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Original article

A comprehensive experimental study on thermal conductivity of ZrO_2-SiC /DW hybrid nanofluid for practical applications: Characterization, preparation, stability, and developing a new correlation

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A R T I C L E I N F O

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A B S T R A C T

This study mainly intended to identify changes in the thermal conductivity of distilled water (DW) because of the addition of Zirconium oxide (ZrO_2) and Silicon carbide (SiC) nanoparticles. Keeping this in view, the study considered hybrid nanofluid samples developed with the help of ZrO_2 (dp: 20 nm)-SiC (dp: 45—60 nm) nanoparticles. Initially, the research involved conducting XRD, TEM, EDX and FESEM tests which allowed for conducting phase and structural analysis and also facilitated the study of nanoparticles' microstructure. In the next step, a magnetic stirrer and ultrasonic vibrator were used in sequential steps for dispersing and homogenizing Nanomaterials in distilled water. The volume concentration (φ) was kept between 0.025 and 0.1 % during the synthesis of samples. Then the samples were checked to evaluate their thermal conductivity through the transient hot wire method. In this way, the thermal conductivity of all samples was evaluated for temperatures between 20 and 60 °C. The results indicated a positive association of the thermal conductivity of nanofluid with parameters like temperature and solid volume fraction. It was noted that ZrO_2-SiC/DW hybrid nanofluid depicted a nearly 25.75 % increase in thermal conductivity at a 0.1 % volume fraction of nanoparticles and a temperature of 60 °C. The value of the thermal conductivity ratio of ZrO_2-SiC/DW was determined using the proposed mathematical correlation. The fitting method was applied to experimental data which depicted the R-Square value of 0.9906 which is considerably high. It was found that the proposed equation gave an acceptable value of the maximum margin of deviation (i.e.,1.15 %).

1. Introduction

Nanofluids can be used in various heat transfer applications owing to their unique properties. The main property of nanoparticles is their significantly high thermal conductivity as compared to base fluids leading to a notable improvement in the heat transfer efficiency and better thermal conductivity of the base fluids. Choi (1995) discovered nanofluids which are colloidal solutions based on a fluid with insoluble solid nanoparticles dispersed in it. The main components of nanoparticles mainly include oxides, metals, or carbon nanotubes (CNTs). Mainly nanoparticles are used in the manufacturing of electronics, solar collectors, heat pipes and heat exchangers. Several studies have also confirmed the high thermal conductivity of nanofluids and the consequent positive effects of this thermal conductivity on the base fluid. Studies have also indicated strong effects of factors like size, temperature, and concentration of nanoparticles on the thermal conductivity of nanofluids (Angili et al., 2023; Bagherifard et al., 2020; Hemmat Esfe et al., 2023a; Khan et al., 2019).Currently, experts have been showing interest in hybrid nanofluids which have been discovered recently as a type of nanofluid with great potential of enhancing the heat transfer properties of base fluids. The preparation of hybrid nanofluids involves the immersion of different nanoparticles in the base fluids. Nanofluids and their Thermal conductivity property has been investigated extensively in the last 10 years which revealed that nanofluids cause a significant improvement in the thermal (Ajeena et al., 2022; Baneshi et al.,

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Nomenclature

T	Temperature (°C)
APS	Actual particle size (nm)
m	Mass (kg)
k	Thermal conductivity (W/m·k)
μ	Viscosity (Pa. s)
φ	Solid volume fraction (%)
Γ	Shear rate ($s-^{1}$)
τ	Shear stress (Pa)
ρ	Density (g/cm^3)
SSA	Specific Surface Area (m^2 /g)
U	Uncertainty
nf	Nanofluid
bf	Base fluid
TCR	Thermal conductivity ratio
MOD	Margin of Deviation
Exp	Experimental data
Pred	Predicted value
EDX	Energy Dispersive X-Ray spectroscopy
FESEM	Field Emission Scanning Electron Microscope
DW	Distilled water
XRD	X-ray diffraction
DLS	Dynamic Light Scattering
THW	Transient hot wire

2021; Cao et al., 2021; Heydary et al., 2015; Jasemi et al., 2022; Karamian et al., 2014; Sone et al., 2020).

During the same period, nanofluids were prepared by various experts associated with synthetic science by dispersing nanoparticles in base fluids. They also explored various properties of nanofluids particularly the thermo-physical properties to identify the feasibility of applying the nanofluids in different applications and industries. They determined the positive and negative effects of the nanofluids. The heat transfer properties of nanofluids are specifically determined by their thermo-physical properties. The main focus of the research was to explore the thermal conductivity property which determines if the nanofluid can be used in heat transfer applications. They found that the thermal conductivity of nanofluids was significantly higher than conventional fluids (Aissa et al., 2023; Khandan et al., 2018; Khandan and Ozada, 2017; Mokarian and Ameri, 2022; Mostafizur et al., 2022; Najafinezhad et al., 2017; Vallejo et al., 2022).

Presently, various experts in this field have studied the thermal conductivity of nanofluids through empirical research and contributed to the extant literature relevant to the thermal conductivity of hybrid nanofluids. Several studies have been conducted recently in the domain of thermal conductivity of hybrid nanofluids. Li et al. (2017) prepared the SiC/TiO_2- waste cooking oil nanofluids and studied these nanofluids and their properties of viscosity, thermal conductivity and dielectric constant. Using a dual-step technique, the researchers investigated the relationship between the thermo-physical properties of nanofluids and the factors like temperature, dispersant and nanoparticles concentration. They observed a considerable increase in the rheological behaviour and the rate of heat transfer when nanoparticles are added to waste cooking oil. Nano-particle addition was also found to cause a reduction in machine loss and the release of pollutant materials by the waste cooking oil. Another study by Sarbolookzadeh Harandi et al. (2016) investigated the relationship between the addition of FMWCNTs-MgO hybrid nanomaterial and the thermal conductivity of EG. This study revealed that there is an increase in the thermal conductivity of the nanofluid as the temperature rises. It was also indicated that an increment in solid volume fraction led to the higher thermal conductivity of the nanofluid. EG was also found to depict 21 % higher thermal conductivity when the volume fraction of nanomaterials was 0.6 %. Esfahani et al. (2018) formulated the ZnO-Ag/water hybrid nanofluid with the help of an ultrasonic device through the dual-step process. In this process, the solid volume fractions and temperatures were altered and the thermal conductivity of nanofluid was evaluated. It was found that the nanoparticles depicted higher thermal conductivity at higher temperatures and greater concentrations. This study showed a maximum increment of nearly 26 % in thermal conductivity with changes in temperature and solid volume fraction. The study also offered a model that was capable of projecting nanofluid's thermal conductivity based on experimental data. Amiri et al. (2016) evaluated the thermal conductivity of the SiO_2-Cu/Water and SiO_2-Cu/EG nanofluids. They chose these nanofluids due to the unique properties of nanoparticles in these fluids. These nanoparticles are almost as dense as SiO_2; however, their thermal properties resemble those of copper. Toghraie et al. (2016) conducted research to identify how thermal conductivity is affected by parameters like volume fraction and temperature. For this research, they considered ZnO-TiO_2/EG hybrid nanofluid. They evaluated the thermal conductivity of suspension with the help of the KD2 Pro thermal properties analyser. They took readings of the thermal conductivity of the nanofluid at different temperatures between 25 °C and 50 °C and at a different volume fraction of nanoparticles (up to 3.5 %). They found an increment in thermal conductivity of the hybrid nanofluid with higher volume fraction and temperature. The highest thermal conductivity of 32 % was observed at a temperature of 50 °C and a nanoparticle volume fraction of 3.5 %. Wei et al. (2017) prepared the solution by immersing hybrid (SiC-TiO_2) nanoparticles in diathermic oil and examined the prepared solution for thermal properties. The diathermic oil depicted a decline in thermal conductivity as the temperature was raised. However, the temperature rise caused a rise in the thermal conductivity of hybrid (SiC-TiO_2/diathermic oil) nanofluid. Hence, they concluded that the Hybrid nanofluid outperformed the single nanofluid (SiC/diathermic oil or TiO_2/diathermic oil) in terms of thermal conductivity. The study by Kannaiyan et al. (2017) considered the experimental and observed thermo-physical properties of (Al_2O_3-CuO)/ water and EG hybrid nanofluids and checked for any discrepancy between the practical and theoretical properties. The thermal conductivity of the hybrid nanofluid could not be projected effectively by either the static or dynamic models. This study determined a 45 % rise in the thermal conductivity of a hybrid nanofluid. Numerical analysis performed by Mehryan et al. (2019) examined the (Al_2O_3-Cu/water) hybrid nanofluid flowing inside a square cavity filled with porous media (aluminium foam and glass ball) to determine the natural convection heat transfer of this nanofluid. The porosity of aluminium foam and glass ball was between 0.3 and 0.9 while the concentration of hybrid nanoparticles was between 0.1 and 2 vol%. The results showed that the thermal conductivity of the hybrid nanofluid outshines that of the base fluid by 1.2 % as evidenced by the highest thermal conductivity value of 0.685 W/m K obtained for the nanofluid with 2 vol% concentration. Rostami et al. (2019) evaluated the thermal conductivity of CuO-GO/Water-EG hybrid nanofluid through an experiment. In this experiment, thermal conductivity was recorded at different volumetric fractions of nanoparticles in the nanofluid (0, 0.1, 0.2, 0.4, 0.8 and 1.6 %) and different temperatures between 25 and 50 °C. The antifreeze was used as the base fluid. Antifreeze is the water and ethylene glycol combination in a 50:50 ratio. Industries commonly use this combination. The results indicated that the thermal conductivity of the nanofluid (comprised of 1.6 % graphene oxide and copper oxide in the ratio of 50:50 dispersed in water-EG) increased by 43.4 % when the temperature reached 50 °C. The research by Nabil et al. (2018) was aimed at investigating the use of (TiO_2-SiO_2/water and EG) hybrid nanofluid in a circular tube and determining its heat transfer potential. The temperature was kept at 30 °C while studying the thermophysical properties of nanofluid. They found that nanofluid depicted a nearly 3.7 % rise in thermal conductivity as the concentration increased by 1 % (i.e., from 2 % to 3 %). The performance and thermal indices of two hybrid nanofluids were evaluated and compared by Hemmat Esfe et al. (2023c) to identify the nanofluid with better thermal conductivity and better performance. The test was conducted keeping the experimental conditions the same for both nanofluids. The first nanofluid was comprised of MWCNT (50 %), CuO (25 %), and SiO_2 (25 %) suspended in water while the second nanofluid comprised of MWCNT (10 %), CuO (20 %), and SiO_2 (70 %) suspended in water. The test revealed higher thermal conductivity enhancement (TCE) for the first nanofluid accounting for 37.10 % while lower values of TCE for the second mixture accounting for 16.20 %. In an attempt to introduce a novel effective nanofluid, Hemmat Esfe et al. (2023b)considered two nanofluids for the first time. He evaluated their properties and made comparisons to find the one with better outcomes in terms of thermal performance. He employed response surface methodology or RSM with experimental methods. The first nanofluid was a hybrid nanofluid (HNF) prepared by dispensing MWCNT and TiO_2 nanoparticles in the ratio of 25:75 in the base fluid containing Water and EG in the ratio of 80:20. The second nanofluid was prepared by dispensing MWCNT and TiO_2 particles in the ratio of 15:85 in the base fluid composed of Water and EG in the same ratio. The researcher evaluated the thermal conductivity of both the prepared suspensions. He found that the first hybrid nanofluid showed TCE (thermal conductivity enhancement) equalling 36.30 %, while the second hybrid nanofluid showed TCE of 17.90 % when the temperature was 50 °C and solid volume fraction was 1.12 %. Hence, it was found that the first hybrid nanofluid is better for use. The study carried out by Hemmat Esfe et al. (2023e) presented a review of studies on the thermal conductivity (TC) of nanofluids. Initially, he used a specific research method to find out relevant studies. Next, the relevant articles in the studies were extracted. All the selected studies were categorized into four categories based on keywords, year of publication, frequently used nanoparticles (NPs), and countries with the most significant contribution to literature. The review indicated highly repetitive use of the keywords NFs, TC, and Al_2O_3. The review indicated that the years of publication in 78 % of studies were 2016——2021. The review also indicated extensive use of some selected nanofluids like Al_2O_3, TiO_2, and CNT. Most of the studies had been conducted in Iran, India, Malaysia, and China. The review indicated a developing interest of scientists all across the globe in the thermal properties specifically the thermal conductivity of nanofluids. The study by Hemmat Esfe et al. (2022) employed the artificial neural network (ANN) for the evaluation of TiO_2 nanofluid in terms of its thermal conductivity.It was concluded from the test that the ANN considered in the study accurately estimates the thermal conductivity of nanofluids. The conclusions were drawn based on the following criteria: the lowest mean square error, the highest regression coefficient, and a 2.5 % maximum error in data approximation. The test also indicated adequate accuracy of the ANN in the estimation of thermal conductivity of water based TiO_2 nanofluid at various angles and temperature conditions. Hemmat Esfe et al. (2023d) considered two hybrid nanofluids and evaluated their relative thermal conductivity (RTC). The first nanofluid was composed of MWCNT and TiO_2 nanoparticles in the ratio of 15:85 suspended in the base fluid composed of Water and EG in the ratio of 80:20. The second hybrid nanofluid was composed of MWCNT and TiO_2 nanoparticles in the ratio of 15:85 suspended in the base fluid composed of Water and EG in equal ratios (50:50). The concentration of nanoparticles in the hybrid nanofluids was different; however, both suspensions were composed of identical nanoparticles. After a thorough analysis, the researcher found that the TCE for the first nanofluid was 33 % and that for the second nanofluid was 17.90 % indicating better thermal performance of the first nanofluid. The study also proposed a correlation for determining the nanofluid composition that yields adequate thermal conductivity (TC). Resultantly, MWCNT-TiO_2(15:85)/Water-EG (80:20) HNF is preferred and more appropriate than MWCNT-TiO2(15:85)/Water-EG (50:50) HNF. Hemmat Esfe et al. (2023f) considered two nanofluids in his study. The first nanofluid was TiO_2/BG-Water (20:80). The other nanofluid was TiO_2/BG-Water (30:70). He used analytical methods for evaluating the rise in the viscosity and thermal conductivity of both the nanofluids. The researcher successfully saved a lot of lab testing costs, time, and effort by making use of simulation methods of NSGA-II, RSM, and ANN. These methods also ensured the accuracy of outcomes. The outcomes of the MLP model indicated a regression coefficient R^2 of 0.9997 for the viscosity and TC of TiO2/BG-Water (20:80) nanofluid. The MLP model also indicated a regression coefficient R^2 of 0.9998 for the viscosity and TC of TiO2/BG-Water (30:70) nanofluid. These values reflect that the estimated model is highly accurate. The ANN determines the optimum MLP structure of both nanofluids. This study also suggested that using the multi-objective optimization method and concurrent application of multiple models can help reap better thermal performance from other nanofluids as well. The experimental study conducted by Esfe et al. (2023) explored the ternary hybrid nanofluid prepared by suspending three types of nanoparticles in the base fluid/water. The nanoparticles used in this fluid were CuO (30 %), TiO_2 (30 %), and MWCNT (40 %). The study investigated the thermal conductivity as well as other properties of this nanofluid at different temperatures and concentrations. Thermal conductivity enhancement (TCE) was found to have a direct association with nanoparticle concentration and fluid temperature. The given ternary hybrid nanofluid THNF showed 35.60 % maximum thermal conductivity at a temperature of 50 °C provided the solid volume fraction is 1.65 %.

