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Curve-fitting on experimental data for predicting the thermal-conductivity of a new generated hybrid nanofluid of Graphene Oxide-titanium oxide/Water

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Abstract

The objective of this experimental study is to study the effects of a hybrid utilization of graphene oxide (GO) and titanium oxide (TiO_2) nano-materials on the water thermal-conductivity. The experiments were carried out for different concentrations of 0.05, 0.1, 0.2, 0.4, 0.6, 0.8 and 1% and in the temperature range of 20 to 50^oC. The experiments showed that higher temperature and concentrations of nano-materials result in a higher the thermal-conductivity. The maximum thermal-conductivity enhancement was 32.8%. Moreover, a new accurate correlation for the thermal-conductivity was presented based on the experimental data obtained in the laboratory in terms of temperature and nano-materials volume fraction.

Keywords: Curve-fitting; Hybrid nanofluid; Thermal-conductivity; Graphene and titanium oxides;

1. Introduction

Today, convective heat transfer has a key role in most industrial heat exchangers. This type of heat transfer needs an appropriate fluid. One of the most commonly used fluids in heat exchangers is water. Special properties of water distinguish it from other liquids. It is one of the most abundant compounds on earth. Water is odorless, tasteless, and colorless and it has other properties which make this liquid valuable. Low thermal conductivity of water is one of the weaknesses of using it in heat exchangers. It is clear that a fluid with high thermal conductivity should be used to improve heat transfer in heat exchangers. In order to compensate for this fault and to use other advantages of water, addition of fine metal/metal oxide, carbon materials, etc. to a base fluid is recommended as one of the most effective methods to increase thermal conductivity and consequently convective heat transfer. "*Nanofluid*" is a fluid containing fine metal or non-metal materials (copper oxide, iron oxide, etc.) with dimensions of less than 100 nm in a base fluid (which is mainly water and/or ethylene glycol) as a dispersed stable suspension. The use of nanofluids in the oil, gas, petrochemical, air conditioning and automotive industries improves the performance of heat exchangers. The working fluid has the main role in the heat exchangers. Optimizing the heat transfer properties of these fluids can be an important step in optimizing the performance of the heat exchanger and ultimately increasing productivity in the industry. Today, the issue of reducing or optimizing energy consumption is very important considering the expiration of fossil fuel resources. Consequently, engineers believe that the use of nanofluids can significantly reduce energy consumption in thermal systems, which leads to a reduction in fuel consumption and better protection of the environment [1-6].

Results of heat-transfer experiments on different nanofluid samples showed that they performed better than their expected theoretical performance [7, 8]**.** In fact, it is possible to reduce the size of heat exchangers using the nanofluids that lead to further heat transfer [9, 10]. Production of smaller and lighter heat exchangers saves costs and energy [11, 12]

Many studies have been reported on the thermophysical properties of nanofluids and it has become specified that it is possible to change the transfer and heat properties of a nanofluid by adding nano-materials. The use of a small amount of nano-materials may even improve heat transfer. Adding a small percentage of nanoparticles improve nanofluid thermal conductivity significantly as compared with a base fluid. Table 1 shows some studies reported on the thermal conductivity of nanofluids. Studies show that nanofluid thermal conductivity depends on the combination of percentage of nanoparticles and nanofluid chemical, mass percentage of nanoparticles, shape and size of particles, surface active agents (surfactants), temperature, etc..

Table 1. A review on the studies that reported the thermal conductivity of nanofluids

Author	**Base fluid**	**Dispersed particles**	**Concentration**	**Maximum enhancement (%)**
Abareshi et al. [13]	Water	Fe_3O_4	Up to 3 vol.%	15.1
Afrand et al. [14]	Water	Fe_3O_4	Up to 3 vol.%	90
Jung et al. [15]	Water	Al_2O_3	Up to 1 vol.%	14.4
Mintsa et al. [16]	Water	Al_2O_3	Up to 6 vol.%	34
Das et al. [17]	Water	CuO	Up to 4 vol.%	28.7
Li and Peterson [18]	Water	CuO	Up to 6 vol.%	51
Liu et al. [19]	Water	Cu	Up to 0.1 vol.%	24
Paul et al. [20]	Water	Au	Up to 0.00026 vol.%	48
Li and Xuan [21]	Water	Al	Up to 5 vol.%	27
Kang et al. [22]	Water	Ag	Up to 0.39 vol.%	11
Li et al. [23]	Water	Fe	Up to 5 vol.%	14.9
Wen and Ding [24]	Water	TiO_2	Up to 0.68 vol.%	6
Duangthongsuk and Wongwises [25]	Water	TiO_2	Up to 2 vol.%	13.2
Ahmadi Nadooshan [26]	Water-EG	ZnO	Up to 4 vol.%	20
Singh et al. [27]	Water	SiC	Up to 4 vol.%	22.5
Huminic et al. [28]	Water	FeC	Up to 4 vol.%	24.2
Adhami Dehkordi et al. [29]	Water-EG	SWCNTs	Up to 0.65 vol.%	52.7
Shamaeil et al. [30]	EG	DWCNTs	Up to 0.6 vol.%	24.9
Soltanimehr and Afrand [31]	Water-EG	MWCNTs	Up to 1 vol.%	34.7
Yu et al. [32]	EG	Graphene oxide	Up to 0.05 vol.%	61

