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Estimation of thermal conductivity of ethylene glycol-based nanofluid with hybrid suspensions of SWCNT–Al_2O_3 nanoparticles by correlation and ANN methods using experimental data

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Abstract In the present paper, the effects of temperature and volume fraction on thermal conductivity of SWCNT–Al_2O_3/EG hybrid nanofluid are investigated. Single-walled carbon nanotube with outer diameter of 1–2 nm and aluminum oxide nanoparticles with mean diameter of 20 nm with the ratio of 30 and 70%, respectively, were dispersed in the base fluid. The measurements were conducted on samples with volume fractions of 0.04, 0.08, 0.15, 0.3, 0.5, 0.8, 1.5 and 2.5. In order to investigate the effects of temperature on thermal conductivity of the nanofluid, this characteristic was measured in five different temperatures of 30, 35, 40, 45 and 50 °C. The results indicate that enhancement of nanoparticles' thickness in low volume fractions and at any temperature causes a considerable increment in thermal conductivity of the nanofluid. In this study, the highest enhancement of thermal conductivity was 41.2% which was achieved at the temperature of 50 °C and volume fraction of 2.5%. Based on the experimental data, an experimental correlation and a neural network are presented and for thermal conductivity of the nanofluid in terms of volume fraction and temperature. Comparing outputs of the experimental correlation and the designed artificial neural network with experimental data, the maximum error values for the experimental correlation and the artificial neural network were, respectively, 2.6 and 1.94% which indicate the excellent accuracy of both methods in prediction of thermal conductivity.

Keywords Hybrid nanofluid · SWCNT–Al_2O_3/EG · Heat conduction · Experimental correlation · Artificial neural network

Nomenclature

b	Bios
k	Thermal conductivity (Wm^{-1} K^{-1})
P	Number of input neuron
T	Temperature (°C)
w	Weight of neural network
x	Input neuron
y	Output neuron

Greek

φ	Solid volume fraction

Subscripts

f	Base fluid
nf	Nanofluid
Pred	Predicted value
Exp	Experimental value

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Introduction

In recent years, thermophysical properties of fluids being used in heat conduction have been an interesting subject for many researchers. For the first time, Choi [1] suggested the concept of nanofluid in 1995 and it was signified that adding particles smaller than 100 nm into common fluids would result in changes in their thermophysical properties.

Nanofluids have many applications in air-conditioning, electronic components cooling, medicine and motors cooling and lubrication [2–4]. One of the most important thermophysical properties of nanofluids which are being used in applications concerned with heat conduction process is thermal conductivity, and it has been studied in many research works due to the numerous applications of nanofluids [5–12]; some equations and models are presented for prediction of thermal conductivity variations [13–22]. Dynamic viscosity is another thermophysical property which is investigated vastly by researchers [23]. These two properties affect heat transfer properties of nanofluid directly [24–26].

In recent years, a new type of nanofluids had been studied which is called hybrid nanofluids. These nanofluids are generally composed of two or more different nanoparticles which are dispersed in a base fluid. The studies conducted on thermophysical properties of hybrid nanofluids signify that the properties of the hybrid nanofluids are entirely different from the ingredients properties [27]. Carbon nanotubes (CNT) are one of the nanoparticles which are vastly being used [28–33], and they are also being used to compose hybrid nanofluids. Alumina (Al_2O_3) is one of the most common and inexpensive nanoparticles which is used to make hybrid nanofluids [34–37]. Many studies had been conducted on hybrid nanofluids composed of alumina. Some of the studies on hybrid nanofluids are listed in Table 1. According to this table, alumina and carbon nanotubes are used in many studies.

In most of the researches on carbon nanotubes, multi-walled carbon nanotubes (MWCNT) are used, and only in a few of them single-walled nanotubes are studied. SWCNT/epoxy composites are the most studied nanofluid in which single-walled nanotubes were used [38, 39]; in some researches, water was chosen as the base fluid [37, 40]. Ethylene glycol (EG) is also used in some studies. In 2008 Amrollahi et al. [41] conducted a research on SWCNT/EG nanofluid while the effects of temperature, volume fraction and ultrasonic blending time on thermal conductivity of the nanofluid were studied. The measurements were taken for volume fractions of 0.5 and 2.5 and at temperatures of 25 and 50 °C.

Harish et al. [42] studied on SWCNT/EG. They increased volume fraction to 0.2%, and they observed that relative thermal conductivity of the nanofluid was enhanced to 14.8%. They compared their experimental results with present models.

In the present research, for the first time the hybrid nanofluid composed of Al_2O_3 and MWCNT nanoparticles and ethylene glycol base fluid is studied and the effects of temperature and solid volume fraction on thermal conductivity of the nanofluid are investigated. Volume fraction variations were within 0.04 and 2.5%, and the temperature

Table 1 A literature review on thermophysical properties of hybrid nanofluids

Authors	Base fluid	Dispersed particles	
Munkhbayar et al. [43], Chen et al. [44]	Water	MWCNT	Ag
Jana et al. [45]	Water	MWCNT	Au, Cu
Chen et al. [46]	Water	MWCNT	Fe_2O_3
Baghbanzadeha et al. [47, 48]	Water	MWCNT	Silica
Aravind et al. [49]	Water	MWCNT	Graphene
Aravind and Ramaprabhu [50]	Water, EG	MWCNT	Graphene
Baby and Ramaprabhu [51–53]	Water, EG	MWCNT	Ag, HEG
Sundar et al. [54]	Water	MWCNT	Fe_3O_4
Zhang et al. [55]	Oil	CNT	MoS_2
Megatif et al. [56]	Water	CNT	TiO_2
Rajesh and Venkatasubbaiah [57]	Water	SWCNT	Cu
Ho et al. [58, 59]	Water	Al_2O_3	PCM
Suresh et al. [60, 61]	Water	Al_2O_3	Cu
Han et al. [62]	Water	Al_2O_3	Ag
Bhosale et al. [63]	Water	Al_2O_3	CuO
Zhang et al. [64]	Oil	Al_2O_3	SiC
Jiao et al. [65]	Oil	Al_2O_3	SiO_2
Kalita et al. [66]	Oil	Al_2O_3	MoS_2
Hemmat Esfe et al. [67]	Water	Ag	MgO
Hemmat Esfe et al. [68]	Water/EG	Cu	TiO_2
Hemmat Esfe et al. [69]	Water/EG	DWCNT	ZnO

variations were 30–50 °C. At the end of this research, the experimental results are compared and modeled with an experimental correlation and a neural network.

