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Eco-friendly production of nanoparticles

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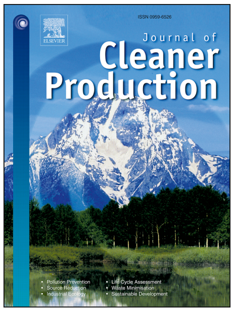

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An experimental study on stability and thermal conductivity of water/silica nanofluid: eco-friendly production of nanoparticles

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Abstract

In the present experimental study, an eco-friendly process (synthesized from rice plant source) was used to produce silica nanoparticles. Silica nanoparticles are environmentally friendly nanoparticles that have high heat transfer potential due to its abundant natural resources, low cost synthesis and mass production. The surface and atomic structure of the nanoparticles have been investigated through SEM and FTIR tests. After production of nanoparticles, water/silica nanofluid samples were prepared using two-step method that called eco-friendly nanofluid. Stability and thermal conductivity of the eco-friendly nanofluid were examined. Investigating the stability of the prepared samples, the DLS and TEM tests have been conducted as well as periodic visual observation of possible sedimentation over a period of six months through photography. The stability results indicated that the prepared samples possess excellent nano-structure and it showed long-time stability even after six months of preparation. The thermal conductivity measurement of the samples has been done in different temperatures ranging from 25 to 55 ℃ and solid volume fractions of 0.1, 0.25, 0.5, 1, 1.5, 2, 2.5, and 3 %. The results showed the maximum thermal conductivity

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enhancement of 33 % which took place at the temperature of 55°C and solid volume fraction of 3 %. Moreover, new precise correlation to predict the thermal conductivity of the eco-friendly nanofluid has been proposed with the maximum deviation of 2.58 %. Finally, according to the results, it can be claimed that synthesis of environmentally friendly nanoparticles of silicon oxide with a plant source for nanofluid production is important, and this type of nanofluid can be introduced as an environmentally friendly alternative fluid with high heat transfer potential in thermal systems.

Keywords: Eco-friendly Nanofluid; Stability; Thermal conductivity; Silica nanoparticles; new correlation; Experimental;

Nomenclature		**Greek Symbol**	
DLS	Dynamic light scattering	φ (%)	Solid volume fraction
GO	Graphene Oxide	$\mu \; kg/m.s$	Dynamic viscosity
$h \; (W/m^2.K)$	Heat transfer coefficient	$\rho \; (kg/m^3)$	Density
$k \; (W/m.K)$	Thermal conductivity		
SiO_2	Silicon Oxide	**Subscripts**	
SEM	Scanning electron microscope	bf	base fluid
$T \; (^{\circ}C)$	Temperature	Exp	Experimental
TCR	thermal conductivity ratio	nf	nanofluid
TEM	Transmission electron microscope	r	Ratio
$V \; (ml)$	Volume	np	Nanoparticle
XRD	X-ray crystallography	$pred$	Predicted

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1. Introduction

Highly efficient and environmentally friendly thermal systems are among the most crucial requirements of most industries. Considering the critical role of energy and environmental debate, increasing the heat transfer rate to achieve high-efficiency, reduce fuel consumption, reduce air pollution, and compact thermal systems are great importance [1-3]. A convenient way to improve the heat transfer rate is to employ fluids with a higher heat transfer potential compared to other conventional fluids such as water, ethylene glycol, and oils [4]. To this end, nanofluids could be used as a smart heat transfer fluid which demonstrates a high heat transfer potential [5].

Nanofluids are in fact the suspensions of Nano-sized particles (less than 100 nm) in conventional heat transfer fluids such as water, oil, and ethylene glycol [6]. Considering their prominent heat transfer characteristics, different types of nanofluids have been studied by researchers to gain a better understanding of the behavior of such fluids [7-9]. Thus nanofluids are expected to be extensively employed to improve the efficiency and reliability of a wide range of products such as industrial heat exchangers [10, 11], computer processors [12], cooling system of car engines [13], solar energy systems [14, 15], production and manufacturing processes [16, 17], and nuclear reactors [18]; however, that if the source of nanoparticle production and its synthesis method is environmentally friendly, it could, in addition to the benefits, reduce the chemical and environmental impact of the process. Chemical synthesis techniques may harm the construction of nanoparticles, which in turn affects the electrical, thermal, and optical specifications of nanoparticles [19, 20]. These methods can also lead to other harms such as health hazards, equipment erosion and environmental contamination. Therefore, there is a serious requirement for the development of a functional approach that is environmentally friendly to counteract the above issues [20, 21].

Heat transfer coefficient has been widely investigated as an important and effective parameter in the applications of nanofluids as the alternative fluids. An overview of the results of some studies on

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the thermal conductivity enhancement of nanofluids, considering their environmental effects, is presented in Table 1.

Table 1. An overview of the results of some studies on the thermal conductivity enhancement of nanofluids

Ref.	**Nanoparticle**	**Base fluid**	**Temperature** $(^{\circ}C)$	**Concentration** (%)	**Enhancement** %	**Environmental effect**
[20]	MWCNT	Water	20 - 50	0.075 – 0.175	20.15	Eco-friendly
[22]	SiO_2	Ethanol	25 - 70	0.15 – 1.17	9.5	-
[23]	CuO	Water/ Ethylene glycol	20 - 50	0.1 – 2.0	36.97	-
[24]	GNP	Water	20-45	0.025-0.1	22	Eco-friendly
[25]	Reduced graphene oxide	Water	15 - 40	1.0 – 4.0	45.1	Eco-friendly
[26]	SWCNT	Water	10 - 50	0.25 wt%	36.5	-
[27]	ZnO	Water	25	0.1-5.0	33	Eco-friendly
[28]	Graphene	Water	20 - 60	0.5 – 1.0 wt%	32	-
[29]	Graphene	Water	20-45	0.05	0.25	Eco-friendly

Literature suggests that the heat transfer coefficient of nanofluids is considerably improved compared to that of the base fluid by adding a limited amount of nanoparticles. This characteristic of nanofluids can further help to facilitate the applications of nanofluids in different industries.

Maxwell was among the firsts to analytically examined the thermal conductivity of a suspension. He considered a very diluted suspension containing sphere particles by neglecting the particle-base fluid interactions and reported the results as an analytical correlation (Eq. 1) [30].

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2(k_{np} - k_{bf})\varphi}{k_{np} + 2k_{bf} - (k_{np} - k_{bf})\varphi} \tag{1}$$

In this equation, k is the thermal conductivity and φ is solid volume fraction. Subscripts of nf, np and bf denote nanofluid, nanoparticles and base fluid, respectively.

Thermal conductivity of TiO_2-deionized water nanofluid has been studied by Murshed et al. [31]. They used the rod-shaped (Ø 10 nm× 40 nm) and spherical-shaped (Ø15 nm) nanoparticles. Their

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results showed 33 % and 30 % enhancement in thermal conductivity by adding rod-shaped and spherical-shaped nanoparticles, respectively. Their results also indicated that the size and shape of the nanoparticles have certain effect on thermal conductivity of the nanofluid. The effect of adding different surfactants (CTAB, SDS, and Oleic Acid) and applying different sonication time (10, 30, 50, 80, 160 min.) on the stability and thermal conductivity of $Mg(OH)_2$-water nanofluid has been experimentally studied by Asadi et al. [32]. They reported that the CTAB surfactant and 30 min sonication time showed the best effect on the stability and thermal conductivity enhancement of the nanofluid. Hemmat et al. [33] studied the effect of temperature and solid volume fraction on thermal conductivity of MgO/EG-water(60-40) nanofluid using artificial neural network (ANN). Based on the experimental results, they proposed a new correlation to predict the thermal conductivity of the nanofluid with respect to temperature and solid volume fraction.

