Arabian Journal of Chemistry (2023) **16**, 104689

King Saud University

Arabian Journal of Chemistry

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ORIGINAL ARTICLE

Theoretical -Experimental study of factors affecting the thermal conductivity of SWCNT-CuO (25:75)/water nanofluid and challenging comparison with CuO nanofluids/water

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Received 13 October 2022; accepted 13 February 2023
Available online 16 February 2023

KEYWORDS

Thermal conductivity;
CuO;
SWCNT;
RSM;
Water base fluid;
Challenging comparison

Abstract In this theoretical–experimental study, the basic parameters effect such as solid volume fraction (SVF or φ) and temperature on thermal conductivity (TC) of SWCNT-CuO (25:75)/water nanofluid (NF) has been investigated. The used NF in this study has been prepared and used for the first time. Monitoring and investigation of TC were done in $T = 28$ to 50℃ and $SVF = 0.03$ % to 1.15 %. The role of SVF effective in relative thermal conductivity (RTC) with changing of the temperature shows the importance of this factor in improving the RTC; results show that the better TC is $T = 50$ °C compared to other temperatures. Also, the maximum enhancement of TC compared to the base fluid (BF) (36 %) was observed at the mentioned temperature. In addition to the laboratory tests such as the margin of deviation (MOD) and RTC sensitivity within the range of $-1.90\ \% < MOD < 1.42\ \%$ in the theoretical section, a new relationship was predicted using the response surface methodology (RSM). A comparison was also made between SWCNT-CuO (25:75)/water NF and other NFs at the same temperature and SVF, which shows the increased RTC of the NF after using SWCNT (25 %).

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https://doi.org/10.1016/j.arabjc.2023.104689
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Nomenclature

Abbreviation

Eq.	Equation
THNF	Ternary Hybrid NanoFluid
MOD	Margin Of Deviation
N	Number of measurements
NPs	Nanoparticles
SWCNT	Single-Walled Carbon NanoTubes
RSM	Response Surface Methodology
RTC	Relative Thermal Conductivity
S	Standard Deviation
SSA	Specific Surface Area
SVF	Solid Volume Fraction
TEM	Transmission Electron Microscopy
XRD	X-ray Diffraction
U	Standard Uncertainty
Xi	The measured value in each experiment
$\bar{x}$	Average measured data

Greek letters

ρ (kg/m^3)	Density
$\boldsymbol{\varphi}$	Solid Volume Fraction
TC$(Wm^{-1}K^{-1})$	Thermal Conductivity

Latin letters

C.V. %	Coefficient of Variation
k (W/(mśK)	Thermal Conductivity
k_{rel}	Relative Thermal Conductivity
m(kg)	Mass
W (kg/mol)	Molecular Mass

1. Introduction

Nanotechnology is one of the new branches of technology that highlighted between the 60 s and the 80 s and created huge developments in various fields of industry and provided huge opportunities in science and industry in the microscopic world. Nanotechnology is a huge phenomenon that has entered all scientific trends. It is one of the new technologies that is developing at the fastest possible speed (Dwijendra et al., 2022; Sharifpur et al., 2022; Qu et al., 2022; Wang et al., 2021; Zhang et al., 2023). Since the beginning of the 1980 s, the scope of building design and construction has witnessed innovations in the field of efficient materials, thermoresistance, malleability, durability and ability compared to traditional materials (Luo et al., 2021; Ruhani, 2022; Ruhani, 2019; Ruhani, 2019; Afrand et al., 2016). Thermal conductivity (TC) is a very significant property of coolants. It is defined as the ability for heat conduction. Among various methods, the solid–liquid mixture displayed the maximum of heat transfer, but had limitations of short-term stability of the clogging, suspension, and wear of pipelines due to the deposition of solid particles of millimeter and micrometer sizes. The use of NFs helps overcome these limitations (Singh et al., 2020). In these years, the advent of colloidal and interface science has opened up new possibilities for the extraordinary synthesis of nanometers. Nanofluids, an innovative class of heat transfer with enhanced thermal efficiency, emerged in 1995 when Eastman and Choi pioneered the colloidal synthesis of metal NPs and conventional liquids (Choi and Eastman, 1995). However, the basic idea of suspending SP in a fluid to increase TC could be found in a study by Maxwell (Maxwell, 1873). Dispersion of NPs in a base fluid (BF) can affect the thermophysical properties of the BF (Arora and Gupta, 2022; Senniangiri et al., (2022, January).). NFs have attracted the attention of many scholars on their ability to improve heat transfer (Li et al., 2020; Li et al., 2020; Coccia et al., 2021). Many studies have been carried out to investigate the increase in TC using different types of NPs (Said et al., 2021; Yasir et al., 2022; Hemmat Esfe et al., 2018).

Table 1 Some experimental models in TC prediction of NFs.