Experimental

In order to compose the nanofluid, the nanoparticles of alumina and carbon nanotubes were weighted with the proportion of 70 and 30%, respectively, and then they were dispersed in ethylene glycol base fluid with volume fractions of 0.04, 0.08, 0.15, 0.3, 0.5, 0.8, 1.5 and 2.5. Specifications of SWCNTs and Al_2O_3 nanoparticles are listed in Tables 2 and 3.

The outer diameter of SWCNT was 1–2 nm, and the diameter of Al_2O_3 was 20 nm. To identify morphological properties of nanoparticles, the transmission electron microscopy (TEM) method was used. TEM sample of Al_2O_3 nanoparticles and SWCNTs is shown in Fig. 1.

After premixing the nanoparticles with the base fluid, the nanofluid was mixed using a magnetic blender for 1 h; afterward in order to reach an excellent dispersion as well as to enhance the stability of the nanofluid, the mixture was homogenized for 8 h in an ultrasonic vibrator (1200 W, 19.9 kHz) which was produced by Kimia Nano Danesh Co.

The high production cost of carbon nanofluids that have superior thermal properties in addition to undesirable properties of oxide nanofluids which are cheap and available has encouraged researchers to combine these two types of particles. Hybrid nanofluids have a practical combination of superior properties and reasonable cost and can be introduced as a new generation of practical nanofluids.

Table 2 Physicochemical property of Al_2O_3 nanoparticle

Parameter	Value
Color	White
Purity	+%99
SSA	>138 $m^2\ g^{-1}$
APS	20 nm
Density	3890 kg m^{-3}
Morphology	Nearly spherical
Specific heat capacity	880 J $Kg^{-1}\ K^{-1}$

Table 3 Physicochemical characteristics of SWCNTs

Parameter	Value
Color	black
Purity	Single-walled nanotubes >90 mass%
Outside diameter	1–2 nm
Inside diameter	0.8–1.6 nm
Length	5–30 um
Thermal conductivity	50–200 W $m^{-1}\ K^{-1}$
SSA	>380 $m^2\ g^{-1}$
Ash	<1.5 mass%
Tap density	0.14 g cm^{-3}
True density	~2.1 g cm^{-3}
Electric conductivity	>100 S cm^{-1}
Manufacturing Method	CVD

Thermal conductivity measurement

KD2 Pro (Decagon Devices, USA) thermal property analyzer was utilized for measuring thermal conductivity. The accuracy of this device is 5%, and it is capable of measuring thermal conductivity in w mk^{-1} range from 0.02 up to 2. It uses the transient line heat source method to measure thermal conductivity. This device is equipped with KS1 sensor which is made of stainless steel, and its diameter and length are, respectively, 1.28 and 60 mm. It should be noted that the error is minimized when natural convection is minimum; therefore, the probe must be inserted perpendicularly into the fluid [70]. In order to verify the measured values, each measurement was repeated for five times.

Experimental results

In the present study, thermal conductivity of SWCNT–Al_2O_3/EG hybrid nanofluid was investigated empirically, and then a nonlinear correlation was extracted for prediction of thermal conductivity of the nanofluid. Carbon nanotubes and aluminum oxide were used in volume fractions of 70 and 30%, respectively. The measurements were taken at the temperatures of 30–50 °C. A variety of different suspensions with solid volume fractions of 0.04, 0.08, 0.15, 0.3, 0.5, 0.8, 1.5 and 2.5 had been studied in this research.

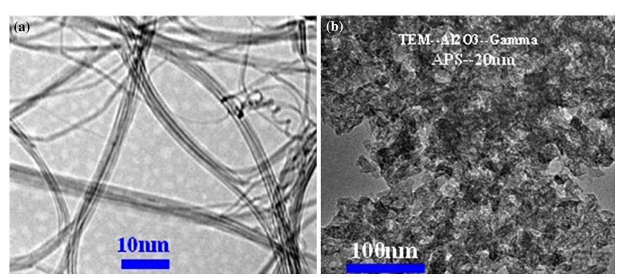


Fig. 1 TEM images for (**a**) SWCNTs and (**b**) Al_2O_3 nanoparticles

In Fig. 2, the changes of thermal conductivity in terms of temperature are depicted for different volume fractions. According to this figure, in every volume fractions thermal conductivity is increased due to temperature increment. The cause of this behavior could be correlated with the increment of nanoparticles kinetic energy which results in more collision and enhanced Brownian movement. For samples with lower solid volume fractions of nanoparticles, thermal conductivity is less influenced by temperature changes, but as for higher volume fractions the increment of thermal conductivity is relatively intense. This could be clearly observed by investigating the diagram slopes for each of the volume fractions. For instance, thermal conductivity mean variations ratio in terms of temperature (slope of the diagram) for the sample with 0.04% volume fraction is significantly lower than the sample with volume fraction of 2.5.