Ijam et al. [34] conducted an experimental study on thermal conductivity with respect to temperature and solid volume fraction of water-EG/graphene oxide nanofluid. The experiment was conducted over different temperatures ranging from 20 to 45 ℃ and solid volume fractions of 0.01 to 0.1 %. They reported the maximum enhancement of 10.47 % at the solid volume fraction of 0.1 % and temperature of 45 ℃. The thermal conductivity of Cu/TiO_2-water/EG hybrid nanofluid, over different range of temperatures and solid volume fraction, has been studied by Hemmat et al. [35]. They correlated the thermal conductivity behavior of the studied nanofluid using ANN and proposed a new correlation for thermal conductivity prediction. Sabiha et al. [36] studied the stability and thermo physical properties of water-based nanofluid containing single-walled carbon nanotubes (SWNTs) in different solid volume fractions and temperatures. They used Sodium Dodecyl Sulfate (SDS) surfactant to well disperse the nanoparticles into the base fluid and achieve long-term stable nanofluid. They reported the thermal conductivity enhancement of 37 % at the temperature of 60 ^{o}C and solid volume fraction of 0.25 %.

Among the various nanofluids, eco-friendly or green-produced nanofluids can transform and transfer energy, reduce dimensions and sizes in heat exchangers, increase productivity, reduce fuel

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consumption and save costs. In addition, these can be very helpful to the environment in terms of eliminating toxic and dangerous substances from the cycle of nature and the elimination of harmful elements [37-39].

Water is extensively used in industrial systems as the heat transfer fluid. The results of studies conducted on water-based nanofluids revealed that enhancement in the thermal characteristics are directly related to their microstructure details [40, 41]. In the present study, at the first, an eco-friendly procedure is employed to produce SiO_2 nanoparticles from the plant source of rice bran. Then, during the following steps applying two-step method, silicon dioxide nanoparticles, which have low production cost, has been dispersed into water. After examining the stability of the prepared nanofluid, its thermal conductivity was measured with respect to the effective variables; temperature and solid volume fraction. Finally, based on the experimental results, a new correlation to predict the thermal conductivity of the nanofluid has been presented in terms of temperature and solid volume fraction. The purpose of this paper is to show the effect of the silica nanoparticles, produced by an eco-friendly method, on the thermal conductivity of water.

2. Experimental procedure

Considering the extensive applications of water in heat exchangers, the present research investigated the thermal characteristics of water-based nanofluid containing silica nanoparticles. Hence, the objective of this study is to further identify the existing challenges and their solutions so that this nanofluid can be practically employed.

2.1 Production of silica nanoparticles from plant source of rice bran

The silica nanoparticles possess high specific surface area, hydrophilicity, and non-solubility. Another interesting characteristic of silica nanoparticles is their low production cost, which enables the practical applications of this nanofluid. On the other hand, we know rice is an important nutritional grain in the world. Since its production leaves behind a large amount of wastes, called rice husk, the employed nanoparticles in this research were produced from the plant source of rice bran during the following steps. First, the rice bran was washed several times with distilled water to

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remove contaminations and dust and then dried in an oven for four hours at 105 °C. It was then burned in the furnace for 8 hours at 580 ° C and was ashes. During the burning process, the bran was stirred several times from the furnace to allow the carbonaceous compounds to be completely burnt and destroyed.

Extracted silica was dispersed in NaOH aqueous solution and heated at 100 °C for 4 h under magnetic stirring to solve silica and produce sodium silicate (Na_2SiO_3). The obtained solution was filtered to remove the non-reactive contaminations. The clear filtrate of Na_2SiO_3 solution cooled to room temperature and titrated with 10% H_2SO_4 to pH=7 under dynamic stirring. Na_2SiO_3 was neutralized by dilute sulfuric acid to precipitate silica. After this, the solution was initially stirred for 24 hours and then aged for 48 h to allow the silica gel to gently precipitated. In order to eliminate the sulfate salt, the formed gel was fragmented, filtered, and washed using water. The clean silica gel was freeze-dried overnight to remove water. The schematic of the eco-friendly process for synthesizing silica nanoparticles is presented in Fig. 1.

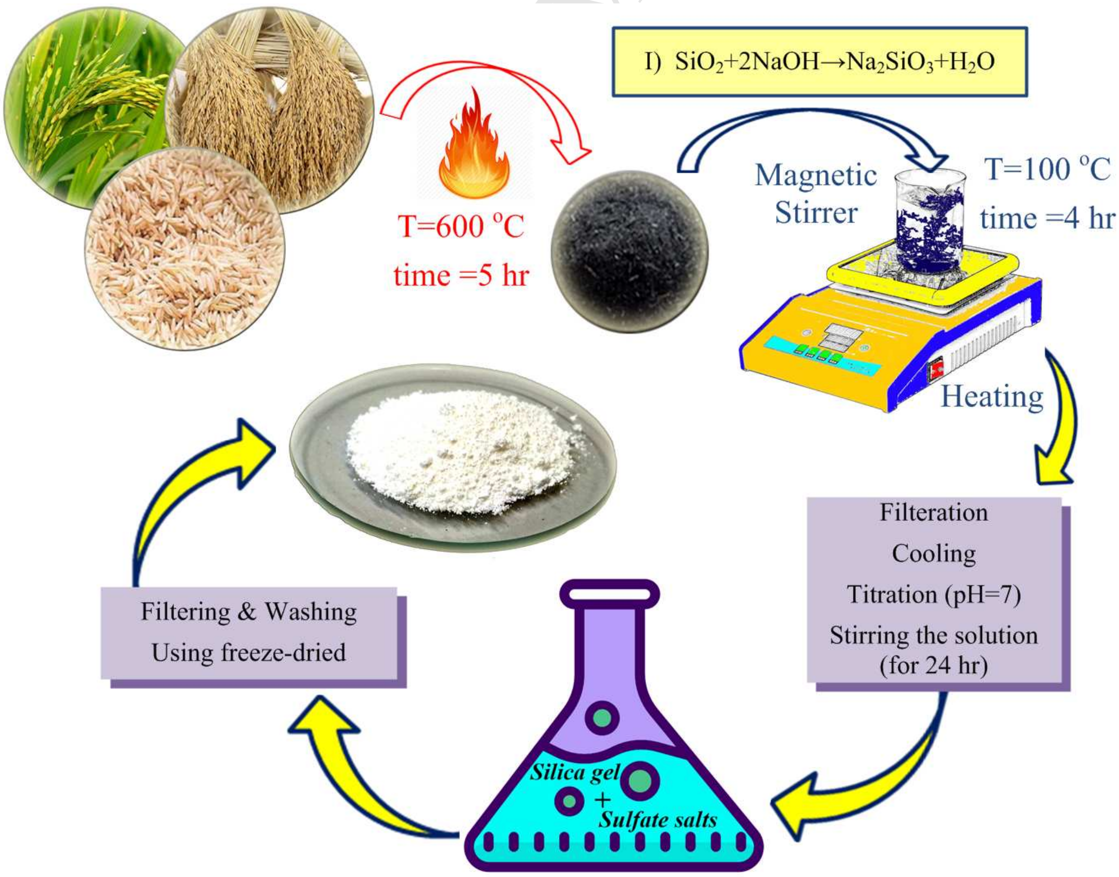

Fig. 1: Schematic of the eco-friendly process for synthesizing silica nanoparticles

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Scanning electron microscope (SEM) image was used to confirm the nanoparticles structure. The result of SEM analysis is presented in Fig. 2. As seen in this figure, the SEM image confirms a size smaller than 50 nm for silica particles.

