Enhancing thermal conductivity of water/CeO_2-MWCNTs hybrid nanofluid: experimental insights and artificial neural network modeling

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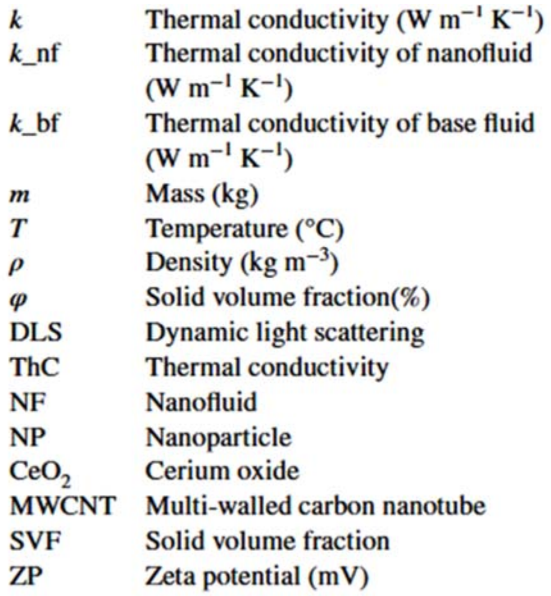
Abstract

Water/CeO_2-MWCNTs hybrid (NF) is a novel type of NF that has potential applications in heat transfer and thermal energy storage. However, the thermal conductivity (ThC) of this NF is not well understood. In this study, we aim to estimate the stability and investigate the ThC of water/CeO_2-MWCNTs hybrid NF experimentally. We prepared the NF by dispersing CeO_2-MWCNTs nanoparticles in deionized water using ultrasonication spanning 5–30 min. We measured the ThC of the NF at different temperatures and concentrations using a transient hot-wire method. Assessment of hybrid NF stability involved measurements of zeta potential and particle size distribution through dynamic light scattering (DLS). Meanwhile, ThC assessments were conducted across different solid volume fractions ($0.007 \leq \text{SVF} \leq 0.112\%$) and temperatures (20–50 °C). Results underscored the hybrid NF's impressive stability and notably enhanced ThC. Longer sonication times, particularly at 30 min, positively impacted both stability and ThC. SVF and temperature also exerted substantial effects, with the most significant enhancement occurring at 0.112% SVF and 50 °C. To forecast the hybrid NF's ThC, a novel correlation and artificial neural network model were developed with a commendable level of accuracy (*R*-squared = 0.9918 and maximum deviation of 0.438%). We compared our results with similar hybrid NFs reported in the literature and discussed the possible mechanisms of ThC enhancement. Our study provides new insights into the thermal behavior of water/CeO_2-MWCNTs hybrid NF and its potential application in thermal engineering systems.

Keywords: Hybrid nanofluid; Two-step method; Thermal conductivity; Sonication time; Volume fraction; Temperature

Abbreviations



k	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_nf	Thermal conductivity of nanofluid ($W\ m^{-1}\ K^{-1}$)
k_bf	Thermal conductivity of base fluid ($W\ m^{-1}\ K^{-1}$)
m	Mass (kg)
T	Temperature (°C)
ρ	Density ($kg\ m^{-3}$)
φ	Solid volume fraction(%)
DLS	Dynamic light scattering
ThC	Thermal conductivity
NF	Nanofluid
NP	Nanoparticle
CeO_2	Cerium oxide
MWCNT	Multi-walled carbon nanotube
SVF	Solid volume fraction
ZP	Zeta potential (mV)

Introduction

The heightened interest in improving heat transfer has led to a growing fascination with Nanofluids (NFs) in recent years. These NFs consist of nanoparticles (NPs) suspended within base fluids, presenting intriguing possibilities for various applications [1,2,3]. NFs can provide higher thermal conductivity (ThC) compare to their base fluids, improving the performance of various heating/cooling systems such as heat exchangers, solar collectors, nuclear reactors, and microelectronics cooling. However, the stability of NFs is a major challenge that affects their ThC and rheological properties. Hence, it is important to investigate the factors that influence NFs' stability and ThC [4,5,6].

One of the factors that can affect the stability and ThC of NFs is the type and size of NPs. Among various NPs, metal oxides widely used as NF additives due to their high ThC, low cost, and easy availability [7, 8]. Cerium oxide (CeO_2) has garnered significant interest among metal oxides thanks to its distinctive characteristics, including a high specific surface area, remarkable oxygen storage capacity, and exceptional catalytic activity. The CeO_2 is a high-potential NP that can increase the ThC of water-based NFs. Water/CeO_2-MWCNTs hybrid nanofluid has been reported to exhibit enhanced thermal conductivity, specific heat capacity, and viscosity compared to pure water. These properties make it a promising candidate for various applications, such as solar desalination, water-based lubrication, and heat transfer enhancement [9, 10].

Another factor affecting NFs' stability and ThC is the presence of hybrid NPs [11, 12]. Hybrid NPs are composed of two or more different materials that can synergistically improve the properties of NFs. For instance, multi-walled carbon nanotubes (MWCNTs) have been used as hybrid NPs with metal oxides to enhance NFs' stability and ThC [13,14,15].

Sonication time is another important factor affecting the ThC of hybrid NFs. Sonication is a common technique to disperse NPs in base fluids by applying ultrasonic waves that generate cavitation bubbles and shock waves [16,17,18]. Sonication can break the agglomerates of NPs and improve their dispersion and stability in NFs. However, sonication can also cause damage to the NPs and change their morphology and size. In addition, temperature can influence the viscosity, density, specific heat, and ThC of both base fluids and NPs. Temperature can also affect the Brownian motion, thermophoresis, and convection of NPs in NFs, which can alter their distribution and interaction. Therefore, it is fundamental to study the temperature-dependent behavior of NFs [19,20,21].

Understanding and optimizing these factors can help design and develop NFs with enhanced and tunable properties for various applications. Moreover, developing novel NFs with hybrid or functionalized NPs can offer new opportunities and challenges for heat transfer research. In this paper, we focus on one of the promising types of NFs, namely water/CeO_2-MWCNT hybrid NF, and experimentally investigate its stability and ThC under different conditions.

Minea and Moldoveanu presented an overview of the development and benefits of hybrid NFs [22]. This article provides an overview of the development and uses of hybrid NFs. The authors review the various types, properties, preparation methods, and applications of hybrid NFs. They highlight the advantages of hybrid NFs over single-component NFs in terms of stability, ThC, viscosity, heat transfer coefficient, and heat transfer enhancement. They also discuss the challenges and future prospects of hybrid NFs research.

The effective ThC of NFs, which are dispersions of solid particles in a liquid continuous phase, was investigated experimentally by Berger Bioucas et al. [23]. The authors used a steady-state guarded parallel-plate instrument to measure the ThC of water-based NFs with TiO_2, SiO_2, and polystyrene NPs of varying sizes and shapes. They also used microscopy, sedimentation, and dynamic light scattering to analyse the particle size, shape, and distribution, and dispersion stability. Utilizing a theoretical framework, they incorporated considerations for heat transfer mechanisms within the base fluid and particles, along with micro-convection generated by the Brownian motion of these particles. The model undergoes re-evaluation and refinement to align with experimental findings and existing models. The authors found that the effective ThC of NFs is moderately dependent on the solid volume fraction (SVF) and the ThC of the particles. The authors suggested that the proposed model can be used for predicting the ThC of NFs containing fully dispersed particles.

Pourrajab et al. [24] conducted experimental research to significantly improve the ThC of a water-based NF comprising MWCNTs–COOH and Ag NPs. This article presents their experimental findings related to the ThC of this hybrid NF. The authors created the hybrid NF using a two-step method, varying sonication times and SVFs. ThC measurements were conducted using the transient hot-wire method at different temperatures. Their results revealed that the hybrid NF outperformed water/Ag NF regarding ThC. Additionally, they introduced a novel correlation for predicting the ThC ratio of the hybrid NF.