Figure 3 illustrates the variations of relative thermal conductivity in terms of solid volume fractions. According to this figure at a constant temperature along with increasing solid volume fraction of nanoparticles, thermal conductivity would be enhanced. This phenomenon may be related to increasing number of nanoparticles which results in more collisions between the nanoparticles. Also with regard to this figure, it can be seen that in low volume fractions, temperature has negligible influence over thermal conductivity, but in high volume fractions temperature significantly affects thermal conductivity. For instance in 0.04 volume fraction, thermal conductivity is not changed considerably due to temperature variations, but the sample with 2.5 volume fraction is egregiously affected by temperature variations. The cause of this phenomenon is that in lower volume fractions, the base fluid plays the main role in heat conduction and the temperature variations have insignificant influence over the thermal conductivity of the base fluid; therefore, in samples with low volume fractions, temperature has negligible influence over the thermal conductivity of the composed nanofluid. On the other hand, when the volume fraction of nanoparticles enhances, their participation in heat conduction process would be considerable, and due to the fact that the thermal conductivity of the nanoparticles is more affected by temperature, then the nanofluid thermal conductivity will be more influenced by temperature variations. Also it can be observed in Fig. 3 that at a constant temperature along with volume fraction increment up to a specific amount, the ratio of thermal conductivity variations (slope of the diagram) would be increased. When volume fraction is increased from a specific amount, this ratio would be decreased. The cause of this behavior is the fact that when the volume fraction of nanoparticles is very low, the base fluid plays the major role in heat conduction, but when the number of the nanoparticles is increased, their participation in heat conduction process is more significant, and because the thermal conductivity of the nanoparticles is considerably higher than the base fluid, thermal conductivity of the composed nanofluid will be increased significantly. When the volume fraction of the nanoparticles is increased furthermore, almost complete chains of carbon nanotubes would be formed in the fluid; subsequently the role of nanoparticles in heat conduction process becomes dominant. At this point since the base fluid is saturated with nanoparticles, adding more nanoparticles would not change the thermal conductivity of the composed nanofluid. With

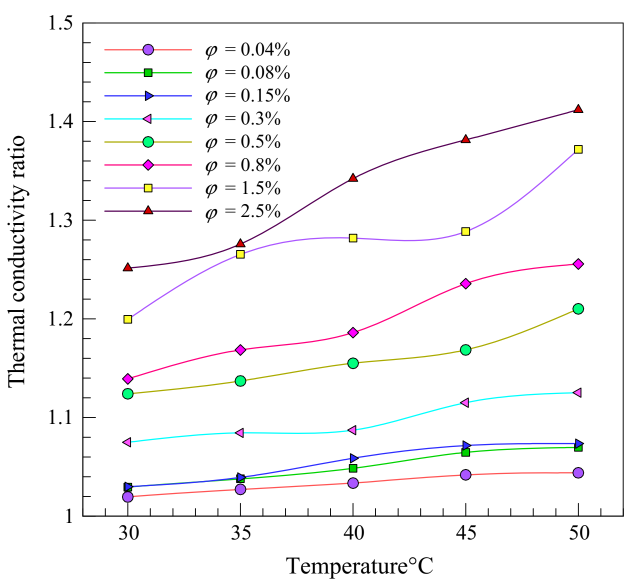


Fig. 2 Thermal conductivity changes in terms of temperature

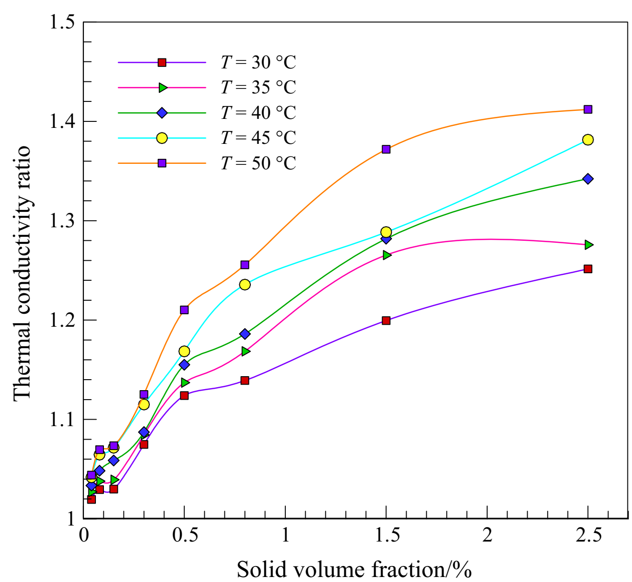


Fig. 3 Relative thermal conductivity of SWCNTs–Al_2O_3/EG versus solid volume fraction for different temperatures

regard to these results, it was revealed that for cooling applications, using nanoparticles with 1.5 volume fraction is more cost efficient.

For further investigation of temperature and volume fraction effects on relative thermal conductivity, the curve of thermal conductivity in terms of temperature and volume fractions is depicted separately in Fig. 4. As it can be seen, thermal conductivity enhancement due to volume fraction variation is more observable in higher temperatures. Also in high volume fractions, the increment of thermal conductivity due to temperature variation is more drastic than in low volume fractions. In fact the presence of more nanoparticles in high volume fractions would cause the temperature to affect the Brownian movement more significantly which results in thermal conductivity enhancement.

Equation 1 defines thermal conductivity enhancement.

$$\text{Thermal conductivity enhancement } (\%) = \frac{k_{nf} - k_{bf}}{k_{bf}} \times 100 \quad (1)$$

In Table 4, the maximum thermal conductivity enhancement of the hybrid nanofluid in this study is compared with the results of previous researches. The results signify that the maximum enhancement of thermal conductivity of the hybrid nanofluid was 41.2% which is considerably higher in comparison with the previous researches.

