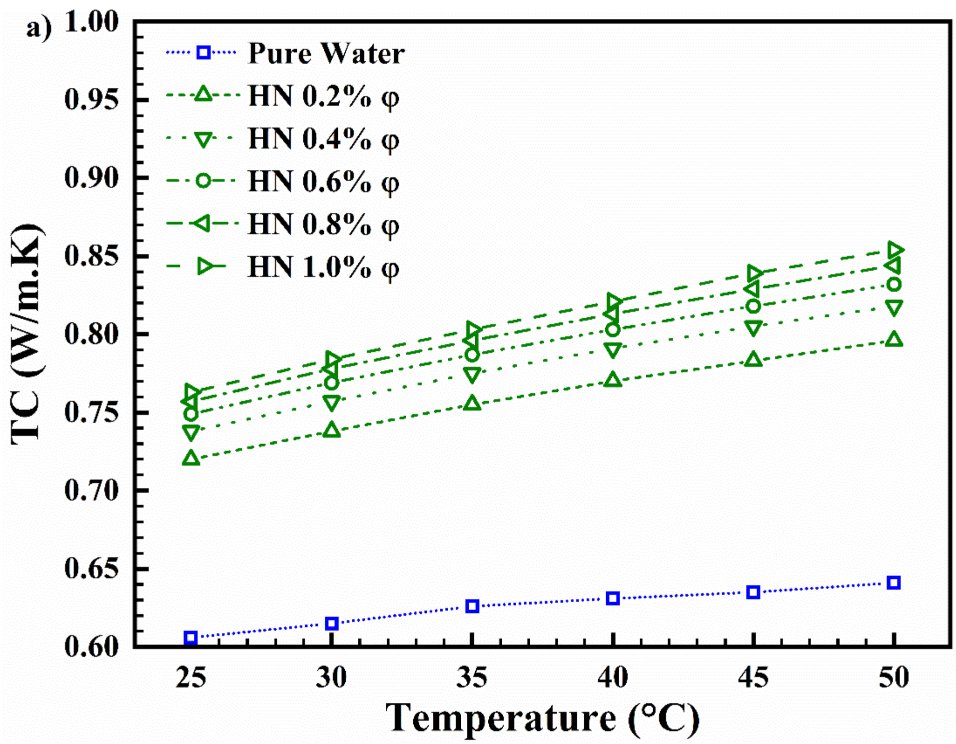


Figure 8. Changes in (a) Thermal conductivity and (b) Thermal conductivity ratio – by volume fraction at different temperatures



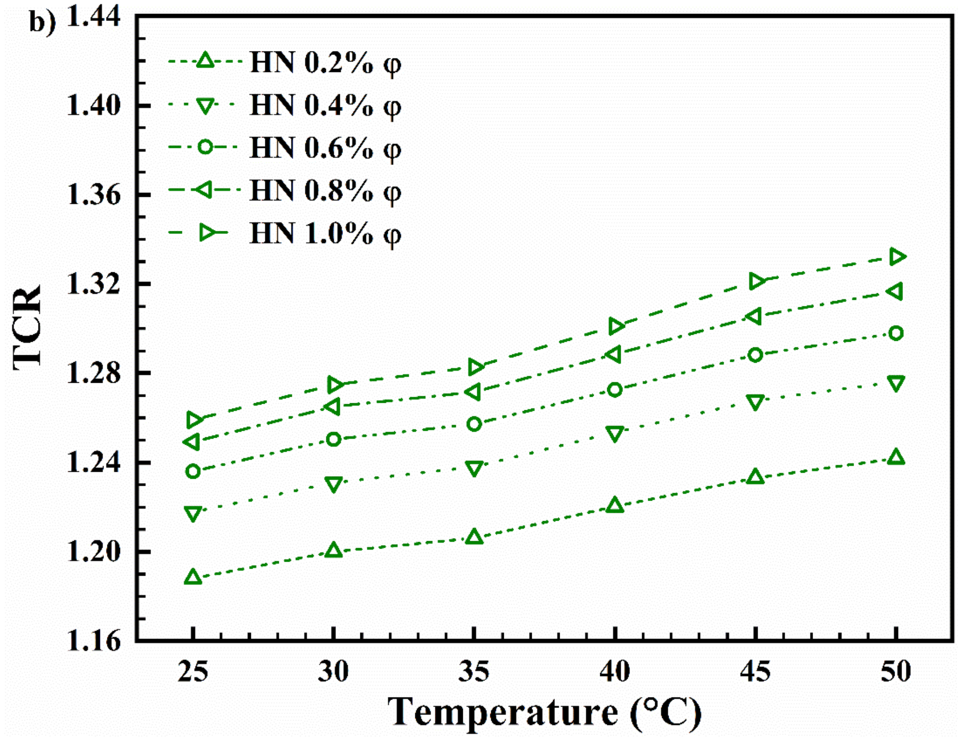


Figure 9. Changes in (a) Thermal conductivity and (b) Thermal conductivity ratio - by temperature at different volume fractions

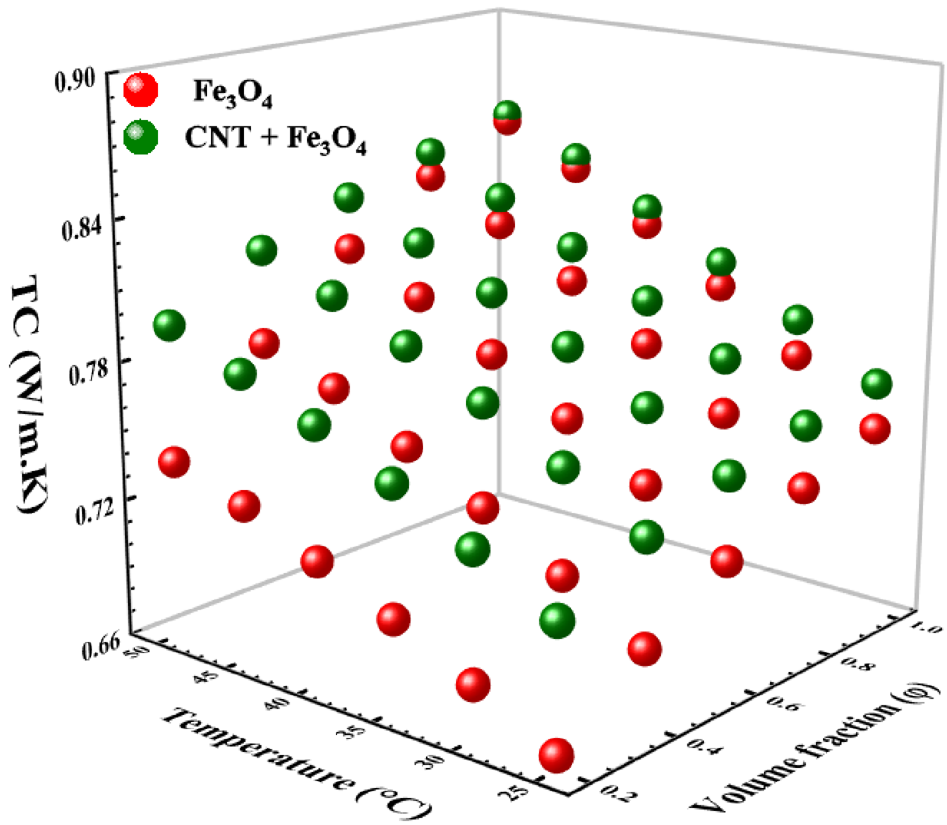


Figure 10. 3D-Thermal conductivity data compare at various nanofluid volume fractions and temperatures

Thermal Conductivity Enhancement

When the temperature increase, interactions between the nanoparticles (NPs) increase too. Brownian motion refers to augmentation in number of suspended NPs by increment in volume fraction, which leads to growth in surface to volume ratio [33].

For Fe_3O_4 mono nanofluid

Figure 11 shows the thermal conductivity enhancement (TCE) of MN. It can be seen that the maximum TCE for Fe_3O_4/Water mono nanofluid is about 32.76% which is at the most volume fraction and temperature. Nanoparticles number and thus, Brownian motion increase at upper temperature and volume fraction. So, TCE percentage of MN at this state, is more than that at lower temperature [34].

For MN 0.2 Vol%, Thermal conductivity enhancement raised 5.08% (9.9 to 14.98 from 25°C to 50°C);

For MN 1.0 Vol%, Thermal conductivity enhancement raised 10.16% (22.6 to 32.76 from 25°C to 50°C);

Which means when volume fraction increased about 0.8%, Thermal conductivity enhancement raised about 5.08% [35].

Thermal conductivity enhancement of various particles in MN noticed at Table 3.

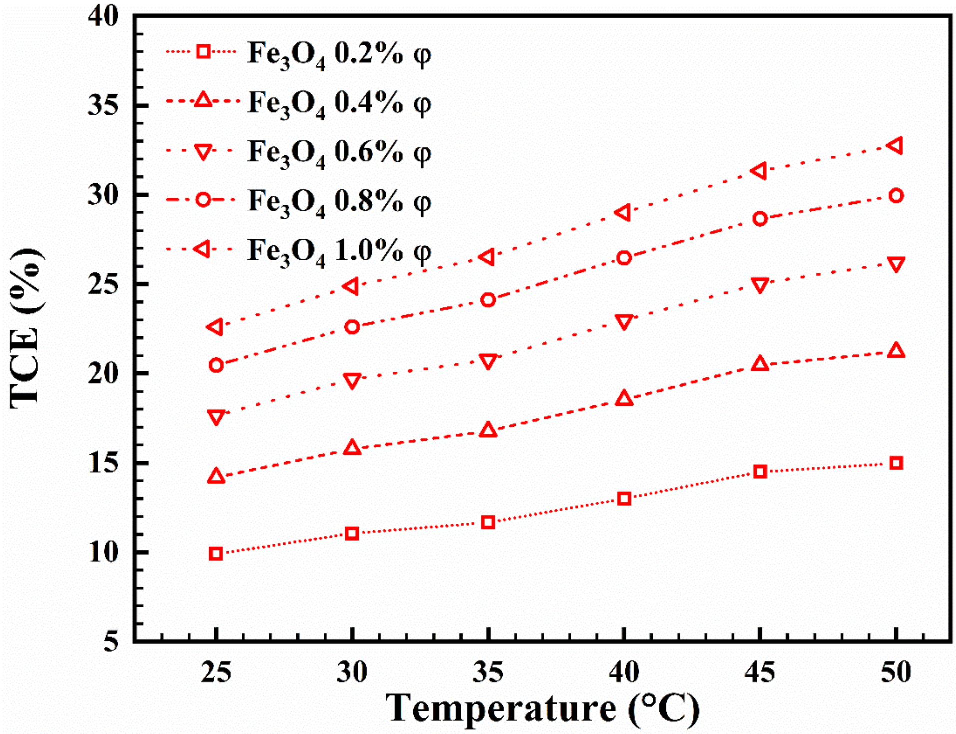


Figure 11. Variations in Thermal conductivity enhancement by nanofluid temperature at different volume fractions