Guan et al. [25] employed molecular dynamics simulations to investigate the enhanced ThC in a hybrid nanofluid (Cu–Ag/Ar). They explored why hybrid nanofluids perform better and used various tools like the Green–Kubo equation and diffusion coefficients for analysis. They discovered that ThC initially increased with the hybridization ratio, peaking at 50% Ag content before declining. They attributed this to nanolayer structures and Ar atom diffusion. The study suggests that selecting the right materials and ratios can enhance ThC in nanofluids, with implications for heat transfer applications.

One of the recent studies on hybrid NFs was conducted by Hemmat Esfe et al. [26], who compared the ThC of two hybrid NFs with the same NPs of MWCNT and TiO2, but different base fluids (BFs) of water-EG with 50:50 and 80:20 ratios. They prepared the hybrid NFs using a solid-state reaction method and measured their ThC using a hot-wire method and a KD2-Probe machine1. They found that the ThC of hybrid NFs increased with temperature and SVF, and that the hybrid NF with water-EG (80:20) showed higher ThC enhancement than the HNF with water-EG (50:50). They also introduced a new index called price performance factor to evaluate the economic feasibility of hybrid NFs. They concluded that the MWCNT-TiO_2 (15:85)/Water-EG (80:20) hybrid NF was the most desirable hybrid NFs for industrial applications.

Artificial neural networks (ANNs) are powerful machine learning tools that can be used to model and predict the thermophysical properties of nanofluids, such as viscosity and thermal conductivity, based on experimental or theoretical data [27, 28]. Aylı and Kocak [29] proposed a supervised learning method based on a hybrid genetic algorithm (GA) and artificial neural network (ANN) to predict the heat transfer coefficient and Nusselt number of nanofluids. The method is applied to Al_2O_3/water and TiO_2/water nanofluids and agrees well with experimental data. We focus on the thermal conductivity of water/CeO_2-MWCNTs hybrid nanofluid, a novel nanofluid type with promising applications in heat transfer systems.

In this study, we experimentally investigate the stability of water/CeO_2-MWCNTs hybrid NF. We prepare the hybrid NF by using a two-step method with different sonication times. We measure the stability of the hybrid NF by using zeta potential and measuring particle size by dynamic light scattering technique. Moreover, in this study, we investigate the ThC of water/CeO_2-MWCNTs hybrid NF using both experimental and computational methods. We measure the ThC of the hybrid NF by using the transient hot-wire method. We analyse the influences of sonication time, temperature, and SVF on the ThC of the hybrid NF. We provide a comprehensive and reliable analysis of the effects of various parameters on the ThC of the hybrid NF. This is the first study to develop a novel correlation and an artificial neural network model to predict the ThC of water/CeO_2-MWCNTs hybrid NF. The proposed models are based on the experimental data obtained in this study and have high accuracy and applicability. The models can be used to estimate the ThC of the NF for different concentrations and temperatures at different sonication times, without the need for costly and time-consuming experiments. We compare our results with those reported in the literature for similar NFs.

Materials and methods

Nanoparticles

The CeO_2 NPs were purchased from US Research Nanomaterials Inc. The CeO_2 NPs had a purity of 99.97% and a particle size of 10–50 nm. The FESEM results of the CeO_2 NPs are shown in Fig. 1a and b. The CeO_2 NPs were spherical and well dispersed without significant agglomeration. The size distribution of the CeO_2 NPs measured using the Image software and showed. The FESEM images also show the morphology and surface features of the CeO_2 NPs, which indicate their high specific surface area value. The CeO_2 NPs had a light yellow color. The specific surface area of the CeO_2 NPs was 30–50 $m^2\ g^{-1}$ and the bulk density was ~ 0.8–1.1 $g\ cm^{-3}$.

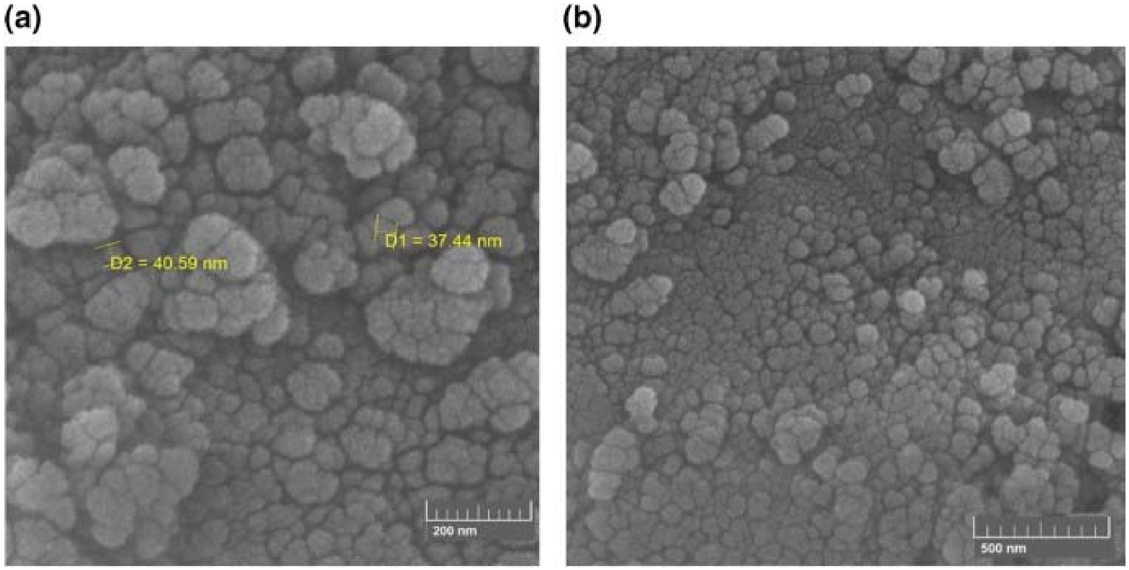


Fig. 1. FESEM images of the CeO_2 NPs employed in this research. **a** The scale bar is 200 nm and **b** The scale bar is 500 nm

The MWNTs NPs were purchased from US Research Nanomaterials Inc. The MWNTs NPs had a purity of more than 95 mass% (CNTs) and more than 97 mass% (CNTs). The MWCNTs NPs were functionalized with –COOH groups, with a content of 0.49 mass%. The MWCNTs NPs had an average outer diameter of 30–80 nm, an average inner diameter of 5–15 nm, and an average length of 10–20 µm. The FESEM image of the MWCNTs is shown in Fig. 2a and b. The MWNTs NPs had a tubular shape and were entangled, forming a network structure. The specific surface area of the MWNTs NPs was more than 40 $m^2 g^{-1}$ and the color was black. The MWNT NPs were synthesized by the chemical vapor deposition (CVD) method.

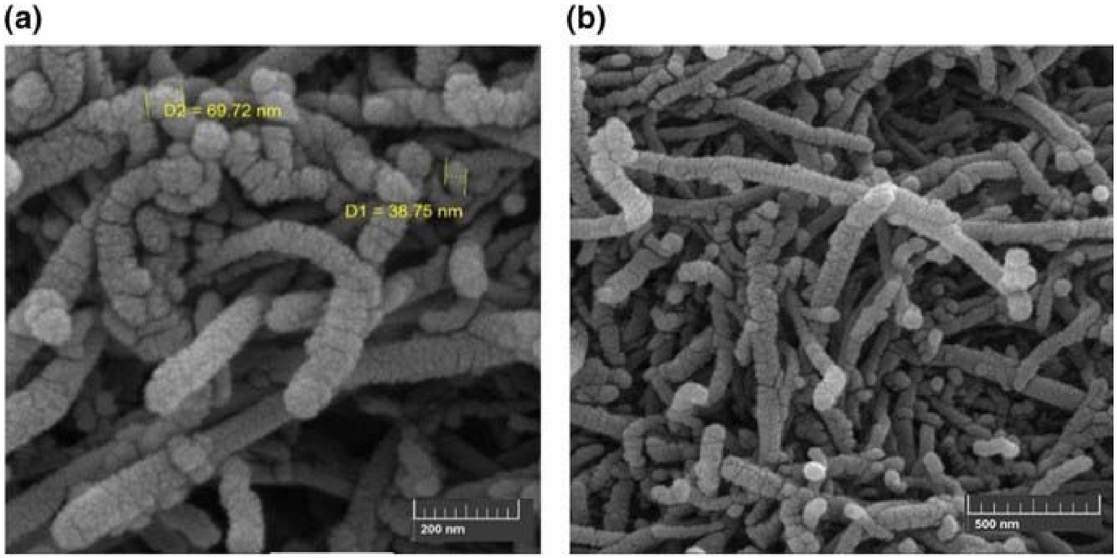


Fig. 2. FESEM images of the MWNTs employed in this research. **a** The scale bar is 200 nm, and **b** the scale bar is 500 nm

The FESEM images of the nanoparticles were obtained using a TESCAN MIRA3 scanning electron microscope with a Schottky field-emission electron source, which offers high-resolution and high-throughput imaging and analysis of materials at the sub-micron scale. The instrument was manufactured by TESCAN in Brno, Czech Republic.

