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Thermal conductivity enhancement of SiO_2–MWCNT (85:15 %)–EG hybrid nanofluids

ANN designing, experimental investigation, cost performance and sensitivity analysis

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Abstract In the present study, measurement and optimization of the thermal conductivity of a hybrid nanofluid are carried out. SiO_2 nanoparticles with average diameter of 20–30 nm and multi-walled carbon nanotube (MWCNT), with internal and external diameter of 2–6 and 5–20 nm, respectively, were dispersed in ethylene glycol and made the hybrid SiO_2–MWCNT (85:15)–ethylene glycol nanofluid. The thermal conductivity of nanofluids in volume fractions of 0.05–1.95 % at temperatures between 30 and 50 °C is measured experimentally. The results indicated that thermal conductivity ratio (TCR) of hybrid nanofluids increases nonlinearly with increasing temperature and concentration. Thus, the greatest increase in TCR at a concentration of 1.94 % and a temperature of 50 °C was 22.2 %. Studying the cost of production and the suspension of hybrid nanofluid and nanofluid containing SiO_2 and MWCNT particles illustrated that using the hybrid nanofluid could be the most optimal one in terms of cost and percentage of TCR. In order to model the thermal conductivity of hybrid nanofluid, two design methods and feed-forward neural network were provided. R^2 value of new methods and artificial neural network (ANN) was obtained 0.9864 and 0.9981, respectively. Comparing these two data estimation methods with experimental data showed that both methods are accurate for predicting data. But ANN has much less error than the correlation outputs.

Keywords Hybrid nanofluid · Artificial neural network · Sensitivity analysis · Thermal conductivity enhancement · Cost performance

List of symbols

T	Temperature (°C)
w	Mass (g)
k	Thermal conductivity (W m^{-1} $°C^{-1}$)

Greeks symbols

ρ	Density (kg m^{-3})
φ	Particle volume fraction

Subscripts

nf	Nanofluid
bf	Base fluid

Introduction

Researchers have achieved in-depth understanding of phase change, mass transfer problems and agglomerative state, by studying the micro-thermophysical properties of materials, in the past three decades [1]. Focus on this knowledge will cause promoting technology and innovation in the miniaturization of industrial equipment. One aspect of this research is studying the heat transfer in the working liquid and different types of this fluid. History of adding particles to the base liquid to increase the thermal conductivity for the first time goes back to Maxwell research [2] in order to model his famous theory. He indicated that the dispersion of the fine solid particles in the liquid causes increase in the thermal conductivity of the solution rather than the primary one. After this, many studies have been carried out on small particles suspended in the liquid. It can be said that the most

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important research has been carried out by Choi [3], which led to innovate new generation of working liquid. He dispersed nanometric-sized particles in a liquid and observed that its thermal conductivity is greatly increased compared to the base one. After the introduction of nanofluid in the scientific community, extensive research in the field of thermophysical properties of it was carried out [4–6]. The viscosity and thermal conductivity of nanofluid have been the most two significant properties [7–12] because these properties affect the heat transfer coefficient of nanofluids [13–16]. Most studies were to evaluate the effect of temperature changes, concentration and particle size on the viscosity [17], where in recent studies, artificial neural network (ANN) is used to model and estimate the viscosity behavior [18–21]. Also in recent years thermal conductivity of nanofluid is an important issue that has been considered by many researchers, and the effect of temperature and concentration on increase in thermal conductivity of nanofluid has been studied [22–26]. According to the most studies, increase in concentration and volume fraction of nanoparticles dissolved in nanofluid could increase thermal conductivity of it [27–31], but the impact of each nanoparticle on this amount is different. Furthermore, many studies on the use of different neural network algorithms to model the experimental data were taken [32–38]. Pang et al. [39] carried out a study on the thermal conductivity of nanofluid SiO_2/methanol at temperature of 20 °C. The results showed that with increasing concentration, the thermal conductivity of nanofluid increases, so that in 0.5 % concentration of nanoparticle volume fraction, the thermal conductivity of nanofluid was 14.29 % higher than the base one. Also, Tavman et al. [40] performed laboratory tests on the thermal conductivity of nanofluid containing water-based SiO_2 at different temperatures and densities. It was found that the

Table 1 Summary of studies on the thermal conductivity of nanofluids

References	Nanoparticle	Base fluid	Conc./%	Temp./°C	Max. k_{nf}/k_{bf}/%
Pang et al. [39]	SiO_2	Methanol	0.01–1	20	10.3
Hemmat Esfe et al. [30]	MgO	Water–EG	0.1–2	20–50	34.5
Sun et al. [42]	SiO_2	Water	1.96–12.85	21	11
Hemmat Esfe et al. [33]	ZnO	EG	0.0625–5	24–50	38
Glory et al. [43]	MWCNT	Water	0.24	15–75	48
Hemmat Esfe et al. [28]	CuO	EG–water	0.1–2	Up to 50	26.71
Hemmat Esfe et al. [25]	MWCNT	Water	0.05–1	25–55	45
Lee et al. [44]	CuO	EG	4	Ambient temperature	20
Hemmat Esfe et al. [29]	Al_2O_3	EG	0.2–5	24–50	40.5
Liu et al. [45]	CNT	EG	1	Ambient temperature	12
Shima et al. [46]	CuO	EG	0.18–1.14	Ambient temperature	14