A new generation of nanofluids has recently been introduced called “hybrid nanofluids”. These nanofluids are potential fluids that provide high heat transfer performance and thermodynamic properties more than heat transfer fluids (oil, water, and ethylene glycol) and nanofluids containing mono type nanoparticles. In fact, hybrid nanofluid is a new nanofluid which is produced through dispersing two different nano-materials into a common heat transfer fluid. Some researchers studied the thermal conductivity of these types of nanofluids. For example, Sundar et al. [33] examined the thermal conductivity of MWCNTs–Fe_3O_4/water hybrid nanofluid and reported the maximum enhancement of 13.88% at volume fraction of 0.3%. Suresh et al. [34] measured the thermal conductivity of Al_2O_3–Cu/water hybrid nanofluid and presented the maximum enhancement of 12.11% at solid volume fraction of 2%. Sarbolookzadeh Harandi et al. [35] investigated the thermal conductivity of MWCNTs–Fe_3O_4/EG hybrid nanofluid. Their results showed the maximum enhancement of 30 at solid volume fraction of 2.3%. Afrand [36] performed measurement of the thermal conductivity of MgO-FMWCNTs/EG hybrid nanofluid. He increased the solid volume fraction of nano-additives to 0.6% and observed a maximum thermal conductivity enhancement of 21.3%. Nasajpour Esfahani et al. [37] performed an experimental study on thermal conductivity of ZnO–Ag/water hybrid nanofluid. They reported that the maximum thermal conductivity enhancement was 26% at solid volume fraction of 2%. Hemmat Esfe et al. [38] presented an experimental work on ZnO-DWCNTs/EG hybrid nanofluid with 24.9% enhancement in thermal conductivity that occurred at solid volume fraction of 1.9%. Other studies have also done on the thermophysical and heat transfer of the nanofluids, all of which have reported their suitability [39-58].

It is clear that saving energy and improving efficiency of systems are highly important today. The increase of thermal conductivity cools a system quicker, saves energy, and improves efficiency. On the other hand, the unique properties of graphene oxide and appropriate stability of titanium oxide allowed us to produce a new water-based hybrid nanofluid in this study by knowing the construction of the hybrid nanofluids as mentioned above. The use of graphene nanoparticles in water increases thermal conductivity considerably; however, the planar shape of nanofluids increases base fluid viscosity, they increase the pumping power of the nanofluid for a cooling operation, and the nanoparticle is costly. Therefore, this study used titanium nanoparticles combined with graphene oxide for the first time to provide a better viscosity and save costs.

2. Statement of the present research

A graphene oxide–titanium oxide/water hybrid nanofluid is produced in this study. Some methods including ultrasound waves, the addition of surfactants, and base-fluid pH control should be used to produce nanofluid stable samples. After producing a stable sample of the nanofluid, photography, UV-Vis absorption spectroscopy, and DLS (Dynamic Light Scattering) methods are used to determine its stability.

The impact of temperature and concentration of the nanofluid on the thermal-conductivity of graphene oxide–titanium oxide/water hybrid nanofluid is examined after making the nanofluid by measuring the thermal-conductivity of samples. It is then attempted to study the effect of duration of ultrasonic waving on nanofluid thermal-conductivity. Finally, the results of the measurement nanofluid thermal-conductivity are compared with the ones of other nanofluids and a mathematical correlation is developed for the thermal-conductivity prediction. Figure 1 shows the flowchart of the route to achieve the research objectives.