Two-step preparation of the hybrid NF

A hybrid NF comprising water/CeO_2-MWNTs was prepared using a two-step method. This approach involves dispersing NPs in the base fluid through physical or chemical techniques [30, 31]. This investigation employed the physical ultrasonication technique to disperse the NPs within the base fluid, which was deionized water with a pH of 7. The NPs, specifically CeO_2 and MWNTs, possessed purities of 99.97% and 95 mass%, respectively, and were procured from the US Research Nanomaterials Inc. To determine the SVF, Eq. (1) was utilized, and the NPs' mass was measured with a precision of 0.001 g using a digital scale. Subsequently, the hybrid NPs were introduced into the deionized water in a beaker and stirred magnetically for one hour. The mixture was then transferred to an ultrasonic device and subjected to sonication for varying durations ranging from 5 to 30 min. The sonication parameters included a power of 400 W and a frequency of 24 kHz. This sonication process was integral for dispersing NPs, breaking their agglomerates, and enhancing their stability within the base fluid. Following sonication, the hybrid NF samples were sealed in bottles for subsequent experiments.

$$\varphi = \frac{\left(\frac{m}{\rho}\right)_{\mathrm{MWNTs}} + \left(\frac{m}{\rho}\right)_{\mathrm{CeO_2}}}{\left(\frac{m}{\rho}\right)_{\mathrm{MWNTs}} + \left(\frac{m}{\rho}\right)_{\mathrm{CeO_2}} + \left(\frac{m}{\rho}\right)_{\mathrm{bf}}} \times 100 \tag{1}$$

In the current equation, φ, ρ, and m represent SVF, density, and mass, respectively, used for cerium oxide (*CeO2*), multi-walled carbon nanotubes (*MWNTs*), and base fluid (bf).

We used a Hielscher UP400St Ultrasonic Processor (Hielscher Ultrasonics, Teltow, Germany) to disperse nanoparticles in the basefluid. This is a powerful and reliable device for the sonication of larger samples in the laboratory or for producing small quantities. It can operate at 400 watts and 24 kHz and can measure and adjust the amplitude and pulse of the ultrasound. The device can sonicate sample volumes from 5 to 4000 mL or up to 50 L h^{-1} in a flow cell.

Thermal conductivity measurement

The measurement of ThC is a crucial step in assessing the heat transfer performance of NFs. ThC measurement provides insights into how factors like nanoparticle concentration, size, shape, and type impact the thermal properties of NFs [32, 33]. In this study, we employed the transient hot-wire method, renowned for its high accuracy in ThC measurements. The transient hot-wire method relies on Fourier's law of heat conduction, which establishes a relationship between heat flux, temperature gradient, and ThC. This method employs a thin metallic wire serving both as a heat source and a temperature sensor. The wire is immersed in the fluid and heated by an electric current, while the temperature rise of the wire is recorded over time. The ThC of the fluid can be calculated using an appropriate mathematical model. To conduct ThC measurements, we used a KD2 Pro thermal analyser device from Decagon Devices in the USA. This portable device can measure the ThC, thermal diffusivity, and specific heat of various materials. It boasts high accuracy and can operate effectively across a range of temperatures. According to the operator’s manual of the KD2 Pro thermal properties analyzer, the experimental error for the KD2 is ± 5% for thermal conductivity.

Stability analysis

Stability analysis is a crucial step to evaluate the quality and performance of NFs. Stability analysis can reveal the degree of dispersion and agglomeration of hybrid particles in the water, which can affect NFs' ThC and viscosity values. In this study, particle size distribution was measured using dynamic light scattering (DLS) technique and stability analysis was performed using zeta potential measurement. DLS analysis is a physical method that can determine the size distribution and mean size of particles in solutions and suspensions. The DLS technique is based on the Mie theory, which relates the intensity of scattered light to the size and concentration of NPs. The mean size of dispersed NPs estimated by using the VASCO™ analyzer. Zeta potential measurement is a chemical method indicating NPs' surface charge and electrostatic repulsion in the base fluid.

The zeta potential of the hybrid nanofluid was measured using a SZ-100 nanoparticle analyzer (HORIBA Scientific, Japan), which can determine the surface charge and electrostatic repulsion of nanoparticles in the base fluid based on the electrophoretic mobility of the particles. The device requires a small sample volume of 100 μL and can measure zeta potential from − 500 mV to + 500 mV2. The measurements were repeated three times for each sample.

Zeta potential measurement can provide information about NPs' stability and aggregation tendency.

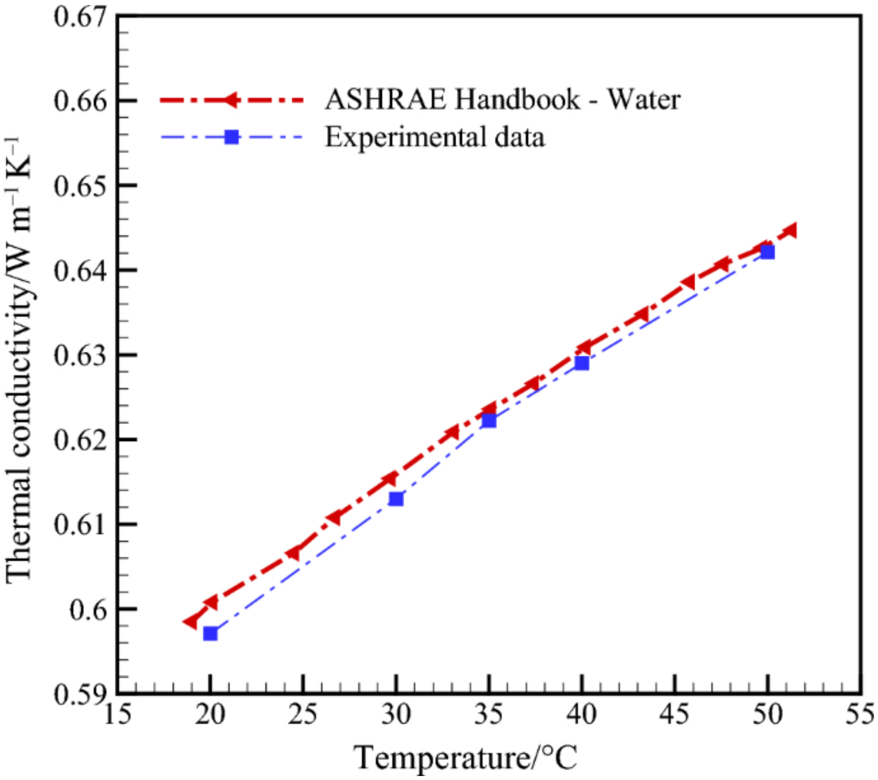


Fig. 3. Comparison of the experimental data with ASHRAE Handbook [34] for water

Validation

The validation analysis was performed to demonstrate the high accuracy of the experimental equipment and method in measuring the ThC of the hybrid NF. The validation analysis was conducted over the studied range of temperatures (20–55 °C). The measured ThC data of the base fluid were compared with the ASHRAE handbook [34] as a benchmark reference. Figure 3 shows the comparison results. As can be seen, the measured ThC data of the base fluid were in good agreement with the reference data, with a maximum deviation of 1%. This indicates that this study's experimental equipment and method were reliable and accurate.