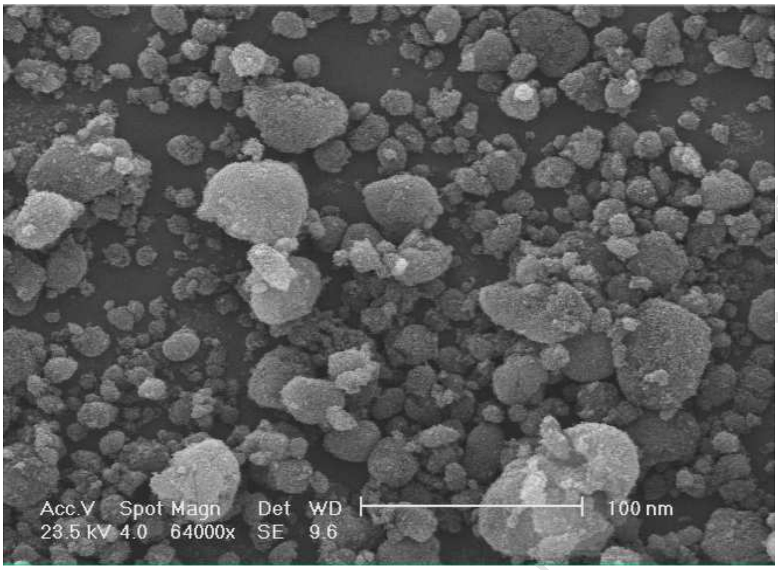

Fig. 2: SEM image of silica nanoparticles

In the present study, a WQF-510A/520A FTIR spectrometer was used to make sure about presence of the functional groups at the surface of silicon oxide nanoparticles and formations of silicate network. The test results are shown in Figure 4-A. The distinguished absorption peaks occur in the range of 1063^{-1} and $562 cm^{-1}$, which is related to the tensile vibration (C-O). Presence of this functional group results in physical absorption of the water (formation of hydrogen bond) on surface of the nanoparticles, and indeed makes the nanoparticles hydrophilic. Likewise, in FTIR spectrum, the peaks occurring at the wavelengths of $844 cm^{-1}$, $2860 cm^{-1}$, and $3406 cm^{-1}$, indicate the presence of Si-O groups, hydroxyl groups, and hydrogen bonds on surface of the nanoparticles. FTIR spectrum results of silicon oxide nanoparticles comply with results of the earlier studies [42] .

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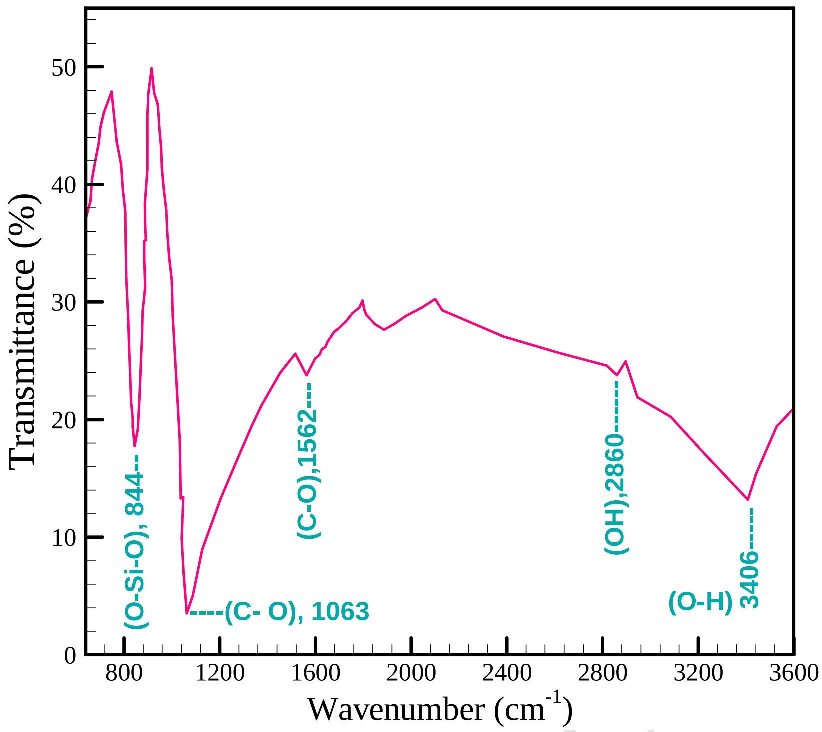

Fig. 3: The FTIR spectrum of silicon oxide

2.2 Preparation methods of SiO_2 nanofluids

Preparing a stable nanofluid is the main challenge when employing nanofluids [43]. Formation of agglomerates, due to the presence of intermolecular forces between nanoparticles, changes the thermophysical properties of nanofluid [44, 45]. Dealing with this problem is a high-priority task in practical applications of nanofluids. The two-step method was used in this study to prepare the water/silica nanofluid. In order to prepare a nanofluid with solid volume fractions of 0.1, 0.25, 0.5, 1, 1.5, 2, 2.5, and 3 %, the required amount of nanoparticles was calculated using Eq. 2. The ANDGR200 digital balance with an accuracy of 0.001 g was used to weighing the nanoparticles.

$$m = \frac{\left(\frac{\varphi}{100}\right)}{1-\left(\frac{\varphi}{100}\right)}\rho_{np}V_{bf} \qquad (2)$$

Where V_{bf}, ρ_{np}, φ, and m represent the volume of the base fluid (ml), nanoparticle's density (gr/cm^3), solid volume fraction (%) and nanoparticles mass (gr), respectively. Nanofluids with

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different concentrations were prepared according to the nanoparticles mass and amount of water (with an electrical conductivity lower than 18 μS containing no ions) shown in Table 2.

Table 2. Masses of nanoparticles and Water used for the preparing a volume of 55 gr of nano Fluid samples

Solid volume fraction (%)	Mass (±0.001) (gr)	
	SiO_2	Water
0.1	0.135	54.865
0.25	0.338	54.662
0.5	0.677	54.323
1.0	1.361	53.639
1.5	2.051	52.949
2.0	2.749	52.251
2.5	3.454	51.546
3.0	4.166	50.834

Preparing the nanofluid, the IKA-Ret BASIC magnetic stirrer was used for 1 h to gradually mix the nanoparticles in the base fluid. Then, an ultrasonic processor (UP400S- 400 W, frequency 24 kHz) was used for 60 minutes to uniformly disperse the nanoparticles in the base fluid. For all the samples, the adjustable pulse and amplitude were set to 0.8 and 80%, respectively. The probe code was selected to be H3 in proportion to the sample volume. The probe entered the mixture at a depth of 4 mm while generating the longitudinal waves. The FTIR test was applied to the nanoparticles to investigate the nanofluid stability, and the TEM & DLS tests were conducted to examine the different stability parameters of the nanoparticles in the base fluid.

Fig. 4-A and 4-B show the nanofluid right after preparation and four months after preparation, respectively. As shown, no color changes can be observed in the nanofluid. Fig. 4-C shows the images which were captured from the particle sedimentation after six months. The results of nanofluid stability analysis after six months indicated that no sediments were formed in the container.

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A

B

C

Fig. 4: The samples of SiO_2-water nanofluid A) right after preparation, B) after 4 months of preparation, and C) after 6 months of preparation.

According to studies, theoretical correlations do not have the ability to predict changes in the thermophysical behavior of the nanofluid because nanofluids do not have the same behavior [45, 46]. Then, due to the mechanism and complex structure of nanoparticles, as well as their different properties, which can result from the synthesis of nanoparticles, the nature and size of the

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nanoparticles, the effect of the base fluid, the temperature, the nanofluid method, the method of creating stability, and so on. The details of this research project are carefully and accurately investigated. The aim of this project, in addition to its scientific aspect, is the feasibility study of mass production of silicon oxide nanoparticles from the plant source and, consequently, the production of stable water-silicon oxide nanofluid for use in thermal systems.

2.3. Thermal conductivity measurement

In this study used the transient hot-wire method, which is among the most accurate methods, to experimentally measure the thermal conductivity of nanofluid with respect to solid volume fraction and temperature. The measurements were conducted using the KD2 Pro thermal property analyzer (Decagon Device, USA). The WNB 7 water-bath was used to keep the temperature constant across the samples. Fig. 5 shows a view of thermal conductivity setup utilized in the present study.