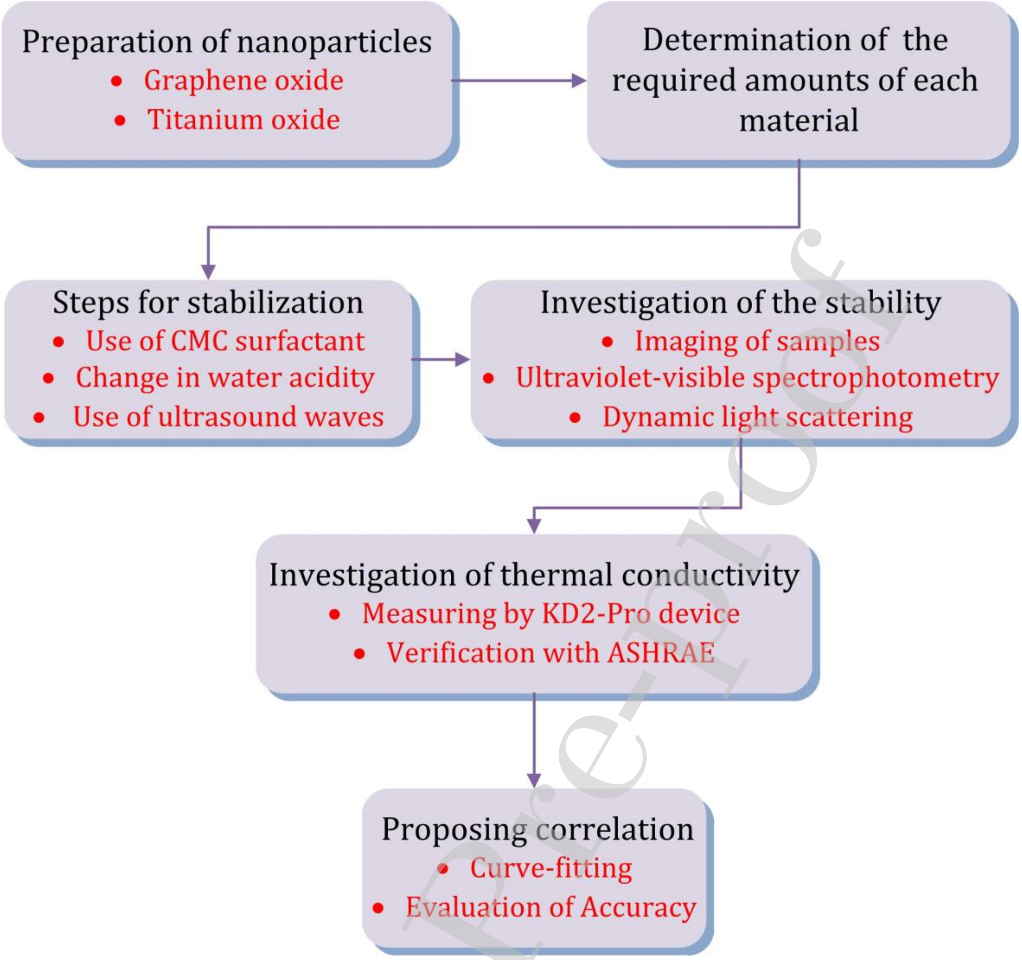

Fig. 1. The process of doing this research

3. Used materials

This study used distilled water as the base-fluid and graphene oxide and titanium oxide as the nanoparticles. The ratio of using nano-materials in all volume fractions of the test was considered 50% of each. The nanoparticles were produced using a chemical analysis method. The nanoparticles were made by *US Research Nanomaterials, Inc*.

3.1. Graphene Oxide

Studies show that graphene oxide nanoparticle, as compared with other common metal nanoparticles such as aluminum oxide, copper oxide, etc., has an appropriate specific surface area, high thermal-conductivity, a very low average of particle size, and very low density. However, the only major problem of this group of nanoparticles is their high cost.

One of the advantages of graphene oxide is its ease of diffusion in water and other organic solvents and various matrices, which is due to the presence of oxygenated agents. Graphene nano-sheets have some features including high thermal-conductivity, large specific surface area, hydrophilicity, insolubility, and low density. Table 2 shows the nanoparticle specifications. The XRD of graphene oxide is shown in Fig. 2.

Table 2. Specifications of graphene oxide

Material	Purity (%)	Appearance	Color	Thickness (nm)	Number of layers	Specific surface area (m^2/gr)
Graphene oxide	99	Sheet	Black	3.4-7	7-11	100-300

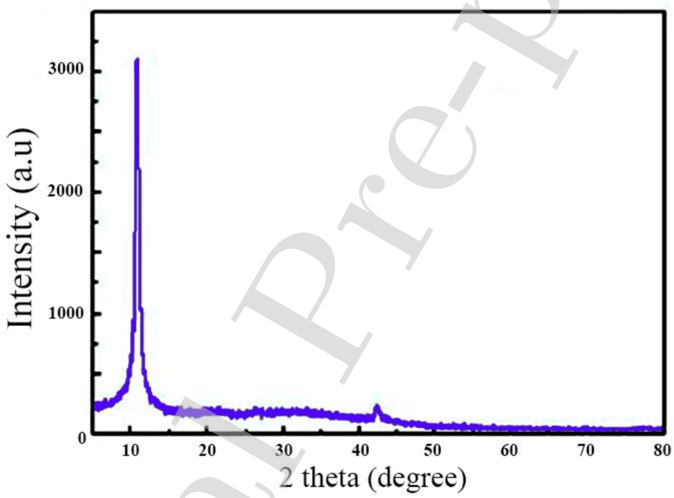

Fig. 2. XRD of graphene oxide nano-sheets

3.2. Titanium Oxide

Titanium oxide nanoparticles have high purity, limited range of particle size, spherical structure, and relatively high specific surface area. Moreover, titanium oxide nano-materials have chemical stability, high thermal-conductivity, and lower thermal expansion coefficient.

The use of titanium oxide nanoparticles in the hybrid nanofluid modifies the physical structure of graphene oxide nano-sheets, which helps to reduce the nanofluid viscosity as compared with graphene oxide/water nanofluid and reduces the production cost of the hybrid nanofluid with the modified feature as compared with graphene oxide/water nanofluid. Table (3) shows the nanofluid specifications and its XRD is respectively shown in Fig. 3.

Table 3. Specifications of titanium oxide

Material	Purity (%)	Appearance	Color	Diameter (nm)	Density (gr/m^3)	Specific surface area (m^2/gr)
Titanium oxide	99.9	Spherical	White	20	3.9	200

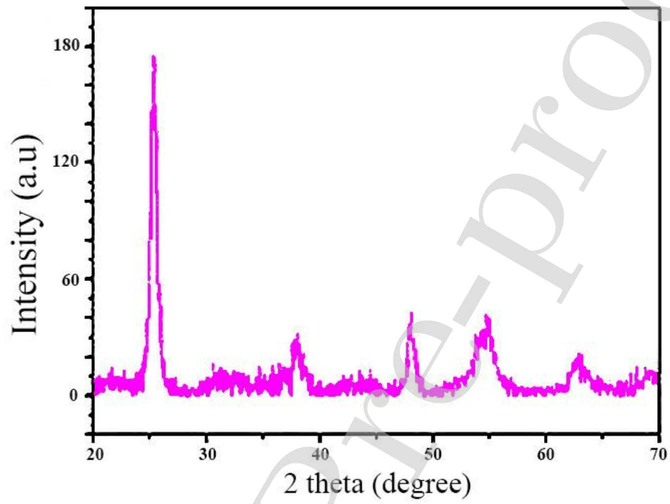

Fig. 3. XRD of titanium oxide nanoparticles

3.3. Base-fluid

The PH of distilled water is neutral (about 7). The specific conductivity of distilled water is very low, as the electrical conductivity of water enhances with the dissolution of salts. The boiling point of distilled water, due to its purity, is lower than the one in ordinary water. It never corrodes due to having no soluble materials. Distilled water is not a desirable and pleasant drink and it has lost its taste due to the removal of ions. Distilled water has commonly been used in industry because of the change in some of its physical properties as compared with ordinary water.