Results and discussion

Stability of the NF

The particle size distribution of the Water/CeO_2-MWCNTs hybrid NF is monodisperse, which means that the NPs have a uniform size and shape. This is desirable for many applications, as it ensures a stable and homogeneous hybrid NF with enhanced thermal properties.

As a physical approach, the dynamic light scattering technique can determine the distribution and mean size of the particles dispersed in the base fluid. The result is shown in Fig. 4. The results demonstrated the diameter of the hybrid particles based on the diffraction of the laser light with a wavelength of 657 mm hitting the NPs. In this analysis, larger particles diffracted at higher intensities. The mean diameter of NPs is 147.0 nm. This indicates the hybrid NPs are small enough to exhibit quantum effects and high surface area. The result confirms that the NF is monodisperse and has a single peak in the frequency graph.

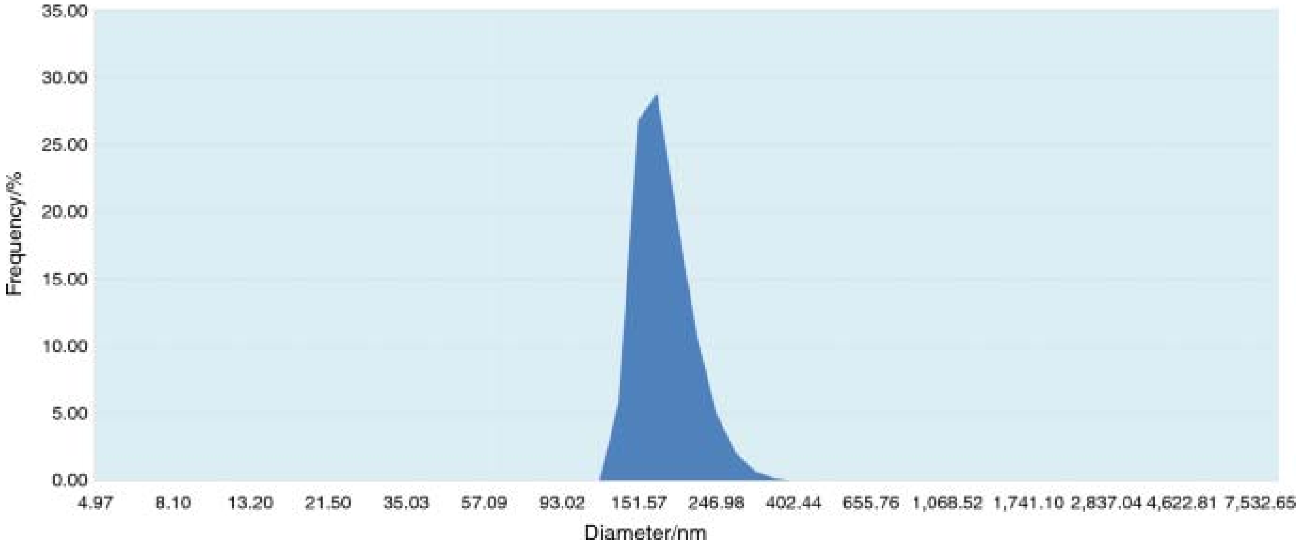


Fig. 4. Distribution of particle diameters measured by DLS

In summary, the DLS test result in Fig. 4 shows that NF has successfully prepared with monodisperse NPs of 147.0 nm in diameter. This is an impressive achievement, as it is not easy to disperse NPs with such a high degree of uniformity. This hybrid NF has excellent potential for various applications, such as heat transfer and energy conversion.

Figure 5 shows that the zeta potential (mean value) of the Water/CeO_2-MWCNTs hybrid NF is − 75 mV, which is a measure of the electrical charge on the surface of the hybrid NPs in the dispersion medium. The zeta potential result indicates the stability of the NF, as it reflects the repulsive force between the NPs that prevents them from aggregating or settling. Figure 5 shows the result. A zeta potential of − 75 mV is considered to be highly negative, which means that the NPs are strongly repelling each other and are well dispersed in the water. This is desirable for many applications, as it ensures a stable and homogeneous NF with enhanced thermal properties.

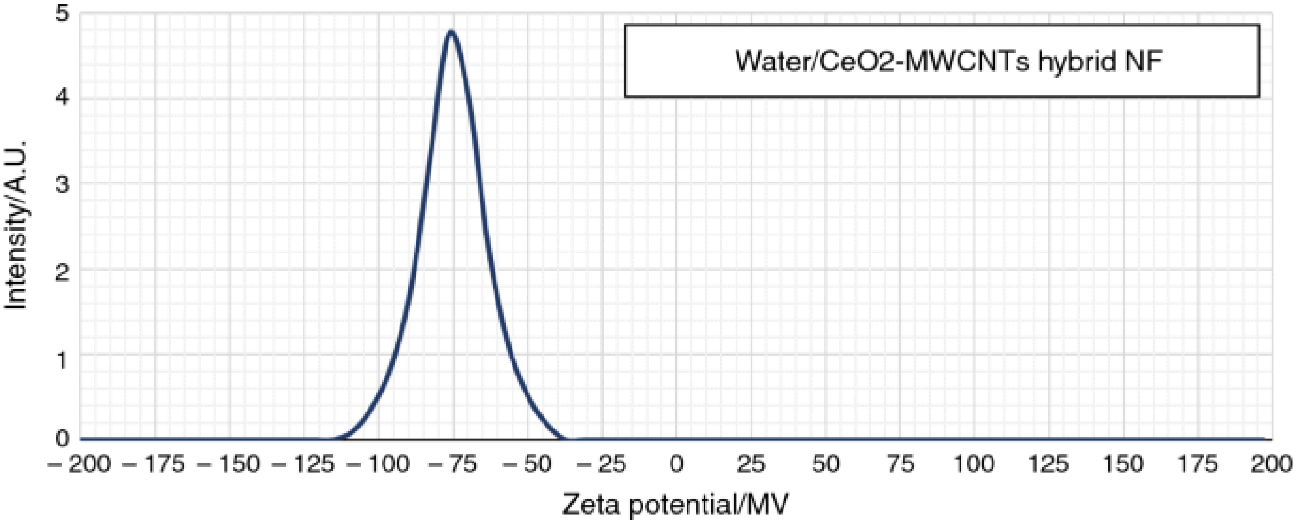


Fig. 5. Zeta potential distribution of water/CeO_2-MWCNTs hybrid NF

The electrophoretic mobility of the hybrid NF was − 0.000581 cm^2/Vs, which measures the velocity of the NPs in an electric field. The electrophoretic mobility is related to the zeta potential by the Smoluchowski equation, which assumes that the NPs are spherical and have a thin double layer. The electrophoretic mobility can be used to calculate the zeta potential, or vice versa, using this equation.

The zeta potential distribution of this hybrid NF shows a single peak at − 75 mV, which means that NPs have a uniform charge and size. This confirms that the NF is monodisperse, as the DLS test results show. A single peak in the zeta potential distribution indicates a low polydispersity index, which measures the width and shape of the distribution curve.

In summary, the zeta potential results showed that the NF was successfully prepared with highly negative and uniform NPs of − 75 mV in zeta potential. This is an impressive achievement.

To conclude, the results for estimating the nanofluid's stability were carried out using Zeta potential outputs and measuring particle size by DLS analyzing. Moreover, we used low concentrations of nanoparticles to avoid sedimentation. Therefore, the obtained results ensure the nanofluid's stability under different conditions.