The above-mentioned review indicated studies revealed extensive research on the properties of nanoparticles specifically when used in nanofluids. Diverse outcomes were obtained from these studies as they were conducted in different conditions. The key objective of these studies was to identify the impact of temperature and nanoparticle concentration on the thermal conductivity of water-based nanofluids. Besides nanofluids, the hybrid nanofluids and their thermophysical properties were also considered in a few studies. The review indicates no detailed investigation of the thermal conductivity of ZrO_2-SiC/DW hybrid nanofluids. Hence, this study intends to evaluate the thermal conductivity of ZrO_2-SiC/DW. Both types of nanoparticles were taken in the ratio of 1:1(50–50 %). The fluid was subjected to different temperatures (20 °C − 60 °C) with changes in concentration (0.025 % − 0.1 %) while evaluating thermal conductivity. The researcher used a dual-phase process for the preparation of distilled water-based ZrO_2-SiC/DW hybrid nanofluid. The following are main of the contributions and novelties of the current study:

- The author realized that despite a wide variety of studies on the preparation of nanofluid, none discusses the preparation of hybrid nanofluid of ZrO_2-SiC in distilled water. Therefore, the author decided to bridge this gap and discuss the preparation of distilled water-based ZrO_2-SiC/DW hybrid nanofluid in different solid volume fractions. Also, this hybrid nanofluid was preferred due to its unique properties listed in the subsequent part of the paper.
- The current study used the values of temperature of fluid and solid volume fraction of nanoparticles to evaluate the thermal conductivity by hot-wires technique using the KD2 pro device.
- The researcher proposed a significantly useful new correlation based on the experimental data. The correlation applied to various engineering applications could be used to determine the thermal conductivity of distilled water-based ZrO_2-SiC/DW hybrid nanofluid.
- The research involved an in-depth study of the given nanofluid and its properties. The study focused on the nanofluid's stability, dimensions, structure, chemical bonds, and distribution. The study used many techniques and tools for this purpose. Some of these have been listed as follows: (a) The dimension of the nanoparticles suspended in the fluid was determined with the help of Dynamic Light Scattering (DLS), (b) The dispersion of nanoparticles in the fluid was

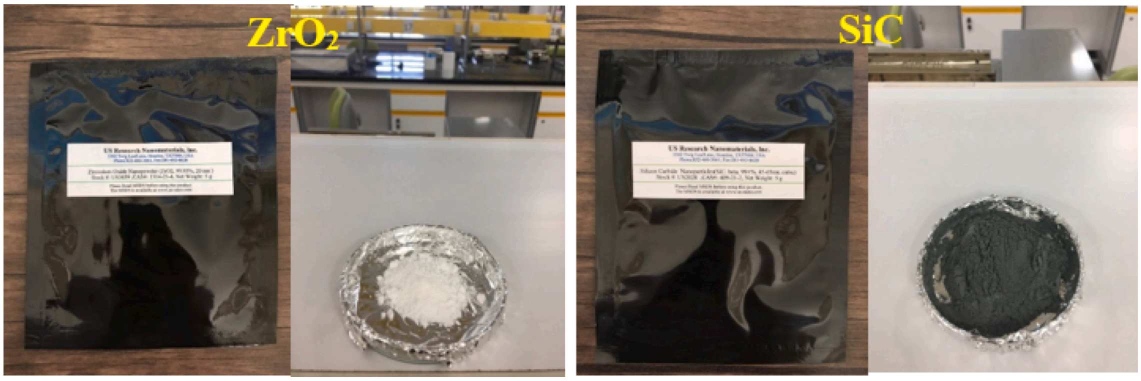

Fig. 1. Images of ZrO_2 and SiC nanoparticles.

Table 1
Thermophysical properties of nanoparticles and base liquid.

Properties	Water (base liquid)	Zirconium Oxide	Silicon Carbide
Chemical formula	H_2O	ZrO_2	SiC
Purity (%)	Distilled water	99.95	99
Color	—	white	Grayish white
Morphology	—	near spherical	cubic
Specific Surface Area (SSA) (m^2 /g)	—	30–60	40–80
Actual particle size (APS) (nm)	—	20	45–65
Stock code	—	US3659	US2028
CAS No.	—	1314–23-4	409–21-2
Density (ρ) (g/cm^3)	0.999	5.89	3.216
Specific heat (J/kg. K)	4187	455	680
Thermal conductivity (W/m·k)	~ 0.6 at (20 °C)	2.7	370

checked to yield Zeta potential which indicated the stability of the nanofluid, (c) X-ray Diffraction (XRD) was used to get images for studying the nanoparticle crystallinity,(d) For a more detailed observation of microstructure, Transmission Electron Microscopy (TEM) was employed, and (f) The researcher used a Field Emission Scanning Electron Microscope (FESEM) to observe the microstructure of the given nanofluid.

- Lastly, the sensitivity analysis determined the effects of temperature and solid volume fraction on the thermal conductivity.

2. Materials and methods

2.1. Materials

The ZrO_2 and SiC nanoparticles were purchased from US Research Nanomaterials, Inc. The NPs have been depicted in Fig. 1 while the thermophysical properties of the nanoparticles and base liquid have been enlisted in Table 1.

2.2. Instrumentations

In this study, ZrO_2 and SiC nanoparticles and samples of hybrid nanofluids were characterized by various techniques. The x-ray diffraction (XRD) (GNR company, model: Explorer, Italy), was recorded using the radiation (X-rays) with wavelength (Cu-Ka = 1.541874 Å) at 20 °C room temperature with a resolution of 0.010 (step size).The shapes and compositions of the ZrO_2 and SiC nanoparticles were studied by field emission scanning electron microscope (FESEM) (Model: TESCAN mira3,Czech) with an energy-dispersive x-ray spectrometer (EDX). The size of ZrO_2 and SiC nanoparticles and distribution within the distilled water were analysed by dynamic light scattering (DLS) technique(Particle Size Analyzer,VASCO, Cordouan, France).Moreover, the stability of ZrO_2-SiC/DW hybrid nanofluids examined by Zeta potential analysis with Zeta compact (Zeta meter, CAD Instruments, FRANCE).For synthesis of hybrid nanofluid with various solid volume fraction of nanoparticles a special amount of zirconium oxide and silicon carbide nanoparticles were weighted by advanced analytical balance (A&D WEIGHING, GE-320, USA).Afterward, The ultrasonic processor (PS 30A 6L,Germany) and magnetic stirrers (HS-12,HU) were used for prevention of nanoparticles agglomeration. The thermal conductivity of hybrid nanofluid was measured by KD2 Pro thermal property analyser (Decagon devices, USA). Some images of the devices used in this study are shown in Fig. 2.