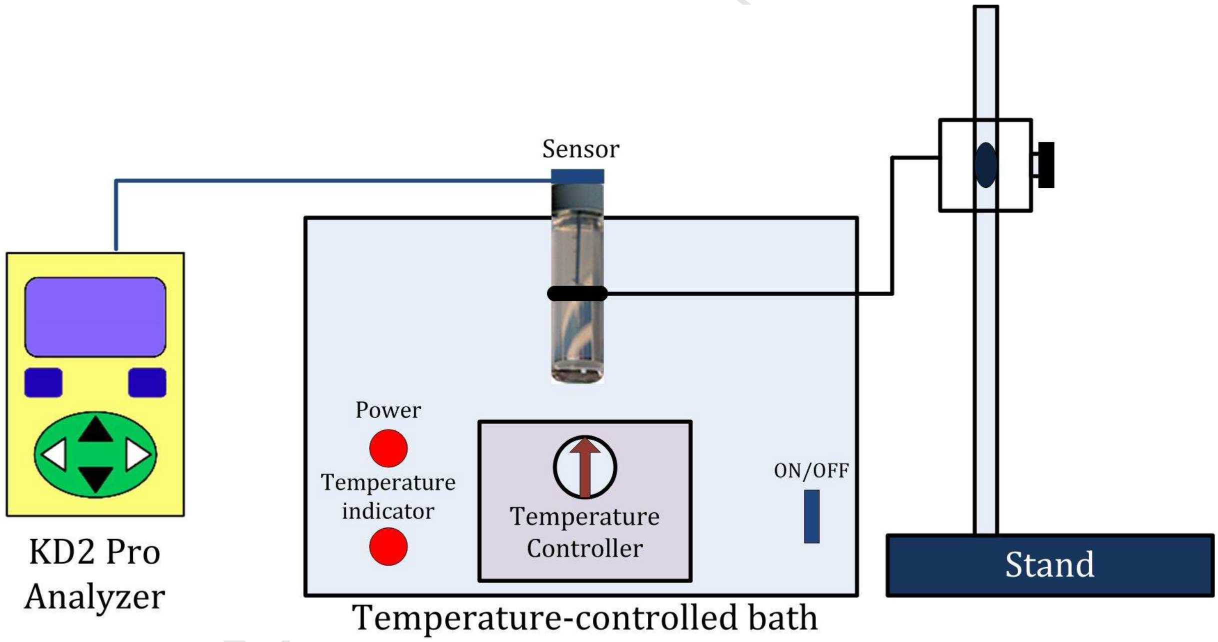

Fig. 5: A schematic view of the thermal conductivity measurement setup

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3. Results and discussion

3.1. Stability of nanofluids

3.1.1. DLS analysis

The use of dynamic light scattering (DLS) is a physical method of determining the distribution and determination of particles' size in different suspensions. This is a non-destructive and quick method. In this research DLS-VASCOTM series has been employed. Laser beam emission at 657 nm on a nanoparticle-containing solution will provide some information on their size range as per Mie theory[47] distribution of other particles was measured in terms of number and intensity variables. The results are shown in figures 6 and 7. As the size of particles was examined by different variables, the results may have industrial application.

Figure 6 shows the particles' diameter distribution in terms of "intensity". This figure displays the intensity that the device's sensors received from laser light diffraction emitted on a specimen in different dimensions. Larger particles diffract further intensity. The particles' diameters are approximately 78 nm or smaller. With respect to the test mechanism in this condition, the nano dimensions of particles in the base fluid are established.

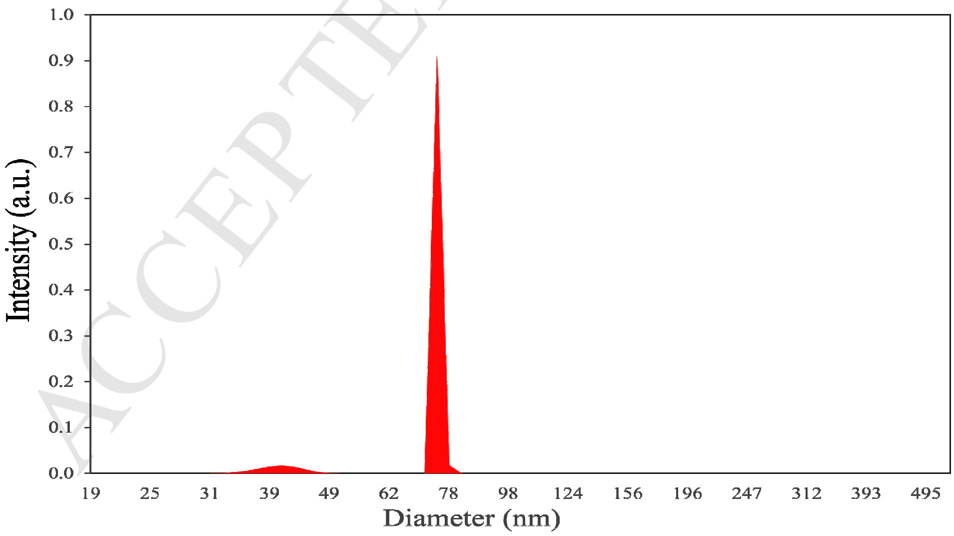

Fig. 6: The diameter of the distributed nanoparticles with respect to intensity

Figure 7 shows the results in terms of "number" variable. The analysis is related to number of particles in each dimension. Consequently, diameters of the particles are determined. It is seen that more than 80 percent of the area is related to the average diameter of 40.77 nm, which corresponds

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to the average diameter of the particles declared in Fig. 2. The result of Figure 6 is usually appropriate for nano material reports.

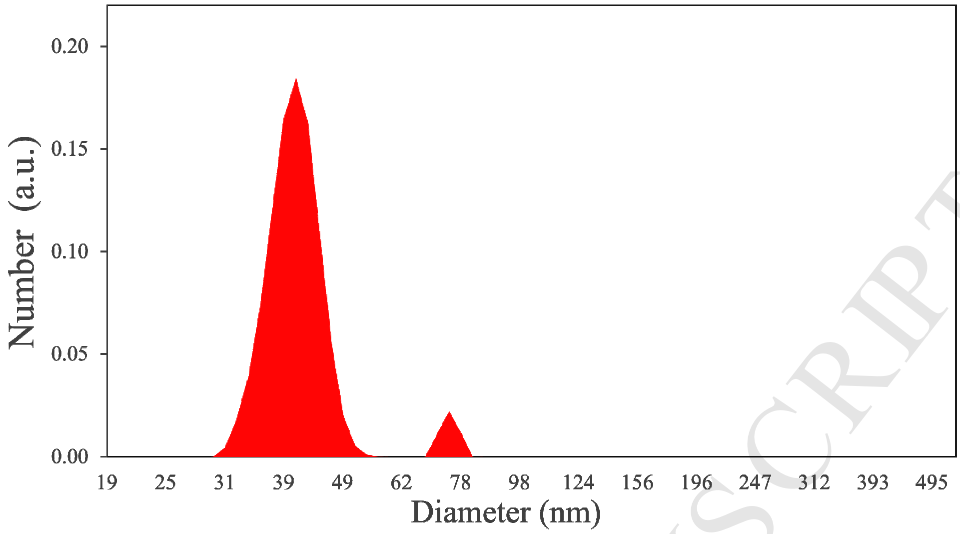

Fig. 7: The diameter of the distributed nanoparticles with respect to the number

Regarding the stability study, the DLS results presented in Fig. 6 are related to the average diameter of the nanoparticles based on intensity. Due to the fact that larger diameter nanoparticles absorb more intense laser radiation, despite a small number of nanoparticles of 78 nm, they cover a large area of the graph. In Fig. 7, the analysis is based on the number of particles. As can be seen, the number of nanoparticles with a mean size of 44.77 nm is much higher, and the results of Fig. 7 actually confirm the results of Fig. 6.

The analyses show that the nano dimensions of the silicon oxide particles in the base fluid can be confirmed. The accuracy of diameter results can be confirmed by different analyses.

3.1.2. TEM analysis

This research uses a TEM test partially and accurately to examine water/silicon dioxide nanoparticle. TEM analysis is used to observe and examine the shape, surface structure of nanoparticles, size, and its distribution on water base fluid. A Dutch-made Philips CM200 STEM was used for the analysis and Figure 8 shows the results.