Table 3. Thermal conductivity enhancement of various particles in mono nanofluids

Dispersed particles	Basefluid	Maximum enhancement/%	Ref.
Fe_3O_4	Water	32.76% @ 1.0 vol%	**This Work**
Graphene	Water	10.3% @ 0.02 vol%	[36]
Graphene Oxide	Water	19.9% @ 0.5 wt%	[37]
Graphene	Water	25% @ 0.1 wt%	[38]
Graphene	Water	27% @ 0.2 vol%	[39]
MWCNT	Water	64.0	[40]
MWCNT	Water	38.0	[41]

MWCNT	Water	11.3	[42]
CuO	Water	37	[43]
ZnO	Water	21	[44]
MgO	Water	22	[45]

For CNT/Fe_3O_4 Hybrid nanofluid (HN)

Figure 12, shows the thermal conductivity enhancement (TCE) of HN. It can be seen that the maximum TCE for MWCNT/Fe_3O_4/Water HN is about 33.23% which is at the most volume fraction and temperature [46]. Nanoparticles number and thus, Brownian motion increase at upper temperature and volume fraction. So, TCE percentage of MN at this state, is more than that at lower temperature.

For HN 0.2 Vol%, Thermal conductivity enhancement raised 5.37% (18.81 to 24.18 from 25^{o}C to 50^{o}C);

For HN 1.0 Vol%, Thermal conductivity enhancement raised 7.32% (25.91 to 33.23 from 25^{o}C to 50^{o}C);

Which means when volume fraction increased about 0.8%, Thermal conductivity enhancement raised about 1.95%.

Results indicated that by adding MWCNT to Fe_3O_4, Thermal conductivity enhanced about 0.47% [47].

Thermal conductivity enhancement of various particles in HN noticed at Table 4.

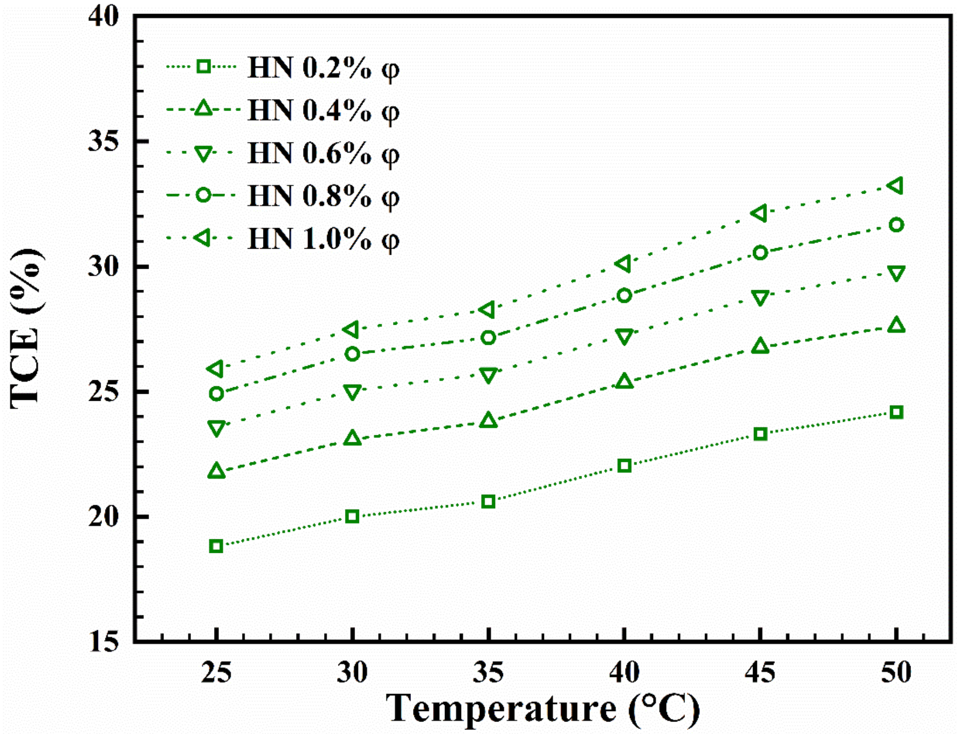


Figure 12. Variations in Thermal conductivity enhancement by nanofluid temperature at different volume fractions

Table 4. Thermal conductivity enhancement of various particles in hybrid nanofluids

Dispersed particles	Basefluid	Maximum enhancement/%	Ref.
Fe3O4-MWCNT	Water	33.23% @ 1.0 vol%	**This Work**
Ag-MWCNT	Water	37.3	[48]
Nano Diamond/Nickle	Water	21	[49]
MWCNT-y Alumina	Water	20.6	[50]
Cu-Al2O3	Water	13.6	[51]–[53]

3.3. Numerical Study

To present a new correlation with 0.9 R-squared, experimental data of thermal conductivity ratio (TCR) in 3-dimentional plotted. Then, Curve-fitting method applied and different types of correlations investigated to find the best fit [54].

Correlation for Fe_3O_4 mono nanofluid

A dependable correlation introduced to calculate TCR of Fe_3O_4/Water mono nanofluid. This correlation can be used to calculate TCR at specific range of volume fraction and temperature. Temperature and volume fraction effect on TCR of mono nanofluid is obvious by this equation. Figure 13 displays the fitted correlation on experimental data.

Proposed correlation is presented in Equation 3.

$$\frac{k_{nf}}{k_{bf}} = 1 + (0.03542 * T^{0.57325} * V^{0.49394}) \quad (03)$$

Where T is Temperature (in ^{o}C) and V is volume fraction (in %) of nanofluid.