Temperature concentration range	Correlation	Ref.
25–50 °C 0–0.6 %.	$RTC = \left(0.83411.1SVF^{+0.243}T^{-0.289}\right)$	Afrand et al. (Afrand, 2017)
25–50 °C 0–0.6 %.	$RTC = \left[0.907exp\left(0.36SVF^{0.3111} + 0.000956T\right)\right]$	Zadkhast et al. (Zadkhast et al., 2017)
25–50 °C 0.125, 0.25, 0.5, 1.0, 1.5 and 2.0 %	$RTC = \left(\frac{9.6128+SVF}{9.3885-0.00010759T^2} - \frac{0.0041}{SVF}\right)$	Parsian et al. (Parsian and Akbari, 2018)
30–70 °C 0.2–1 %	$TC = 409 + 0.00053\ \mathrm{T} + 412\ SVF - 409\ \exp\ (SVF) - 0.023\ \mathrm{T}^{0.3} + \frac{0.000021}{SVF} + 0.006\ \mathrm{T}.\sin\ (SVF)$	Hemmat Esfe et al. (Hemmat Esfe, 2017)
25–50 °C 0.1, 0.5, 1, 1.5, 2, 3, and 5 %	$RTC = \left(0.8217T^{0.06904} + 0.07872SVF^2 - 0.1978SVF^3 + (0.00138SVF^4\right)$	Esfahani et al. (Esfahani and Toghraie, 2017)
20–50 °C 0.02, 0.05, 0.1, 0.25, 0.5, and 0.75 %	$RTC = 1 +)0.04056 \times)SVF\ \mathrm{T}((-)0.003252 \times)SVF\ \mathrm{T}(^{2}(+(\ 0.0001181 \times)SVF\ \mathrm{T}(^{3}(-(0.000001431 \times)SVF\ \mathrm{T}(^{4}($	Rostamian et al. (Rostamian et al., 2017)
26 to 50 °C 0.05–1.68 %	$\mathrm{RTC} = +\ 0.96519 + 1.13476\mathrm{E}\text{-}003\ \mathrm{T} + 0.10240SVF + 2.04104\mathrm{E}\text{-}003\ \mathrm{T} * SVF\text{-}0.032249SVF^2 + 2.61959\mathrm{E}\text{-}005\ \mathrm{T}*SVF^3 + 1.50837\mathrm{E}\text{-}003\ SVF^4$	Hemmat Esfe et al. (Esfe et al., 2022)
25–50 °C 0.125–2 %	$RTC = \left(1 + 0.0008794SVF^{0.5899}\mathrm{T}^{1.345}\right)$	Esfahani et al. (Esfahani et al., 2018)

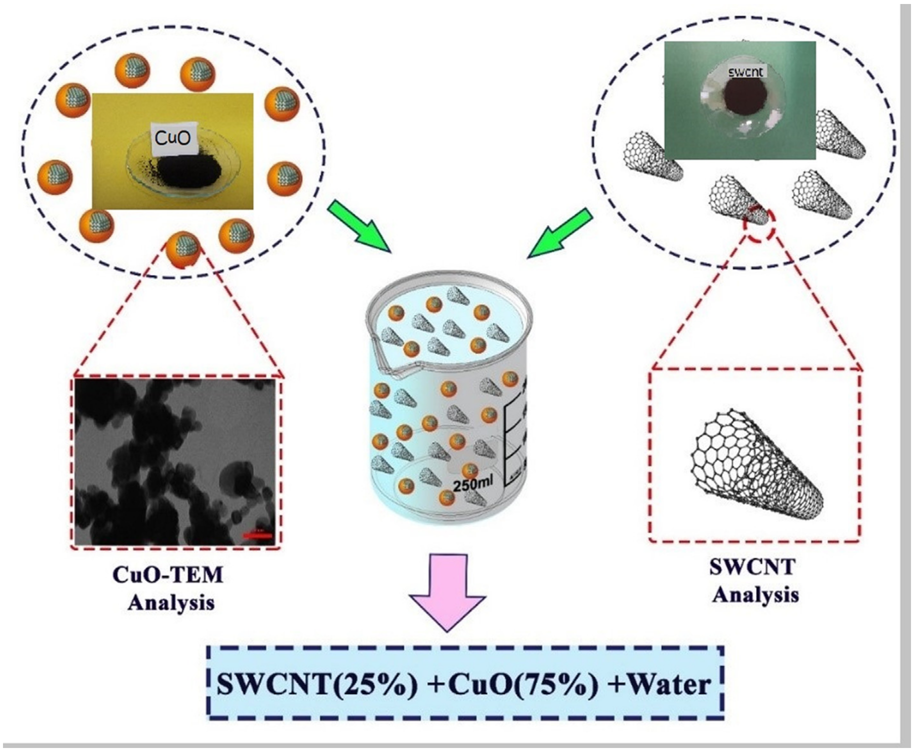

Fig. 1 A schematic of the preparation method and TEM images of NPs.

Table 2 Thermophysical properties of SWCNT and CuO NPs.