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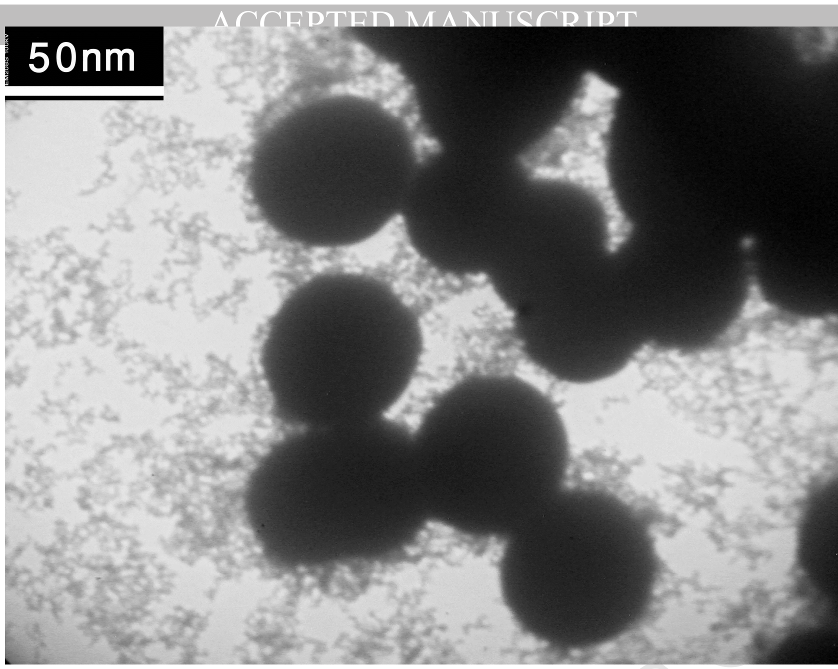

Fig. 8: The TEM image of the silica-water nanofluid

The results show that the nanoparticles are spherical and they have been dispersed throughout the base fluid with the average size of 40-50 nm. Nanofluid quality is observed with respect to the size of particles, their spherical shape, and their dispersion in the based fluid. The results of Figure 8 confirm the DLS analysis results suitably and the results confirm nanofluid stability.

The difference between the results of the TEM and DLS image is due to the intrinsic property of the tests, but in both tests, the areas of the nanoparticles are consistent with one . The objectives of the TEM test include examining the structure of the nanoparticles, how to disperse the intensity of the nanoparticles in the base fluid, and measuring their approximate size, while the test results of the DLS test are applicable. Moreover, in DLS test, a much larger volume of nanofluid is tested compared to TEM. In other similar studies, there are differences between the results of DLS and TEM [48-50]. In fact, the differences in the particle size range are due to the inherent characteristics of these two methods, as well as the type of investigating particle size by these tests. The results of both tests are correct and fully valid.

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3.2. Validation

The validation analysis has been performed over the studied range of temperatures (25-55 ℃) in order to confirm the accuracy of the experimental equipment in measuring the thermal conductivity of the nanofluid. To do this, the measured data in the present study was compared to the data available in ASHRAE handbook [51]. Fig. 9 presents the compared data. As can be seen, the maximum deviation between the measured thermal conductivity and those available in ASHRAE handbook is 1.2 %, which shows the accuracy of the measurement.

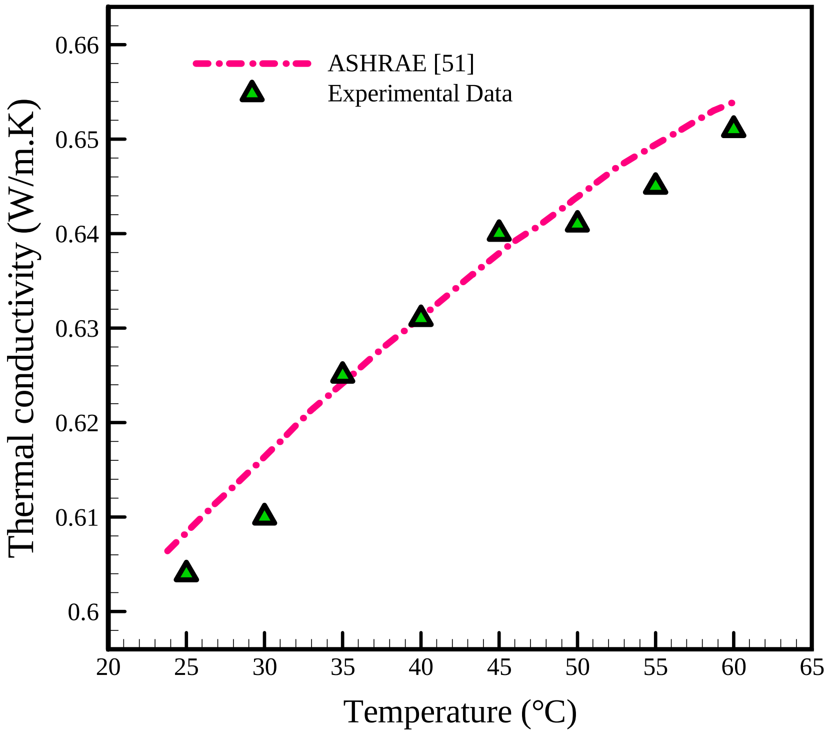

Fig. 9: validation of the measured data of thermal conductivity of water in different temperatures with those available in ASHRAE handbook [51]

3.3. Thermal conductivity

This section presents the experimental results on the measurement of thermal conductivity of water/silica nanofluid over the different solid volume fractions of 0.1-3 % and temperatures of 25-55 °C. The percentage of thermal conductivity ratio of nanofluid to that of the base fluid is defined as Eq. 3.

$$Thermal\ Conductivity\ Ratio = \frac{k_{nf}}{k_{bf}} \quad (3)$$

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The thermal conductivity of the nanofluid with respect to temperature is presented in Fig. 10-A. As shown, the thermal conductivity of the nanofluid increases as the temperature increases. The reason of this enhancement may be attributed to the following reasons: 1) note that the thermal conductivity of silica nanoparticles and that of the base fluid naturally increase in proportion to temperature. Therefore, the thermal conductivity of the nanofluid is expected to enhance as the temperature increases. However, this enhancement is higher than that of the pure water due to the presence of nanoparticles, which counts as a positive characteristic of nanofluids, 2) increasing the temperature leads to increasing the Brownian motion, which in turn improves the nanofluid thermal conductivity. The aforementioned explanations are also consistent with the results reported by Juan and Lee [52] regarding the positive effect of Brownian motion on enhancing the thermal conductivity.

Temperature increase at all the solid volume fractions results in a linear increase in the nanofluid thermal conductivity. Therefore, considering the aforementioned reasons, temperature variations have a significant effect on the thermal conductivity of a nanofluid at higher concentrations. The nanofluid thermal conductivity enhanced from 0.604 to 0.892 (W/m. K) under the effect of temperature and solid volume fraction. Prasher[53] studied the effect of Brownian's motion on the thermal conductivity of the nanofluid, and in his results, unlike some researchers, he reported a positive effect of Brownian's motion on the thermal conductivity of the nanofluid. His results also showed that with increasing temperature the effect of Brownian's motion on the thermal conductivity coefficient increases.

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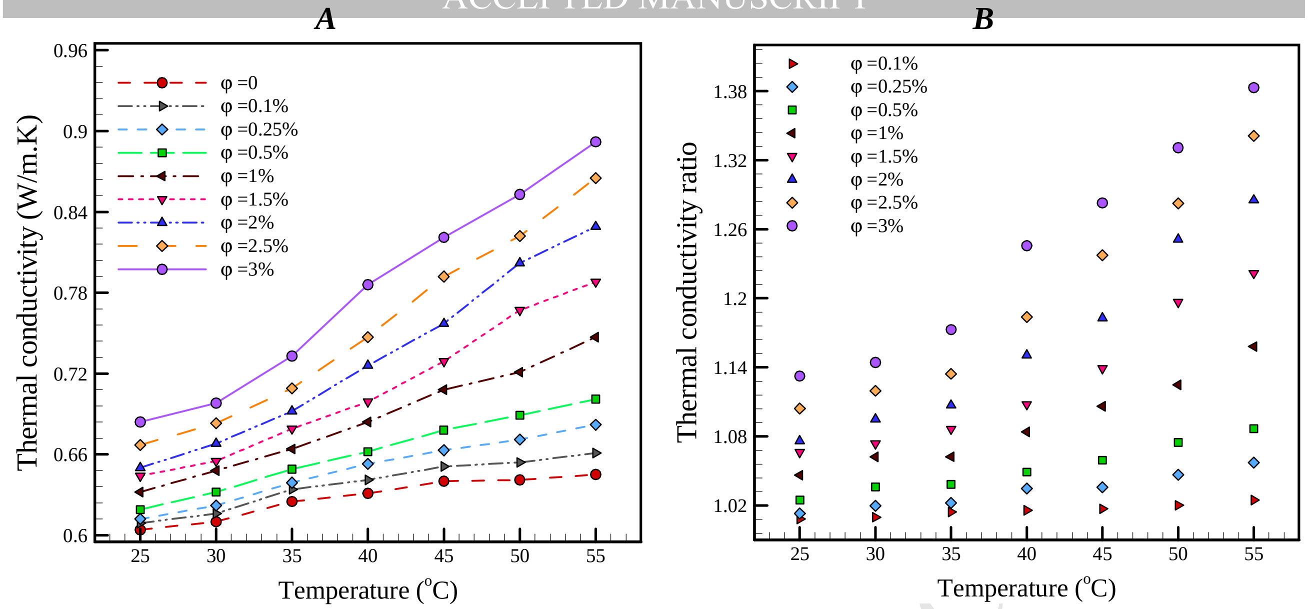