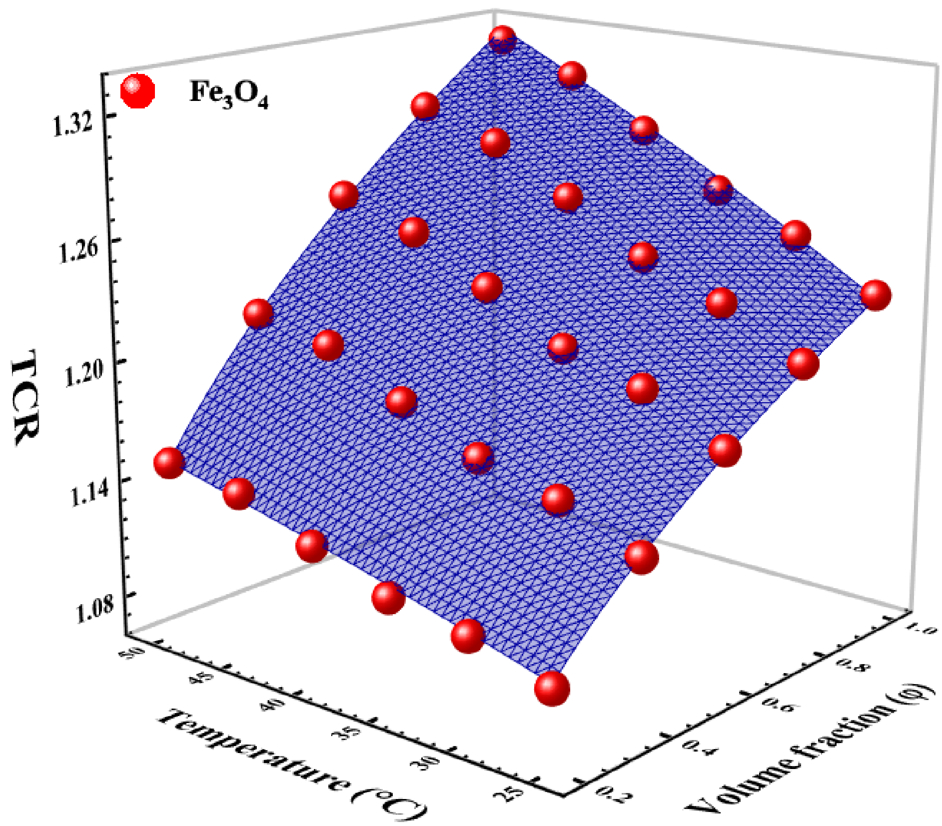
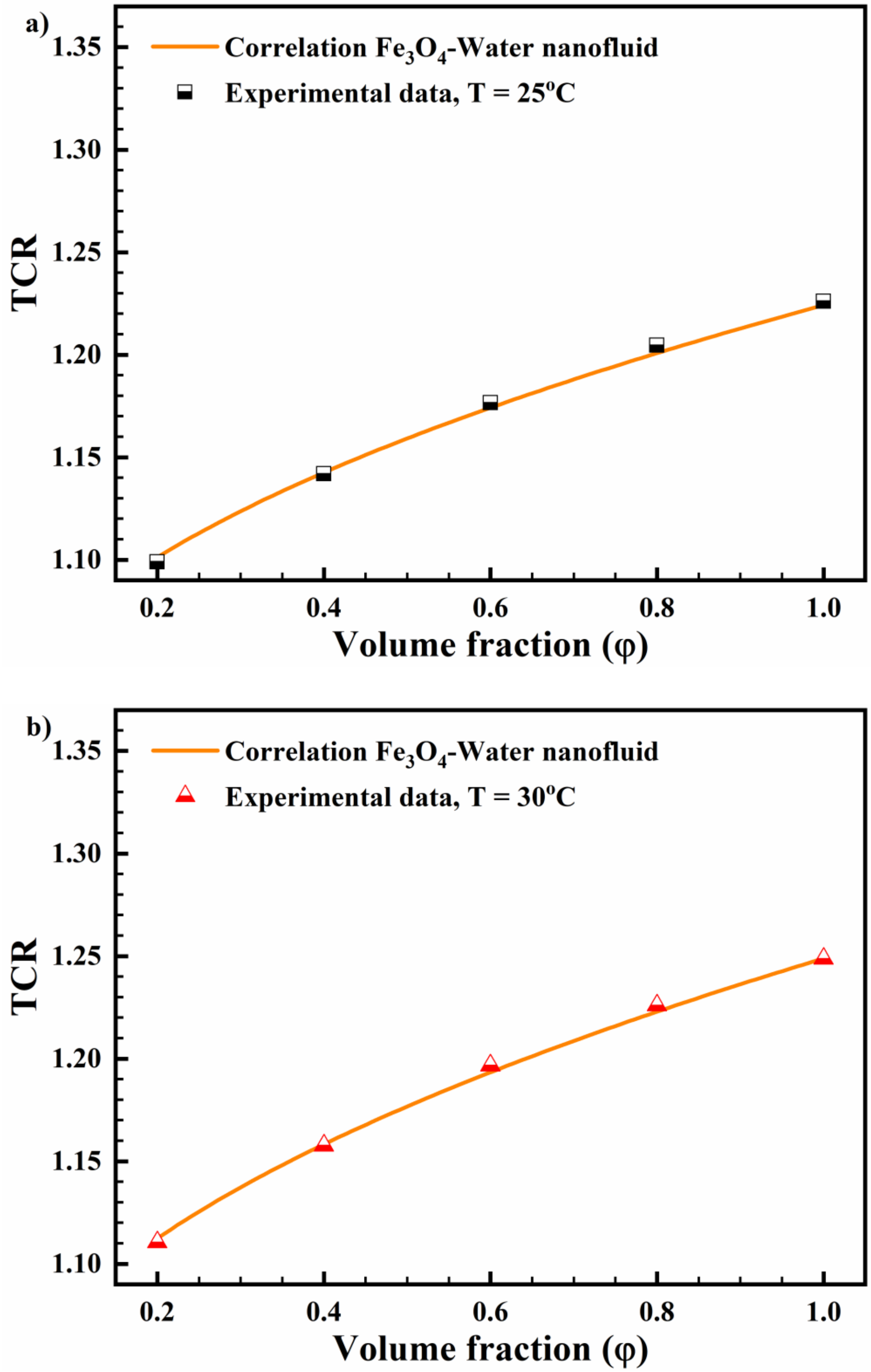
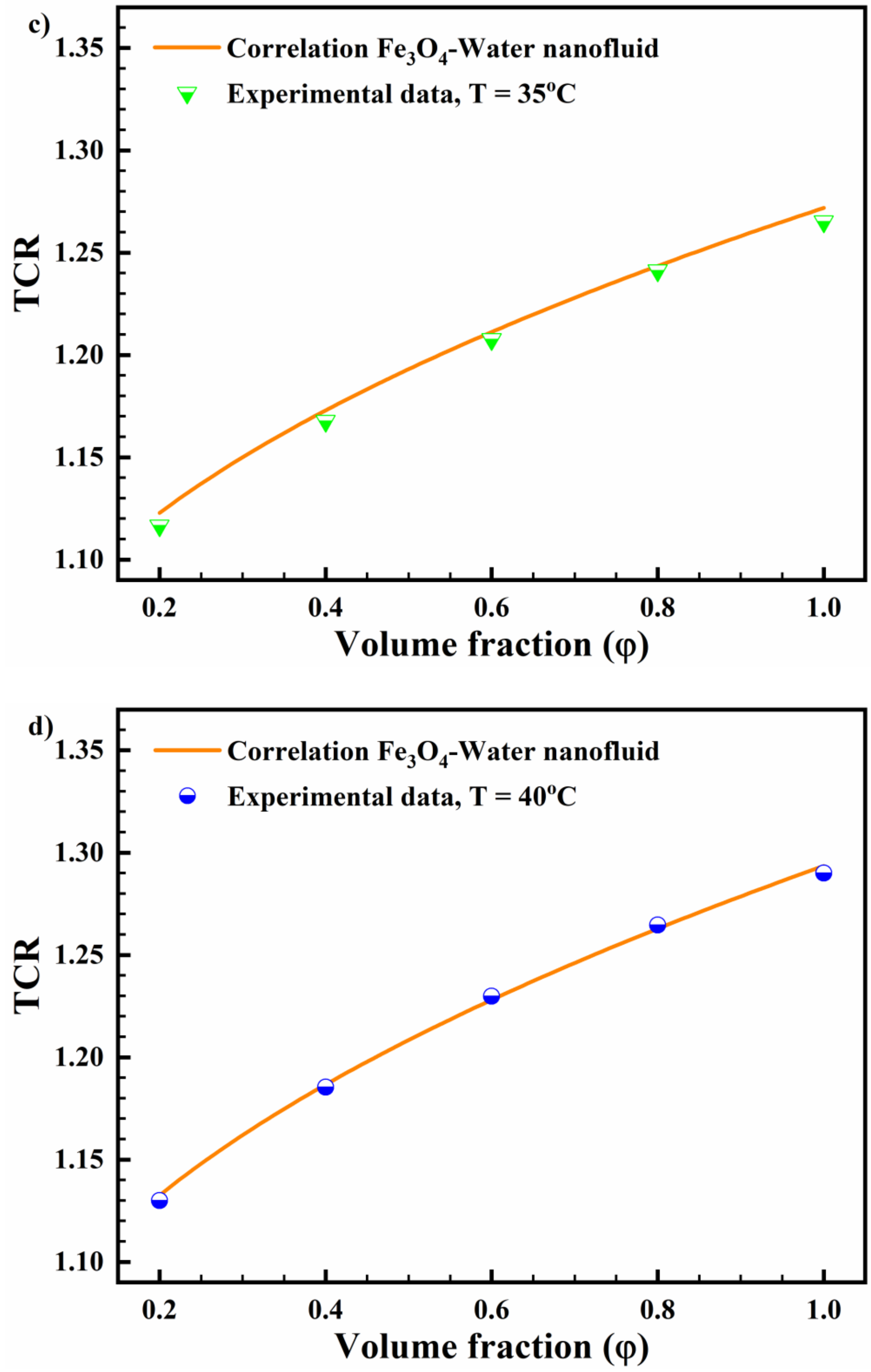
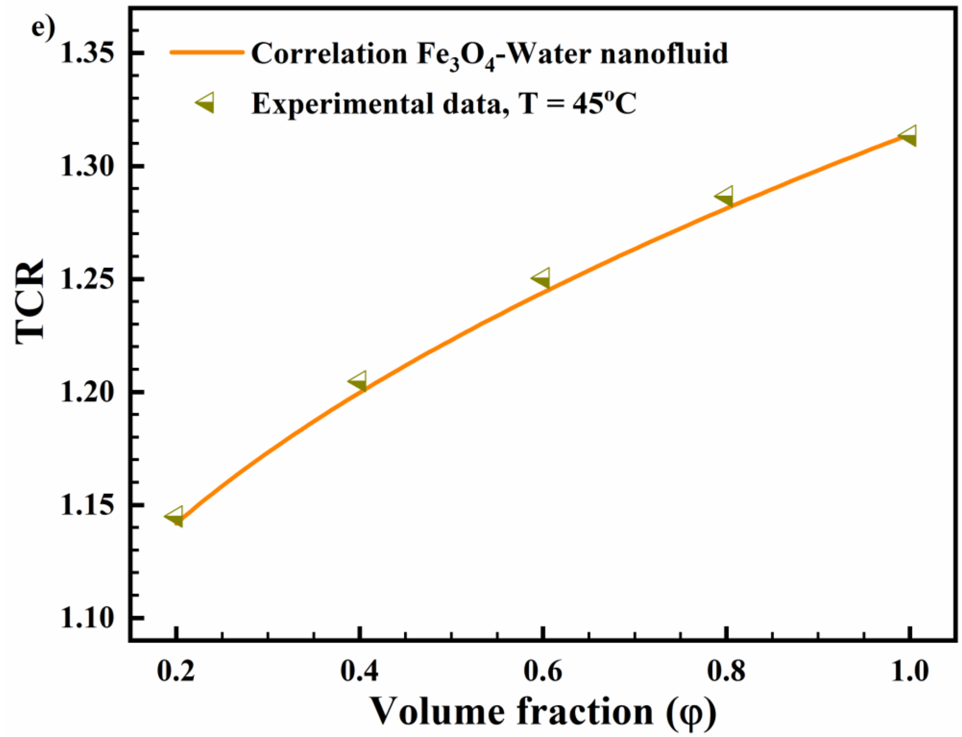


Figure 13. 3D-Applied correlation on thermal conductivity ratio data

Figure 14 displays 6 graphs (for each temperature), to find relation between the experimental results and correlation outputs in all temperatures. This figure, displays TCR by mono nanofluid volume fraction in various temperatures. Also, thermal conductivity correlations were reported for various mono nanofluids, presented in Table 5.




c)
Correlation Fe_3O_4-Water nanofluid
Experimental data, T = 35°C
TCR
1.35
1.30
1.25
1.20
1.15
1.10
0.2
0.4
0.6
0.8
1.0
Volume fraction (φ)
d)
Correlation Fe_3O_4-Water nanofluid
Experimental data, T = 40°C
TCR
1.35
1.30
1.25
1.20
1.15
1.10
0.2
0.4
0.6
0.8
1.0
Volume fraction (φ)