2.3. Preparation of hybrid nanofluid

The experiment initiates with the preparation of hybrid nanofluid comprised of ZrO_2/SiC nanoparticles suspended in water. This study used the base fluid of distilled water. A fixed quantity of pure distilled water was taken. Next, the Nano-additives are added to the base fluid. Nano-additives include zirconium oxide (ZrO_2) and silicon carbide (SiC) nanoparticles in same proportions of both ZrO_2 and SiC 1:1 (50 % of ZrO_2 and 50 % of SiC). It is important that two steps were involved in the method employed for manufacturing the hybrid nanofluid samples containing 0.025 %, 0.05 %, 0.075 %, and 0.1 % of solid volume fractions. The standard Eq. (1) is used to evaluate the appropriate amount of ZrO_2 and SiC nanoparticles essential for preparing nanofluids with the specified volume fractions. The amount of nanoparticles suspended in 200 ml hybrid nanofluids is given in Table 2. The Nano-additives were weighed with the help of a highly accurate electronic balance. In this study, the suspension was subjected to two hours of magnetic stirring to manufacture stable hybrid nanofluid samples; next, the suspension was treated in an ultrasonic processor. The process continued for three hours to break the clusters formed by particles. To prevent sedimentation of nanoparticles in the nanofluid, stirring and sonication were done to make the suspension more stable and prevent nanoparticles from settling down. Consequently, the prepared suspension attained stability and uniformity. Fig. 3 shows preparation steps of ZrO_2-SiC/DW hybrid nanofluid.

$$\varphi = \left[\frac{\left(\frac{m}{\rho}\right)_{ZrO_2} + \left(\frac{m}{\rho}\right)_{SiC}}{\left(\frac{m}{\rho}\right)_{ZrO_2} + \left(\frac{m}{\rho}\right)_{SiC} + \left(\frac{m}{\rho}\right)_{DW}}\right] \times 100 \quad (1)$$

2.4. Advantage and disadvantage of ZrO_2-SiC/DW hybrid nanofluid

The following properties of ZrO_2 and SiC hybrid nanofluids led to the use of these nanofluids in the current study.

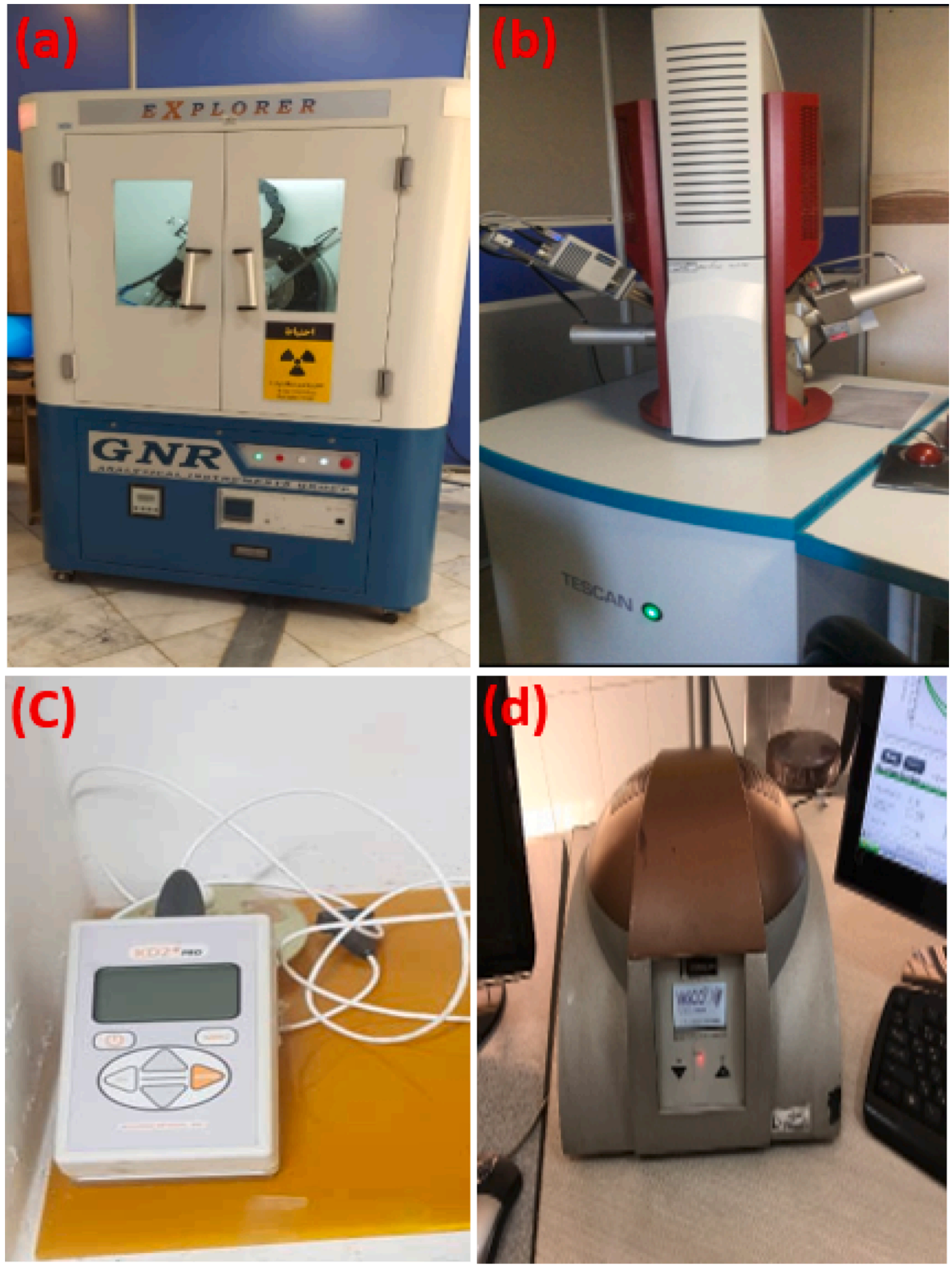

Fig. 2. Laboratory devices: (a) XRD, (b) FESEM, (C) KD2-Pro, and (d) Particle Size Analyzer.

Table 2
Required amounts of ZrO_2 and SiC nanoparticles at different volume fractions.

Volume fraction (%)	Mass of ZrO_2 nanoparticles (grams)	Mass of SiC nanoparticle (grams)
0.025	0.147	0.08
0.05	0. 294	0.16
0.075	0.441	0.24
0.1	0.588	0.32

- The thermal conductivity of the distilled water-based ZrO_2-SiC hybrid nanofluid is higher than the base fluid and the mono nanofluids.
- The high stability of the ZrO_2-SiC hybrid nanofluids results in higher thermal conductivity.
- The functionalized surfaces of the hybrid Nanocomposites promote the transfer of heat between base fluid and nanoparticles due to a greater thermal interface resulting in higher thermal conductivity and more convective heat transfer in the nanofluid.
- The experts prioritize using ZrO_2 and SiC nanoparticles in several applications because these are economical and easily available and can be prepared without complex procedures.
- The low cost of ZrO_2 and SiC nanoparticles prevents waste of resources and ensures sustainability.
- The ZrO_2 and SiC nanoparticles are non-combustible and nontoxic and hence do not to contribute to any environmental damage.
- The distilled water-based nanofluid of ZrO_2 and SiC nanoparticles is used in various applications due to its thermophysical properties. These are mostly used in cooling devices, heat exchangers, thermal storage devices, biomedical, and renewable energy.

Nonetheless, they have limitations influencing their technical and economic feasibility. Some of them are enlisted below:

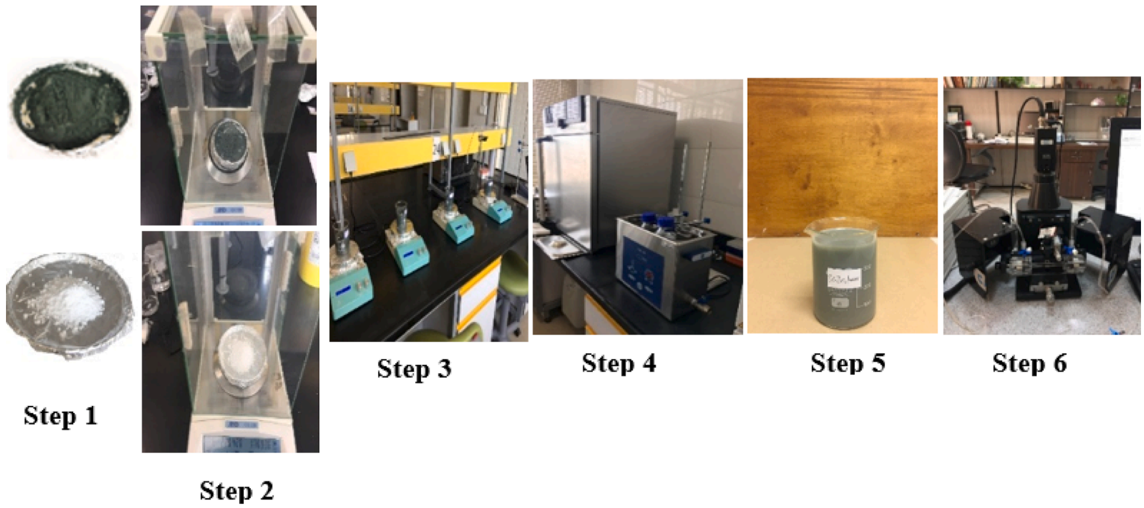

Fig. 3. Preparation steps: (step1) raw materials (nanoparticles), (step2) weigh nanoparticles by electronic scale, (step 3) mixing of nanoparticles and distilled water by magnetic-stirrers, (step 4) ultrasonic processor for ZrO_2-SiC/DW, (step 5) hybrid nanofluids (ZrO_2-SiC/DW), and (step 6) zeta potential measurement.