Fig. 10: Variation of nanofluid thermal conductivity versus temperature in different solid volume fraction Thermal conductivity ratio of nanofluid versus temperature in different solid volume fractions

Fig. 10-B shows the variations of thermal conductivity of the nanofluid with respect to temperature at all the studied solid volume fractions. As can be seen, at the lower solid volume fractions by increasing the temperature, the number of collisions and the amount of energy transferred between the fluid layers are not considerably high due to the low number of nanoparticles in the base fluid. The maximum enhancement was obtained at the solid volume fraction of 0.1 % by 2.48 %; while at higher solid volume fractions, the slope of thermal conductivity ratio experiences a significant improvement. It is interesting to note that the most important reason of this increase can be explained through the increase in the number of nanoparticles in the base fluid. In this case, the molecular motions are activated more quickly by increasing the temperature, which in turn considerably increases the heat transfer rate so that the maximum enhancement of 38.2 % is achieved at the highest solid volume fraction and temperature.

As the concentration of silica nanoparticles increases, the amount of solid materials with a higher thermal conductivity is added to a fixed amount of the base fluid. As a result, the nanofluid thermal conductivity enhances. This dependency is mostly due to the nature of nanoparticles and their

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higher thermal conductivity, which makes the nanofluid thermal conductivity to be affected by the increase in the amount of nanoparticles.

The results presented in Fig. 11-A shows that the nanofluid thermal conductivity increases by increasing the concentration of nanoparticles. These changes can be associated with the intensified effect of nanoparticles Brownian motion within the base fluid and the mixture of nanofluid layers. The temperature effects decrease proportionally at higher concentrations in case the nanoparticle agglomerates form, since their Brownian motion decreases as the agglomeration size increases. In fact, the particles transform from their nanoscale dimensions to larger agglomerates, in which case their movement velocity decreases compared to their initial state. Previous research show that with increasing particle size, the effect of Brownian motion on the increase of the thermal conductivity decrease[53]. In this research the results show that by increasing the volume fraction due to the stability of the nanofluid (No agglomeration in nanoparticles.), the thermal conductivity is always increased.

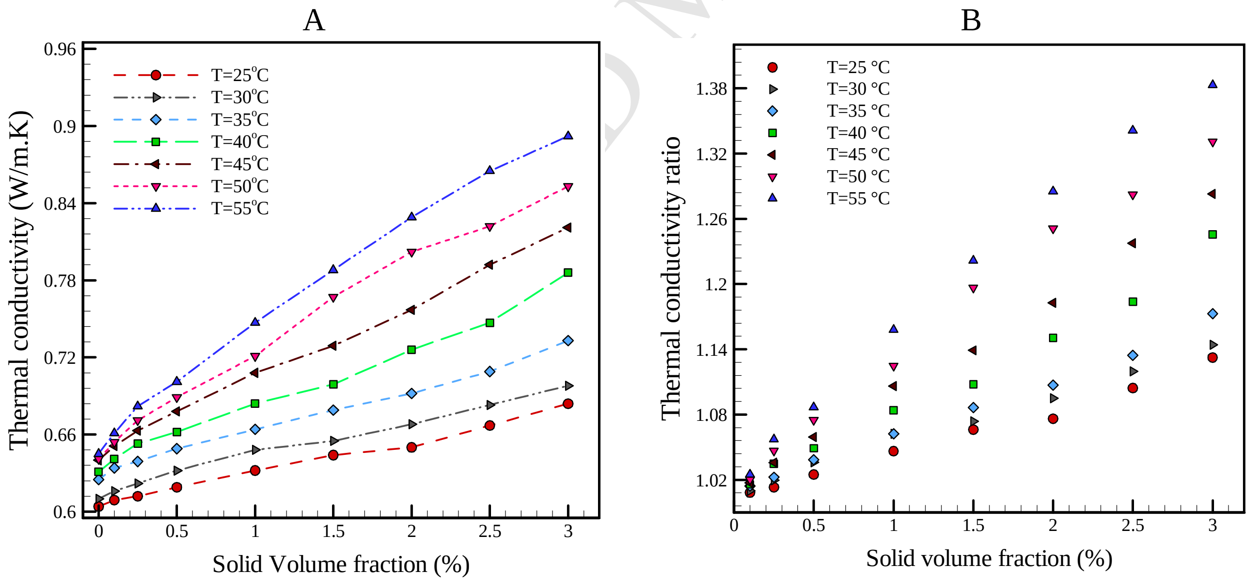

Fig. 11: Variations of thermal conductivity versus solid volume fraction at different temperatures Thermal conductivity ratio of nanofluid versus solid volume fraction at different temperatures

Fig. 11-B demonstrates the results of relative thermal conductivity of the nanofluid with respect to different volumetric fractions. This figure helps to gain a better understanding of the behavior of nanofluid thermal conductivity compared to the base fluid by increasing the volumetric

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concentration. At volumetric concentrations lower than 1 %, the ratio of variations experienced a maximum of 8 % increase, while a considerable improvement is achieved by increasing the amount of nanoparticles in the base fluid.

The nanofluid thermal conductivity always increases by increasing the volumetric fraction. However, excessive increase in the volumetric fraction causes problems such as instability of nanoparticles in the base fluid or a significant increase in the nanofluid viscosity [54]. In some thermal systems, the effect of heat transfer improvements is much higher in comparison with the increased power of the pumping power; thus, using nanofluids can be efficient even with higher volume fractions. In some empirical studies, the effect of the difference between heat transfer and pumping power is investigated and its results are presented [55, 56].

Given that rice plant is a rich source of silica, in this study, silica oxide nanoparticles were synthesized using this natural source. Then, with scientific methods, the process of production and stabilization of the nanofluid was investigated. Then, its thermal properties were investigated under different conditions. The results showed that this nanofluid can be used in thermal systems such as heat exchangers, solar water heaters, car cooling systems and ventilation systems due to long-term stability and favorable thermal properties compared to pure water.

3.4. Proposed Correlation

Nanofluids have a complex structure and their thermal conductivity are affected by different parameters such as temperature, volumetric fraction, particle size, surface, atomic, and chemical structure, nanofluid preparation method, and stability. Numerous studies have confirmed this through the significant difference between the experimental results and those obtained by the classical theoretical correlations [57, 58] . Thus, in the present study, based on experimental data, a new correlation has been proposed (Eq. 4) to predict the thermal conductivity of the studied nanofluid in terms of temperature and solid volume fraction with Rsqr= 0.99. This correlation, in fact, was derived through curve fitting using Levenberg–Marquardt algorithm.