NPs	Purity	Outside diameter	SSA	Color	True density	Morphology
SWCNT	> 95 wt%	1–2 nm	> 580 m^2/g	black	~2.1 g/cm^3	Cylindrical
CuO	99 %	40 nm	20 m^2/g	black	6.4 g/m^3	nearly spherical

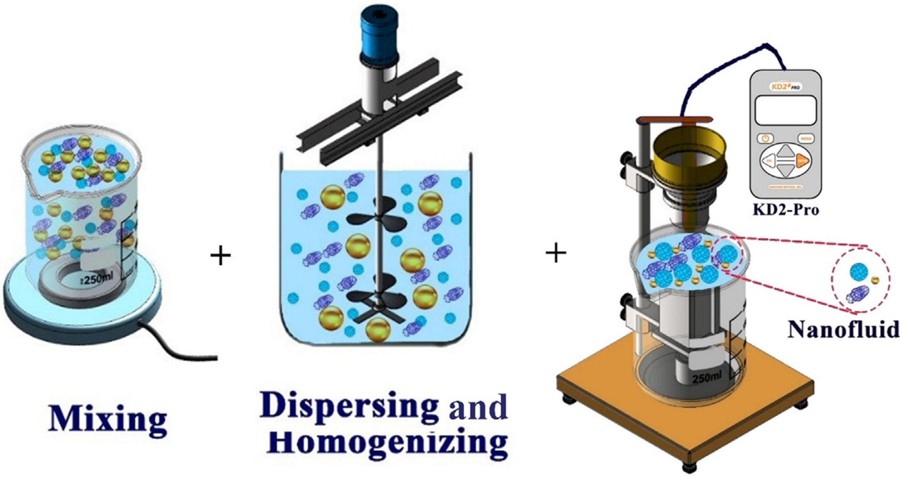

Fig. 2 Schematic of the step-by-step NF stabilization process and TC measurement process.

Dynamic viscosity and TC are among the components that have a great effect on heat transfer capability of liquids (Yalçın et al., 2022). Considering the significance of TC in increasing heat transfer, this is very important to identify the effective components of this feature. According to the literature, SVF and particle size, temperature and type of BF are the most significant factors (Ambreen and Kim,

Table 3 Laboratory equipment used in thisstudy.

No.	Equipment	Model
1	Thermal properties analyzer	KD2 pro
2	Magnet stirrer	ESR-HS7
3	Sensitive scale	GR200
4	Ultrasonic probe	Ultrasonic 1200 W and 20 kHz

2020; Alidoust et al., 2022; Nfawa et al., 2021). In a study (Alidoust et al., 2022) that was recently published, the factors affecting the RTC of SWCNT (15 %)-Fe_3O_4 (85 %)/water hybrid Ferro-nanofluid (HFNF) were investigated. The maximum reported value of RTC is 32.20 %, which has a significant value. RTC and MOD sensitivity were applied to verify the accuracy of RSM predictions. A new correlation with R^2 = 0.9941 is also proposed for the studied HFNF. It is resulted in the highest RTC sensitivity at + 1.58 %. In another study, Khetib et al. (Khetib et al., 2022) predicted the thermal conductivity of Fe_3O_4/water NF using two artificial neural networks (ANNs) with RSM. R^2 values for ANN were 0.999 while it was 0.998 for RSM. Moreover, ANN could predict all points with MOD below 1 %, however 70 % of data points in the RSM technique have MOD below 1 %. In a study by Gelis et al. (Gelis and Akyurek, 2022), the effects of using Al_2O_3-MWCNT /deionized water NFs, in a two-pipe mini heat exchanger (DPMHE), on heat transfer performance and pressure drop have been investigated using RSM. The effects of SVF and Reynolds number (Re), as input parameters, have been investigated in RSM; based on the results, the error rate was between 0.37 % and 1.84 %, while it was in the range of 0.33 % and 2.05 % for f values. As a result, the calculated Nu and f values by the mathematical model and the verification test results are very close to each other and with an acceptable error. Generally, increasing the temperature and SVF leads to improved TC (Yan et al., 2021; Esfe et al., 2019; Shah et al., 2020). In general, due to the desired thermal properties of NFs, they are widely used in various applications and devices such as solar energy systems (Aramesh et al., 2017; Alawi et al., 2022), geothermal energy (Soltani et al., 2022), pulsating heat pipes (Zhang et al., 2022; Rajale et al., 2022), and thermosyphons (Fulpagare et al., 2022) to increase heat transfer. Researchers use various methods of mathematical modeling to reduce costs, save time, increase efficiency, and model the properties of NFs (Rostami et al., 2021; Ibrahim et al., 2021). Statistical models are accurate enough to predict dependent values using appropriate inputs. In addition, these methods can predict TC and dynamic viscosity with acceptable accuracy. In most previous studies about the TC model of nanofluids, SVF and temperature were used as inputs (Ramezanizadeh et al., 2019). In some recent studies, particle size was added as another variable to achieve a more comprehensive regression. According to a study by Ahmadi et al. (Ahmadi et al., 2018), although using temperature and SVF as inputs leads to acceptable predictions in some cases, it increases the accuracy of the proposed model due to the enhanced particle size. Table 1 presents some experimental models proposed by different researchers.

In this paper, for the first time, the TC of a hybrid NF with a new SWCNT-CuO (25:75)/water formulation was investigated in the laboratory. In laboratory tests, the thermal properties of nanofluids are analyzed to study the influence of temperature and SVF, as well as their interactions with TC. The desired NF was compared with previous studies in terms of TC. Finally, the possibility of using RSM, as a novel and cost-effective solution in terms of time and cost, for the experimental study was investigated. Furthermore, a mathematical relationship for predicting TC data based on its affecting variables is presented. The margin of Deviation (MOD) values and TC sensitivity analysis are also included in this study.