The effect of volume fraction on ThC

Figure 6 shows the ThC of water/CeO_2-MWCNTs hybrid NF by SVF as an effective function. The figure also shows the effect of SVF on the NF's ThC at different temperatures. The figure shows that both SVF and temperature are important effective parameters for enhancing ThC.

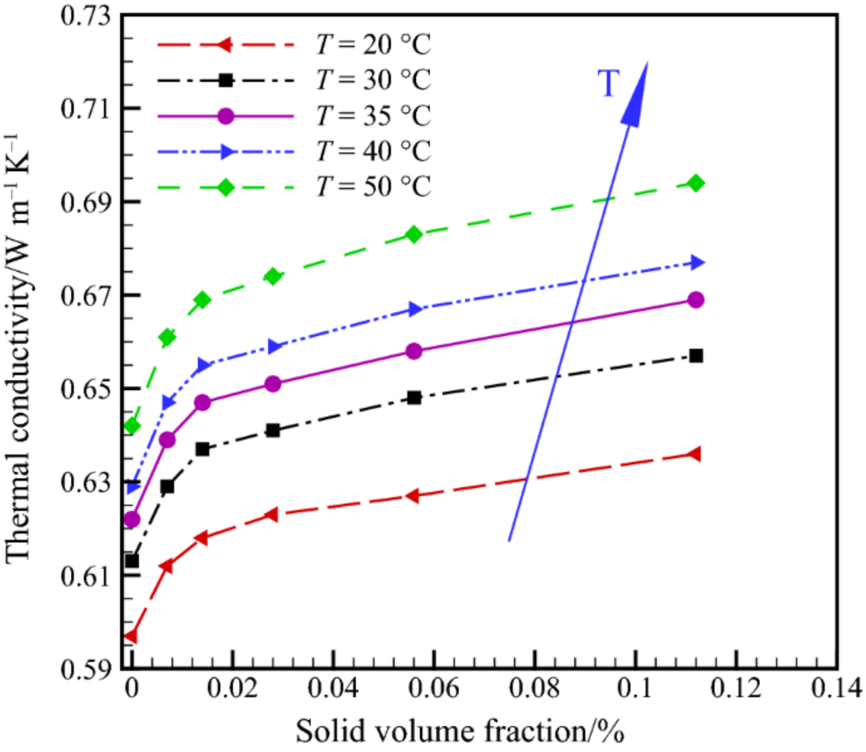


Fig. 6. The effect of SVF on ThC of water/CeO_2-MWCNTs hybrid NF at different temperatures

The enhancement in ThC with SVF can be explained by the fact that the CeO_2-MWCNTs hybrid NPs have higher ThC compared to the base fluid. Thus, they enhance the heat transfer within the NF. As another effective parameter, the Brownian motion is the random movement of NPs due to collisions with base fluid molecules. It creates microscale mixing and turbulence that enhance heat transfer. The results obtained in this study agree with those reported in the literature for similar hybrid NFs.

Convection is the macroscopic movement of fluid due to density differences caused by temperature gradients, and it also contributes to heat transfer. The results obtained in this study have important implications for the applications of water/CeO_2-MWCNTs hybrid NF in heat transfer systems.

The effect of temperature on ThC

Figure 7 shows the ThC of water/CeO_2-MWCNTs hybrid NF as a function of temperature at different SVFs, measured in watts per meter kelvin (W m^{-1} K^{-1}). The NF is a mixture of water, cerium oxide (CeO_2), and multi-walled carbon nanotubes (MWCNTs). The temperature varies from 20 to 50 °C, and the SVF (φ) varies from 0 to 0.112%. The figure shows that ThC increases with both SVF and temperature.

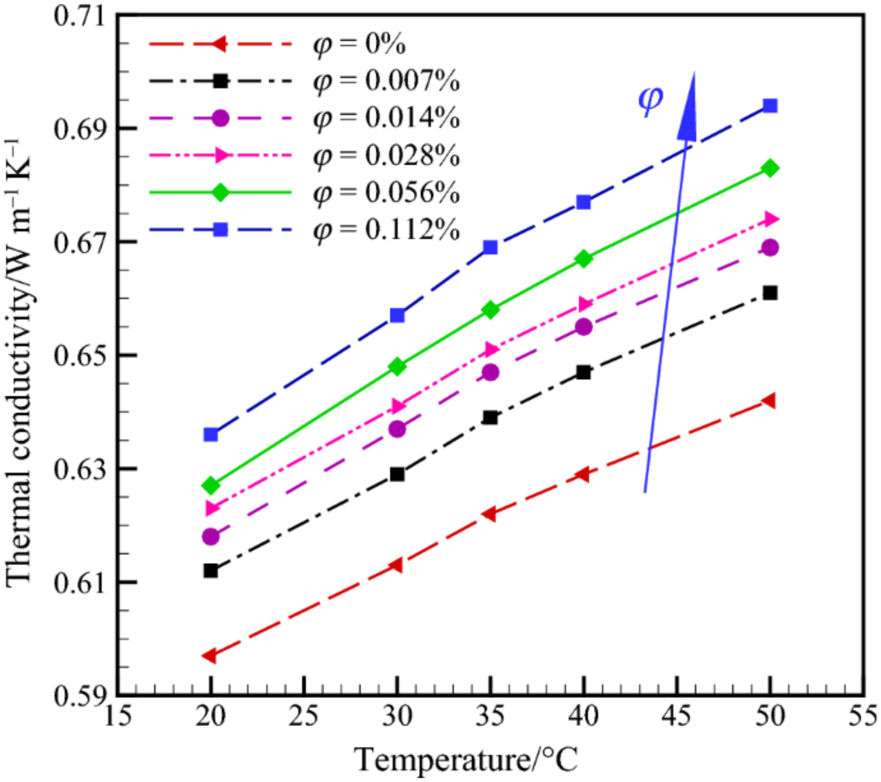


Fig. 7. Effect of temperature on ThC for different SVFs of water/CeO_2-MWCNTs hybrid NF

The enhancement of ThC of water/CeO_2-MWCNTs hybrid NF can be attributed to several factors, such as the high ThC of MWCNTs, the synergistic effect of CeO_2, and MWCNTs and the Brownian motion of NPs. The high ThC of MWCNTs can provide a heat transfer path for the NF, while the CeO_2 NPs can act as spacers to prevent the agglomeration of MWCNTs and improve their dispersion stability. The synergistic effect of CeO_2 and MWCNTs can also enhance ThC by forming a percolation network of NPs in the base fluid. The NPs' Brownian motion can increase the NF's convective heat transfer, especially at higher temperatures and lower SVFs.

The results obtained in this study are consistent with those reported in the literature for similar hybrid NFs. For example, using artificial neural networks, Rostami et al. [35] measured the ThC of MWCNT-CuO water-base hybrid NF. They found that it increased with both temperature and SVF. A synergistic enhancement of ThC was observed under the effect of increasing temperature and concentration of NPs.

Moreover, higher SVF can increase the number of nanoparticles and the thermal contact points in the nanofluid, which can enhance the heat transfer through the nanoparticle chains and clusters.

The results obtained in this study have important implications for the applications of water/CeO_2-MWCNTs hybrid NF in heating/cooling systems, such as solar collectors, heat exchangers, and air conditioning devices. The water/CeO_2-MWCNTs hybrid NF can enhance heat transfer efficiency and reduce the size and cost of these systems.

The effect of sonication time on ThC

Figure 8 shows the effect of sonication time on the ThC of water/CeO_2-MWCNTs hybrid NF, measured in minutes. The results were presented at different temperatures, including 20 °C, 35 °C, and 50 °C. The SVF changed as in the previous parts of the study. The figure shows that the ThC increases with increasing sonication time.