4. Experimental work

4.1. Production Samples

The nanofluid samples used in this study were made of graphene oxide and titanium oxide nano-materials in a hybrid manner in a water-based fluid with the concentrations of 0, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, and 1%. The required amount of each substance for producing 100 ml of nanofluid in a certain volume fraction is given as:

$$m_{TiO_2} = 5 \times 10^{-6} \rho_{TiO_2} \varphi \quad (1\text{-a})$$

$$m_{GO} = 5 \times 10^{-6} \rho_{GO} \varphi \quad (1\text{-b})$$

$$m_{H_2O} = \rho_{H_2O} \left[0.100 - \left(\frac{m_{Go}}{\rho_{Go}} + \frac{m_{TiO_2}}{\rho_{TiO_2}} \right) \right] \quad (1\text{-c})$$

where φ is the nanofluids volume fraction in percent. m_{Go} , m_{TiO_2} , and $m_{H_2O}$are respectively the mass of graphene oxide nano-sheets, titanium oxide nanoparticles, and base-fluid in grams. ρ_{Go} , ρ_{TiO_2} , and $\rho_{H_2O}$are respectively the symbols of the density of graphene oxide and titanium oxide nanoparticles, and the mass density of base-fluid in kg/m^3.

As it is impossible to measure the accurate volume of nanoparticles using the above relation, the values of density and mass of nanoparticles are used to determine different concentrations. A 0.001g digital scale was used for measuring the weight of nanoparticles.

pH is one of the major parameters for maintaining stability in nanofluids. Studies show that water-based nanofluids containing graphene oxide and titanium oxide particles have the highest surface charge of particles for long-term stability at a pH higher than the neutral state [47,48]. This study uses carboxymethyl cellulose (CMC) surfactants to create an alkaline environment and to increase the surface charge of particles. For each specimen of nanofluid, ¼ of nanoparticles mass was used. The surfactants increased pure water pH from a neutral state and pH was approximately 9 for all different test samples. The surfactants were manufactured by Sigma Corporation and it had a considerable effect on the stability of GO-TiO_2/water hybrid nanofluid as compared with the state without surfactants.

A magnetic mixer was employed to scatter nano-materials in the base-fluid and each sample was exposed to the magnetic mixer for an hour. To establish stability, nanofluid samples were exposed to ultrasound waves. A nanofluid sample was exposed to ultrasound waves in an Ultrasonic device for 30, 40, 50, and 60 minutes. It was observed that the sample maintained uniform stability after 50-60 minutes. All the samples were then exposed to ultrasound waves for 45 minutes in different volume fractions. Figure 4 shows an image of a sample during the ultrasound process.

Fig. 4. Image of a sample during ultrasound process

4.2. Stability

Ultraviolet-visible spectrophotometry was used to examine the stability of samples. The results are used for the quantitative description of suspension colloidal stability. One of the features of the device is that it can be used for all base-fluid s. The law used in this method is that light intensity is altered by its absorption or diffusion through the fluid. Suspension stability is often investigated by measuring the deposited volume in terms of deposition time. The disadvantage of this method is that it is not suitable for the nanofluids with high concentration, especially the solution of carbon nanotubes. A *Spectrophotometer-Biochrom WPA Lightwave II* was used to examine nanofluid stability.

An absorption test was carried out to measure the absorption intensity using pure water for calibration of the device and examining the control sample. The graphene oxide-titanium oxide/water hybrid nanofluid was then tested in different periods. Figure 5 shows the absorption test results in 60, 150, and 240 minutes after nanofluid production.

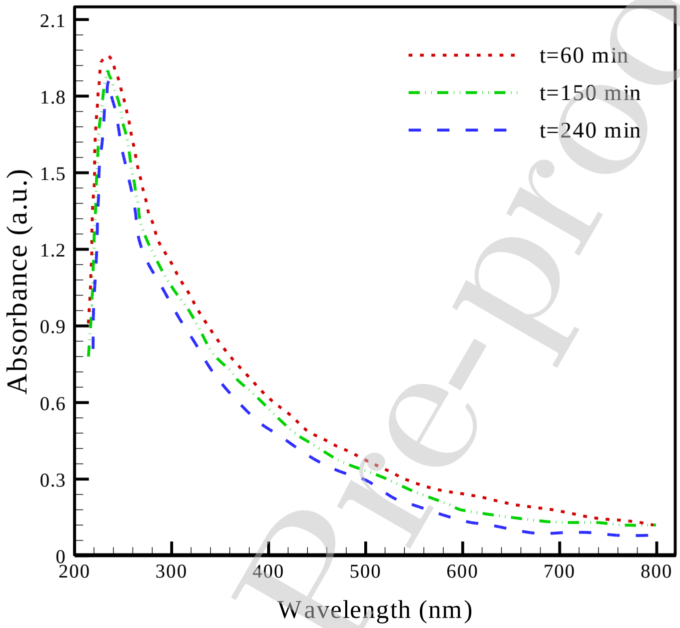

Fig. 5. Absorption test results in 60, 150, and 240 minutes after nanofluid production

The test results show that maximum absorption intensity is at the wavelength of 234 nm. To examine the stability, the test was repeated without any change in nanofluid status at different periods. The intensity of nanofluid absorption reduced from 1.96 to 1.86 within 240 minutes after the first test, which indicates the nanofluid stability is acceptable.