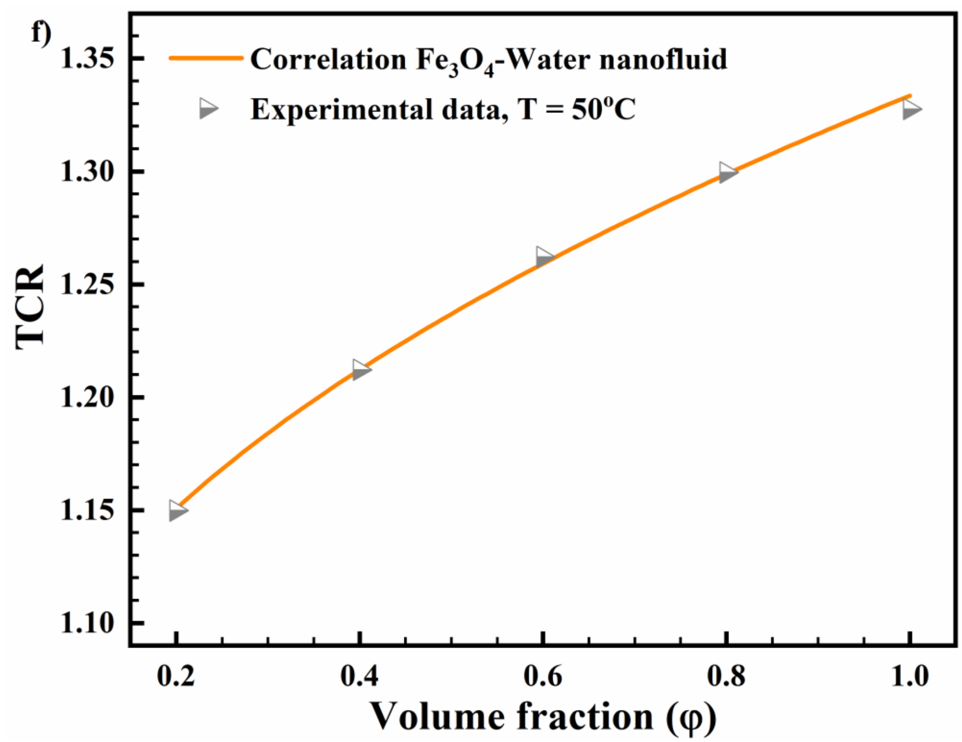


Figure 14. Verify presented method by experimental results regarding to Thermal conductivity ratio by nanofluid volume fraction at different temperatures

Table 5. Thermal conductivity correlations for various mono nanofluids

Nanofluid	**Correlation**	**Ref.**
Al_2O_3/Water	$\frac{k_{nf} - k_{bf}}{k_{bf}} = 0.764481464u + 0.018688867T - 0.462147175$	[55]
CuO/Water	$\frac{k_{nf} - k_{bf}}{k_{bf}} = 3.761088u + 0.017924T - 0.30734$	[55]
ZnO/EG-Water	$\frac{k_{nf} - k_{bf}}{k_{bf}} = (\frac{1.8454 - 5.2302\phi^{0.29216}}{T^{0.29216} - 3.457})*100$	[56]
MWCNT/EG-Water	$\frac{k_{nf}}{k_{bf}} = 0.9212 + 1.0975\phi^{0.319}\exp(0.01286T)$	[57]

Deviation margin, which can confirm the accuracy of presented correlation, is calculated in equation 4.

$$\text{Deviation margin}\,(\%) = \frac{k_{Exp} - k_{Pred}}{k_{Exp}} \times 100 \qquad (04)$$

Where $_{\text{Exp}}$ is experimental and $_{\text{Pred}}$ is predicted values.

Figure 15 shows an acceptable agreement between experimental data and correlation outputs. Maximum positive and negative deviation margins for this correlation are 0.6007% and 0.5221% respectively. Thus, the total deviation margin gap is about 1.1228%.

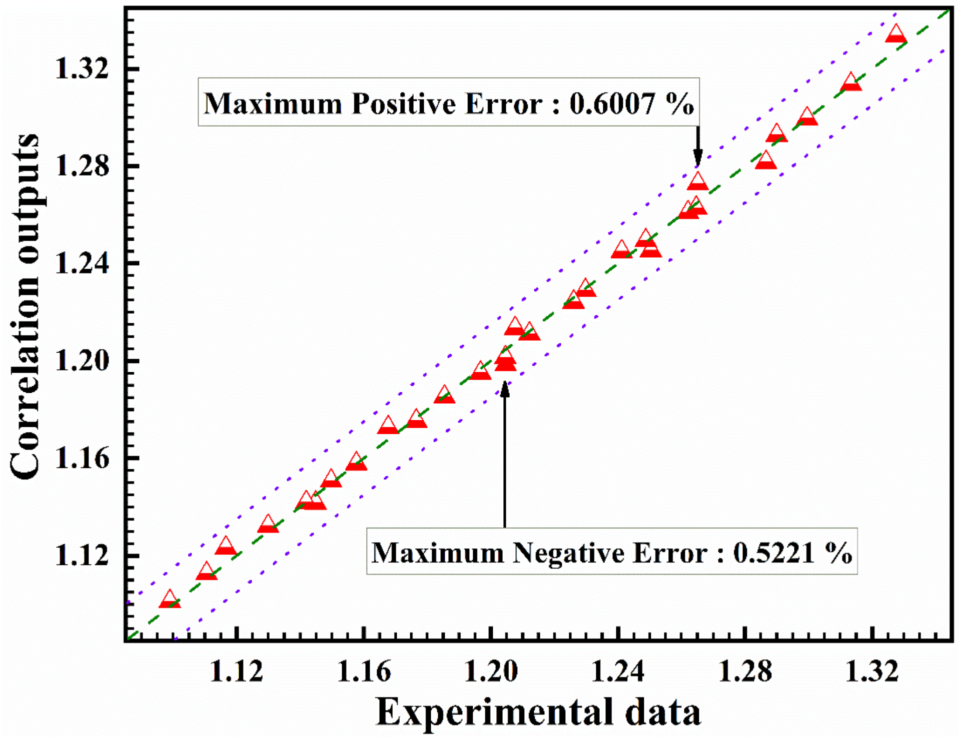


Figure 15. Verify presented method by experimental results

Figure 16 displays margin of deviation by mono nanofluid's volume fraction and also shows comparison between errors of correlation outputs for each temperature. The margin of deviation in this figure calculated by presented correlation. It can be seen that accuracy matter in thermal conductivity predicting [58].

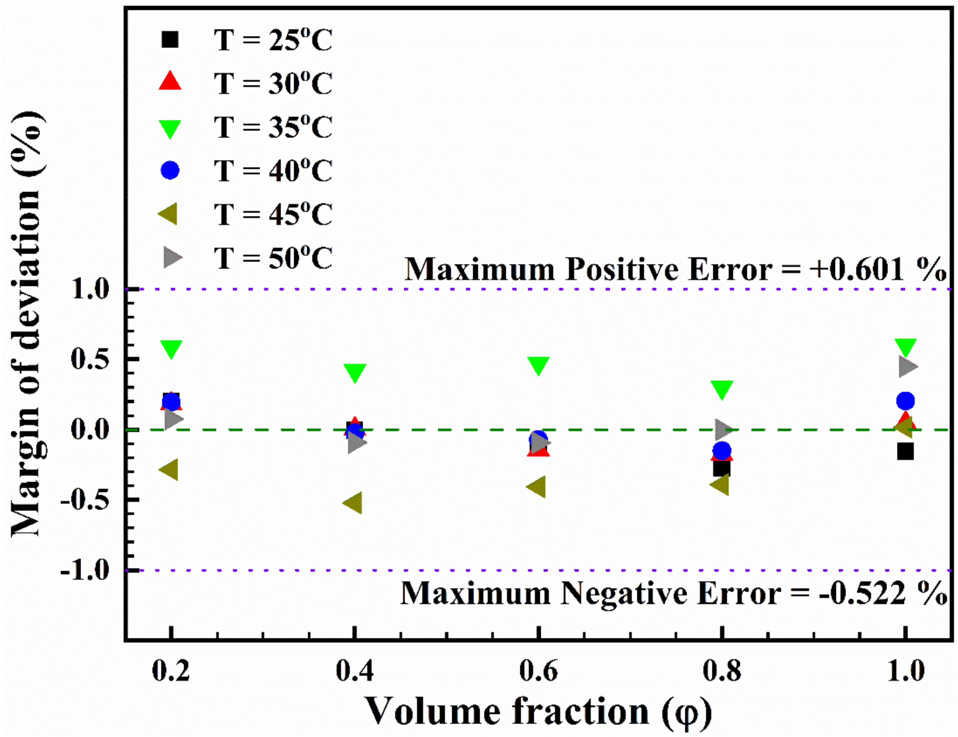


Figure 16. Margin of deviation by nanofluid volume fraction

Correlation for CNT/Fe_3O_4 Hybrid nanofluid

A dependable correlation introduced to calculate TCR of MWCNT/Fe_3O_4/Water hybrid nanofluid. This correlation can be used to calculate TCR at specific range of volume fraction and temperature. Temperature and volume fraction effect on TCR of hybrid nanofluid is obvious by this equation. Figure 17 displays the fitted correlation on experimental data.

Proposed correlation is presented in Equation 5.

$$\frac{k_{nf}}{k_{bf}} = 1 + (0.08134 * T^{0.35753} * V^{0.19655}) \qquad (05)$$

Where T is Temperature (in °C) and V is volume fraction (in %) of nanofluid.