Proposed experimental correlation

In order to facilitate thermal conductivity prediction for the hybrid nanofluid in industrial and commercial applications, with respect to the experimental data a correlation is

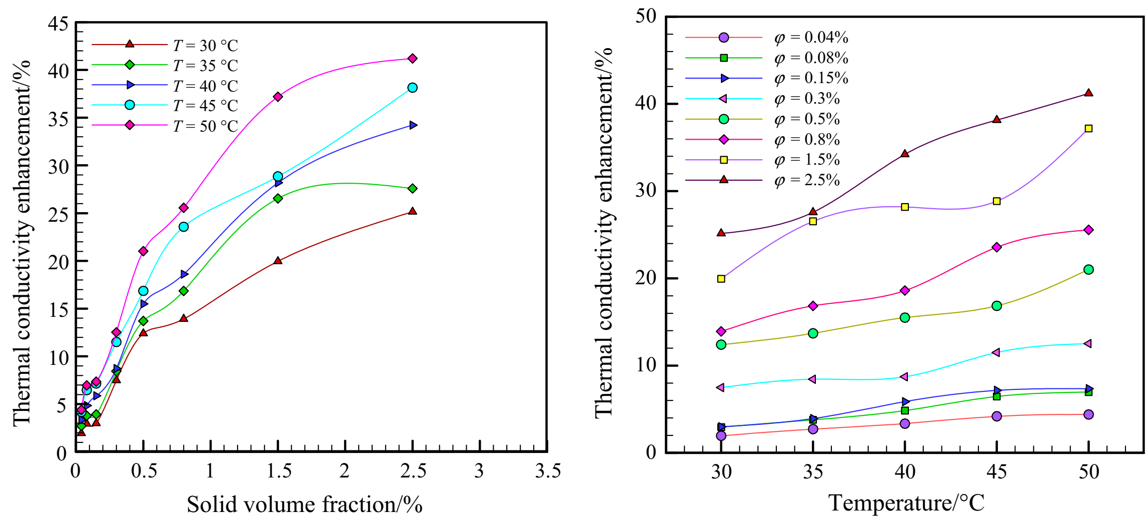


Fig. 4 Thermal conductivity enhancement of SWCNTs–Al_2O_3/EG hybrid nanofluids as a function of solid volume fraction and temperature

Table 4 A comparison of the maximum conduction enhancement of the present study with previous researches

Authors	Base fluid	Dispersed particles	Conditions	Maximum enhancement/%
Suresh et al. [60]	Water	Al_2O_3–Cu	2 vol%	12.11
Baby and Ramaprabhu [52]	Water	MWCNT–HEG	0.05 vol%	20
Abbasi et al. [71]	Gum arabic	MWCNT–Al_2O_3	0.1 vol%	20.68
Hemmat Esfe et al. [69]	Water/EG	DWCNT–ZnO	1% vol	32.9
Paul et al. [72]	EG	Al–Zn	0.1 vol%	16
Hemmat esfe et al. [68]	Water/EG	Cu–TiO2	2% vol	42.6
Baghbanzadeha et al. [47]	Water	MWCNT–silica	0.1 mass% (50% silica, 50% MWCNT)	16.7
Baghbanzadeha et al. [47]	Water	MWCNT–silica	0.1 mass% (80% silica, 20% MWCNT)	12.3
Munkhbayar et al. [43]	Water	MWCNT–Ag	0.05 mass% MWCNT–3 mass% Ag	14.5
Hemmat Esfe et al. [37]	Water	MWCNT–Al_2O_3	1% vol	18
Chen et al. [46]	Water	MWCNT–Fe_2O_3	0.05 mass% MWCNT–0.02 mass% Fe2o3	27.75
Present work	Water	SWCNT–Al_2O_3	2.5 vol%	41.2

presented in this study. In Eq. 2, thermal conductivity of the nanofluid is defined in terms of temperature and solid volume fraction and it is applicable for the volume fractions which are less than 2.5% and at temperatures between 30 and 50 °C. Although the equation may seem simple, it has an excellent accuracy in prediction of SWCNT–Al_2O_3/EG hybrid nanofluid. In this equation, the thermal conductivity ratio of nanofluids to base fluid can be calculated.

$$\frac{k_{nf}}{k_f} = 0.008379 \times \left[(\varphi)^{0.4439} \times T^{0.9246}\right] + 0.963 \quad (2)$$

The values of errors and deviations in terms of solid volume fraction percentage are presented in Eq. 2. As it shown in Fig. 5, the errors and deviations of the data which had been obtained by the presented experimental correlation are not more than 2.6% which signify the excellent accuracy of this equation in thermal conductivity prediction for SWCNT–Al_2O_3/EG hybrid nanofluid. Equation 3 is used for calculating the data deviations

$$\mathrm{Dev} = \left[\frac{\left(\frac{k_{nf}}{k_f}\right)_{Exp} - \left(\frac{k_{nf}}{k_f}\right)_{Pred}}{\left(\frac{k_{nf}}{k_f}\right)_{Exp}}\right] \times 100 \quad (3)$$

Figure 6 depicts the comparison of experimental data with the data obtained from Eq. 2. As it is clear in this figure, the data points are laid on or in the proximity of the bisector line which signifies the proper accordance of the obtained data with the experimental data.

A better comparison between the obtained data and the experimental data in different temperatures is presented in Fig. 7.

Eventually based on Ref. [73], the analysis of thermal conductivity sensitivity was conducted in proportion to volume fraction, and its results are shown in Fig. 8. This analysis determines the sensitivity of thermal conductivity in proportion to volume fraction at different temperatures. In the present research, the analysis is performed considering the effect of variations of volume fractions up to 10% in the base fluid. As it is clear in the figure, as a result of temperature increment, thermal conductivity sensitivity to volume fraction is increased. This means that in a constant volume fraction, adding a specific amount of nanoparticles into the base fluid has a more intense effect on thermal conductivity at high temperatures.