2. Laboratory study

To prepare the desired nanofluid, CuO and SWCNT NPs were used with a combined ratio of 75 to 25 in a water BF. Fig. 1 shows a schematic of the composition of NPs in the BF. The TEM imaging was used to determine the nanoscales as well as the shape, size, and structural recognition of NPs.

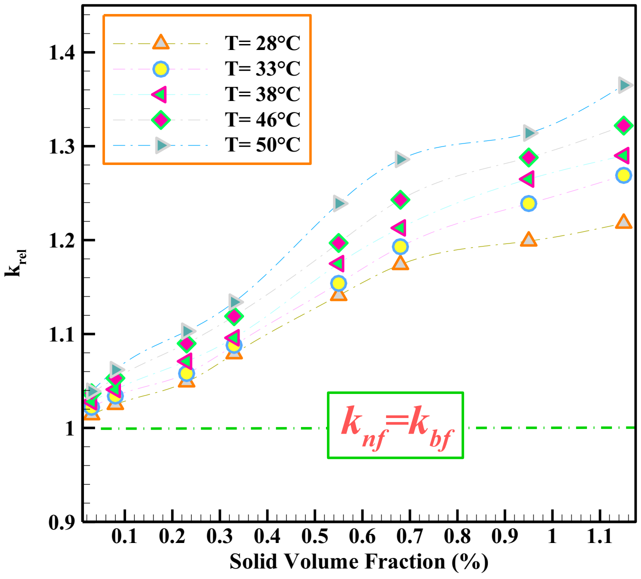

Fig. 3 Relative TC in terms of SVF.

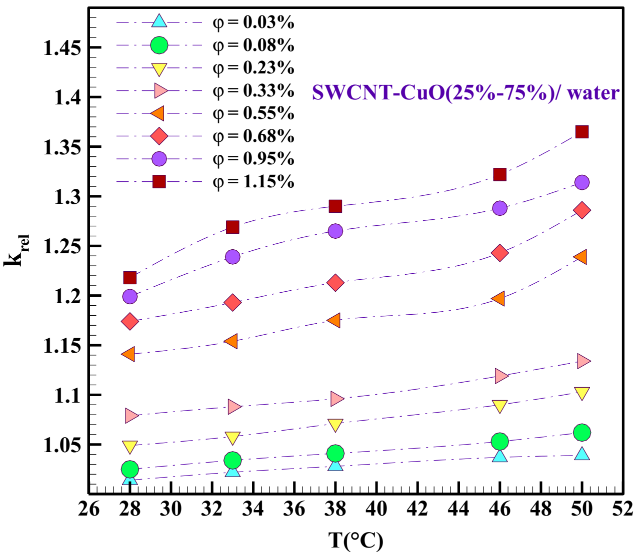

Fig. 4 Relative TC in terms of temperature.

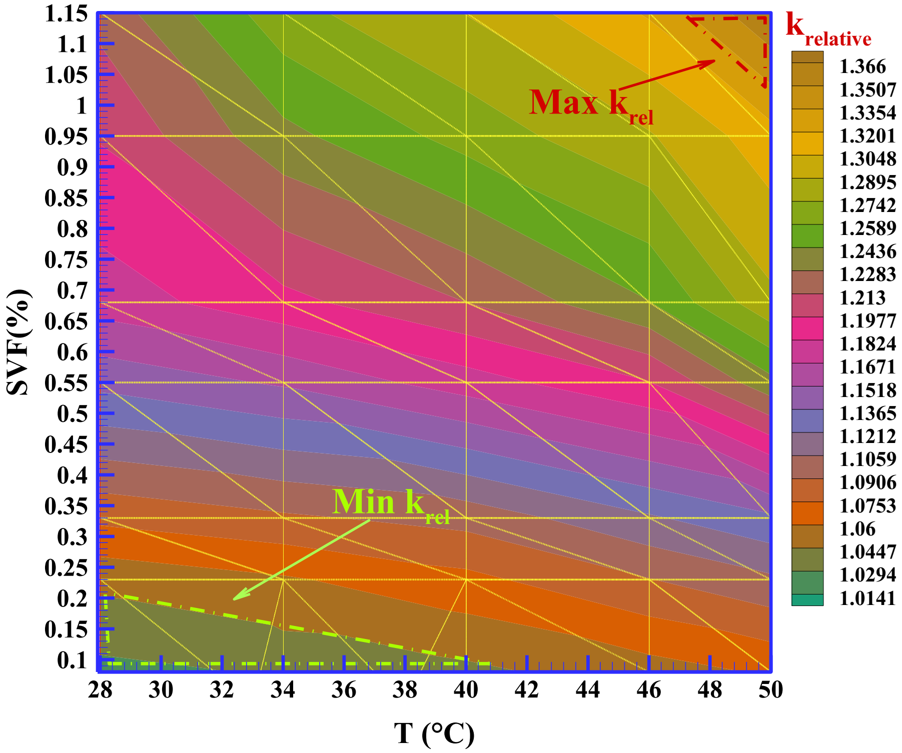

Fig. 5 Study of the simultaneous effect of SVF and temperature on relative TC.