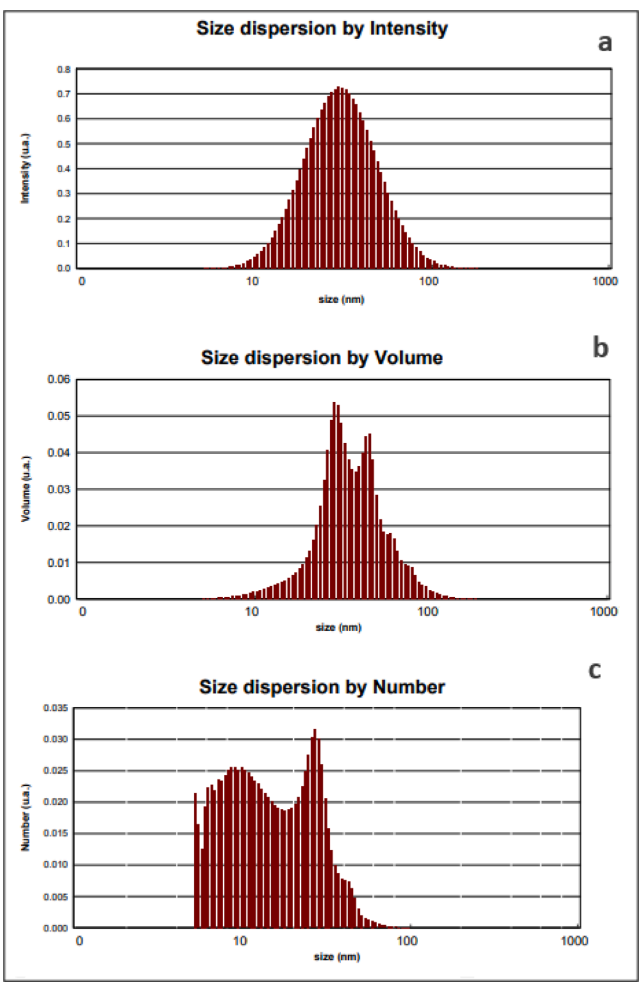

Fig. 4. Size distributions for hybrid nanofluid of ZrO_2-SiC/DW with respect to (a) intensity, (b) number, and (c) volume.

- The nanofluids have low boiling points leading to overheating of the device at higher concentrations of nanoparticles because of a rise in the surface temperature.
- The nanofluid has lower specific heat than the base fluid.
- The nanofluids have a higher viscosity than base fluid because of the presence of nanoparticles. This viscosity gives rise to a higher-pressure drop leading to higher pumping power needs in various engineering applications.
- For an excessively long period, nanofluids do not remain stable and start settling down.
- The walls of the devices used in various applications may undergo corrosion and erosion because of the long-term use of nanofluid and exposure to nanoparticles.

2.5. *Dynamic light scattering (DLS) measurements*

Dynamic Light Scattering (DLS) is a popular technique used extensively to evaluate nanoparticles for their hydrodynamic parameters. This technique is also called quasi-elastic light scattering or photon correlation spectroscopy. DLS method starts with sample preparation by dispersing nanoparticles in distilled water. Clarity and uniformity of the sample must be ensured before taking measurements. The presence of large-sized particles in the sample, poor dispersion, and inadequate sonication may lead to sedimentation. The sample with agglomeration, sedimentation and large-sized particles does not yield high-resolution data because of greater light scattering. The DLS data obtained for nano-sized particles is considered high-resolution data. In this study, the distilled water –based ZrO_2-SiC nanofluid sample is subjected to DLS analysis to find the hydrodynamic diameter of nanoparticles. Fig. 4 shows the DLS outcomes in terms of intensity, volume, and number. The number curves, volume, and intensity curves in DLS showed ZrO_2-SiC particles to have an average size below 100 nm.

2.6. *Measurement of thermal conductivity*

Three techniques are mostly employed for the evaluation of thermal conductivity; the transient hot wire method (THW), temperature oscillation method and steady-state parallel plate method. It is reported that the THW technique effectively estimates the thermal conductivity as well as heat transfer rate in fluids and suspensions. This method involves the insertion of a thin wire of platinum or titanium having a diameter between 5 and 80 μm. The wire is inserted in a vertical direction and then the gradually greater voltage is applied. Consequently, the wire serves as a source of heat and indicates the change in temperature with the application of voltage. Then, the temperature indicated by the inserted wire is noted to evaluate the thermal conductivity of a nanofluid. This measurement allows for obtaining accurate thermal conductivity effectively and quickly. The method is also efficient since it

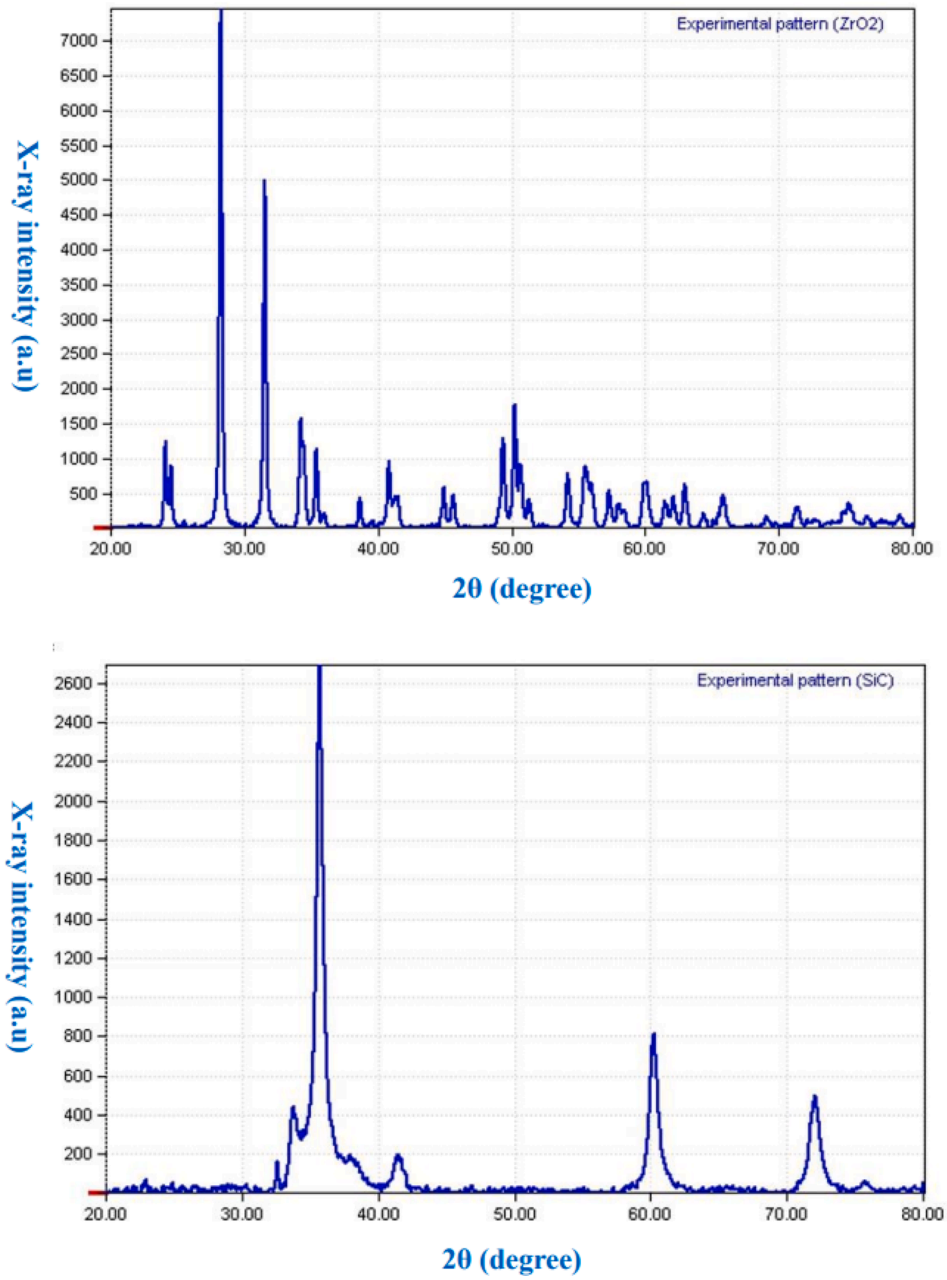

Fig. 5. X-ray diffraction pattern with analysis for ZrO_2 and SiC nanoparticles.

prevents unexpected consequences of heat transfer. This technique enables experts to study various thermal properties of nanofluids. This research uses the KD2 device to implement the THW technique and evaluate the thermal conductivity of nanofluid. It is also possible to use this device for evaluation of the thermal properties of solid and liquid through the THW technique by inserting the 1.27 mm wide stainless-steel single needle sensor with a length of 60 mm in the nanofluid sample. The sample is immersed in a bath at a stable temperature. The device was used to record the thermal conductivity of samples thrice at different temperatures after its calibration.

2.7. Uncertainty analysis

The experiment began with the calibration of the KD2 pro device with the help of a standard fluid. This step is essential to ensure the accuracy of readings. As in the case of any measurement, the evaluation of nanofluid properties is also characterized by errors. The accuracy of the measurement tools plays a critical role in calculating the uncertainties or errors in data measurement. The experimenter performed the uncertainty analysis for each test by individually evaluating the errors encountered in the measurement of temperature, thermal conductivity, and nanoparticle concentration. Firstly, the researcher evaluated the errors in the measurement of thermal conductivity; the KD2 Pro was used with (±5%) accuracy (indicated in the manufacturer's manual), the thermal circulator bath with a temperature of (±0.01 °C), and a weight balance of (±0.004 g). After that, the collected values were inserted in Eq. 2 to calculate the uncertainty in the measurement of thermal conductivity. The outcome showed a maximum error of 4.5 % in thermal conductivity measurement.

$$U_k = \sqrt{\left(\frac{\Delta k}{k}\right)^2 + \left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta T}{T}\right)^2} \tag{2}$$

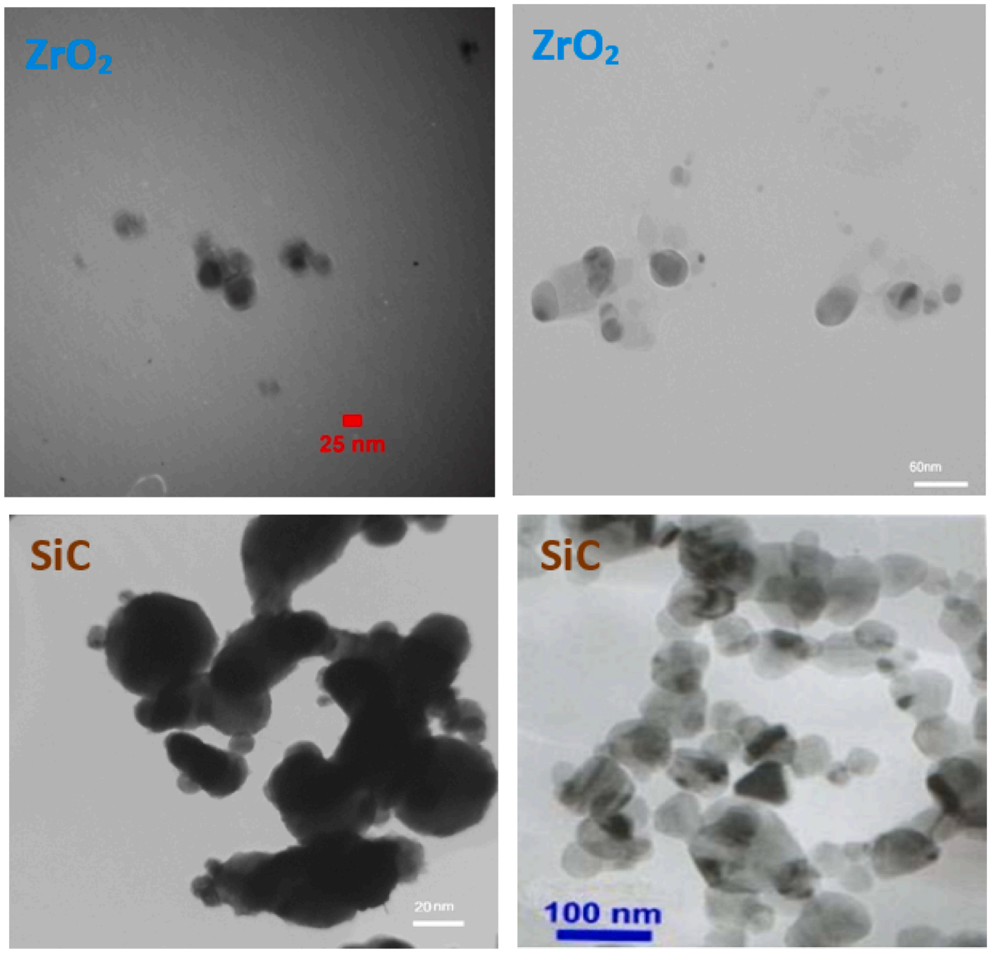

Fig. 6. TEM images with different magnifications on ZrO_2 and SiC nanoparticles.