Figure 6 shows the images taken from the samples three hours after producing nanofluid samples.

3 hours after preparation

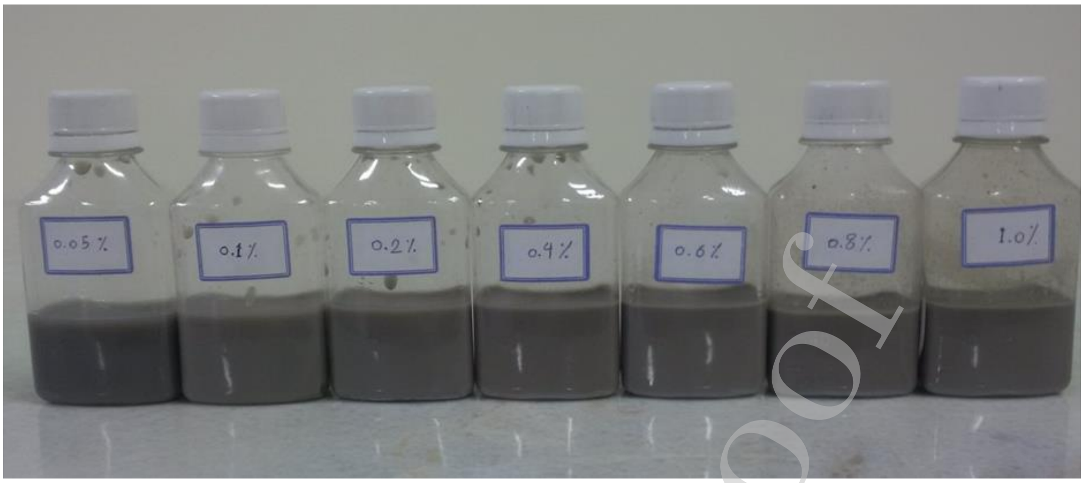

Fig. 6. Images of nanofluid samples at different time periods

4.3. Measurement of Thermal-conductivity

This research used a KD2-Pro device to determine the thermal-conductivity of the hybrid nanofluid. The device mainly operates employing the transient hot-wire method as one of the most precise methods. KD2-Pro is a battery-powered portable device employed for thermal properties measurement of different materials as per EN55022:1987 reference standard. It is used for the thermal and conductivity properties of liquids, solids, and soil. The operating temperature range of the device is 0-50°C and the operation range of the device probes is 50-150. The KS-1 sensor of the device with a maximum precision of 5% was used in this test.

As one of the objectives was to assess the effect of temperature on nanofluid thermal-conductivity, the temperature of the samples should have been maintained at a fixed value during each measurement. The temperature range in the test was 20-50°C. A 7-liter-capacity WNB-7 Memmert bath was employed for maintaining the temperature stability of the samples. Heat transfer in this bath is carried out by natural convection. The temperature range of the device is 25-95°C with a precision of 0.1°C. Chamber temperature sensitivity was adjusted to 0.1°C. The samples were placed in the temperature bath for measurement to reach the desired temperature and the thermal-conductivity of the nanofluid samples were measured by a KD2-PRO device. Figure 7 shows how to measure thermal-conductivity while the sample is in the temperature bath.

Fig. 7. Setup of thermal-conductivity measurement in temperature bath

5. Results and discussion

5.1. Measurements Verification

To verify the measurements, the thermal-conductivity of pure water measured in this study was compared with the values reported for water in the ASHRAE Handbook [59] as shown by Figure 8. The figure shows that the maximum difference is lower than 1%, which indicates an appropriate accuracy for all the measurements.