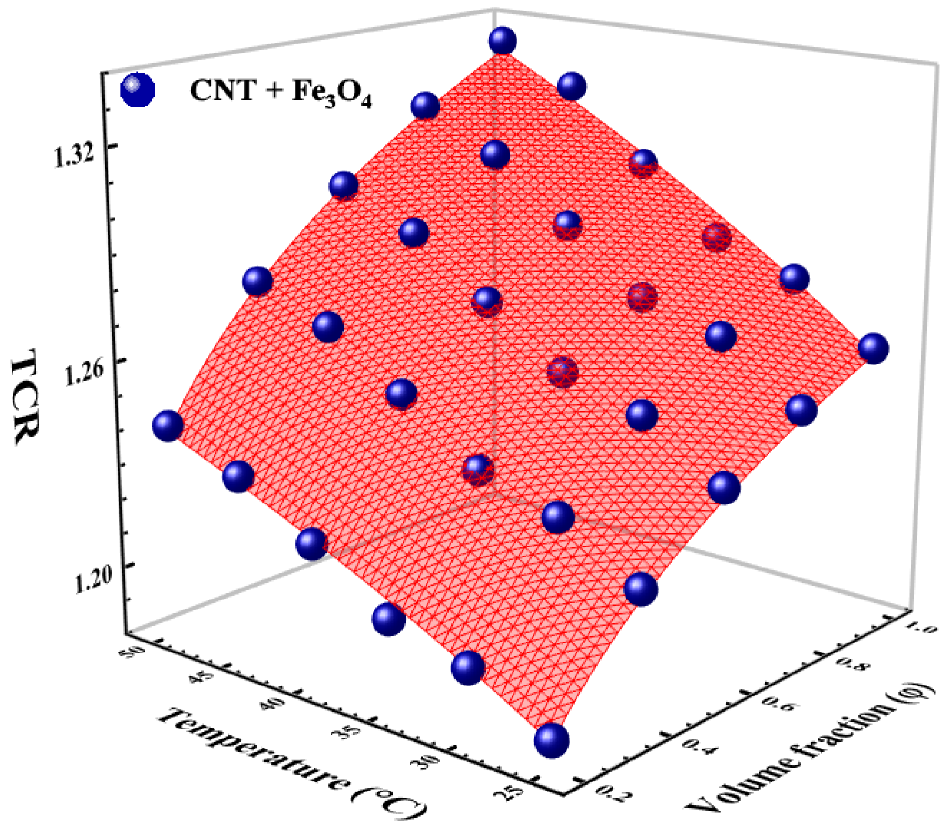
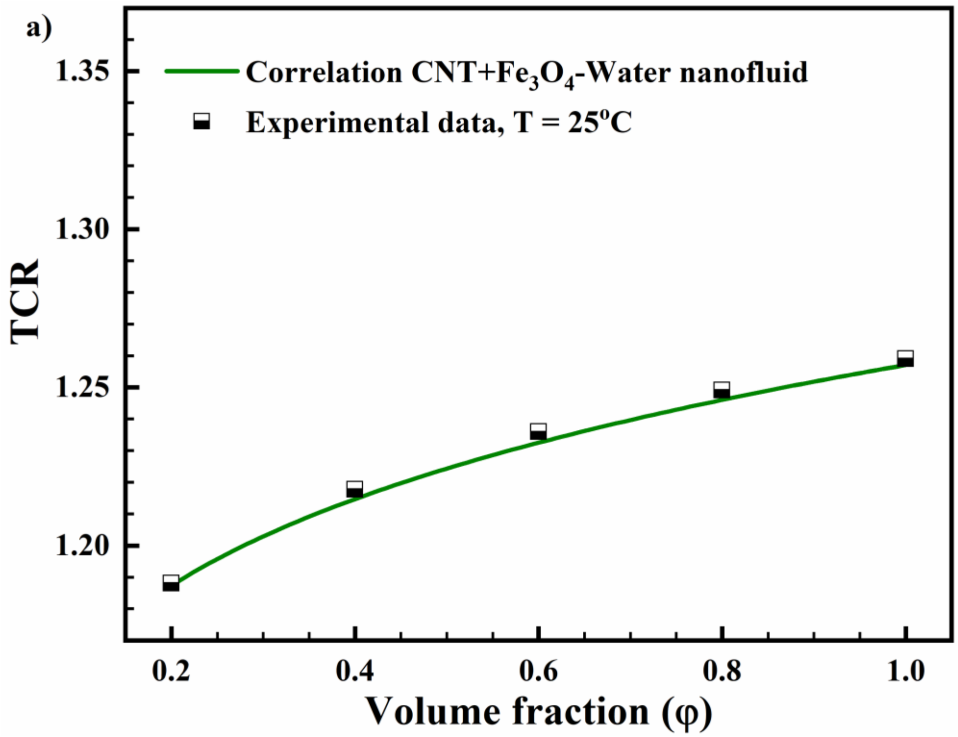
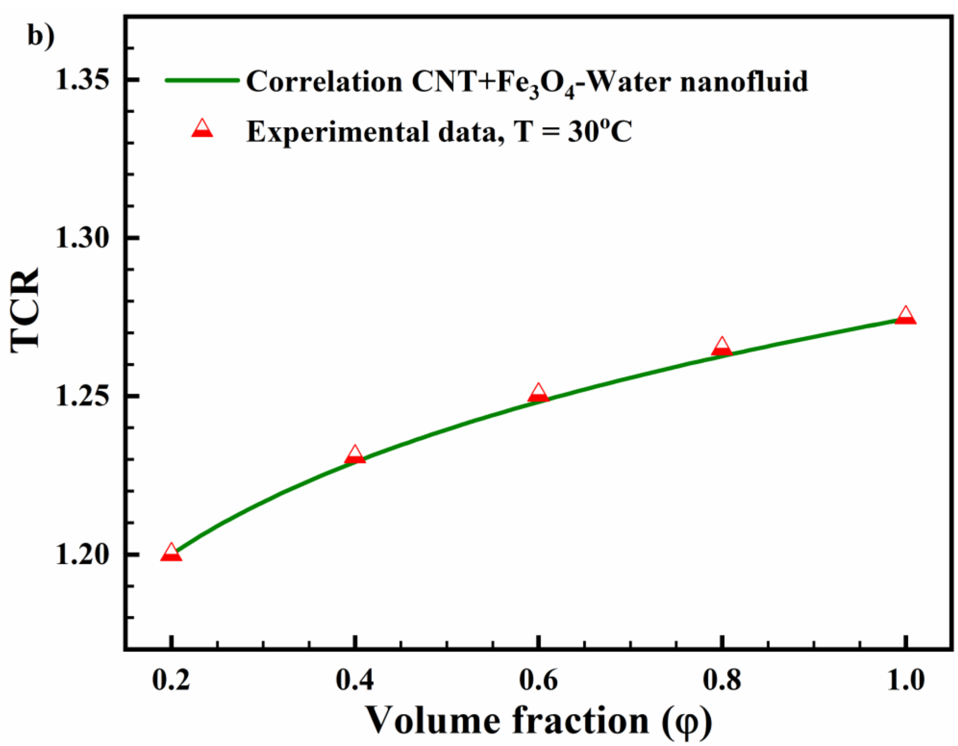
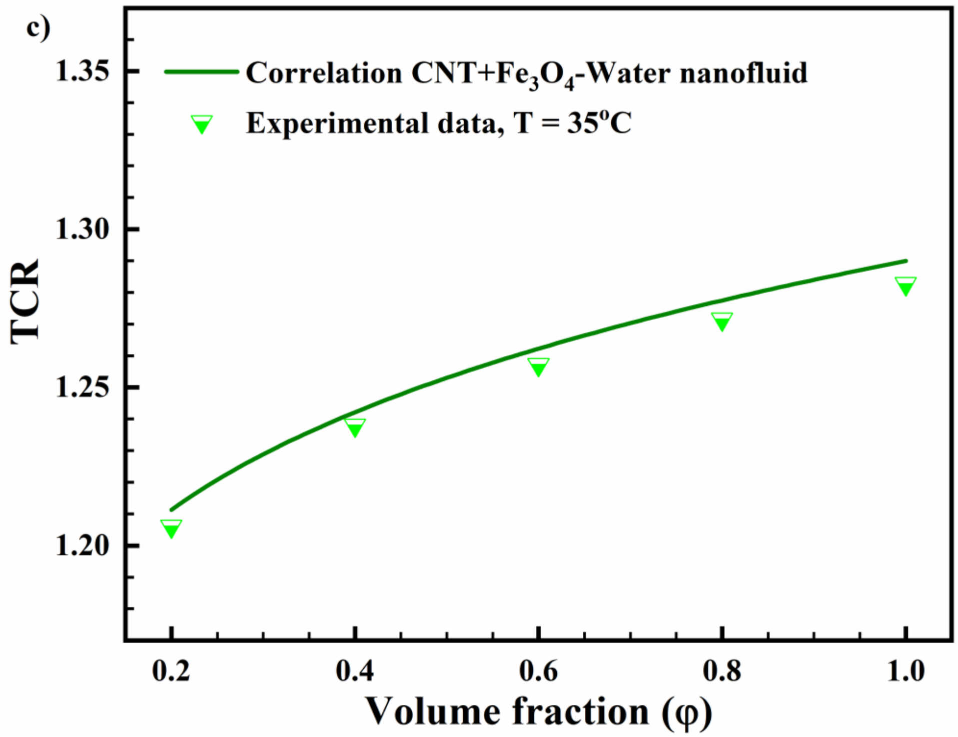


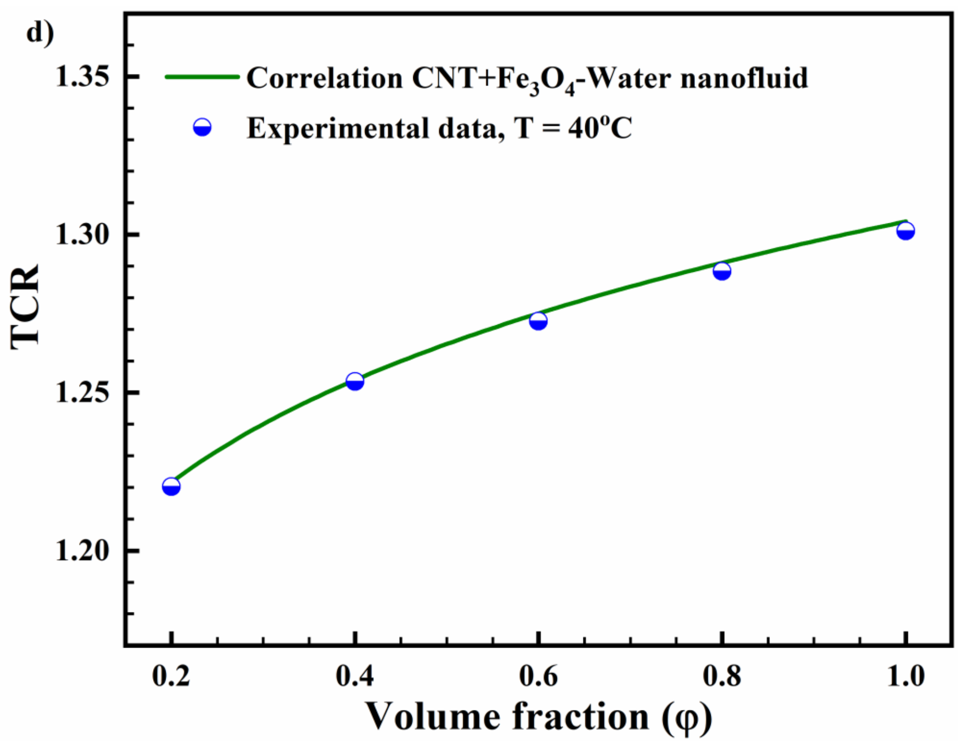
Figure 17. 3D-Applied correlation on thermal conductivity ratio data