3. Results and discussion

3.1. Characterization of ZrO2 and SiC nanoparticles

3.1.1. Phase and structural analysis

The purity, size and crystal structure of the nanoparticles were examined using the XRD technique. In this method, an X-ray beam is passed over the nanoparticle sample that gets spread because of the various atoms, which are used to examine the crystalline size. The ZrO_2 and SiC nanoparticles were subjected to X-ray diffraction analysis. When using an XRD instrument, the positions of X-ray beams (both incident and reflected beams) and samples are changed to achieve an appropriate distance required for better focus. The angle of incidence and the angle of reflection are equal to θ (theta), making the angle between the reflected and incident X-rays equal to 2θ. The sample's crystallinity is reflected graphically from the peak intensity. The researcher used a GNR Explorer, Italy, X-ray diffraction analysis for XRD tests. The test involved the application of (Wavelength, Cu -Kα = 1.541874 Å) radiation at an angle of 2θ (20° to 80°). Fig. 5 presents the position of peaks and their intensities in the XRD analysis of ZrO_2 and SiC nanoparticles. There's a strong peak at an angle of 28.29 degrees (2θ) for ZrO_2 nanoparticles. Also, the SiC nanoparticles showed typically sharp peaks at $2\theta = 35.78°$, and some smaller peaks can be seen on the graph too.

TEM was employed in this study to identify the shape and sizes of dry nanoparticles. The TEM analysis on the sample is applied by dispersing silicon carbide and zirconium oxide nanoparticles in ethanol. Following the complete evaporation of ethanol, the samples were added to TEM. The outcomes of the TEM analysis of SiC particles are presented in Fig. 6. It is shown in the findings of this analysis that SiC nanoparticles had a mean diameter of 55 nm and were typically between 45 and 65 nm. Furthermore, the outcomes of TEM analysis show that the SiC nanoparticles had a cubic morphology. The findings of the TEM analysis of ZrO_2 nanoparticles are also depicted in Fig. 6. It is shown in the outcomes of this figure that ZrO_2 nanoparticles have a mean diameter of almost 20 nm. It can also be seen in this figure that the ZrO_2 nanoparticles had near a spherical morphology.

3.1.2. Morphological analyses

The morphology of the synthesized silicon carbide and zirconium oxide nanoparticles was examined using field emission scanning electron microscopy (FESEM). The FESEM images with the magnification scales of 200 nm, 500 nm and 1 μm of the silicon carbide and zirconium oxide nanoparticles are shown in Fig. 7. Weakly agglomerated and roughly near spherical morphology for ZrO_2 particles and cubic shape for SiC particles with smaller sizes can be seen. A vital part was played by the capping agent in avoiding the tendency of agglomeration and merging of nanoparticles.

EDX analysis was carried out on the FESEM to analyse the chemical constitution and purity of the synthesized nanoparticles. Only the characteristic peaks of silicon carbide and zirconium oxide are shown by the EDX spectrum, which indicates the high purity of the synthesized nanoparticles. EDX analysis that is presented in Fig. 8 was used to determine the chemical constitutions of SiC and ZrO_2 nanoparticles. The results indicate that silicon carbide contains approximately 53.26 % of carbon (C), and 46.74 % of silicon (Si). Also, outcomes displayed that zirconium oxide includes around of 67.88 % of Zirconium (Zr), and 32.12 % of oxygen (O).

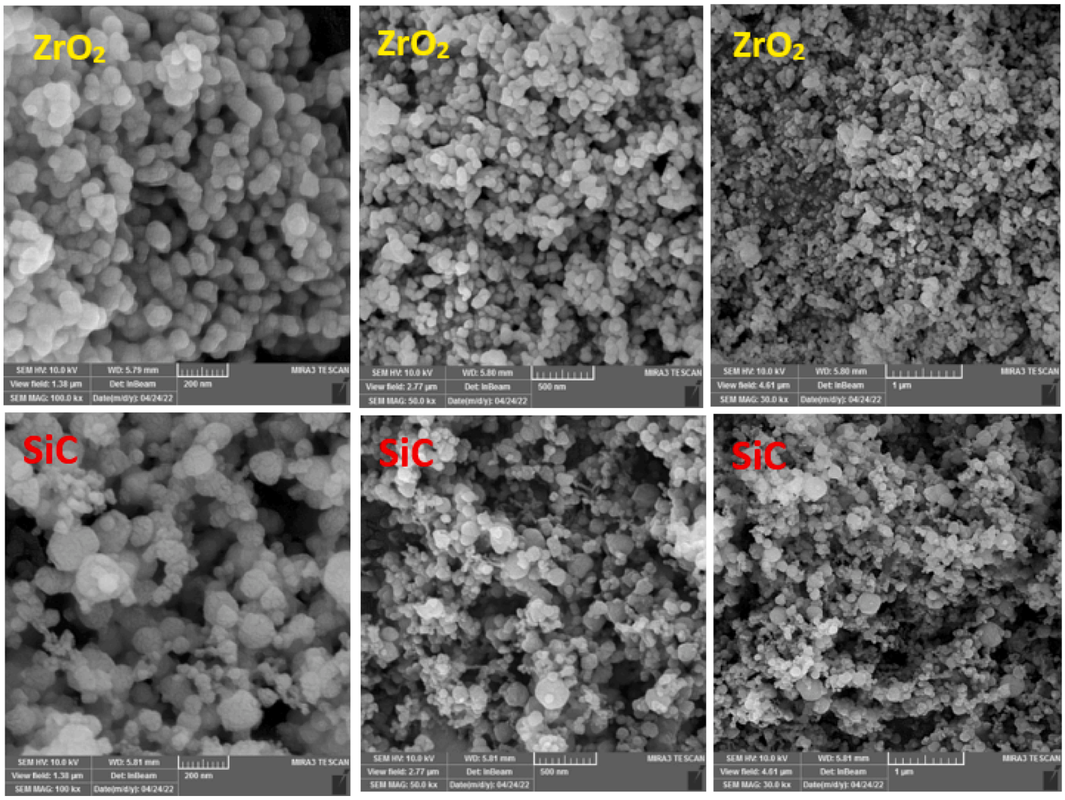

Fig. 7. FESEM images with different magnifications on ZrO_2 and SiC nanoparticles.

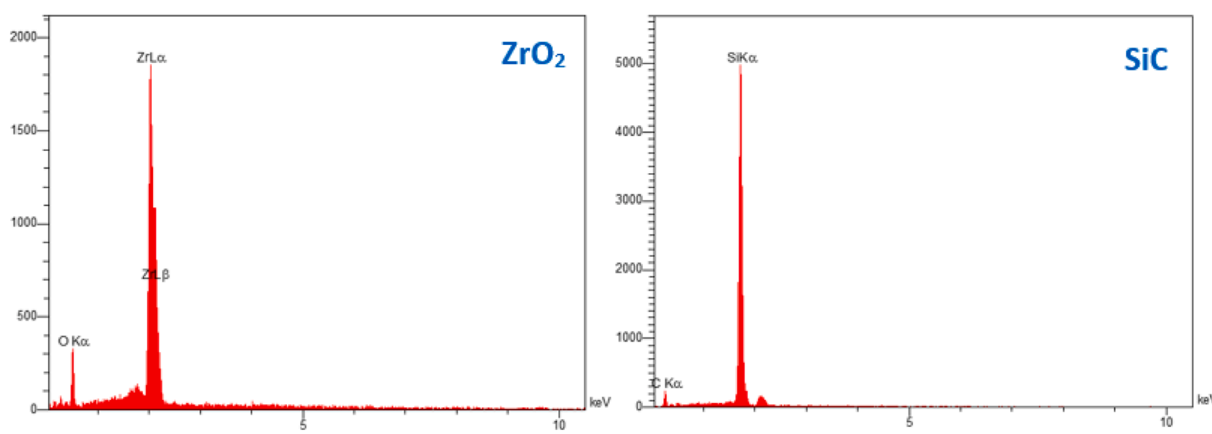

Fig. 8. EDX test for ZrO_2 and SiC nanoparticles.

3.2. *Stability analysis of hybrid nanofluid*

As indicated by Shahsavar et al. (2015), in order to increase the stability of a nanofluid, ultrasonic is employed for disrupting agglomeration and promoting nanoparticle dispersion into the base liquid. Ultrasonic methods are considerable impactful on nanoparticles' structure and surface, and create nanofluids with long-term stability and good dispersion, while also breaking down particles more effectively. Subsequent to conducting various experiments involving the nanofluid of ZrO_2-SiC/DW, it was observed that the stability was reduced when the concentration was increased; therefore, such concentrations were selected. Conversely, the results from reduced concentrations were not good; thus, particle concentrations ranging from 0.025 % to 0.1 % were used. In the current research, a zeta potential device was used for measuring the nanofluid's stability. Fig. 9 presents the various concentrations of ZrO_2-SiC/DW hybrid nanofluid with values of zeta potential during a 15-day timeframe. As previously reported by Syam Sundar et al. (2014), when particles have a higher concentration in a nanofluid (increased volume fraction), agglomeration of nanoparticles tends to occur. Additionally, it was observed that the nanofluid with a reduced nanoparticle volume fraction, combined with the base liquid, retained stability for a more extended duration in comparison to nanofluids whose volume fraction was increased.