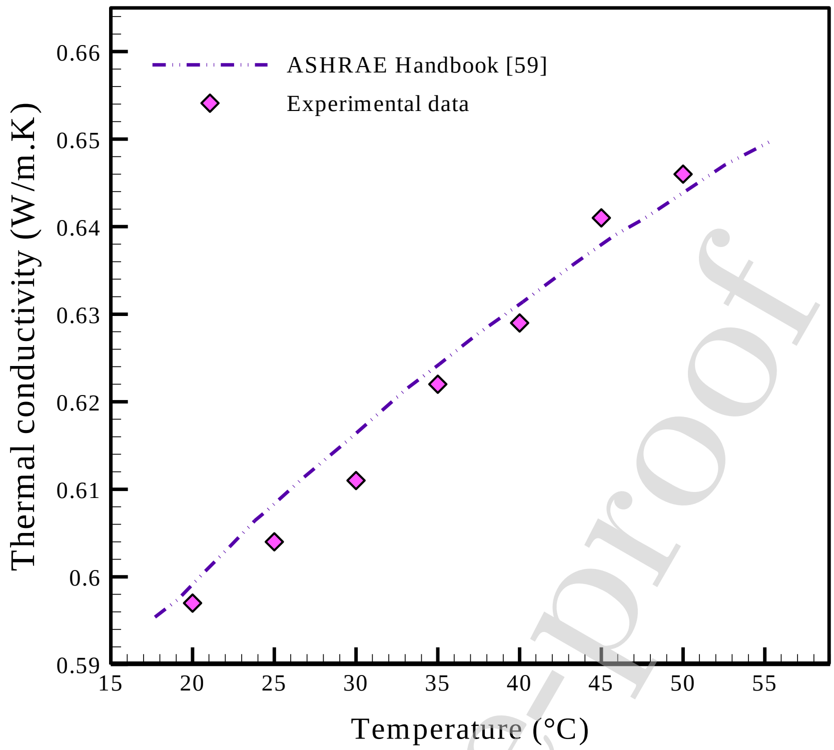

Fig. 8. Measured thermal-conductivity in comparison with ASHRAE data [59]

5.2. Effects of nano-materials volume fraction and temperature

Figure 9 shows the absolute and relative thermal-conductivities of the nanofluid against nano-materials volume fraction at different temperatures. The thermal-conductivity of nanofluid over the base-fluid at an identical temperature is called "relative thermal-conductivity". It shows that the absolute and relative thermal-conductivities enhances with increasing the concentration at all temperatures. The increase is due to the fact that nanoparticles move among base-fluid molecules and sometimes collide with one another through Brownian motion. In a special case, when two particles impact with each other, the heat transfer created between the solid nanoparticles may increase the nanofluid thermal-conductivity. Figure 9 illustrates that the gradient of thermal-conductivity increase is higher in lower concentrations. This phenomenon may be attributed to the fact that nano-materials have a large specific surface area due to the low amount of agglomeration of nanoparticles in lower volume fractions. Larger specific surface area leads to higher thermal-conductivity.

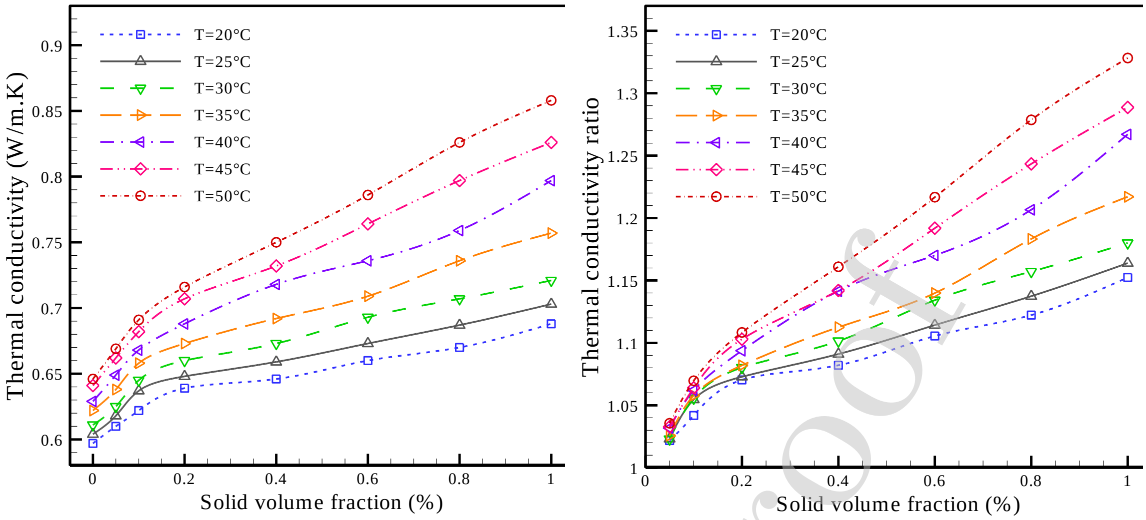

Fig. 9. Absolute and relative thermal-conductivities of the nanofluid against volume fraction at different temperatures

Figure 10 shows the absolute and relative thermal-conductivities of the nanofluid against temperature for all nanofluid samples. As the figure shows, a higher thermal-conductivity is gained from all the samples with increasing the temperature due to the increase of Brownian diffusion and further impacts of particles. The increase is higher in higher volume fractions because the number of nanoparticles exceeds in richer nanofluids and the effect of temperature on Brownian diffusion and random collision of nanoparticles is more tangible. For instance, the relative conductivity increases from 1.023 to 1.180 in the volume fraction of 0.05-1% at 30°C and the maximum volume fraction has the maximum relative heat conductivity. As the figure indicates, the maximum relative heat conductivity, i.e. 1.328%, is related to 50°C in 1 Vol.%.