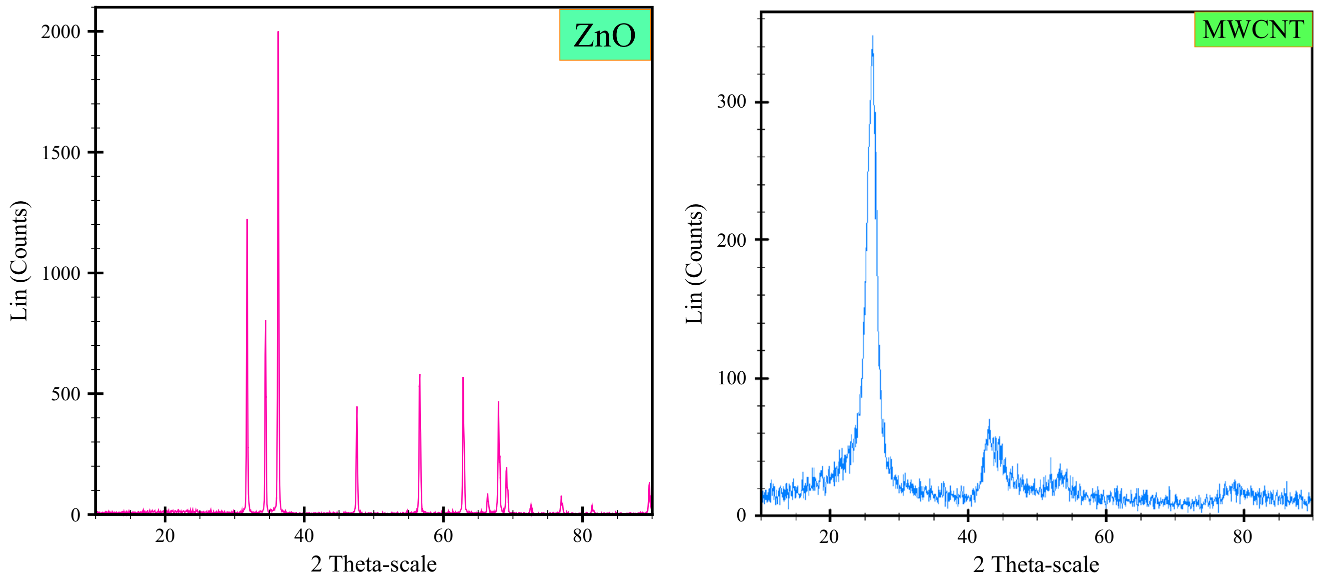

Fig. 1 XRD patterns of ZnO nanoparticles and MWCNTs

thermal conductivity of nanofluids increased slightly with increasing concentration, so that the behavior of nanofluids in this study was similar to the Hamilton–Crosser model [41]. It also showed that this nanofluid did not depend on temperature and by changes in temperature, thermal conductivity changes insignificantly. Also in experiments conducted by Hemmat Esfe et al. [24], thermal conductivity of nanofluids Al_2O_3/water was evaluated at temperatures between 26 and 55 °C and densities up to 5 %. They showed that the sensitivity of thermal conductivity of nanofluid to the increasing concentration increases with increase in temperature. Similar research which has been conducted by other researchers on various materials is listed in Table 1.

One of the main challenges between researchers and scientists in the recent years focused on the commercialization and public use of nanofluids in various industrial and commercial applications. The high-cost production of carbonic nanofluids that have superior thermal features and the undesirable properties of oxidized nanofluids which are available and inexpensive encourage the researchers to combine these two types of particles. Hybrid nanofluids can be considered as a new generation of practical nanofluids because of its superior properties and favorable price. Searching on the literature shows that studying the properties of such nanofluids has not been considered systematically. Special and practical model of thermal properties of nanofluids and its suitable production cost and suspension of it in engineering application is not provided. Due to this subject, the thermal conductivity of hybrid nanofluid containing SiO_2 nanoparticles and multi-walled carbonic nanotubes (MWCNTs) dispersed in ethylene glycol is studied. For the first time, the effect of varying the volume fraction of nanoparticles and temperature on the thermal conductivity of nanofluids besides the economical usage of it has been discussed. In the following, to enhance the application aspect of nanofluids, modeling of thermal conductivity is considered with proposed model and neural network.