3.3. *Thermal conductivity of ZrO_2-SiC/DW hybrid nanofluid*

3.3.1. *Influence of volume fraction on thermal conductivity*

Fig. 10 is an illustration of the thermal conductivity of nanofluid recorded at different solid volume fractions (0.025 %, 0.05 %, 0.075 %, and 0.1 %) and temperatures(20–60 °C). The thermal potentials of the fluid increase with a rising temperature due to intermixing of layers. For instance, at the same temperature (T = 20 °C), a difference of 4.36 % is

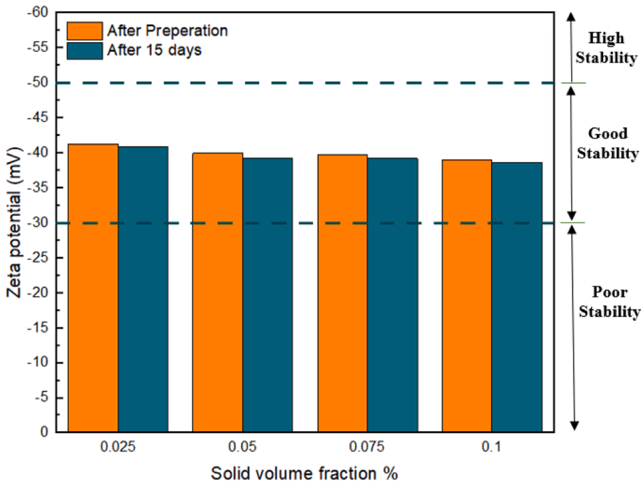

Fig. 9. Zeta potential analysis of ZrO_2-SiC/DW hybrid-nanofluid.

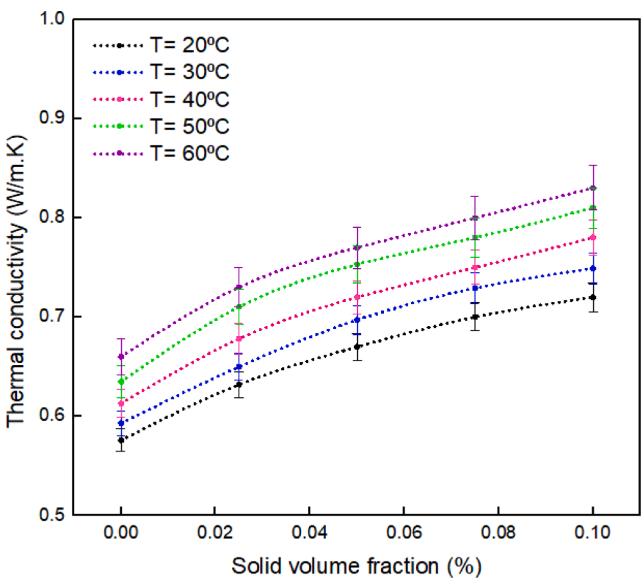

Fig. 10. Thermal conductivity of ZrO_2-SiC/DW at various volume fractions at all temperatures.

seen in the thermal conductivity of the base fluid and the nanofluid prepared by dispersing 0.025 % nanoparticles to distilled water. Moreover, at 20° C, thermal conductivity was enhanced by 9.06 % and 16.1 % respectively as the nanoparticle volume fraction was increased to 0.05 % and 0.075 %. Further increment in volume fraction to 0.1 % at the same temperature yields thermal conductivity of 20.8 %. With increasing concentrations of nanoparticles, they form clusters which result in more rapid heat transfer in comparison to the fluid state, hence enhancing thermal conductivity. The heat transfer is seen to be even more rapid when the size of nanoparticles is smaller due to the presence of a strong van der Waals force of attraction between smaller particles. The results indicate the rise in thermal conductivity from 4.36 % to 20.8 % at 20 °C with increasing volume fraction from 0.025 % to 0.1 % which implies that maximum thermal conductivity is associated with the highest volumetric fraction. As the temperature is increased to 30 °C, the DW shows a rise in the thermal conductivity by 6.03 % in comparison to the base fluid when the volume fraction is enhanced by 0.025 %. Likewise, increasing volume fraction to 0.05 %and 0.075 % yields a 10.44 % and 17.29 % rise in thermal conductivity respectively. In this way, the volume fraction was increased to 0.1 % which yielded thermal conductivity

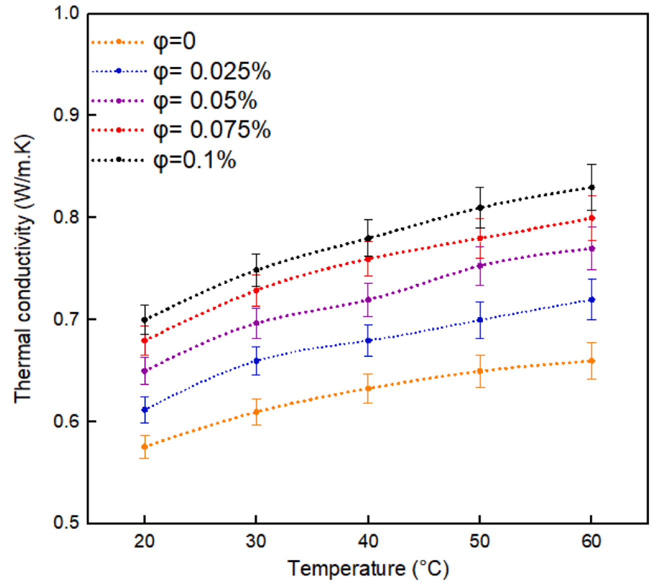

Fig. 11. Thermal conductivity of ZrO_2-SiC/DW at various temperatures at all volume fractions.

of 22.8 % at T = 30 °C. This rise in thermal conductivity with increasing concentrations of nanoparticles indicates that higher nanoparticle concentration in nanofluid and the consequent clustering helps enhance the thermal conductivity specifically at this temperature. The main phenomenon behind this rise in thermal conductivity is that when the temperature is increased, the kinetic energy of nanofluid molecules increases leading to higher energy levels and ultimately higher thermal conductivity. Temperature rise plays an important role in enhancing the thermal conductivity of nanofluids. If the temperature is maintained at T = 40 °C, the thermal conductivity difference between the nanofluid and base fluid reaches 8.68 % when the volumetric fraction is increased to 0.025 %. Hence, at a given temperature, thermal conductivity shows a positive association with increasing the volume fraction of nanoparticles. As the volume fraction was increased to 2.5 % at T = 40 °C, there was about an 23.22 % rise in the thermal conductivity which is the highest rise in the thermal conductivity. As the temperature was increased to 50 °C and the concentration of nanoparticles was increased to 0.025 %, there was a 10.07 % rise in the thermal conductivity. This trend continues and at the volume fraction of 0.1 %, a 25.58 % rise in the thermal conductivity is noted which is quite high in comparison to the thermal conductivity of base fluid at 50 °C. The study also indicated a 20.9 % rise in the thermal conductivity when the temperature of the base fluid changes from T = 20 °C to T = 50 °C and the volume fraction of nanoparticles is increased by 0. 075 %. The nanofluid shows a 10.6 % rise in thermal conductivity at T = 60 °C when the volume fraction is increased to 0.025 %. At a volume fraction of 0.1 %, the nanofluid shows 25.75 % higher thermal conductivity than base fluid provided the temperature is the same. It is, hence, evident that both temperature and volume fraction have a positive effect on thermal conductivity; however, the effect of volume fraction is significant in comparison to temperature.

3.3.2. *Influence of temperature on thermal conductivity*

The changes occurring in thermal conductivity with changes in temperature at various nanoparticle concentrations have been indicated in Fig. 11. The results in this figure indicate that a rise in temperature leads to a rise in the thermal conductivity of the nanofluid specifically when the solid volume fractions are higher. The thermal conductivity increases with a rise in temperature from 20 to 60 °C at a volume fraction of 0.025 %; the maximum thermal conductivity was recorded at 60 °C which is 10.6 % higher than base fluid. Similarly, the thermal conductivity of the base fluid and nanofluid almost showed similar

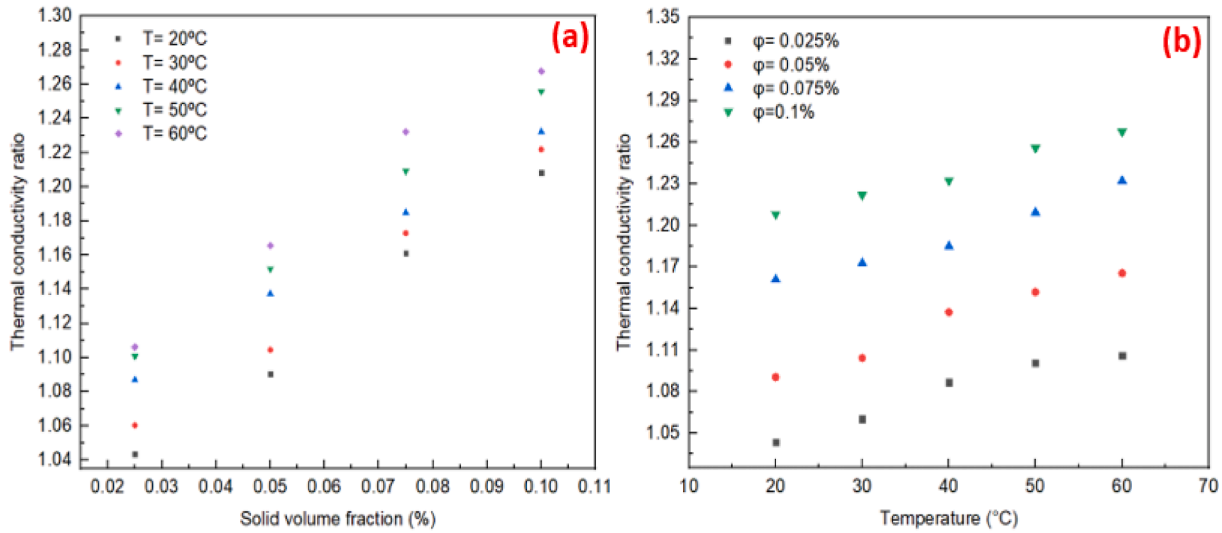

Fig. 12. Thermal conductivity ratio of ZrO_2-SiC/DW: (a) At various volume fractions at all temperatures (b) At various temperatures at all volume fractions.

values at a volume fraction of 0. 025 %. However, at a volume fraction of 0.05 %, the thermal conductivity of nanofluid showed the greatest change in comparison to that of base fluid when the temperature rose to 60 °C. The pattern of change suggests that the thermal conductivity showed a rise from 9.06 to 15.15 % as the concentration of nanoparticles in the base fluid was increased to 0.05 %. It is also noted that thermal conductivity depicts the maximum increment of 21.21 % at a volume fraction of 0.075 % at 60 °C. As the concentration is further increased to 0.1 %, a thermal conductivity enhancement of 25.75 % is obtained relative to the base fluid (DW) at 50 °C. It is also evident that thermal conductivity increases more proportionately when both temperature and volume fraction is higher. The greater rise in thermal conductivity may be attributed to greater movement of the particles and more clustering at higher temperatures and higher concentrations. Consequently, clusters facilitate heat transfer and thermal conductivity. In short, it can be said that thermal conductivity improves with increasing concentration of nanoparticles provided the temperature remains the same. The highest value of thermal conductivity was recorded at the volume fraction of 0.1 % and a temperature of 60 °C.