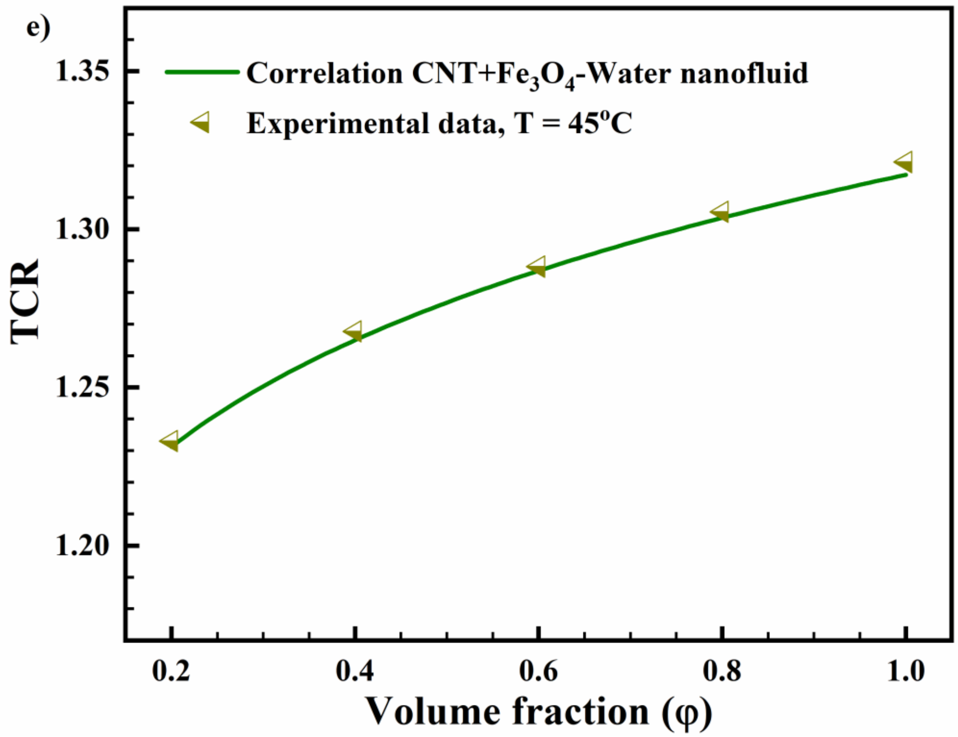
Figure 18 displays 6 graphs (for each temperature), to find the relation between the experimental results and correlation outputs in all temperatures. This figure, displays TCR by hybrid nanofluid volume fraction in various temperatures [59]. Also, thermal conductivity correlations were reported for various hybrid nanofluids, presented in Table 6.


a)
Correlation CNT+Fe3O4-Water nanofluid
Experimental data, T = 25oC
TCR
1.35
1.30
1.25
1.20
0.2
0.4
0.6
0.8
1.0
Volume fraction (φ)


b)
Correlation CNT+Fe3O4-Water nanofluid
Experimental data, T = 30oC
TCR
1.35
1.30
1.25
1.20
0.2
0.4
0.6
0.8
1.0
Volume fraction (φ)


c)
Correlation CNT+Fe3O4-Water nanofluid
Experimental data, T = 35oC
TCR
1.35
1.30
1.25
1.20
0.2
0.4
0.6
0.8
1.0
Volume fraction (φ)


d)
Correlation CNT+Fe3O4-Water nanofluid
Experimental data, T = 40oC
TCR
1.35
1.30
1.25
1.20
0.2
0.4
0.6
0.8
1.0
Volume fraction (φ)



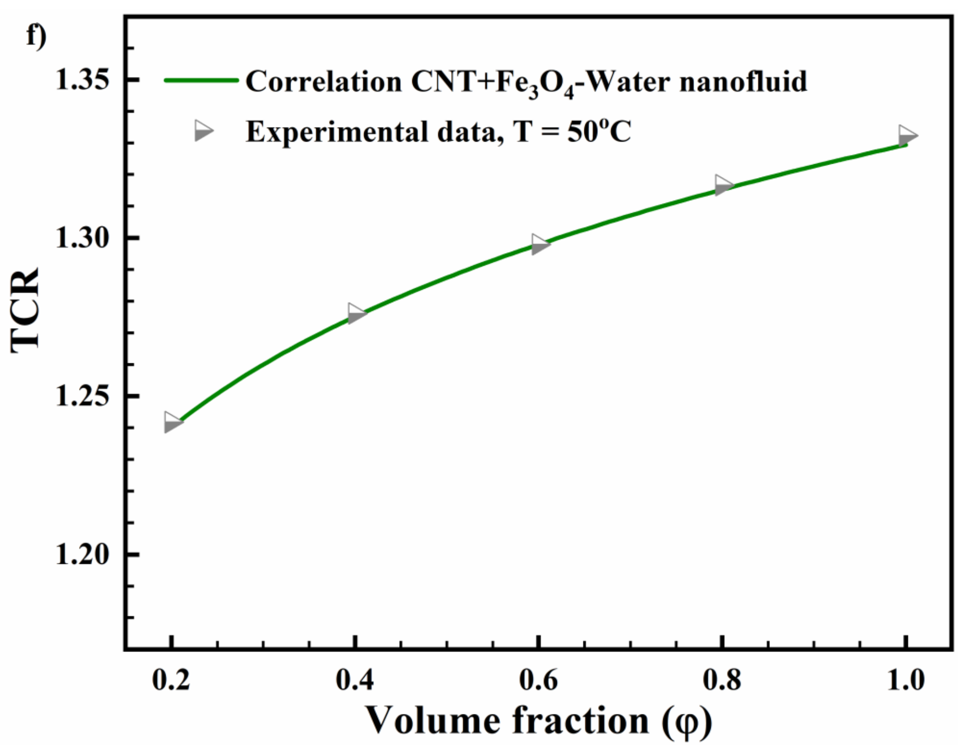


Figure 18. Verify presented method by experimental results regarding to Thermal conductivity ratio by nanofluid volume fraction at different temperatures

Table 6. Thermal conductivity correlations for various hybrid nanofluids

Nanofluid	Correlation	Ref.
MWCNT-TiO_2/EG-Water	$\frac{k_{nf}}{k_{bf}} = 0.006*(\phi^{1.099})*T^{1.051} + 1.014$	[60]

Deviation margin, which can confirm the accuracy of presented correlation, is calculated in equation 6.

$$\text{Deviation margin}\,(\%) = \frac{k_{Exp-HN} - k_{Pred-HN}}{k_{Exp-HN}} \times 100 \quad (06)$$

Where $_{Exp\text{-}HN}$ is hybrid nanofluid's experimental and $_{Pred\text{-}HN}$ is hybrid nanofluid's predicted values [61].

Figure 19 shows an acceptable agreement between experimental data and correlation outputs. Maximum positive and negative deviation margins for this correlation are 0.6096% and 0.3247% respectively. Thus, the total deviation margin gap is about 0.9343%.

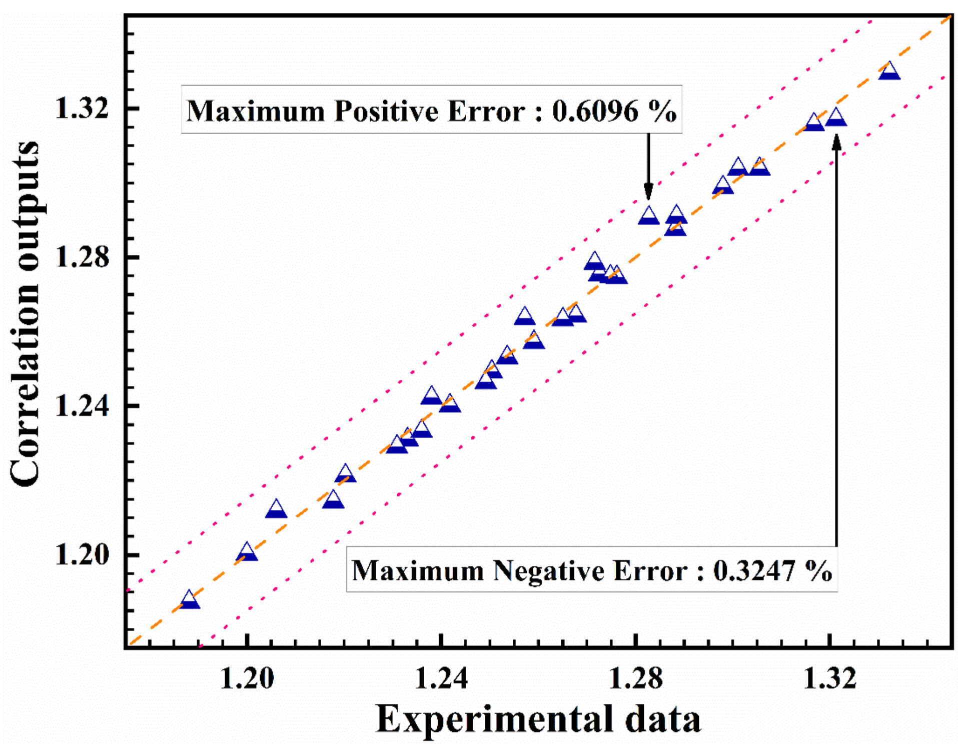


Figure 19. Verify presented method by experimental results

Figure 20 displays margin of deviation by hybrid nanofluid's volume fraction and also shows comparison between errors of correlation outputs for each temperature. The margin of deviation in this figure was calculated by presented correlation. It can be seen that accuracy matter in thermal conductivity predicting.