Table 2 Physicochemical specification of SiO_2 nanoparticles

Parameter	Value
Color	White
Purity	99.5 %
SSA	180–600 $m^2 g^{-1}$
Diameter	20–30 nm
True density	2.4 $g cm^{-3}$

Table 3 Physicochemical specification of multi-walled carbon nanotube

Parameter	Value
Color	Black
Purity	>97 %
Outer diameter	5–20 nm
Inner diameter	2–6 nm
SSA	>233 $m^2 g^{-1}$
True density	2.1 $g cm^{-3}$

Experimental

In the conducted experiments, multi-walled carbon nanotubes (MWCNTs) with an internal and external diameter of 2–6 and 5–20 nm, respectively, and SiO_2 with an average size of 20–30 nm were chosen as nanoparticles

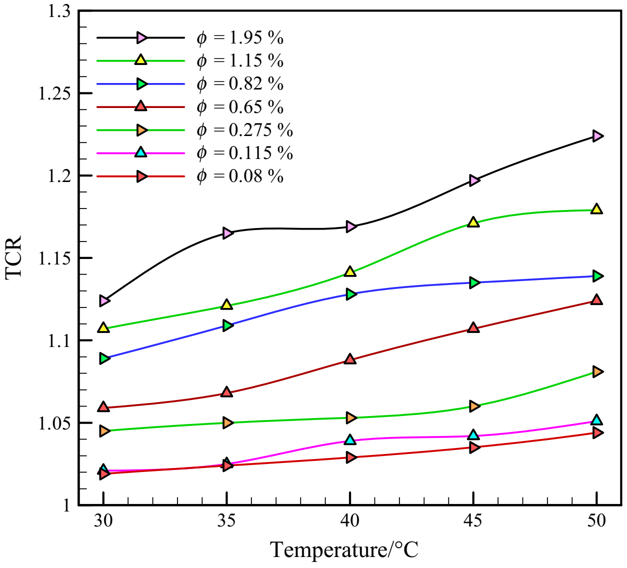

Fig. 2 TCR as a function of temperature at different concentrations

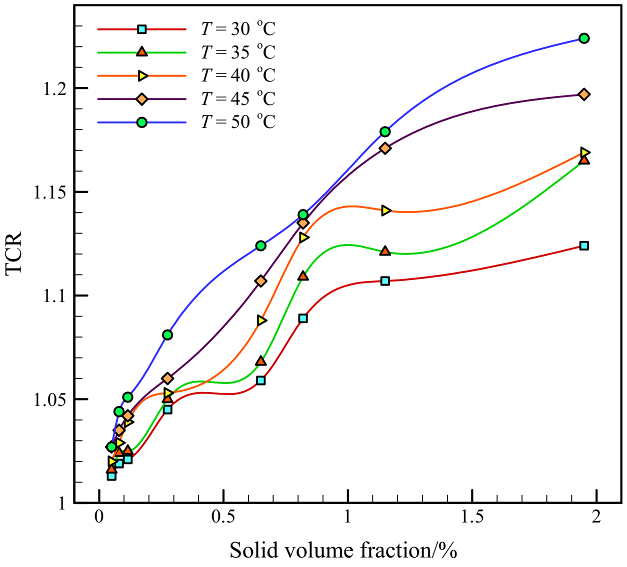

Fig. 3 TCR as a function of concentration at different temperatures

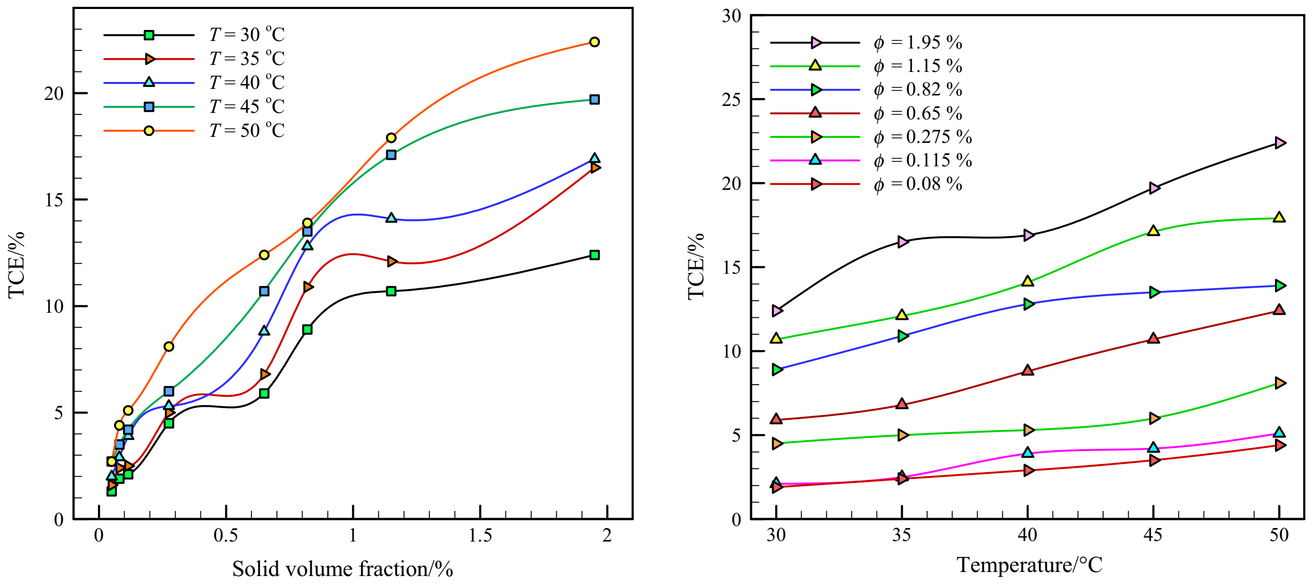

Fig. 4 TCE as a function of temperature at different concentrations

and were dissolved with proportional mass of 15–85 in ethylene glycol, respectively. Equation 1 is used to obtain the mass of each particle. Figure 1 shows the XRD samples of SiO_2 and CNT nanoparticles. These samples were used to obtain the exact size of the particles.

$$\%\varphi = \frac{\left(\frac{w}{\rho}\right)_{\mathrm{MWCNT}} + \left(\frac{w}{\rho}\right)_{\mathrm{SiO_2}}}{\left(\frac{w}{\rho}\right)_{\mathrm{MWCNT}} + \left(\frac{w}{\rho}\right)_{\mathrm{SiO_2}} + \left(\frac{w}{\rho}\right)_{\mathrm{EG}}} \times 100 \qquad (1)$$