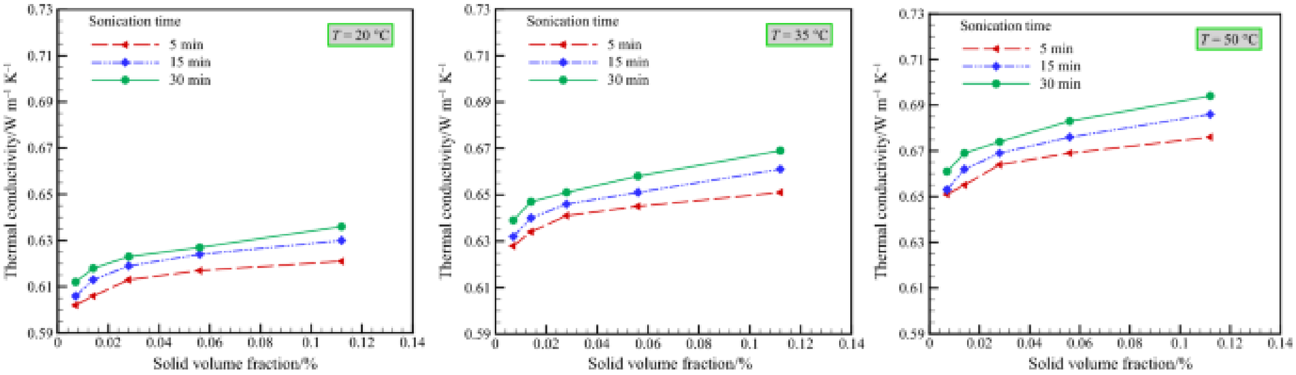


Fig. 8. ThC of water/CeO_2-MWCNTs hybrid NF under the effect of sonication time at different temperatures

The increase in ThC with sonication time can be explained by the fact that sonication is a process that uses high-frequency sound waves to break up the agglomerates of NPs and disperse them uniformly in the base fluid. Sonication also creates cavitation bubbles that collapse and generate microjets that enhance the mixing and heat transfer of the NF. The results obtained in this study are in agreement with those reported in the literature for similar hybrid NFs [36, 37].

Sonication time affects the ThC of the NF by influencing the size, shape, and distribution of the NPs. This indicates that sonication improves the heat transfer performance of the NF by reducing the interfacial thermal resistance and enhancing the Brownian motion and convection of the NPs. However, excessive sonication may cause damage to the NPs and degrade their thermal properties. Longer sonication times can enhance the dispersion and deagglomeration of nanoparticles in the base fluid, increasing the effective surface area and reducing the thermal resistance at the interface between the nanoparticles and the base fluid [38, 39].

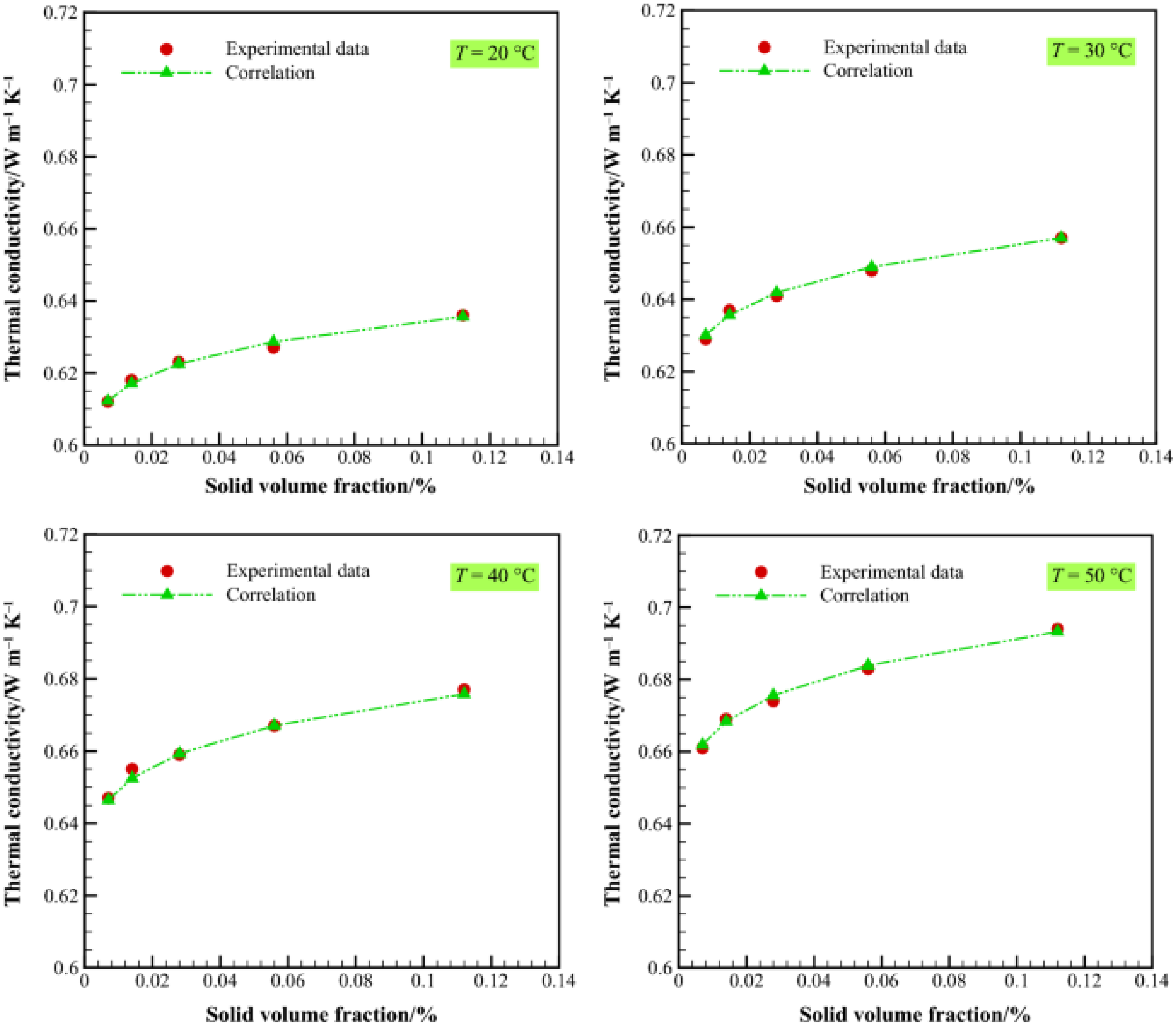


Fig. 9. Comparison between the predicted ThC with experimental data under the effect of SVF and temperature

Proposed correlation

Various factors, such as SVF, temperature, NP size, shape, material, NF preparation method, and stability, influence hybrid NFs' ThC. Many studies have reported significant discrepancies between the experimental results and the theoretical predictions based on classical models [40, 41]. Therefore, the present study developed a new high-accurate empirical correlation based on the experimental data to estimate the ThC of the water/CeO_2-MWCNTs hybrid NF as a function of effective parameters like temperature (20 °C $\leq$ T $\leq$ 50 °C) and SVF (0.007% $\leq$ SVF $\leq$ 0.112%). This correlation, expressed in Eq. (2), is a function of temperature and SVF. This correlation was derived by using curve-fitting techniques.

$$k_{\mathrm{nf}} = 0.54808 \times \mathrm{T}^{\left(0.05152 \times \varphi^{0.16061}\right)} + 0.001233 \times T \tag{2}$$

Figure 9 compares the experimental results of the ThC with those obtained by the proposed model. The results are presented for different SVFs and temperatures. As can be seen, the proposed model shows excellent agreement with the measured data. The proposed correlation in this study can be used to calculate the thermal properties of water/CeO_2-MWCNTs hybrid NF for numerical simulations.

The deviation analysis was performed to evaluate further the accuracy of the proposed new correlation (Eq. 2). Figure 10 shows the deviation between the predicted results by the new proposed model and the measured data. As can be seen in the following graph, the maximum deviation between the experimental data and the proposed model is less than 1%, confirming the proposed model's accuracy.