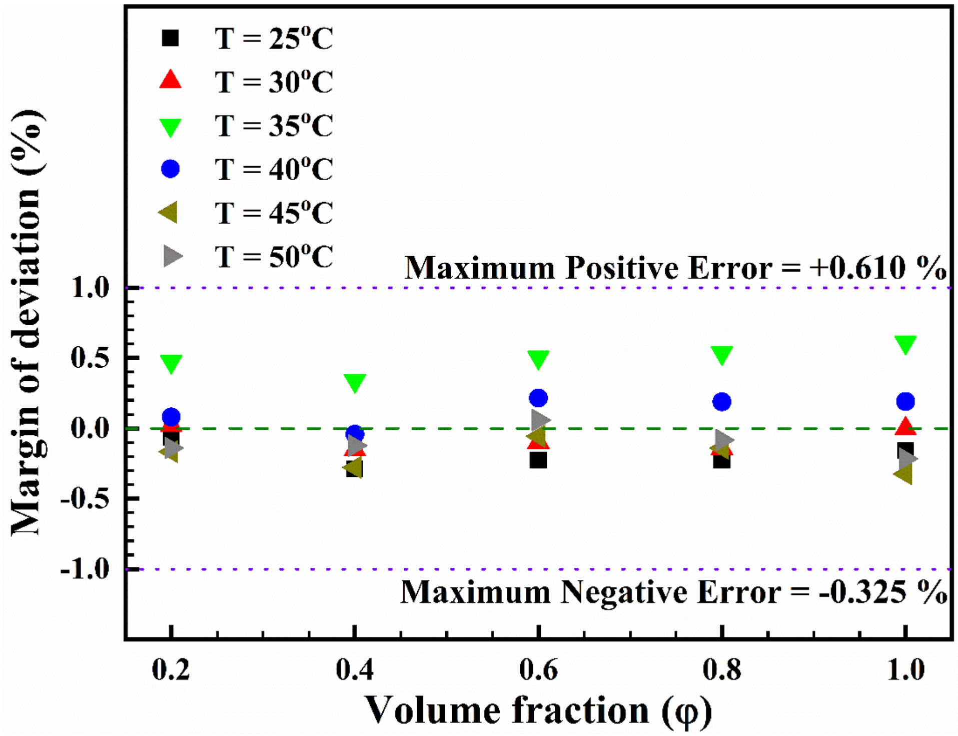


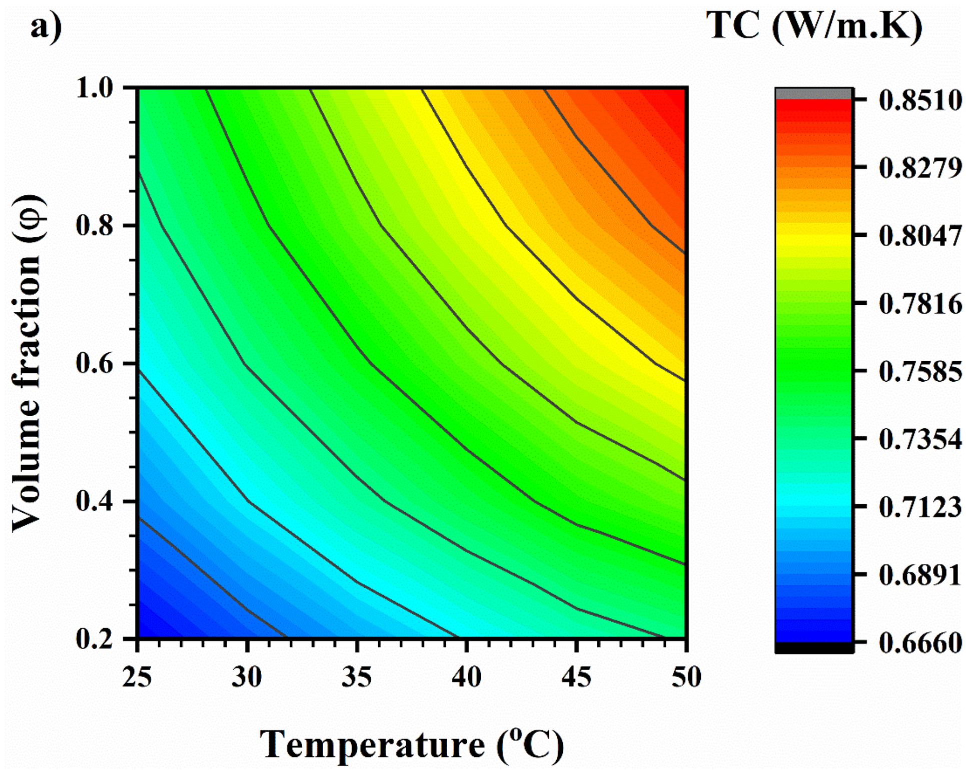
Figure 20. Margin of deviation by nanofluid volume fraction

Artificial Neural Network

In this paper, the experimental data was measured. After that, an algorithm was proposed to determine the best neuron number in the hidden layer. By using curve-fitting method, the ANN outputs were compared to experimental results [62]. Thermal conductivity was predicted by ANN based on the volume fraction and temperature. 100 Data points (divided into test, validation and train categories) were set. 15 data considered as test, 15 data for validation and 70 data points were considered as train data. While Train data was used in training the ANN, validation data monitors and modifies the training process. Also, the test data points were used to evaluate the accuracy and reliability of ANN. To model ANN, thermal conductivity considered as output and nanoparticle temperature-volume fractions considered as input. Thus, Levenberg-Marquardt backpropagation algorithm is used and a general two-layer, feed-forward network with 20 sigmoid hidden neurons and linear output neurons trained [63].

For Fe_3O_4 mono nanofluid

Fe_3O_4/Water mono nanofluid's thermal properties can be predicted by an Artificial Neural Network (ANN) model. Figure 21 shows a color fill contour for trained data and experimental data. With 30 experimental data, lines in Figure 21.a are wavy, however, with 1000 trained data (estimated from ANN model), lines are smooth in Figure 21.b.



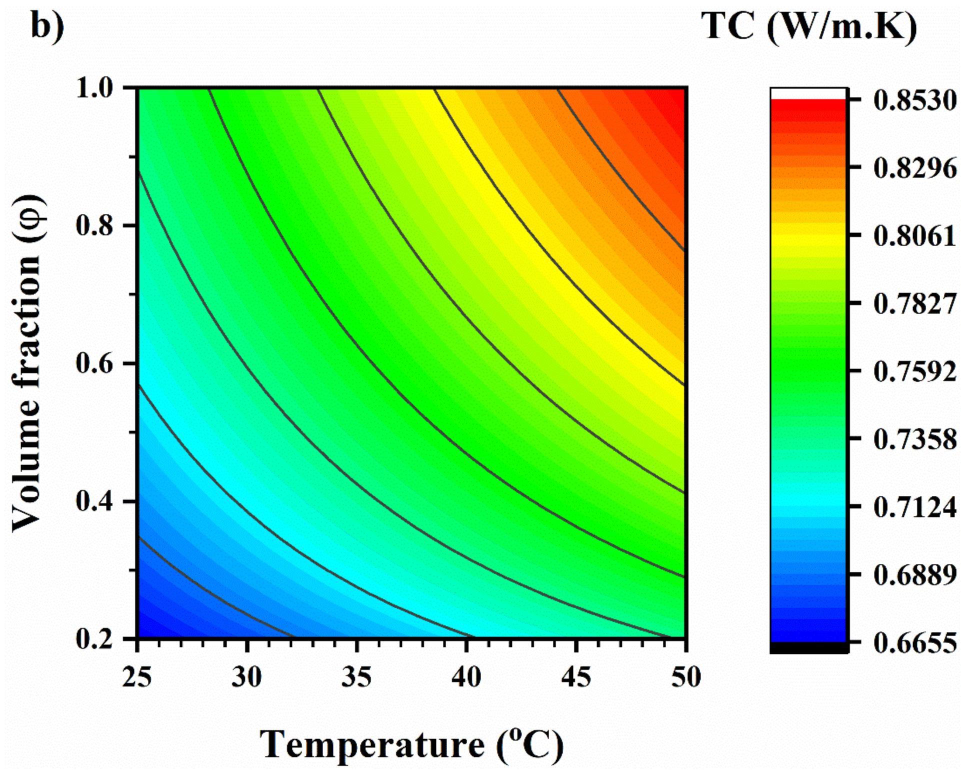


Figure 21. Contour – Color fill of (a) main data and (b) trained data

Figure 22 shows an acceptable agreement between experimental data and trained model outputs. Maximum positive and negative deviation margins for this model are 0.5862% and 0.3987% which are 0.0145% and 0.1234% less than maximum deviation margin of presented correlation. Also, the total deviation margin gap is about 0.9849% which is 0.1379% less than correlation [64].