In this equation, φ represents required percentage volume fraction, ρ is concentration (kg m^{-3}), and w is mass (kg).

For more information about nanoparticles, the properties of SiO_2 and MWCNT particles are listed in Tables 2 and 3, respectively.

Procedure for preparing nanofluids was as follows: First, a solution containing EG, SiO_2 and MWCNT is stirred for 2–3 h by a mechanical stirrer. Then, the solution using ultrasonic processor, purchased from Kimia Nano-Danesh (KND) Company of Iran, was stirred for 7 h. Frequency and power of ultrasonic device were set to 20 kHz and 1200 W, respectively. The purpose of using ultrasonic device is to eliminate agglomeration of the solution. The samples with 0.05, 0.08, 0.115, 0.275, 0.65, 0.82, 1.15 and 1.95 % volume fraction of hybrid nanofluids SiO_2–MWCNT (85:15)–EG were prepared. Thermal conductivity of the samples was measured using KD2 Pro purchased from Decagon Devices,

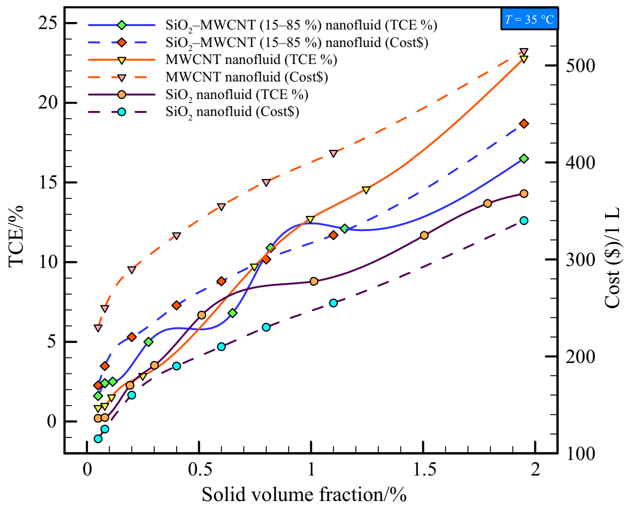

Fig. 5 Economical evaluation of hybrid nanofluid

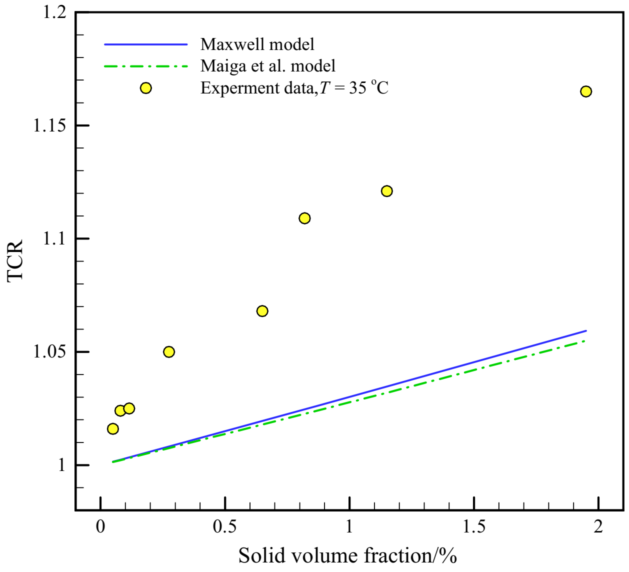

Fig. 6 Comparing the experimental data with theoretical models

Inc., USA. The maximum error of this device was about 5 % and uses transient hot wire (THW) to measure. The stainless steel single needle Model KS-1 is used to measure the thermal conductivity in the temperature range of 30–50 °C.