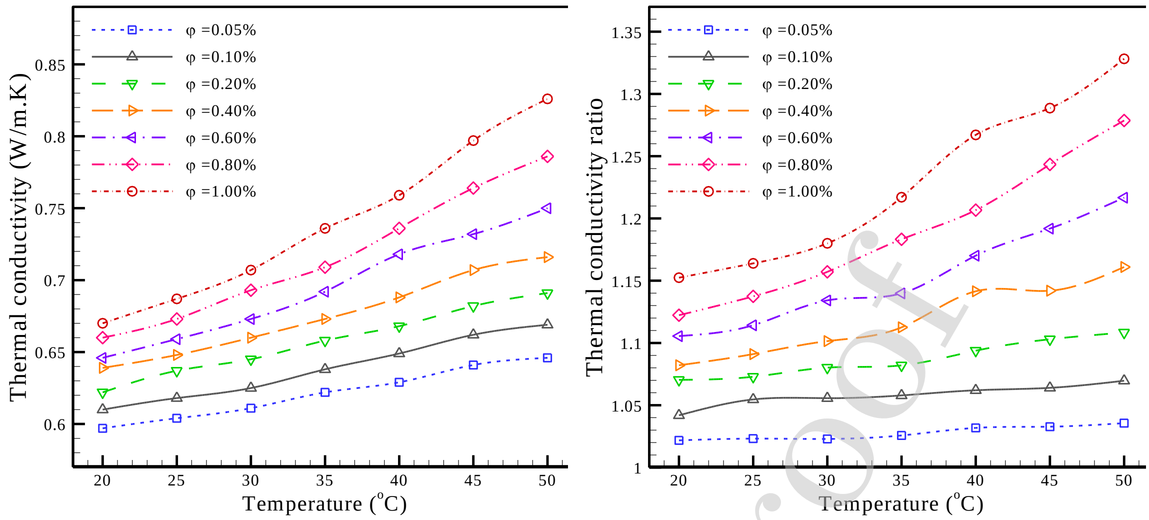

Fig. 10. Absolute and relative thermal-conductivities of the nanofluid in terms of temperatures at for all nanofluid samples

5.4. Introducing a new correlation

Literature has shown that conventional models would not be able to predict the nanofluids thermal-conductivity. Soltanimehr and Afrand [31] proved that maximum thermal-conductivity of nanofluid in the volume fraction of 1% was only 3% Based on the Maxwell model; while their proposed nanofluid in the same volume fraction showed an approximate increase of 35%. This research showed that thermal-conduction increased by about 34% in the volume fraction of 1%. Therefore, it can be argued that the Maxwell Model is useless to predict the nanofluid thermal-conductivity. Consequently, this section introduces a new model to determine the thermal-conductivity of graphene oxide-titanium oxide/water hybrid nanofluid based on the results and measurements in terms of concentration and temperature. Curve fitting is used first to present Equation 2 for water thermal-conductivity based on temperature. Then, Equation 3 is presented for predicting the thermal-conductivity of nanofluid using the values in proportion to thermal-conductivity.

$$k_{bf} = 0.5642e^{0.002748T} \quad (2)$$

$$\frac{k_{nf}}{k_{bf}} = (1.017 + 0.072 \times 1.029^{T} \times \varphi^{0.773}) \quad (3)$$

In Equations 2 and 3, k is the thermal-conductivity in W/m.K, T is the temperature in °C, and φ is the volume fraction in %. Indices *bf* and *nf* refer to the base-fluid and the nanofluid, respectively.

Figure 11 compares the values of the thermal-conductivity calculated by Equation 3 and the experimental values to assess the accuracy of the proposed relation. The figure shows that most experimental data are in agreement with the predicted line showing the accuracy of the proposed relation.

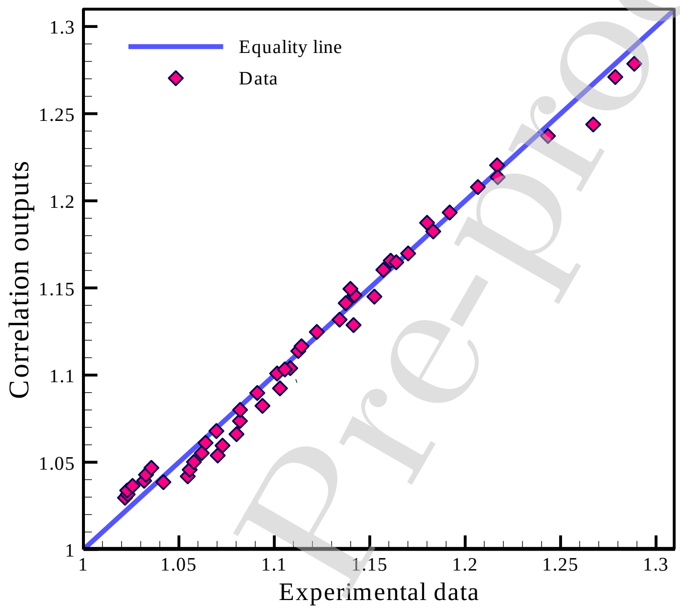

Fig. 11. Thermal-conductivity ratio obtained by proposed equation in compared with the experimental data

6. Conclusion

In this research, the thermal-conductivity of GO-TiO_2/water hybrid nanofluid in the temperature range of 20 to50°C for samples with volume fractions of 0.05, 0.1, 0.2, 0.4, 0.6, 0.8 and 1% was examined and the following results are obtained:

- The thermal-conductivity enhanced for a higher concentration and temperature. The highest thermal-conductivity enhancement was 32.8%, which was related to the temperature of 50°C and a volume fraction of 1%.
- The slope of variation of thermal-conductivity ratio in the concentrations range of 0.4 to 1% was higher than that in range of 0.05 to 0.4%.

- To achieve proper stability, samples were exposed to ultrasonic waves for 45 minutes. 45 minutes was an optimal time. In this way, two samples with volume fractions of 0.1 and 0.6% have been subjected to ultrasound over different times.
- In the UV-Vis absorption spectroscopy test, the absorption rate of nanofluid reduced from 1.96 to 1.86 after 240 minutes of the first experiment, which showed acceptable nanofluid stability.
- An accurate equation was presented in terms of volume fraction and temperature to determine GO-TiO_2/water thermal-conductivity.
- At the end, the results of experimental data and the proposed model were compared showing the accuracy of the proposed equation as well as the comparison of these results with the ASHRAE Handbook of the appropriate validation.