Artificial neural network designing

Neural networks are being used in order to classify, identify, reconstruct the pattern, generalize and optimize the data. In the science of mechanical engineering, this method is vastly being used for recognizing a specific pattern between the obtained experimental data, so neural network will be capable of predicting new data with excellent accuracy after it recognized the pattern of the data. Neural network may use complex mathematical equations such as nonlinear equations on output and input data to find a pattern between them. Choosing appropriate inputs in terms of number, type and true configuration of neural network is very effective on the accuracy of the neural network. The inputs must be chosen in a way that they are compatible with the physics of the problem. As for the configuration of the model, if the number of the neurons of hidden layer is chosen too low, the neural network cannot appropriately model the behavior of the data, so the error of

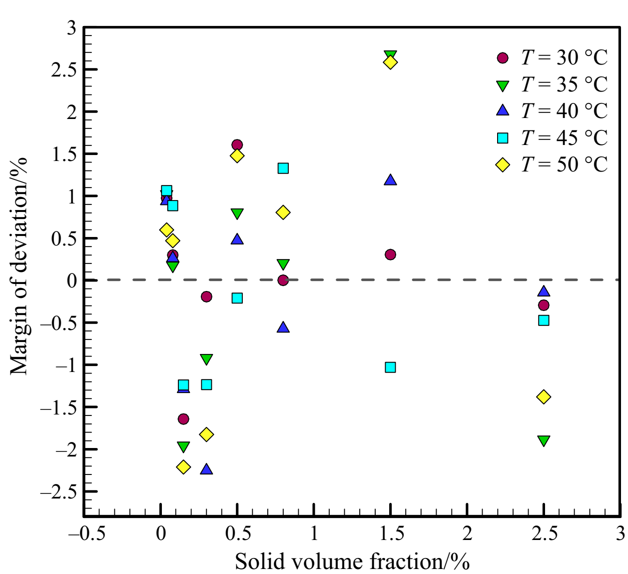


Fig. 5 Margin of deviation of the presented correlation