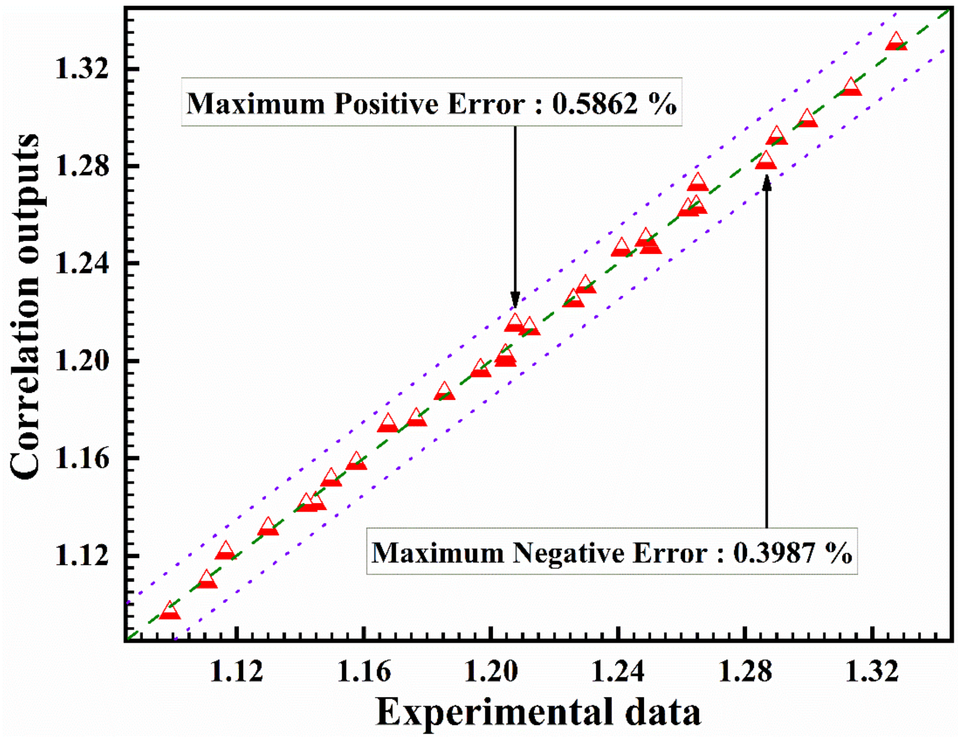


Figure 22. Verify trained data by experimental results

For CNT/Fe_3O_4 Hybrid nanofluid

MWCNT/Fe_3O_4/Water mono nanofluid's thermal properties can be predicted by an Artificial Neural Network (ANN) model [65]. Figure 23 shows a color fill contour for the trained data and experimental data. With 30 experimental data, lines in Figure 23.a are wavy, however, with 1000 trained data (estimated from ANN model), lines are smooth in Figure 23.b.

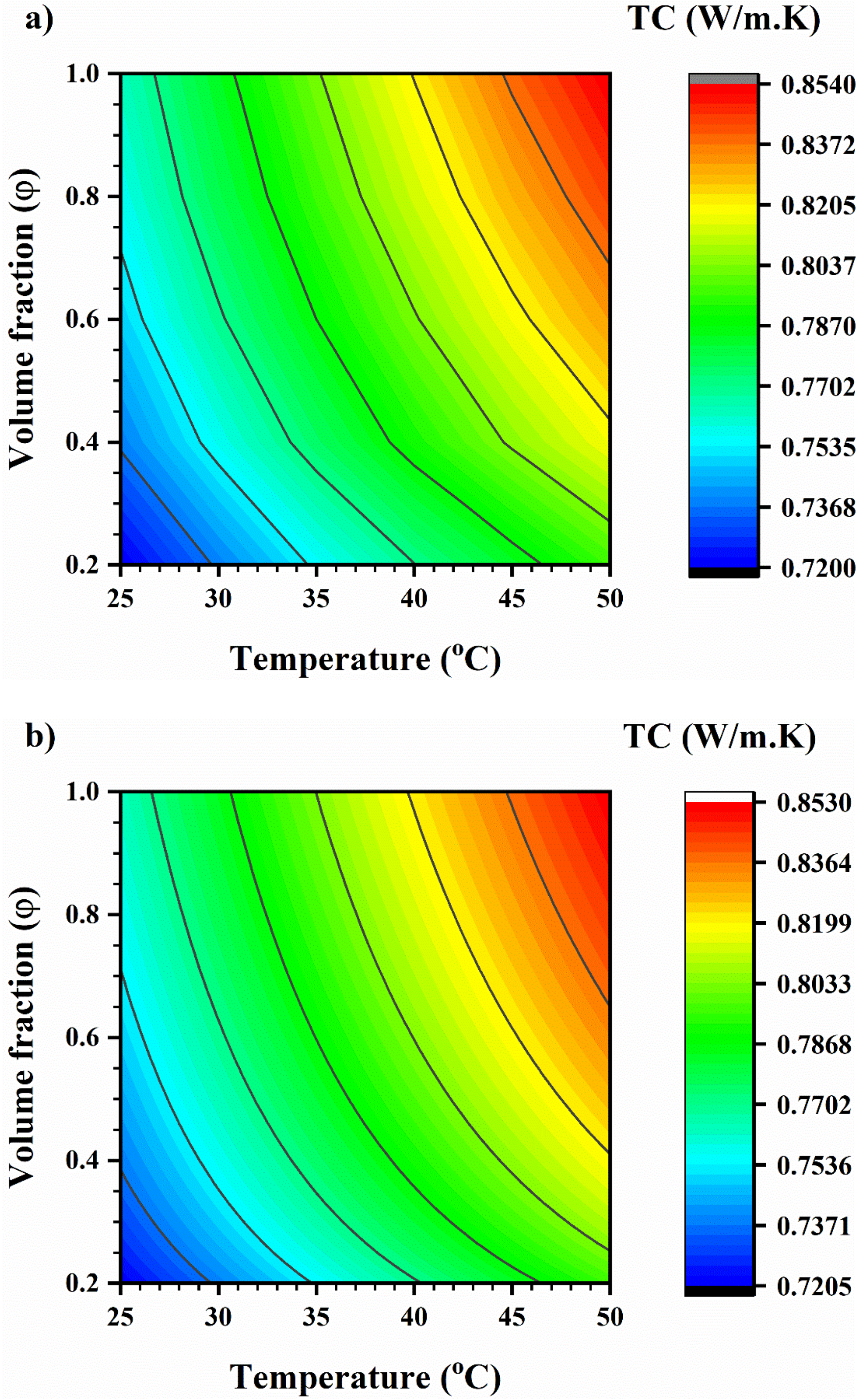


Figure 23. Contour – Color fill of (a) main data and (b) trained data

Figure 22 shows an acceptable agreement between experimental data and trained model outputs. Maximum positive and negative deviation margins for this model are 0.6057% and 0.3139% which are 0.0039% and 0.0108% less than maximum deviation margin of the presented correlation. Also, the total deviation margin gap is about 0.9196% which is 0.0147% less than correlation [66].

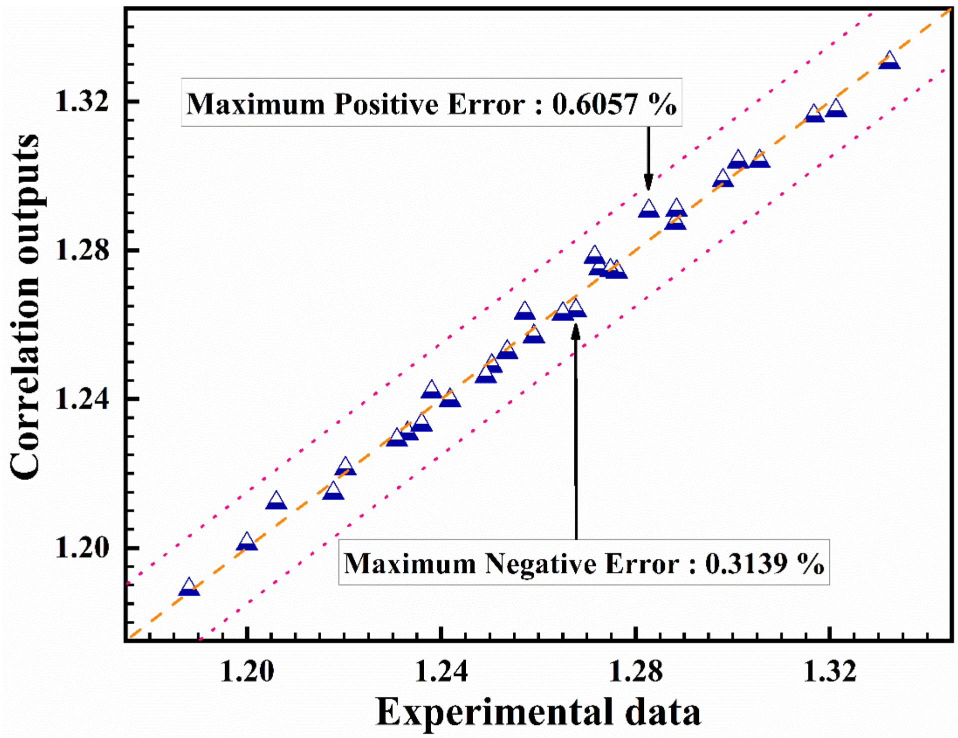


Figure 24. Verify trained data by experimental results

4. Conclusion

In this research, multi-walled carbon nanotube (MWCNT) was added to Iron (III) Oxide (Fe_3O_4) / Water nanofluid to measure enhanced thermal conductivity. So, to improve the Water (base fluid) thermo properties, mono nanofluid (MN) and hybrid nanofluid (HN) prepared solely. For thermal conductivity measurements, MN and HN volume fraction ranges were 0.2, 0.4, 0.6, 0.8 and 1.0%. Also, temperature ranges were 25, 30, 35, 40, 45 and 50^{o}C. Then, new correlations for MN and HN have been calculated by using curve-fitting method on experimental data. These correlations, can calculate Fe_3O_4/Water and MWCNT (50%) /Fe_3O_4 (50%)/Water thermal conductivity in another research. Also, Artificial neural network (ANN) has been modeled for both MN and HN. At the end, calculated data (which obtained by correlation or trained model) was compared with experimental data which shows a high accuracy [67]. Thus, ANN models which trained in this research, can predict thermal conductivity properties with acceptable error.

The main results include:

- After dispersing mono Fe_3O_4 and hybrid MWCNT/Fe_3O_4 to water, homogeneous and durable nanofluid (for more than 2½ months) have been made.
- Thermal conductivity of MN and HN were measured at volume fraction ranges up to 1.0% and temperature ranges up to 50°C.
- By adding MWCNT/Fe_3O_4, basefluid's thermal conductivity improved and raised by increasing in temperature and volume fraction.
- Maximum thermal conductivity enhancements (TCE) of 32.76% and 33.23%, were measured at 1.0% volume fraction and 50°C temperature for MN and HN, individually. These results showed that by adding MWCNT to Fe_3O_4, TCE increased about 0.47%.
- 0.6007% and 0.6096% deviations were calculated for MN and HN at presented correlations with R^2=0.9, individually.
- 0.5862% and 0.6057% deviations were calculated for MN and HN at trained models with R^2=0.999, individually

Conflicts of Interest

There is no conflict of interest.

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