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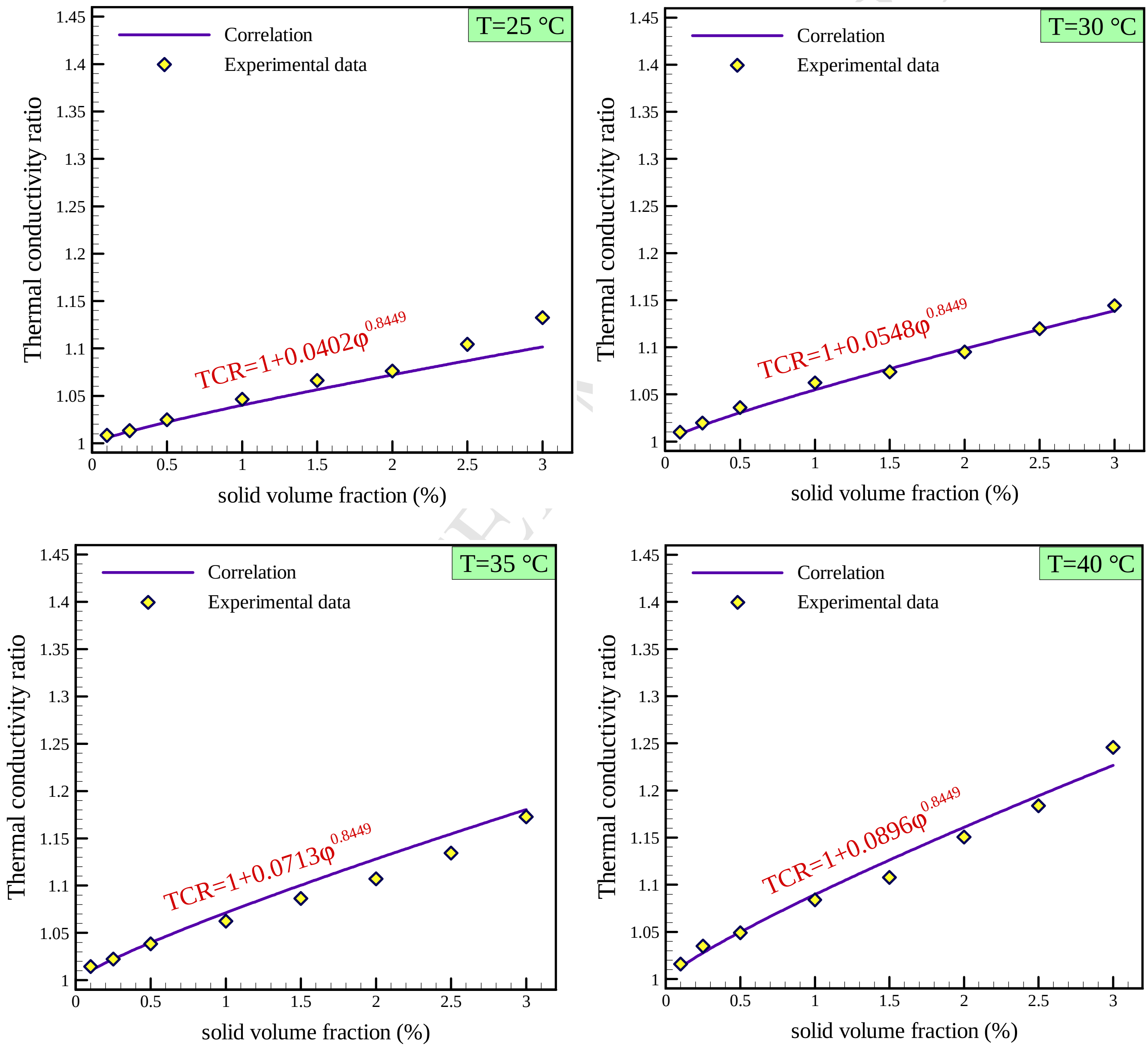
$$TCR = \frac{k_{nf}}{k_{bf}} = 1 + 0.4281\left(\frac{T}{100}\right)^{1.707} \varphi^{0.8449} \tag{4}$$

Fig. 12 compares the experimental results on the ratio of thermal conductivity with those obtained by the proposed model. The results are presented with respect to volumetric fractions and the ratio of thermal conductivity in all the temperatures. As can be seen, the calculated results by the proposed model are in excellent agreement with the experimental results. The proposed correlation can be used to calculate the thermal characteristics of water/silica nanofluid in numerical studies.



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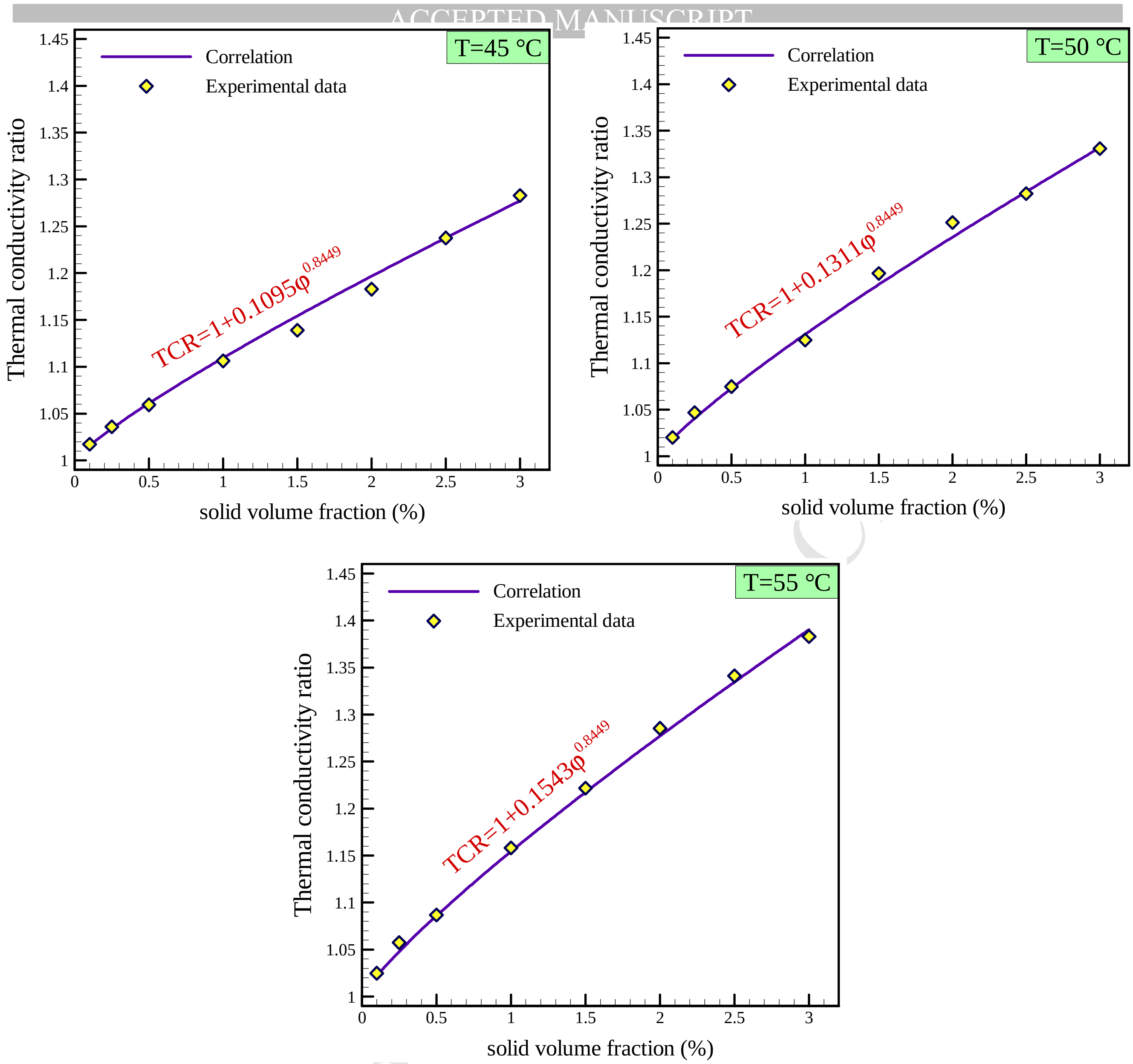

Fig. 12. Comparison between the predicted TCRs by the proposed model with those of experimental data with respect to solid volume fraction at different temperatures

To further investigate the accuracy of the proposed correlation (Eq. 4), the margin of deviation analysis has been done using Eq. 5:

$$\text{Deviation margin}\,(\%) = \left(\frac{k_{Exp} - k_{Pred}}{k_{Exp}}\right)\times 100 \tag{5}$$

Where k_{Exp} represents the measured thermal conductivity in the present study, and k_{Pred} is the predicted thermal conductivity by the proposed model. Fig. 13 displays the difference between the predicted results by the proposed model and the experimental data. As can be seen, the maximum

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margin of deviation between the experimental data and those predicted by the proposed model is 2.72 % which proofs the accuracy of the proposed model.