Results and discussion

Experimental

Figure 2 shows the effect of temperature on the thermal conductivity ratio (TCR) at various concentrations. As it can be seen, TCR increases with increasing temperature in all concentrations. It can be noted that the Brownian motion is responsible for the increase. Raising the temperature causes the collisions between suspended particles in nanofluids and base fluid molecules higher, so the thermal conductivity increases. At lower temperatures, the rise of TCR was less effective. Also it is noticed that the TCR increases in low concentration linearly, but at higher concentration, the temperature effect is highly nonlinear for hybrid nanofluid.

In Fig. 3, the effect of changes of concentration on TCR of hybrid nanofluids SiO_2–MWCNT (85:15)–EG is investigated. According to the figure, in each temperature, increase the volume fraction of nanoparticles have a nonlinear impact on TCR of nanofluids and TCR has increase nonlinearly. The number of particles in nanofluid becomes more than before with increase in the concentration. Two results of this increase are: (1) increased surface-to-volume ratio; (2) the number of collisions increases. Therefore, it expects to increase in TCR.

Table 4 Quality of the proposed relation

SSE	R^2	Adjusted R^2
0.001798	0.9864	0.9844

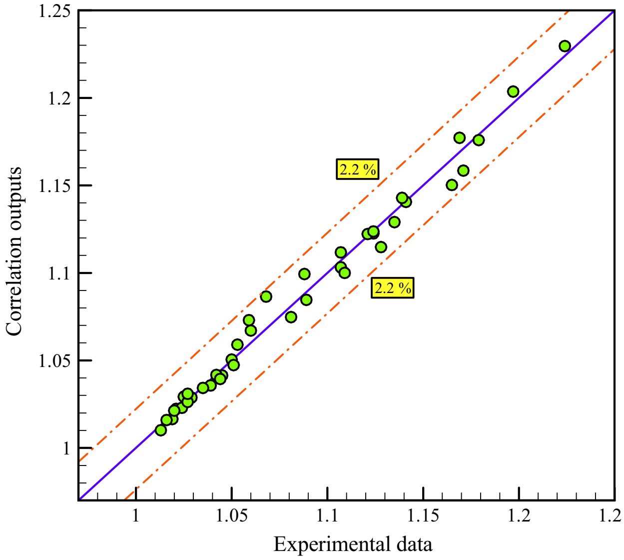

Fig. 7 Prediction error data by correlation

In Fig. 4, percent increase in thermal conductivity enhancement (TCE) at different temperatures and solid volume fractions is presented. According to this figure, increase in TCE percent proportion to temperature is lower at low concentrations. Between temperatures of 30 and 35 °C for two concentrations of 0.08 and 0.115 %, TCE percent is the same and so using the volume fraction of 0.115 % at this temperature is not recommended. But it can be seen that the impact of temperature on 1.95 % concentration is higher, which caused TCE increase as much as 10 % with increase in temperature from 30 to 50 °C. The highest percentage of TCE has been observed at temperature of 50 °C and concentration of 1.95 %, where its value was 22.2 % increase compared to the base fluid. For the temperatures of 30 and 35 °C and volume concentrations 0.275–0.65 %, it does not find any increase in the percentage of TCE actually. Consequently, this temperature and concentration range can't be helpful in thermal conductivity and is not recommended for industrial applications.

Evaluation of economic value

Also hybrid nanofluid can be studied in another aspect. Numerous studies have proven that the use of carbon nanotubes (CNTs) in nanofluid has caused dramatic increase in its properties of it such as thermal conductivity. But due to the high price of CNT, using them as a separate nanoparticle is limited. On the other hand, using it as an additive material can be very optimal in two perspectives, TCE and price. In Fig. 5, hybrid nanofluid SiO_2–MWCNT (85:15)–EG, nanofluid containing MWCNT and nanofluid containing SiO_2 are compared in terms of TCE percentage and price. The thermal conductivity of nanofluid MWCNT measured experimentally, and laboratory data of SiO_2 nanofluid are extracted from [47]. According to the figure, the overall trend of curves determines that the price of SiO_2–MWCNT (85:15)–EG hybrid nanofluids is not as expensive as price of MWCNT nanofluid, while its TCE is more than SiO_2 nanofluid. Of course, in small areas of concentration, SiO_2 nanofluid can be used, but in general, we can say that use of hybrid nanofluid is more valuable.