The size, shape, morphology, and thermophysical properties of NPs are reported in Table 2.

Eq. (1) was used to compute the required amount of NPs in different SVFs. Then, a digital scale with a precision of 0.0001 g has been used for weighing. In Eq. (1), the desired weight can be calculated and NFs can be prepared using the desired density and SVF values.

$$\mathrm{SVF} = \frac{\left(\frac{w}{\rho}\right)_{SWCNT} + \left(\frac{w}{\rho}\right)_{CuO}}{\left(\frac{w}{\rho}\right)_{SWCNT} + \left(\frac{w}{\rho}\right)_{CuO} + \left(\frac{w}{\rho}\right)_{Water}} \times 100 \tag{1}$$

After the dispersion of NPs in the BF, the resulting mixture was homogenized using a magnetic stirrer. The advantage of using a magnetic stirrer is that it can remove the clumpy NPs dispersed in the base fluid. In addition, to increase the stability of NFs, an ultrasonic vibration device was used for 2 h. Fig. 2 displays a schematic of the NF stabilization process.

TC measurement is required to analyze the thermal behavior of NFs. For this purpose, the KD2 pro device (Decagon device, Inc., USA) was used; the specifications of which are shown in Table 3, and a schematic view of the measurement process is presented in Fig. 2. TC of NFs was measured at the temperature range of 28–50 °C and SVF range of 0.03–1.15 %. The results were recorded and averaged after five repetitions.

2.1. Uncertainty

For the KD2 Pro device, the accuracy was ± 5 % [49]. Eq. (2) calculates the uncertainty of the measured data (Ahmadi et al., 2018):

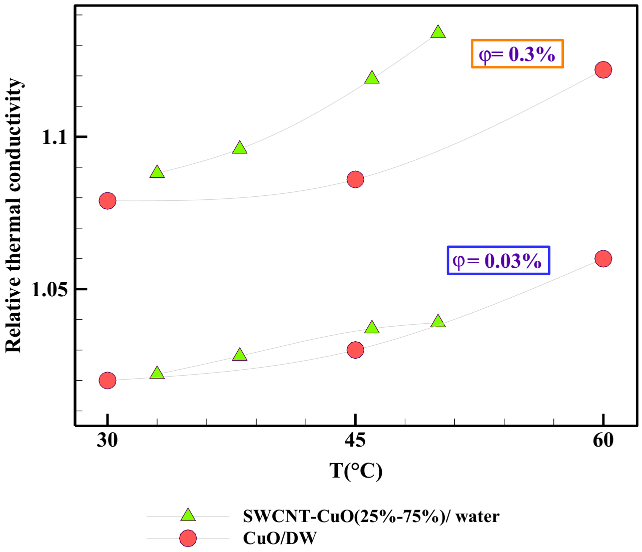

Fig. 6 Comparison of Relative TC in terms of temperature at SVF = 0.03 % and 0.3 %.

$$\mathrm{U} = \frac{S}{\sqrt{N}} \tag{2}$$

In Eq. (2), U is the standard uncertainty, N is the number of measurements, and S is the standard deviation. S has been calculated using Eq. (3).

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(Xi - \bar{X}\right)^2} \tag{3}$$

According to Eq. (3), at T = 28 °C and SVF = 1.15 %, the uncertainty of TC was 5.098 %.

2.2. *Monitoring the stability of NFs*

The stability of NFs after preparation can be measured by special methods visually, zeta potential, or density test. In this study, the stability of NFs was measured for 4 weeks using the density test. According to the results, during the storage time of 28 days, the apparent density changes were very small (0.01 %). The slight changes in density indicated the properstability of the studied NFs.

3. Results and discussion

In this study, effective factors such as SVF and temperature on TC of SWCNT-CuO (25 % –75 %)/water NFs were investigated. According to Fig. 3, with increasing SVF, the TC of NFs increases relative to the TC of BF. At T = 50 °C and SVF = 1.15 %, a 36 % increase in TC was observed. It can be said that the increase in relative TC is usually observed in the studied temperatures in two stages; so that, the maximum increase was made observed when SVF = 0.03 %-0.68 %, and the second increase occurred again in the range of 0.95 %-1.15 %. The SVF changes at the same temperature that are shown with the lines connecting the points indicate the direct relation between the TC and SVF. The increase in TC was more intense when the SVF was increased from 0.03 to 0.68 %. But in the final three SVFs (0.68–1.15 %), it became more uniform and increased with a gentler slope.

Fig. 4 examines the relative TC in terms of temperature. In this figure, an increase in SVF from 0.03 % to 1.15 % shows an increase in Relative TC, as expected. Relative TC changes in this curve can be divided into two distinct quadrants (SVF = 0.03 %-0.33 %) and (SVF = 0.55 % –1.15 %). In the first group (0.03 % –0.33 %), the changes were accompanied by a uniform slope, while the changes were more intense and not uniform in the second group (0.55 %-1.15 %). According to this figure, at a minimum concentration of SVF = 0.03 %, the TC increase at T = 28 °C was equal to 1.014 (1.4 %). At other temperatures and SVFs, the increase in TC was greater than this value to the extent that its maximum value, as mentioned, was achieved at T = 50 °C and SVF = 1.15 %. In addition, Fig. 4 shows the insignificant effect of temperature on TC enhancement (unlike Fig. 3, where the SVF had a considerable effect on the increase of TC).