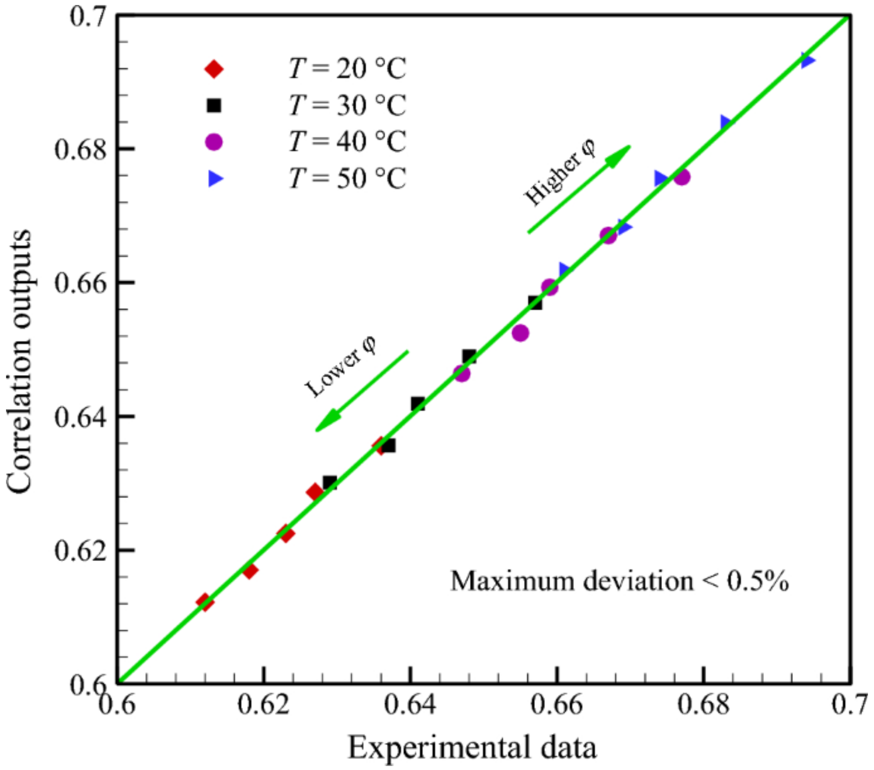


Fig. 10. Comparison between experimental ThC results by our new model

Applying artificial neural network

Today, the capabilities of the artificial neural network have been proven to everyone. In the field of NF properties, the neural network can reduce the number of experiments by trending the laboratory data. An artificial neural network consists of several computers called neurons. These neurons are divided into three parts and create a layer (Fig. 11). Each layer has a specific task. The number of neurons should be specified according to their tasks.

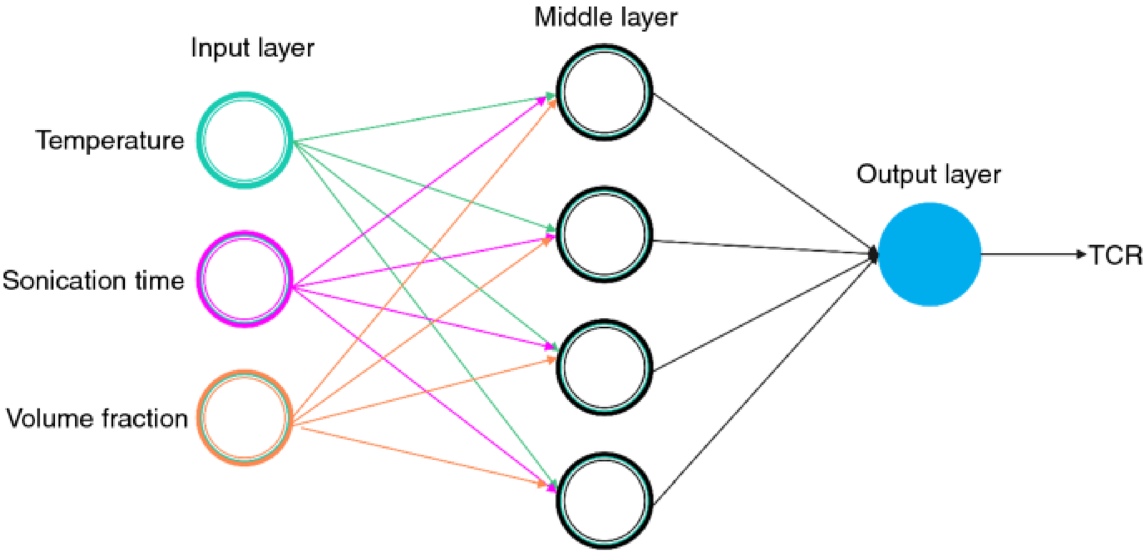


Fig. 11. Neural network diagram

In one of the (middle) layers, the number of neurons is not known because the correlations between the data are detected. More complex data relations certainly affect the number of neurons. There is usually no straight method to determine the optimal number of neurons in the middle layer, and it must be determined by trial and error. If the purpose of establishing a neural network is data prediction, the optimal number of neurons in the middle layer can be obtained by considering the minimum error. In this study, it was determined by trial and error that loading four neurons in the middle layer would give optimal results.

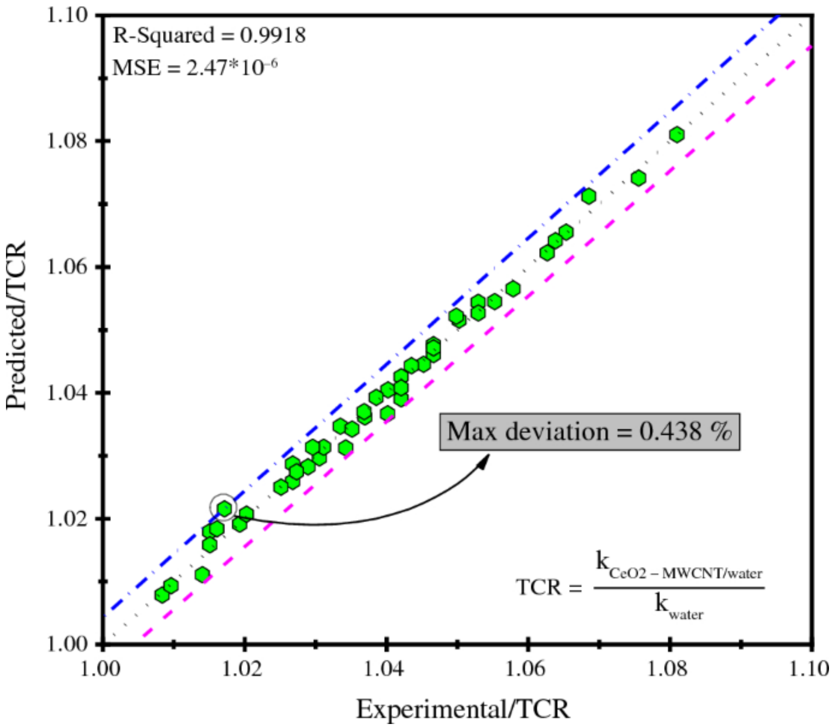


Fig. 12. Accuracy of neural network in TCR estimation considering three input parameters of temperature, SVF, and sonication time