Proposed correlation

In this study, experimental data were compared with theoretical models of Maxwell [2] and Maïga et al. [48]. Figure 6 shows the comparison of the results of these two models with TCR data at temperature of 35 °C. According to this figure, these two theoretical models could not estimate the TCR data in any volume fraction. In Maxwell model, it is assumed that the particles have a spherical shape and the concentration of solution is low. This assumption could be one of the reasons for the deviation of experimental data and the model one.

Due to the large error in the data prediction, a new correlation based on temperature and concentration of SiO_2–MWCNT (85:15)–EG hybrid nanofluids is presented below to predict the TCR.

$$\frac{K_{\mathrm{nf}}}{K_{\mathrm{bf}}} = 0.905 + 0.002069\varphi T + 0.04375\varphi^{0.09265}T^{0.3305} - 0.0063\varphi^{3} \qquad (2)$$

In this correlation, φ is nanofluid concentration, T is temperature, and bf and nf are the base fluids and nanofluid, respectively. The quality of this suggested relation to estimate the experimental data is listed in Table 4.

The difference between the data predicted by this correlation and experimental TCR data is shown in Fig. 7. According to the figure, the data had been predicted with a

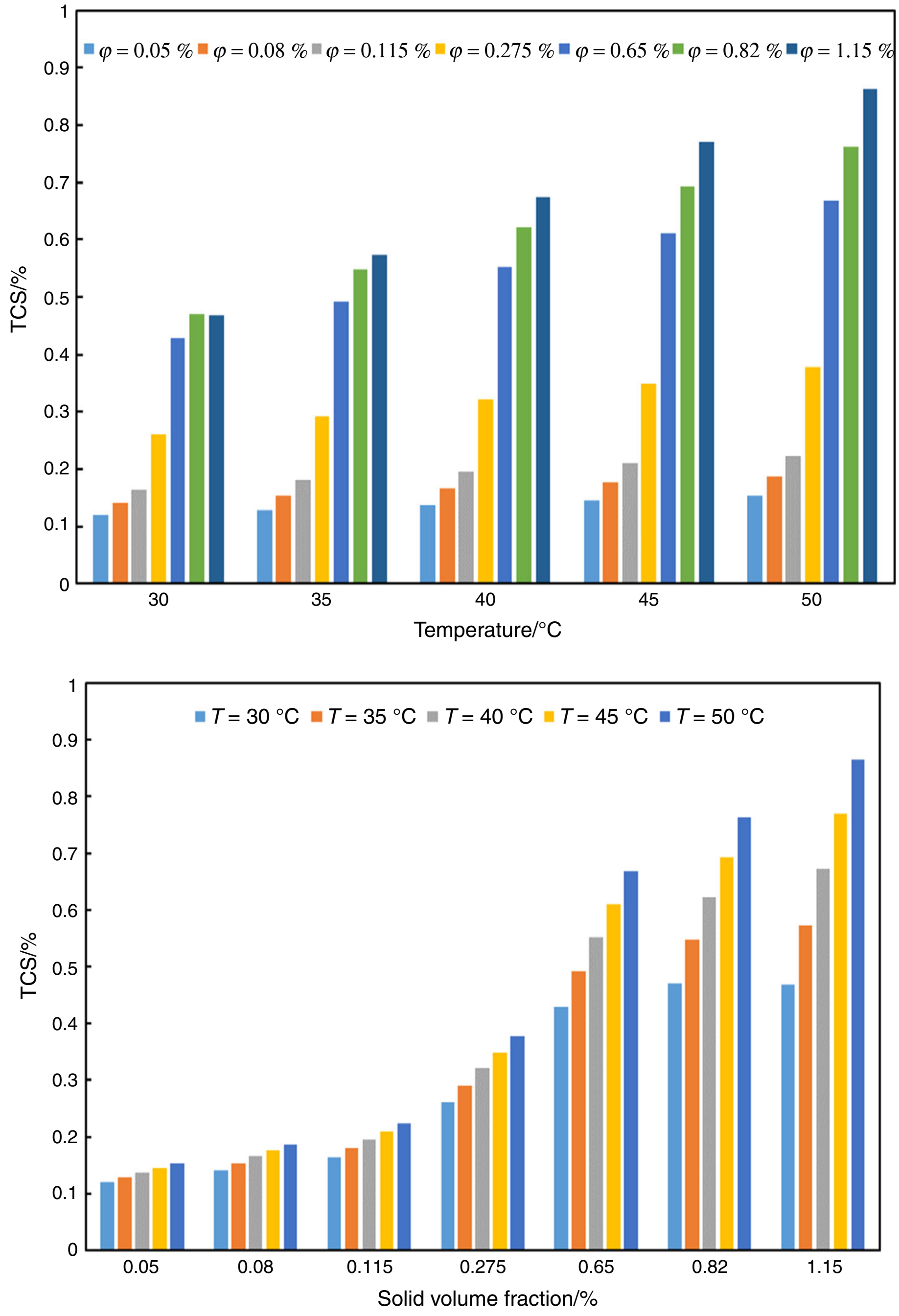

Fig. 8 TCS as a function of concentration at different temperatures

Table 5 Designed neural network

Number of hidden neurons	R^2	MSE	Transfer function
[1]	0.9634	2.5767e−04	[Radbas]
[2]	0.9927	4.8104e−05	[Radbas]
[3]	0.9953	3.1119e−05	[Radbas]
[4]	0.9942	4.1219e−05	[Radbas]
[5]	**0.9981**	**1.2845e−05**	**[Radbas]**
[6]	0.9976	1.95289e−5	[Radbas]
[7]	0.9967	2.22591e−5	[Radbas]
[1 1]	0.9675	2.2147e−05	[Radbas Radbas]
[2 2]	0.9901	6.5501e−05	[Radbas Radbas]
[3 3]	0.9949	3.5259e−05	[Radbas Radbas]
[4 4]	0.9853	1.097e−04	[Radbas Radbas]

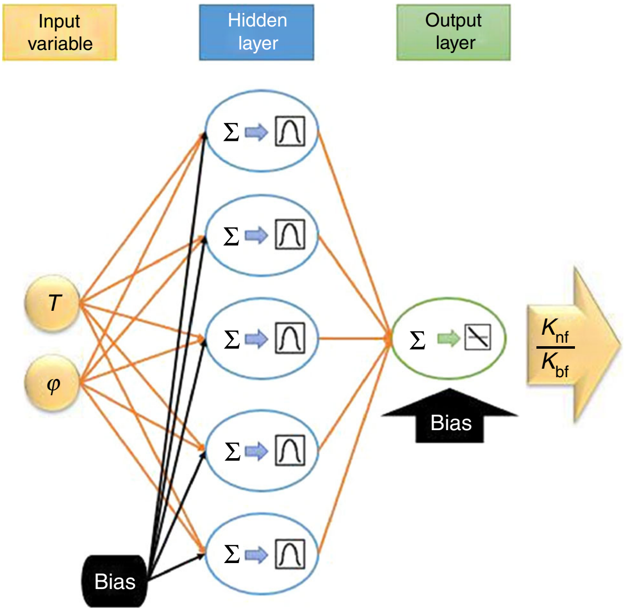

Fig. 9 ANN structure

maximum error of 2.2 %. In TCR of <1.05, the prediction data have very little error and are on the bisector line. It can be said that in TCR between 1.05 and 1.2, the forecast error is high.

Thermal conductivity sensitivity (TCS) of SiO_2–MWCNT (85:15)–EG hybrid nanofluid as a function of concentration is calculated using the following equation:

$$\%\,\text{Sensitivity of TC} = \left(\frac{(k_{nf})_{\text{After Change}}}{(k_{nf})_{\text{Base Condition}}} - 1\right) \times 100 \qquad (3)$$