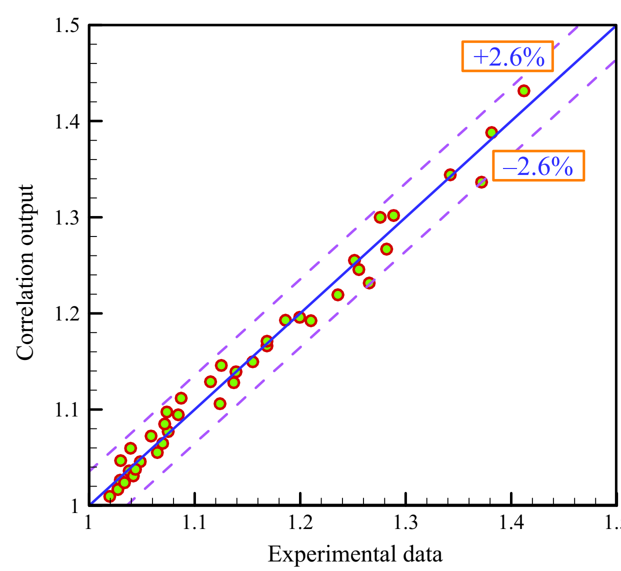


Fig. 6 Comparison between experimental data and correlation outputs

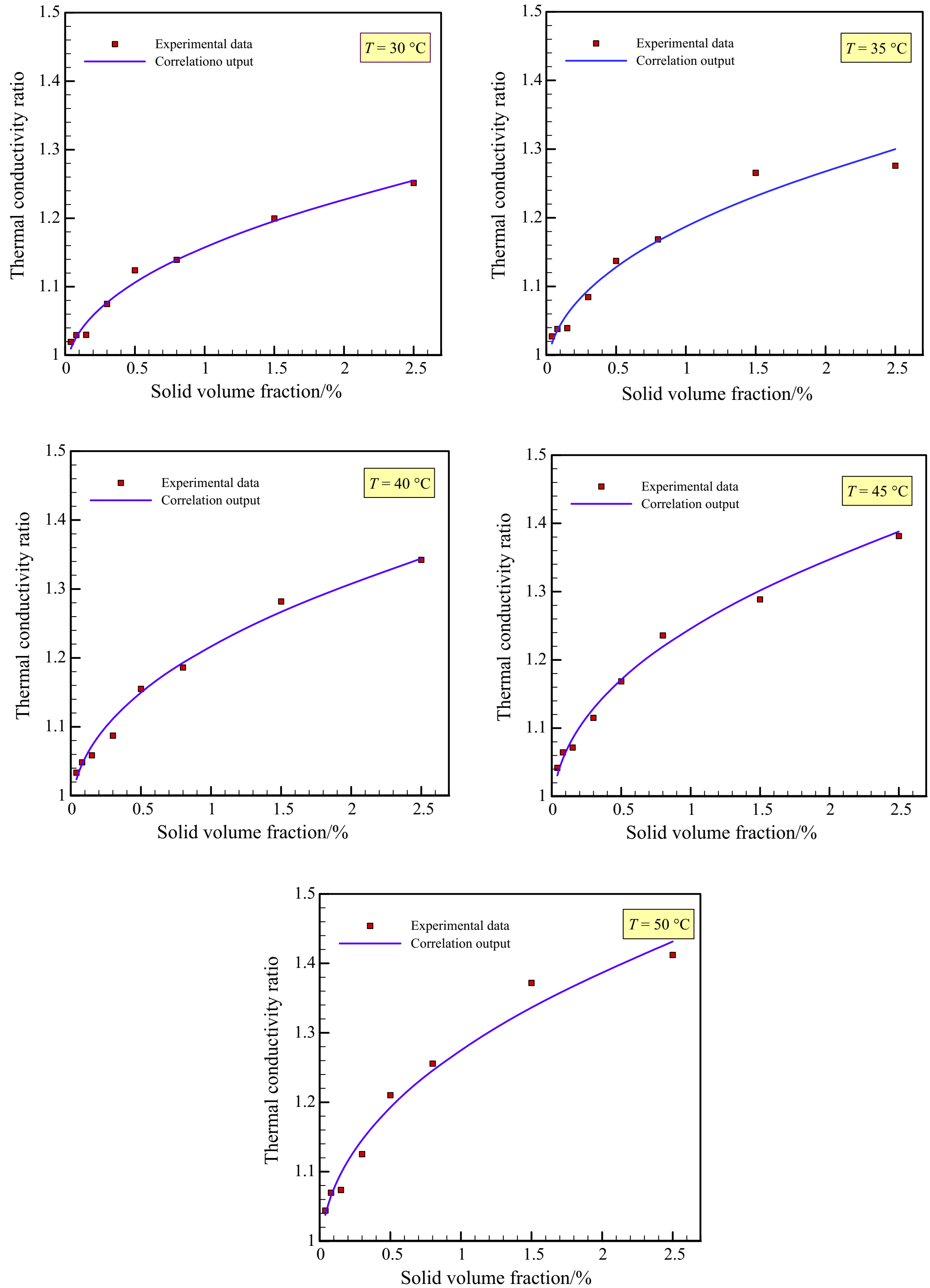
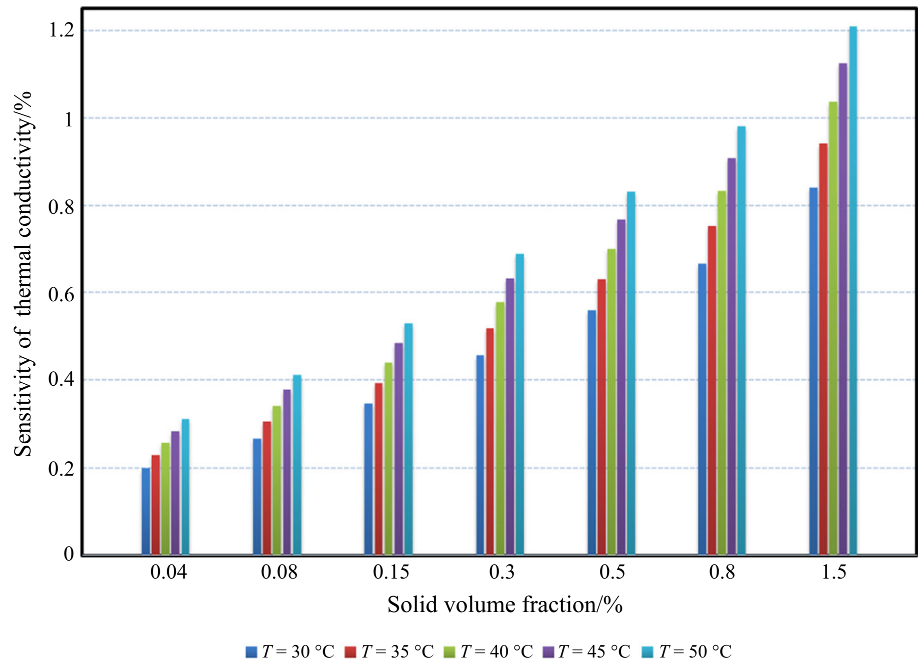


Fig. 7 Comparison between the measured data and correlation data

Fig. 8 Sensitivity analysis of thermal conductivity at different temperatures and concentrations



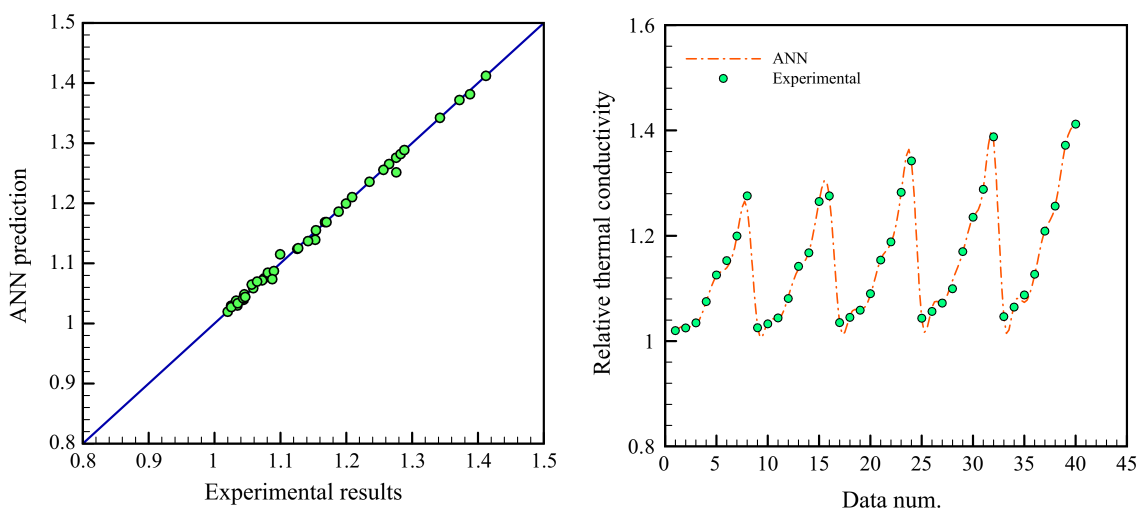


Fig. 9 Comparison between ANN models and experimental data

the model will be too high. If too much of neurons are chosen for the hidden layer, the training process would be extended and it may be laid in local minimum.

Each neural network is made up of some neurons, and these neurons are laid in input, output and hidden layers. These neurons behave according to Eq. 4.

$$y_{\mathrm{j}} = \sum_{i=1}^{p} \omega_{\mathrm{ji}} x_{\mathrm{i}} + b_{\mathrm{j}} \quad (4)$$

where x_i is input neuron, P is number of input neurons, w_{ij} is the corresponding weight between the i and j neurons, and b_j is the bios of j neuron. The output neuron is shown by y_j which is obtained by setting w_{ij} of the network.