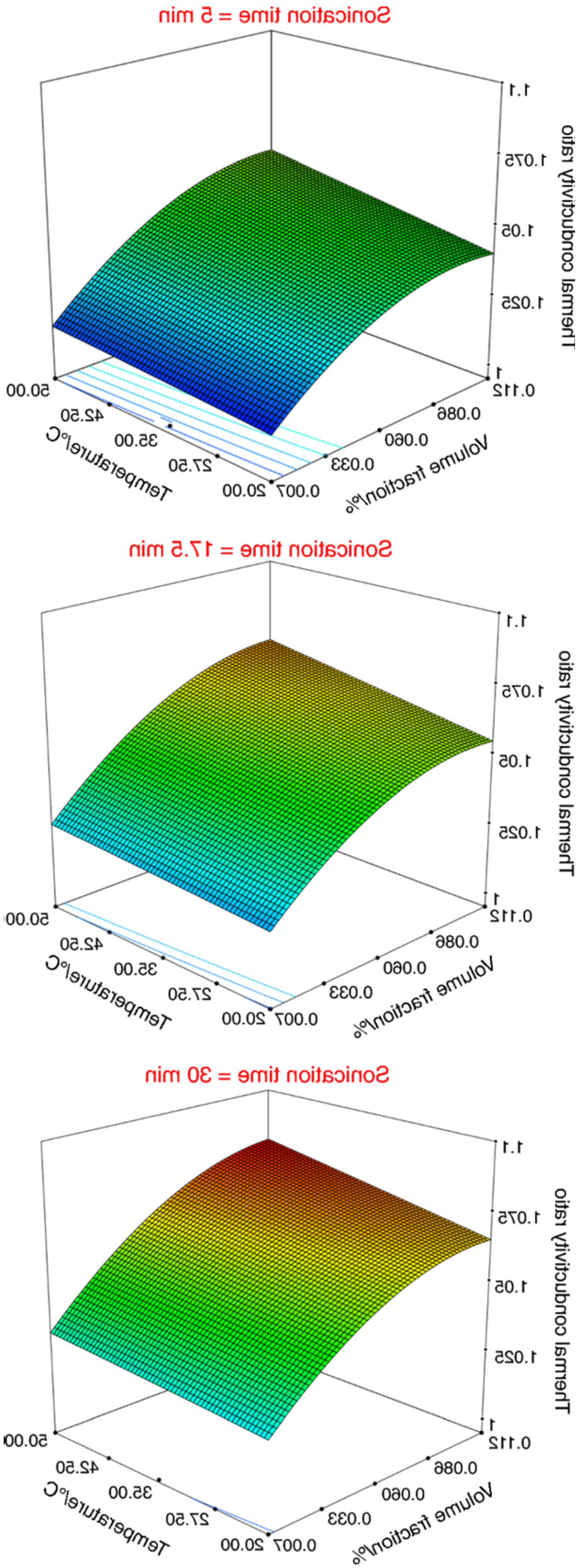


Fig. 13. TCR dependency in three sonication times of 5, 17.5, and 30 min

The results obtained from the neural network indicated that the accuracy of this method is very high (Fig. 12). The proof of this claim is the value of 0.9918 for *R*-square and 2.47 x 10^{-6} for mean square error along with a maximum error of 0.438%.

The neural network can be used to check the effect of sonication time. In Fig. 13, the TCR parameter is specified in three sonication times. It can be seen that the TCR parameter improves with increasing sonication time. Because the distribution of NPs in the base fluid is enhanced and therefore the ThC increases. Therefore, sonication time can improve the positive effects of NPs.

Comparison of the ThC of this study with others

This section compares the ThC of the water/CeO_2-MWCNTs NF studied in this research with the results of other research on similar hybrid NFs. Table 1 compares the ThC ratio, which is the ratio of the ThC of the NF at a given temperature to the ThC of base fluid with the same temperature, for different hybrid NFs at different temperatures and SVFs. The table also shows the type and size of the NPs and the base fluid in each study.

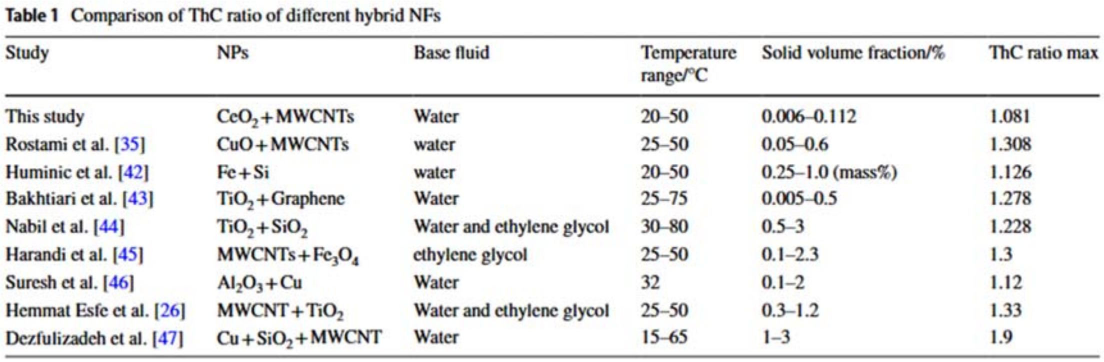


Table 1 Comparison of ThC ratio of different hybrid NFs

Study	NPs	Base fluid	Temperature range/°C	Solid volume fraction/%	ThC ratio max
This study	CeO_2 + MWCNTs	Water	20–50	0.006–0.112	1.081
Rostami et al. [35]	CuO + MWCNTs	water	25–50	0.05–0.6	1.308
Huminic et al. [42]	Fe + Si	water	20–50	0.25–1.0 (mass%)	1.126
Bakhtiari et al. [43]	TiO_2 + Graphene	Water	25–75	0.005–0.5	1.278
Nabil et al. [44]	TiO_2 + SiO_2	Water and ethylene glycol	30–80	0.5–3	1.228
Harandi et al. [45]	MWCNTs + Fe_3O_4	ethylene glycol	25–50	0.1–2.3	1.3
Suresh et al. [46]	Al_2O_3 + Cu	Water	32	0.1–2	1.12
Hemmat Esfe et al. [26]	MWCNT + TiO_2	Water and ethylene glycol	25–50	0.3–1.2	1.33
Dezfulizadeh et al. [47]	Cu + SiO_2 + MWCNT	Water	15–65	1–3	1.9

The difference in ThC ratio among different hybrid NFs can be attributed to several factors, such as the type, size, shape, and material of the NPs, the base fluid's type and composition, and the NF's preparation method and stability [32, 48,49,50].

The results of this paper have potential applications in various fields that require efficient heat transfer fluids, such as solar energy, electronics cooling, and heat exchangers. The water/CeO_2-MWCNTs hybrid nanofluid prepared in this paper has shown remarkable stability and significant enhancement in thermal conductivity compared to conventional fluids. Moreover, the paper has developed a novel empirical correlation and an artificial neural network model to predict the thermal conductivity of the hybrid nanofluid based on experimental data, which can be helpful in numerical simulations and design optimization.

The shortcomings of this paper are mainly related to the limited scope and scale of the experimental study. The paper has only investigated the thermal conductivity of the hybrid nanofluid. At the same time, other thermophysical properties, such as viscosity, density, specific heat, and heat transfer coefficient, have not been measured or analyzed. We recommended to study this critical parameter.

Conclusions

This study delved into the experimental exploration of water/CeO_2-MWCNTs nanofluid with promising applications in heat transfer. The hybrid nanofluid was prepared through a two-step process involving different sonication durations. Zeta potential and particle size distribution were quantified using dynamic light scattering to assess its stability. Thermal conductivity of the hybrid nanofluid was determined at varying solid volume fractions and temperatures through the transient hot-wire method. Validation was performed by comparing the experimental data with established benchmarks, demonstrating a favorable agreement. Results highlighted the hybrid nanofluid's remarkable stability and significant thermal conductivity enhancement. The duration of sonication, solid volume fraction, and temperature notably impacted thermal conductivity, with the most substantial enhancement recorded at solid volume fraction of 0.112% and temperature of 50 °C. An empirical correlation was established to forecast thermal conductivity based on critical parameters, namely temperature and solid volume fraction. Furthermore, the artificial neural network correlation in this paper has shown high accuracy and reliability in predicting the thermal conductivity of the hybrid nanofluid, as well as the ability to capture the complex interactions between the input parameters. The model can be used as a powerful tool for numerical simulations and design optimization of heat transfer systems using the hybrid nanofluid. This positions the water/CeO_2-MWCNTs hybrid nanofluid as a promising candidate for enhancing the performance of diverse thermal systems.

Data availability

Data will be made available on request.

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Contributions

S.A. contributed to the data curation; J.M., S.M.S, and J.M. were involved in the investigation; S.M.S and M.S.assisted in the methodology; J.M. and M.S. contributed to the project administration; S.A. was involved in the writing—original draf; S.A., J.M., and M.S assisted in the writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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