To calculate TCS, in each concentration, nanoparticles in amount of 10 % of that concentration were added and the changes were investigated. In this relation, the subscript, after change, related to after adding nanoparticles and, base condition, is also related to before adding nanoparticles. TCS results in different temperatures and densities are shown in Fig. 8. According to this figure, in each temperature at concentration of 0.05–0.115 %, TCS increases slowly, but in densities more than 0.275 %, TCS increased significantly. Also, TCS in concentration of 0.82 % and temperature of 40 °C is more than TCS in concentration of 1.1 % and temperature of 35 °C. It can be found from the figure that the difference between TCSs in different temperatures increases with increase in concentration. For example, TCS difference in temperatures between 30 and 50 °C and concentration of 1.15 % was 0.4 % while this difference was equal to 0.04 % in concentration of 0.05 %.

Neural network modeling

Using neural network modeling, TCR experimental data of SiO_2–MWCNT (85:15)–EG hybrid nanofluid were estimated. The feed-forward neural network algorithm was used. Experimental data used for modeling include 40 TCR data that can be divided into two input types, 1–5 temperature set and 2–8 concentration set. Input data were divided into three parts: 70 % for training, 15 % for test and 15 % for validation. Total mean square error (MSE) and R^2 were selected as a criterion for optimization of neural network and are listed in Eqs. 4 and 5, respectively. These criteria reflect the accuracy of the model to predict the TCR data of SiO_2–MWCNT (85:15)–EG hybrid nanofluid which is designed with different amounts of inputs.

$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left(\left.\frac{k_{nf}}{k_{bf}}\right|_{\text{EXP}} - \left.\frac{k_{nf}}{k_{bf}}\right|_{\text{pred}}\right)^2 \qquad (4)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\left.\frac{k_{nf}}{k_{bf}}\right|_{\text{EXP}} - \left.\frac{k_{nf}}{k_{bf}}\right|_{\text{pred}}\right)_i^2}{\sum_{i=1}^{N}\left(\left.\frac{k_{nf}}{k_{bf}}\right|_{\text{EXP}}\right)_i^2} \qquad (5)$$

In this equation, N represents the number of data. With the change in the number of hidden layers and neurons to design neural network, the most optimal number of hidden layers and number of neurons are obtained and they are shown in Table 5.