Fig. 5 measures the effects of two parameters T (°C) and SVF (%) on Relative TC, simultaneously. In the contour of Fig. 5, the maximum and minimum ranges of the increase are marked with red and green triangles, respectively. Based on this figure, the contribution of SVF changes to Relative TC can be more significant than temperature. For example, at a certain temperature (T = 50 °C), + 32.6 % enhancement in Relative TC is observed from the initial SVF to the final SVF. This change in specific SVF (SVF = 1.15 %) about + 14.7 % when T was increased from 28 °C to 50 °C. Therefore, as mentioned, the SVF can be considered more effective.

3.1. *Comparing the thermal performance of the studied NFs with similar cases*

Since the SVF was very effective on TC, so in this section, the results of the present study were compared with a similar study by Singh et al. (Singh et al., 2020). In Fig. 6, the results of the present study are compared at T = 30–60 °C and SVF = 0.03 % –0.3 %, with studies. At similar conditions in the two studies, the effect of slight addition (25 %) of SWCNT NPs on increasing and improving relative TC can be observed in Fig. 6. The curves show that in both SVFs (SVF = 0.03 % and 0.3 %), SWCNT-CuO (25:75)/water

Table 5 Accuracy of modeling experimental data.

Std. Dev.	9.503E-003
Mean	1.15E + 000
C.V. %	8.30E-001
PRESS	4.502E-003
R-Squared	9.93E-001
Adj R-Squared	9.91E-01
Pred R-Squared	9.89E-01
Adeq Precision	8.79E + 01

Table 4 Analysis of variance (ANOVA) for Response Surface Reduced Cubic model.

Analysis of variance table

Source	Sum of		Mean	F	p-value	
	Squares	df	Square	Value	Prob > F	
Model	4.00E-001	6	6.70E-002	7.42E + 002	< 0.0001	significant
A-T	2.897E-003	1	2.897E-003	3.21E + 001	< 0.0001	
B-SVF	5.90E-002	1	5.90E-002	6.55E + 002	< 0.0001	
AB	6.601E-003	1	6.601E-003	7.31E + 001	< 0.0001	
B^2	5.056E-003	1	5.056E-003	5.60E + 001	< 0.0001	
A^3	3.456E-004	1	3.456E-004	3.83E + 000	5.89E-002	
B^3	1.645E-003	1	1.645E-003	1.82E + 001	2.00E-004	
Residual	2.980E-003	33	9.030E-005			
Cor Total	4.00E-001	39				