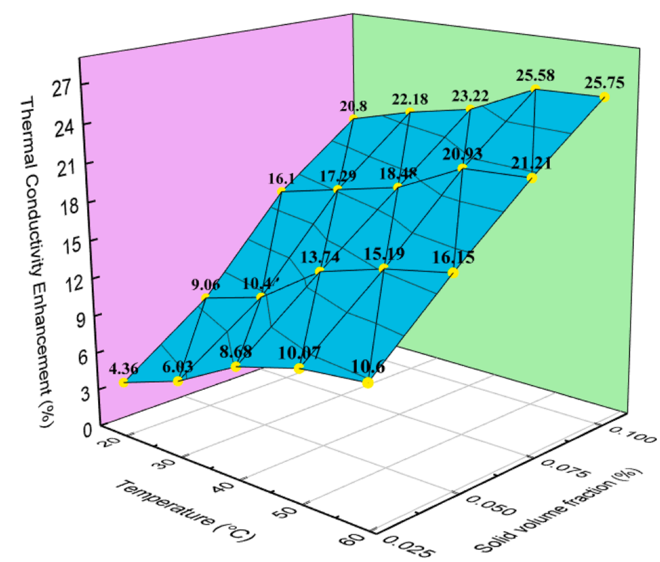

Fig. 13. TCE value of ZrO_2-SiC/DW hybrid nanofluid at different temperatures and volume fractions.

3.4. Thermal conductivity ratio

3.4.1. Influence of volume fraction on thermal conductivity ratio

The comprehension of thermal conductivity enhancement needs to understand the meaning of thermal conductivity ratio, expressed in Eq. (3), which is the thermal conductivity of a nanofluid divided by the thermal conductivity of the base fluid provided the temperature remains the same. thermal conductivity ratio allows comparison of the rise in thermal conductivity coefficient of the nanofluid and base fluid at various temperatures which enables the experts to gain valuable insight into how increasing volume fraction affects the thermal conductivity. Relative thermal conductivity is also explained with the help of a diagram that shows changes in thermal conductivity because of changes in volumetric fraction. The relative thermal conductivity is recorded at different temperatures to plot the graph of relative conductivity shown in Fig. 12a. It is evident from the figure that relative thermal conductivity increases with a rise in a volume fraction and temperature. This may be attributed to the clustering of particles at higher concentrations of nanoparticles in the fluid. The clustering is a useful process; however, when volume fractions are extremely high, it results in sedimentation which affects the stability of nanofluid. Besides this, there is also a significant effect on the fluid's viscosity due to the increasing concentration of nanoparticles in the fluid. Consequently, more viscous suspension calls for greater pumping power. Hence, thermal conductivity enhancement must be done using an ideal number of nanoparticles that increases thermal conductivity without making the suspension highly viscous. The thermal conductivity depicts the same behaviour at all temperatures which implies that the thermal conductivity of base fluid rises when nanoparticles are added to it. It is also noted that the surface-to-volume ratio also rises with increasing volume fraction which may be attributed to a rise in thermal conductivity. In short, a rise in temperature and volumetric fraction leads to higher thermal conductivity.

$$\text{Thermal conductivity ratio(TCR)} = \frac{k_{nf}}{k_{bf}} \quad (3)$$

3.4.2. Influence of temperature on thermal conductivity ratio

Different values of thermal conductivity were observed at different temperatures and different solid volume fractions which have been given in Fig. 12b. The values indicate that relative thermal conductivity does not show significant change with rising temperature provided the solid volume concentration is low since the Brownian motion is lower at lower concentrations. But, when the volume fraction is higher, the thermal conductivity rises due to the presence of a greater quantity of

Table 3
A summary of reports about hybrid nanofluids thermal conductivity enhancement compared to the present study.

Authors	Nanoparticle	Base fluid	Concentrationrange (%)	Temperature range (°C)	Maximum enhancement of thermal conductivity (%)
Zadkhast et al. (2017)	MWCNT-CuO	Water	0.05–0.6	25–50	30.38
Sarbolookzadeh Harandi et al. (2016)	FMWCNTs–Fe_3O_4	EG	0.1–2.3	25–50	30
Toghraie et al. (2016)	ZnO–TiO_2	EG	0.1–3.5	25–50	32
Soltanimehr and Afrand (2016)	COOH-MWCNTs	EG-Water	0.025–1	25–50	34.7
Moghadam et al. (2020)	GO + TiO_2	Water	0.05–1.0	20–50	32.8
Taherialekouhi et al.(2019)	GO + Al_2O_3	Water	0.1–1.0	25–50	33.9
Esfe et al., 2015a	Ag–MgO	Water	0–2	25	16
Esfe et al., 2015b	Cu-TiO_2	Water-EG	0.1–2	30–60	24
Hemmat Esfe et al.(2016)	CNT–Al_2O_3	Water	0.02–1	30–60	18
Moradi et al. (2020)	TiO_2-MWCNT	EG-water	0.0625–1	20–60	34.31
Abbasi et al. (2013)	Al_2O_3–MWCNT	H2O	0.1	20–50	14.75
Moldoveanu et al. (2018)	SiO_2- Al_2O_3	Water	1–3.0	20–50	23.61
Nabil et al. (2017)	TiO_2-SiO_2	Water	0.5—3.0	30–80	22.8
Hemmat Esfe et al. (2018)	MWCNT-SiO_2	EG	0.025–0.86	30–50	20.1
Hemmat Esfe et al. (2017)	SWCNTs-MgO	EG	0.05–2	30–50	18
Present study	ZrO_2-SiC	Water	0.025–0.1	20–60	25.75

fluid particles at higher concentrations leading to the clustering of particles. The clustering accelerates heat transfer since heat transfers more quickly from a solid phase in comparison to the fluid phase. Considering temperature changes, as the temperature rises, the Nano-particles move faster leading to higher relative conductivity because of more frequent collisions of surface atoms with fluid molecules. The highest relative thermal conductivity was noted at 60 °C when the solid volume fraction was 0.1 %. Different values were obtained for the relative thermal conductivity of the nanofluid at different temperatures between 20 and 60 °C at different volume fractions. By observing the results, the recorded values indicated that rising temperature and increasing volume fraction caused an increment in relative thermal conductivity.

3.5. Thermal conductivity enhancement

Fig. 13 shows the results of the thermal conductivity enhancement (TCE) of ZrO_2-SiC/DW hybrid nanofluid recorded at various solid volume fractions and temperatures. The maximum thermal conductivity enhancement noticed for hybrid nanofluids is about 25.75 %. The highest value of thermal conductivity enhancement, expressed in Eq. (4), was observed at the highest volume fraction of 0.1 % and a temperature of 60 °C. The main reason behind the higher thermal conductivity of nanofluids than base fluid is that there is a greater number of nanoparticles in the nanofluids which depict greater movement at higher temperatures resulting in more nanoparticle collisions and consequently higher energy levels. Hence, we conclude that the introduction of hybrid nanofluids is a landmark in improving the nanofluids in terms of their thermal performance. Likewise, this study is an important contribution to the literature relevant to nanofluids since it suggests replacing the conventional fluids with hybrid nanofluids. The results obtained in the current study for the thermal conductivity of hybrid nanofluids were compared with the results of earlier studies as depicted in Table 3.

$$\text{Thermal conductivity enhancement}\,(\%) = \frac{k_{nf} - k_{bf}}{k_{bf}} \times 100 \quad (4)$$

3.6. Experimental correlation

Due to the absence of a correlation for effectively predicting the thermal conductivity of ZrO_2-SiC/DW hybrid nanofluid, this work will use measurement results to put forward a mathematical correlation that considers thermal conductivity as a function of temperature and volumetric fraction. This study uses the Sigma Plot program based on the use of the Levenberg–Marquardt algorithm as well as the fitting method to analyse experimental data. As a result, the study came up with a new

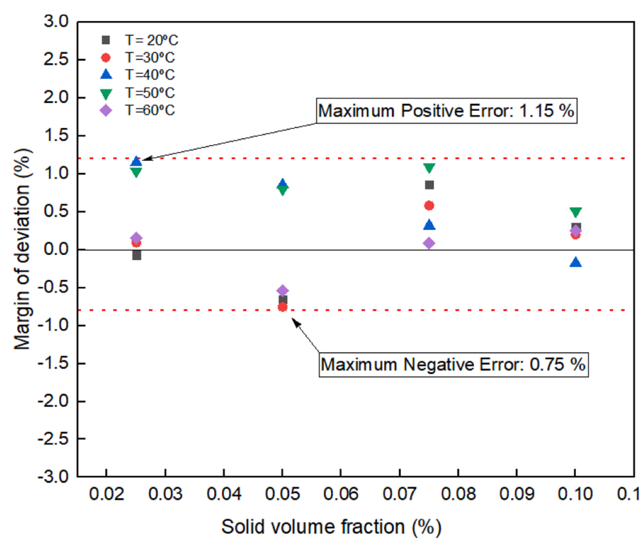

Fig. 14. Margin of deviation.

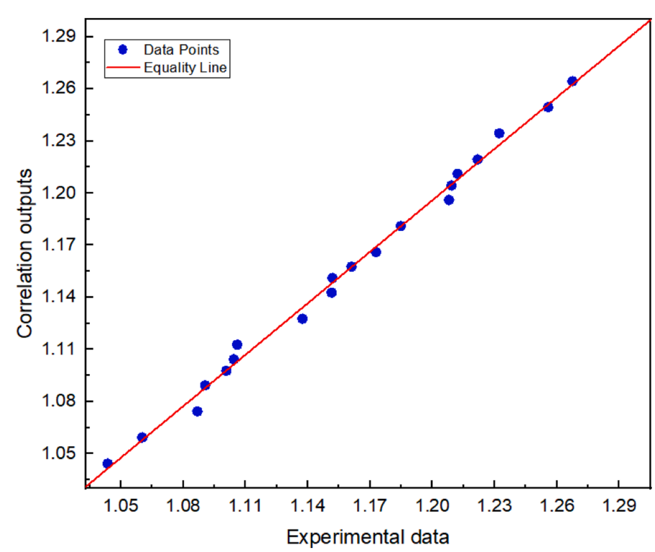

Fig. 15. Comparison between laboratory results and outcomes of proposed correlation.