On the whole, creating a neural network is consisted of three steps: training, verification and model testing. A considerable number of available data are being used for training purpose. The remaining data are being used for verification and testing of the neural network. In this research, 40 sets of data are used, and temperature and volume fraction are considered as input while thermal conductivity of the nanofluid is the output. A better comparison between the experimental data and the artificial neural network data in different temperatures is presented in Fig. 9.

As it can be seen for all 40 sets of data, the results are compatible with the experimental data and the error and deviation values for relative thermal conductivity were

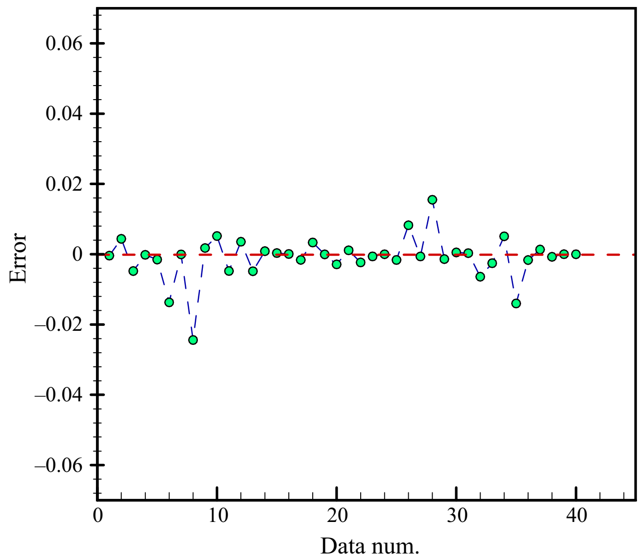


Fig. 10 Difference between experimental and ANN results

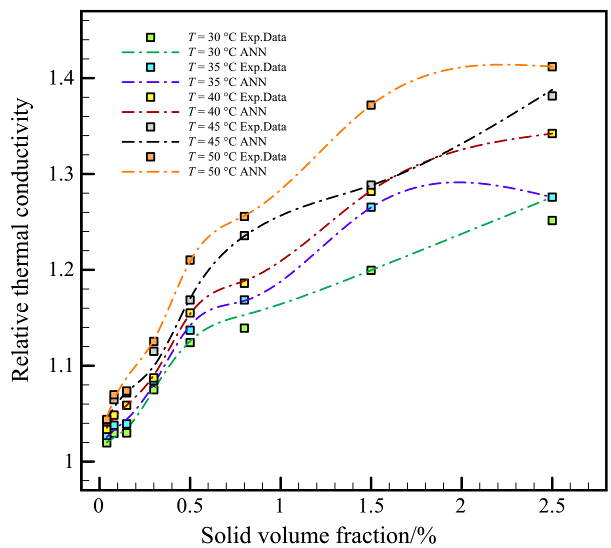
lower than 1.94% for all volume fractions and at any temperature, which is considerably lower than corresponding values of experimental correlation. The relatively low deviation signifies excellent accuracy of the artificial neural network in predicting relative thermal conductivity of SWCNT–Al_2O_3/EG hybrid nanofluid.

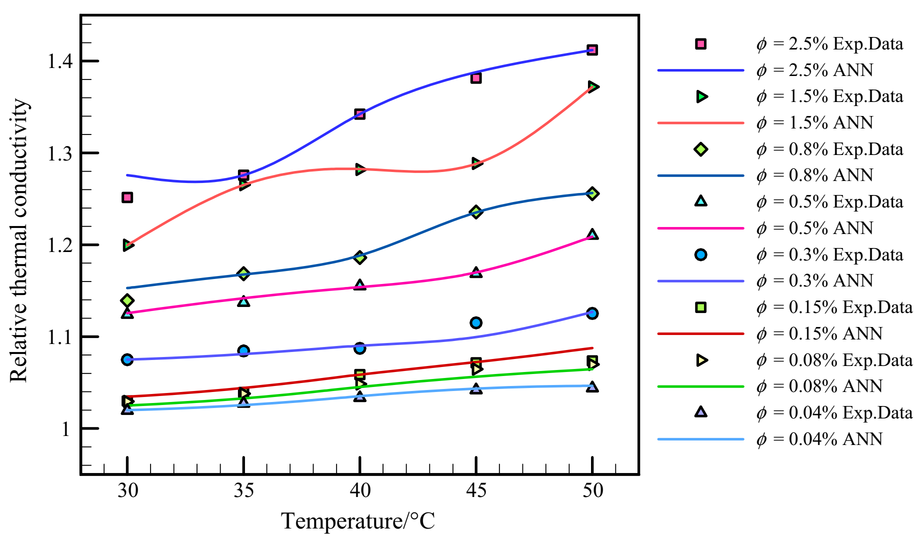
In order to calculate deviation of data, Eq. 3 is used. Figure 10 illustrates the difference between neural network outputs and experimental results in which the maximum deviation is 0.0244.

Figure 11 presents thermal conductivity in various volume fractions and temperatures. In this figure, the accordance of neural network outputs and experimental results at temperature range of 30–50 °C and in volume fractions from 0.04 up to 2.5% are clearly observable.

Figure 12 illustrates the training, verification and testing steps of artificial neural network, and it indicates the error for each of the steps.