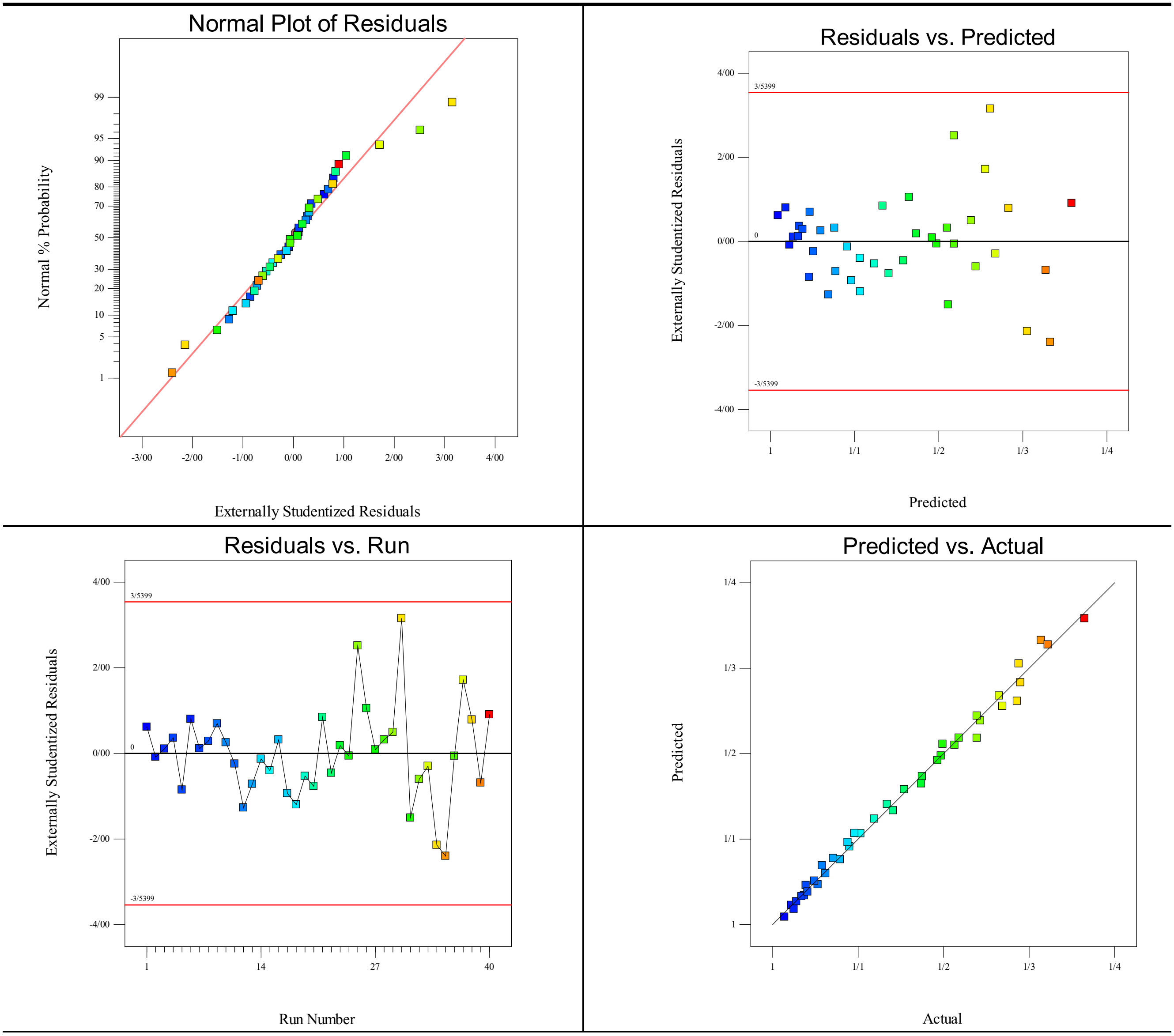

Fig. 7 Results of the model used in the RSM.

NF had improved thermophysical properties. In comparison with SVF = 0.3 % and high temperatures, the difference in relative TC between the two compared nanofluids reaches its maximum value, which will be considered in terms of use in industry.

4. Impractical result

Studying using the RSM allows researchers to investigate the TC of NFs with higher accuracy and speed, to achieve a new relationship. It also avoids laboratory expenses and possible errors in tests. In the impractical analysis section, a new TC prediction formulation was presented using the RSM. RSM is one of the statistical techniques to determine the relation between independent and dependent variables. In this method, experimental data of temperature and SVF are recognized as inputs and TC data as outputs. The two-variable-three-degree model was identified as the best predictor model, which is observed in Eq. (4).

$$\begin{aligned} RelativeTC = {} & +9.93\mathrm{E}-001+3.54412\mathrm{E}-004\,\mathrm{T}+4.26\mathrm{E} \\ & -02SVF+4.16712\mathrm{E}-003\mathrm{T}SVF+2.44\mathrm{E} \\ & -01\,SVF^{2}+2.10258\mathrm{E}-007\,\mathrm{T}^{3} \\ & -0.19177\,SVF^{3} \end{aligned} \qquad (4)$$

Quantitative and qualitative specifications of the predictor model are reported in Tables 4 and 5. The criterion for determining the quality of the model is based on P-value, R-Squared, and also the statistical diagrams presented in Fig. 7.

In the diagrams provided in Fig. 7, the predicted data were in the allowable range of the software, which confirms the accuracy of the model.

Fig. 8 shows the correlation between the modeled data and the experimental data, relative to the quality line. Given the

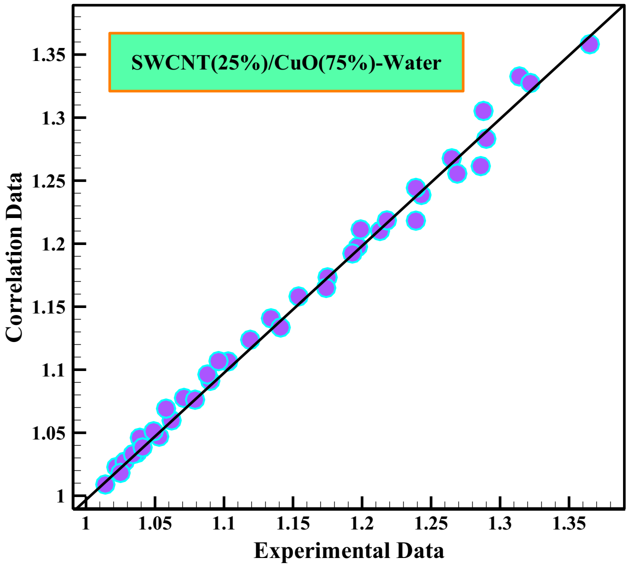

Fig. 8 Consistency of experimental results and predicted data.

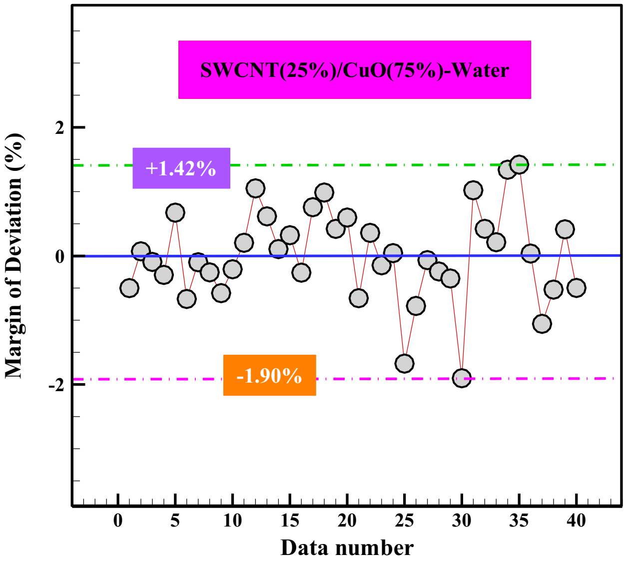

Fig. 9 MOD range in all laboratory data.

high correlation of the data, it could be concluded that using the proposed model is reasonable.