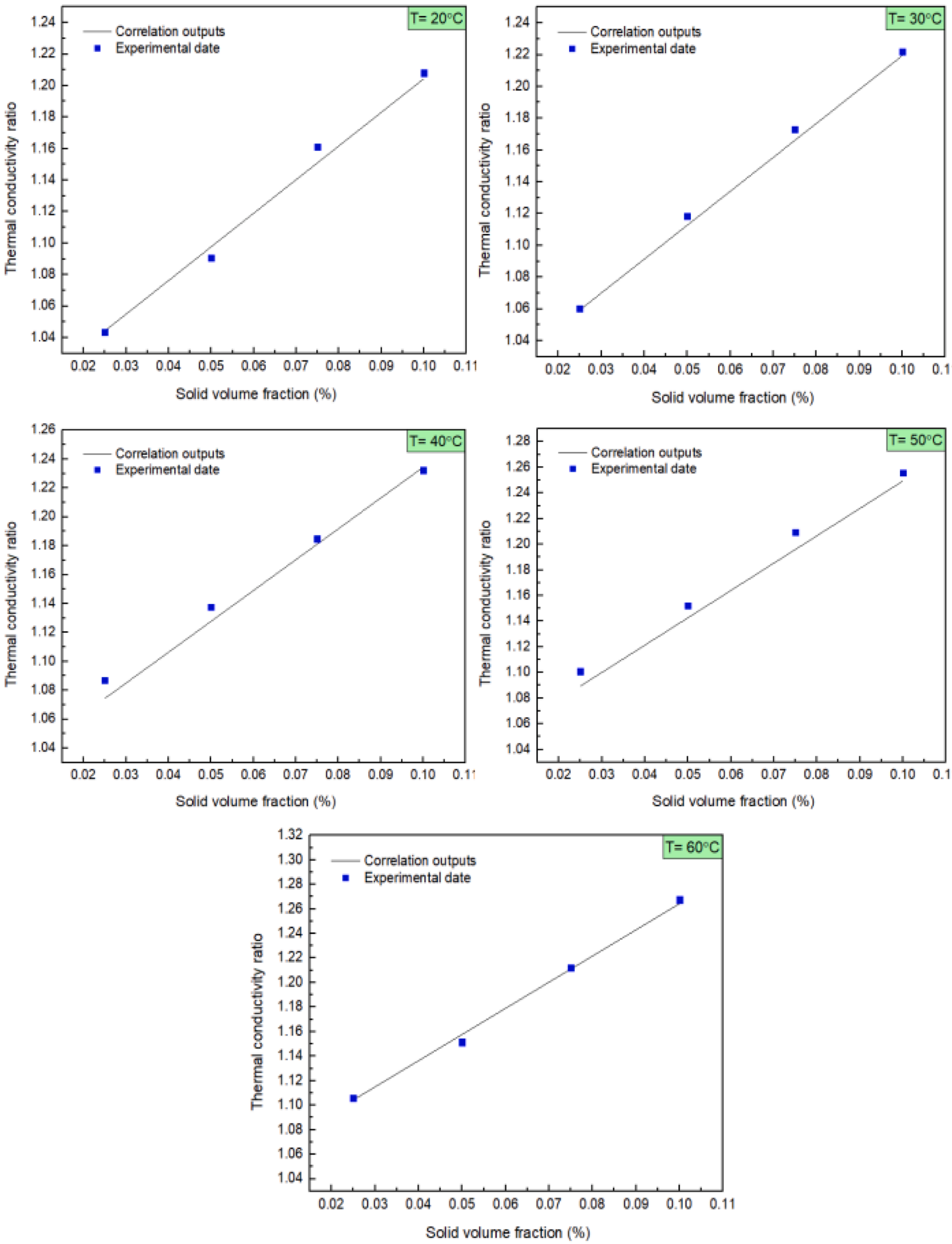

Fig. 16. Comparisons between the laboratory results with the outputs achieved from proposed correlation at different temperatures.

model. The new model enabled the researcher to use the temperature and concentration values of the given nanofluids to estimate their thermal conductivity. In short, the study yields a mathematical expression to determine the relative thermal conductivity of ZrO_2-SiC/DW hybrid nanofluids by inserting experimental values in the expression. This correlation, as shown in Eq. (5), applies to engineering implementations due to high accuracy ($R^2 = 0.9906$).

$$\frac{k_{nf}}{k_{bf}} = 0.961197 + 2.13426\,\varphi + 0.00157\,T \quad (5)$$

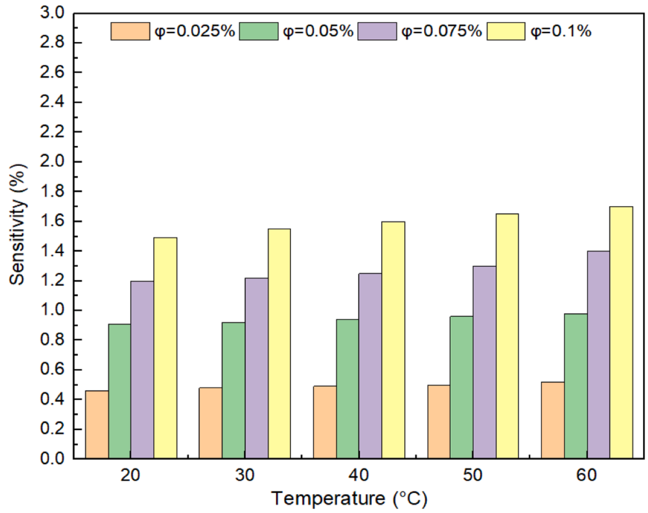

Fig. 17. Sensitivity analysis.

3.7. Exactness of the proposed correlation

The proposed correlation is checked for exactness by considering the experimental results of nanofluid samples. The relationship is considered as a margin of deviation (MoD), expressed in Eq. (6), to check the accuracy of the proposed correlation. Fig. 14 shows the values of the maximum and minimum margin of deviation between the correlation and results obtained in a laboratory. The maximum value is 1.15 % while 0.75 % was the lowest. This MoD value is an acceptable for an experimental correlation. According to Fig. 15, the most of points are adjoining the bisector or on it depicted that there is a high match between the values achieved by laboratory and the findings of the correlation.

$$\mathrm{MoD}\,(\%) = \left[\frac{\left(\frac{k_{nf}}{k_{bf}}\right)_{Exp} - \left(\frac{k_{nf}}{k_{bf}}\right)_{Pred}}{\left(\frac{k_{nf}}{k_{bf}}\right)_{Exp}}\right] \times 100 \quad (6)$$

This section entails Fig. 16 which depicts the values of the thermal conductivity ratio at different temperatures recorded during the experiment as well as the values evaluated from the proposed correlation. The graphs present a clear comparison of output mathematical equation and the laboratory results at different temperature and volume fractions. It is also evident from graphs that despite the diversity in the temperatures, the relation depicts similar behaviour.

3.8. Sensitivity analysis

Fig. 17 shows the sensitivity analysis performed for examining the thermal conductivity ratio of ZrO2-SiC/DW nanofluid. The sensitivity analysis, expressed in Eq. (7), involved consideration of four different nanoparticle concentrations or solid volume fractions (0.025 %, 0.05 %, 0.075 %, and 0.1 %). Moreover, the analysis considers five different temperature points (20 °C, 30 °C, 40 °C, 50 °C and 60 °C). Each column in the analysis shows a certain temperature and the corresponding solid volume fractions. The analysis revealed that as the solid volume fraction rises from 0.025 % to 0.1 %, the thermal conductivity ratio shows increasing sensitivity. The same kind of observations was indicated by various experts with several studies. Hence, it can be said that the sensitivity analysis is widely used by industrial engineers all over the world to help them make educated guesses and offer economic feasibility about the impact that different variables will have on a given decision.

$$\mathrm{Sensitivity}\,(\%) = \left[\frac{\mathrm{TCR}_{\text{after change}}}{\mathrm{TCR}_{\text{before change}}} - 1\right] \times 100 \quad (7)$$

4. Future recommendations

The authors highlighted that research needs to focus on factors that affect nanofluid properties. An insight into these factors will be useful when applying nanofluids in various engineering devices and applications. The following are some of the recommendations put forward in this study for potential work in the domain of nanofluid.

- This study is limited in terms of considering the changes in hybrid nanofluid thermal conductivity under the effect of solid volume fraction and temperature. As per the study outcomes, nanofluid thermal conductivity increased with increasing temperature and an increase in the solid volume fraction of nanoparticles. Therefore, it is suggested to study the effect of other factors like base fluid, dimensions of nanoparticles, their aggregation, structure, pH value, and sonication time to facilitate better estimation of nanofluid thermal conductivity. As a result, researchers will be able to develop more efficient thermal systems by using the appropriate type of nanofluid.
- The hybrid nanofluid preparation is both complex and costly. Future research must try to figure out economical nanofluids with good thermal performance.
- The thermophysical and rheological properties of hybrid nanofluids depicted in this study have not been discussed extensively. Therefore, the study also emphasizes more research on these properties of nanofluids. These properties enable the experts to prepare hybrid nanofluids that enhance the performance of different engineering applications.
- Another drawback is the inclination of nanoparticles to undergo hybridization or dispersion in base fluids. There is a need for further researches into this property of nanoparticles and to determine combinations of nanoparticles and base fluid that correspond to better efficiency.

5. Conclusion

In this work, ZrO_2 and SiC nanoparticles dispersed in distilled water to create a hybrid nanofluid, and then, to evaluate its effect on thermal conductivity. XRD, TEM, FESEM, and EDX were used to analyses the morphological characteristics of the nanoparticles. The preparation of a hybrid nanofluid was conducted exclusively for enhancing the thermal conductivity of base fluid, DW. The thermal conductivity was evaluated at a different volume fraction of hybrid nanofluid (i.e., at 0.025 %, 0.05 %, 0.075 %, and 0.1 %). Moreover, the thermal conductivity evaluations were conducted at different temperatures of 20, 30, 40, 50, and 60 °C. Next, the fitting method was applied to the data obtained from the experiment to obtain new hybrid correlation. This correlation was used for the evaluation of the thermal conductivity of ZrO_2-SiC/DW hybrid nanofluid. Next, the accuracy of the data derived from correlation was checked by comparing it with practical data which revealed high accuracy of data. The following list entails the research outcomes:

- The stability of ZrO_2-SiC/DW hybrid nanofluid, which was tested by zeta potential analysis, was good stability.
- The thermal conductivity of the examined nanofluid increased with rising temperature and higher solid volume fraction.
- Maximum thermal conductivity ratio was noted in solid volume fraction of 0.1 % at 60 °C.
- It was discovered that the effect of higher volume fraction on thermal conductivity on nanofluid outshines the effects of temperature.
- When the thermal conductivity of hybrid nanofluid was checked at different temperatures (20 °C-60 °C) and different volume fractions

(0.025 % − 0.1 %), the nanofluid was found to show the highest value of thermal conductivity enhancements (TCE) of 25.75 % in the presence of volume fraction of 0.1 % and temperature of 60 °C.
- The comparison of the results obtained from the proposed correlation with the experimental data showed a 1.15 % margin of deviation and R^2 value of 99.06 %.
- Maximum sensitivity of thermal conductivity of hybrid nanofluid is 1.7 %.

CRediT authorship contribution statement

Ahmed M. Ajeena: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Istvan Farkas:** Conceptualization, Methodology, Supervision. **Piroska Víg:** Conceptualization, Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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