Fig. 11 Relative thermal conductivity versus temperature (comparison of ANN model and experimental data)





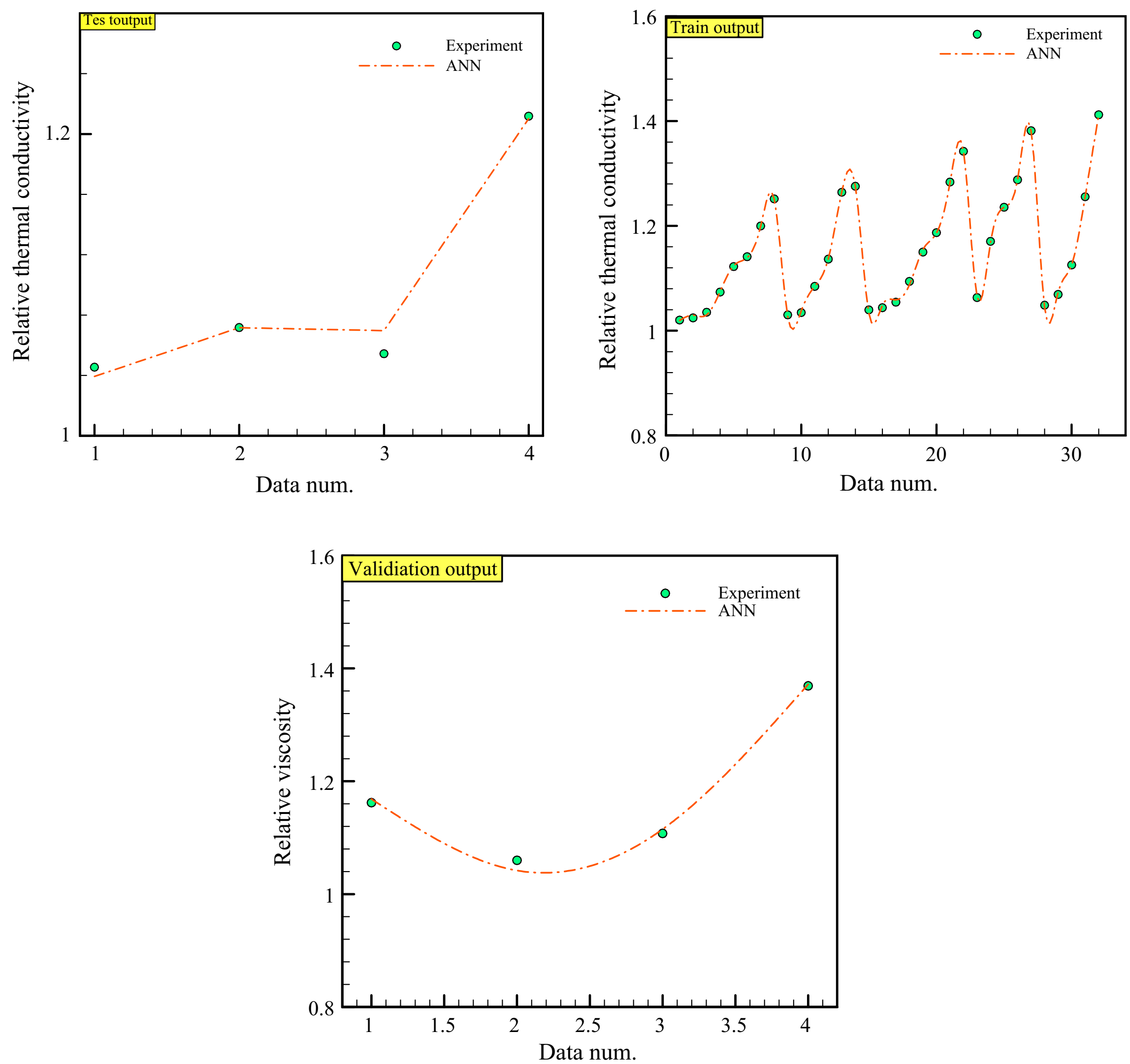


Fig. 12 Training, cross validation and test step results of ANN design

Conclusions

In the present study, thermal conductivity of SWCNT–Al_2O_3/EG hybrid nanofluid is investigated for volume fractions of 0.04, 0.08, 0.15, 0.3, 0.5, 0.8, 1.5 and 2.5 at temperatures from 30 to 50 °C. In this study, alumina nanoparticles and carbon nanotubes with the ratio of 70 and 30%, respectively, were dispersed in the base fluid. Increase in volume fraction and temperature was resulted in relative thermal conductivity enhancement. It was also revealed that the increment of thermal conductivity due to the variation of volume fraction at high temperatures was significantly higher than the corresponding increment at low temperatures. Also in high volume fractions, thermal conductivity of the nanofluid is more sensitive to temperature variations. On the other hand in low volume fractions along with temperature variation, thermal conductivity was changed slightly. The most important difference between this research and the previous studies is that a nanofluid with high nanoparticle content was studied in the present research. In the previous researches on nanofluids with the base fluid of ethylene glycol and CNT nanoparticles, solid volume fractions were lower than 1%, and volume fractions up to 2.5% were studied in this paper. From the results of the test, it was revealed that the ratio of thermal conductivity variations was increased as a result of volume fraction increment, but when the volume fraction reaches to a specific value, this ratio would be decreased. The maximum thermal conductivity enhancement of 41.2% was achieved at 50 °C and for the volume fraction of 2.5%. This increment is significantly higher in comparison with the results of the previous studies.

An experimental correlation for thermal conductivity of the nanofluid in terms of volume fraction and temperature was proposed based on the experimental results. Also an artificial neural network was designed based on temperature and volume fraction inputs and thermal conductivity output. From the comparison of the proposed correlation and empirical data, the maximum error calculated was equal to 2.6% which signifies the acceptable accuracy of the proposed experimental correlation. This correlation is only applicable for volume fractions less than 2.5% and the temperatures within 30–50 °C. The maximum data deviation for the outputs of the neural network was 1.94% that testifies the excellent accuracy of the neural network in predicting thermal conductivity.

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