Neural network structure is shown in Fig. 9.

Figure 10 shows the accuracy of the predicted data versus experimental data. The figure shows the high accuracy of the modeling, so that the maximum error was 1.2 %. All data are located on the bisector line or near it.

In Fig. 11, experimental results, feed-forward model and the new correlation proposed for the TCR of SiO_2–MWCNT (85:15)–EG hybrid nanofluid presented in Eq. 2 in terms of data numbers have been compared. The neural

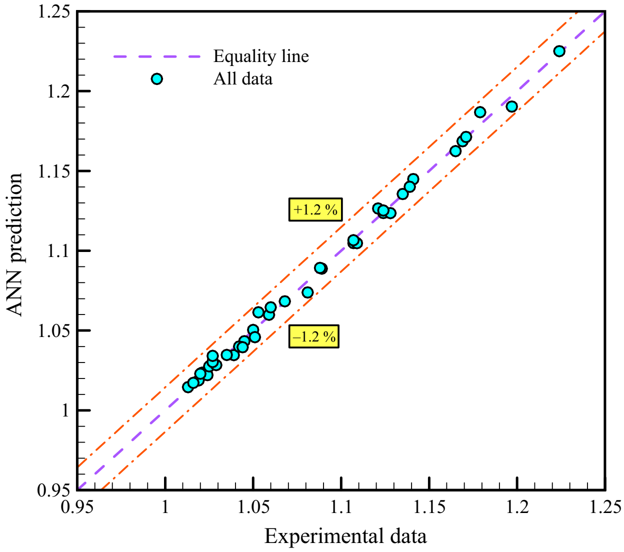

Fig. 10 Comparing ANN outputs with experimental data

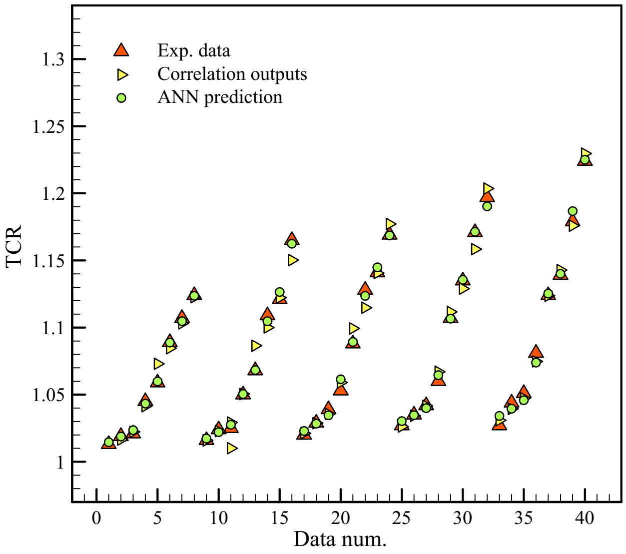

Fig. 11 Comparing the performance of ANN and correlation with experimental data

network model and the new correlation can predict the experimental data with an acceptable error, so that the R^2 of neural network and correlation is 0.9981 and 0.9864, respectively. It can be concluded from figure that the neural network model has higher prediction accuracy.

Conclusions

In this study, SiO_2 nanoparticles with an average diameter of 20–30 nm and MWCNT with an internal and external diameter of 2–6 and 5–20 nm, respectively, were dispersed in the ethylene glycol fluid with ratios of 85:15 %. Then, uniform and homogeneous hybrid nanofluids, SiO_2–MWCNT (85:15)–EG, were formed using ultrasonic device. So the thermal conductivity of the volume fraction of 0.05, 0.08, 0.115, 0.275, 0.65, 0.82, 1.15 and 1.95 % of hybrid nanofluids was measured at temperatures between 30 and 50 °C. The results indicated that TCR of hybrid nanofluid increases with increasing temperature and concentration directly. Thus, the greatest increase in thermal conductivity happened at temperature of 50 °C and concentration of 1.94 %, which is equivalent to 22.2 %. TCE–concentration–cost graph for hybrid nanofluids and nanofluids containing SiO_2 and MWCNT particles showed that use of hybrid nanofluids is the most efficient one. A new correlation based on temperature and concentration for TCR of hybrid nanofluids was proposed and its R^2 was equal to 0.9864. Also, feed-forward neural network was designed and its MSE and R^2 were 1.2845e−05 and 0.9981, respectively. Comparing these two methods of estimation data with experimental data showed that both methods are accurate for predicting, but ANN has much less error than the correlation outputs.

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