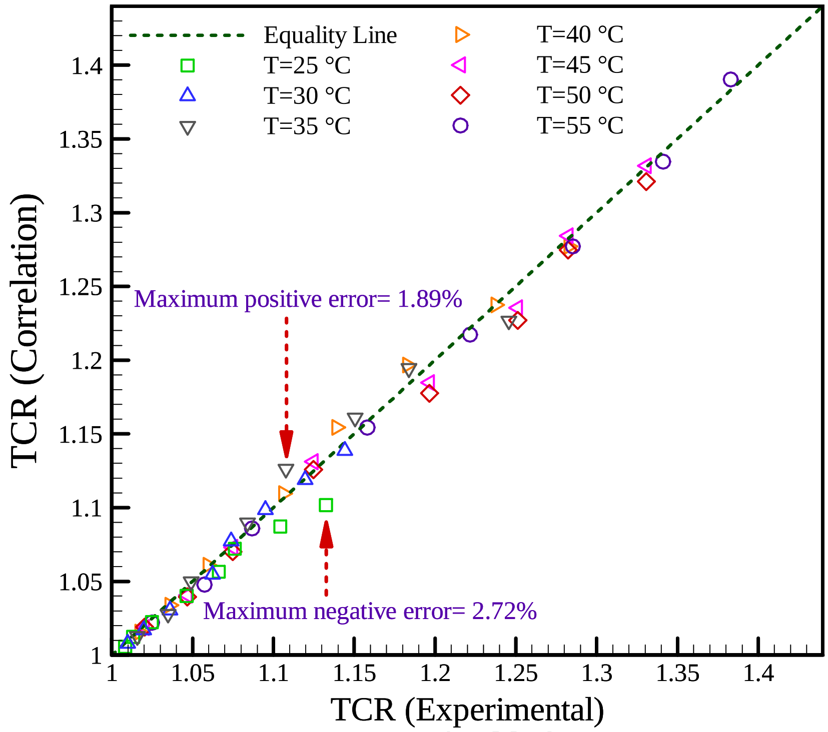

Fig. 13: Comparison between TCRs predicted by the proposed model and those of experimental data.

3.5. Comparison of the thermal conductivity of the studied nanofluid with some other nanofluids

The present investigation accurately and comprehensively examined the silicon oxide nanoparticles due to several reasons such as improving the thermal conductivity of the base fluid, low cost, production and abundance of its resources in nature, and long-term stability. This section compares the results obtained from the thermal conductivity of the studied nanofluid and the results presented for other nanofluids. Fig. 14 compares the experimental results of the present study and the results presented by other researchers at the temperatures of 30 and 50°C in different solid volume fractions.

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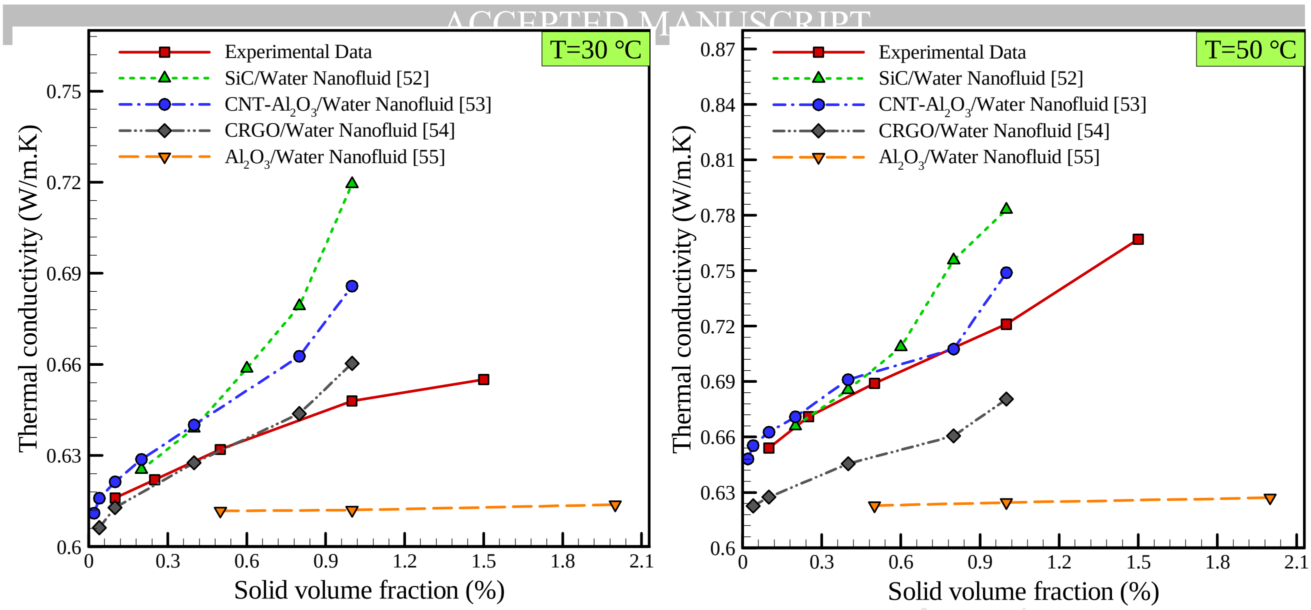

Fig. 14: Comparison of the measured thermal conductivity of Silica-water nanofluid with other published researches in different solid volume fractions and at the temperature of 30 and 50 °C

Fig. 14 reveals that there is no considerable difference between the results of the studied nanofluid in the present study with other combination of nanoparticles including water/CNT-Al_2O_3. Therefore, the comparison between the results at 30 and 50°C shows that the thermal conductivity of the studied nanofluid enhances by a greater ratio as the temperature increases. However, the cost and favorable conditions of production and long-term stability of water/silicon oxide nanofluid allows it to be used as a functional and reliable fluid in thermal systems.

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4- Conclusion

In the present investigation, in order to improve the thermal properties of the deionized water (the base fluid), the stability, and thermal conductivity of the silica-water nanofluid have been experimentally examined. An eco-friendly process was used to synthesis the silica nanoparticles. Applying SEM and FTIR tests, the nano-structure of the produced silica nanoparticles has been scrutinized. Then, applying two-step method, the nanofluid has been prepared and its stability has been accurately examined. The thermal conductivity of the prepared nanofluid has been experimentally measured in a wide range of temperatures and solid volume fractions. The results can be summarized as follows:

1- Regarding the chemical structure of the studied nanoparticle and the preparing process of the nanofluid, as well as achieving the nano size of the particles in the base fluid, a long-term stable nanofluid (for more than 6 months) has been produced.

2- Fourier Transform Infrared Spectroscopy method, also known as FTIR, can be employed to investigate the stability of the silica-water nanofluid with acceptable results.

3- The results of TEM and DLS stability test have revealed that the produced nanofluid possess excellent stability.

4- Thermal conductivity enhancement in higher temperatures is more noticeable compared to those lowers. The temperature increase leads to the thermal conductivity enhancement of the nanofluid by increasing the Brownian motion of the particles. The maximum enhancement of 38.2 % took place at the solid volume fraction of 3 % and temperature of 55 ℃.

5- Predicting the thermal conductivity of the studied nanofluid, a new highly precise correlation in terms of temperature and solid volume fraction has been proposed based on the experimental data. The maximum margin of deviation of the proposed model is 2.72 %.

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Highlights

- Using eco-friendly process to synthesis the silica nanoparticles
- Performing SEM, XRD, and FTIR tests to investigate the surface and chemical structure of nanoparticles
- Sedimentation analysis has been done using TEM and DLS tests.
- Thermal conductivity of the eco-friendly nanofluid was measured and compared with other nanofluids
- The maximum thermal conductivity enhancement of 33 % has been observed.

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