4.1. Margin of deviation (MOD)

One of the important methods in examining the accuracy of the mathematical model is using the MOD method, which is according to Eq. (5),

$$MOD = \frac{TC_{rel_{exp}} - TC_{rel_{pre}}}{TC_{rel_{exp}}} \times 100 \qquad (5)$$

The MOD range for laboratory data is plotted in Fig. 9, which was set at $-1.90\ \% < \text{MOD} < +1.42\ \%$. Due to the small error of the MOD value, it can be concluded that the proposed model is valid and of good quality.

4.2. TC sensitivity

The extent of influence of the objective function on the independent variables, in a statistical model, was determined using TC sensitivity analysis. Eq. (6) was used to determine the TC sensitivity.

$$TC\,sensitivity\,analysis = \frac{\left(Tc_{\,after\ change}\right)_{Pre} - \left(TC_{\,before\ change}\right)_{Pre}}{\left(TC_{\,before\ change}\right)_{Pre}} \times 100 \qquad (6)$$

In Fig. 10, the sensitivity analysis to the SVF variable with + 10 % changes is investigated. that the minimum impact was observed at low SVFs. This is while increasing the SVF up

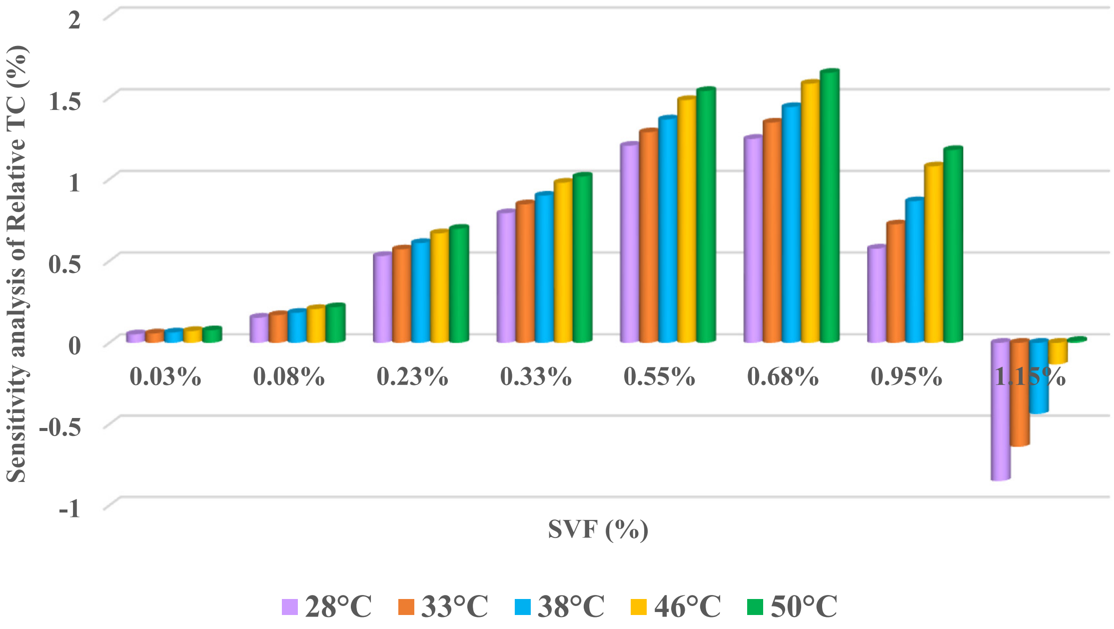

Fig. 10 Sensitivity analysis of Relative TC.

to 0.95 % has increased the sensitivity to changes. With increasing the SVF up to 1.15 %, the sensitivity has a decreasing and negative trend.

5. Conclusion

In this study, the laboratory results for TC of SWCNT-CuO (25:75)/water NFs and the basic effective parameters were investigated. RSM was also utilized to provide a new correlation and measure the relative MOD and TC sensitivity. The use of the theoretical method prevents spending too much time and cost in the laboratory. Based on the results, the maximum TC increase in nanofluid relative to BF was 36 %. The minimum TC increase relative to the BF was occurred at T = 28 °C, which was equal to 1.4 %. In this study, the SVF effect and temperature on TC was investigated and it was found that the SVF parameter plays a major role in this change. In the theoretical study section, a new correlation was proposed using the RSM with a suitable and accurate R-Squared value equal to 0.9926. Also, the MOD range was calculated as $-1.90\ \% < \text{MOD} < +1.42\ \%$. Comparing the studied NFs with CuO/DW NF indicates that the NF of this study is relatively superior. According to the results, the studied NF has the required factors to be used in various industries such as cooling-lubrication in the automotive industry, increased yield in oil extraction industries, and cooling and heating systems.

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