References

[1] Alnaqi, A.A., Hal, S.S.T., Aghaei, A., Soltanimehr, M., Afrand, M., Nguyen, T.K., "Predicting the effect of functionalized multi-walled carbon nanotubes on thermal performance factor of water under various Reynolds number using artificial neural network", Physica A: Statistical Mechanics and its Applications, vol. 521, pp. 493-500, 2019.

[2] Al-Rashed, A.A., Ranjbarzadeh, R., Aghakhani, S., Soltanimehr, M., Afrand, M., Nguyen, T.K., "Entropy generation of boehmite alumina nanofluid flow through a minichannel heat exchanger considering nanoparticle shape effect", Physica A: Statistical Mechanics and its Applications, vol. 521, pp. 724-736, 2019.

[3] Alsarraf, J., Moradikazerouni, A., Shahsavar, A., Afrand, M., Salehipour, H., Tran, M.D., "Hydrothermal analysis of turbulent boehmite alumina nanofluid flow with different nanoparticle shapes in a minichannel heat exchanger using two-phase mixture model", Physica A: Statistical Mechanics and its Applications, vol. 520, pp. 275-288, 2019.

[4] Firouzi, M., Bagherzadeh, S.A., Mahmoudi, B., Hajizadeh, A., Afrand, M., Nguyen, T.K., "Robust Weighted Least Squares Support Vector Regression algorithm to estimate the nanofluid thermal properties of water/graphene oxide-silicon carbide mixture", Physica A: Statistical Mechanics and its Applications, vol., pp., 2019.

[5] Irani, M.H., Afrand, M., Mehmandoust, B., "Curve fitting on experimental data of a new hybrid nano-antifreeze viscosity: Presenting new correlations for non-Newtonian nanofluid", Physica A: Statistical Mechanics and its Applications, vol., pp., 2019.

[6] M. Hemmat Esfe, H. Rostamian, S. Esfandeh, M. Afrand, Modeling and prediction of rheological behavior of Al2O3-MWCNT/5W50 hybrid nano-lubricant by artificial neural network using

experimental data, Physica A: Statistical Mechanics and its Applications, 510 (2018) 625-634.

[7] K. Goudarzi, H. Jamali, Heat transfer enhancement of Al2O3-EG nanofluid in a car radiator with wire coil inserts, Applied Thermal Engineering, 118 (2017) 510-517.

[8] Afrand, M., Esfe, M.H., Abedini, E., Teimouri, H., "Predicting the effects of magnesium oxide nanoparticles and temperature on the thermal conductivity of water using artificial neural network and experimental data", Physica E: Low-dimensional Systems and Nanostructures, vol. 87, pp. 242-247, 2017.

[9] Shahsavani, E., Afrand, M., Kalbasi, R., "Using experimental data to estimate the heat transfer and pressure drop of non-Newtonian nanofluid flow through a circular tube: applicable for use in heat exchangers", Applied Thermal Engineering, vol. 129, pp. 1573-1581, 2018.

[10] Nadooshan, A.A., Eshgarf, H., Afrand, M., "Evaluating the effects of different parameters on rheological behavior of nanofluids: A comprehensive review", Powder technology, vol., pp., 2018.

[11] Abedini, E., Zarei, T., Rajabnia, H., Kalbasi, R., Afrand, M., "Numerical investigation of vapor volume fraction in subcooled flow boiling of a nanofluid", Journal of Molecular Liquids, vol. 238, pp. 281-289, 2017.

[12] Afrand, M., Abedini, E., Teimouri, H., "Experimental investigation and simulation of flow boiling of nanofluids in different flow directions", Physica E: Low-dimensional Systems and Nanostructures, vol. 87, pp. 248-253, 2017.

[13] M. Abareshi, E.K. Goharshadi, S.M. Zebarjad, H.K. Fadafan, A. Youssefi, Fabrication, characterization and measurement of thermal conductivity of Fe3O4 nanofluids, Journal of Magnetism and Magnetic Materials, 322 (2010) 3895-3901.

[14] M. Afrand, D. Toghraie, N. Sina, Experimental study on thermal conductivity of water-based Fe3O4 nanofluid: Development of a new correlation and modeled by artificial neural network, International Communications in Heat and Mass Transfer, 75 (2016) 262-269.

[15] J.-Y. Jung, J.Y. Yoo, Thermal conductivity enhancement of nanofluids in conjunction with electrical double layer (EDL), International Journal of Heat and Mass Transfer, 52 (2009) 525-528.

[16] H.A. Mintsa, G. Roy, C.T. Nguyen, D. Doucet, New temperature dependent thermal conductivity data for water-based nanofluids, International Journal of Thermal Sciences, 48 (2009) 363-371.

[17] S.K. Das, N. Putra, P. Thiesen, W. Roetzel, Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids, Journal of Heat Transfer, 125 (2003) 567-574.

[18] C.H. Li, G. Peterson, Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids), Journal of Applied Physics, 99 (2006) 084314.

[19] M.-S. Liu, M.C.-C. Lin, C.Y. Tsai, C.-C. Wang, Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method, International Journal of Heat and Mass Transfer, 49 (2006) 3028-3033.

[20] G. Paul, T. Pal, I. Manna, Thermo-physical property measurement of nano-gold dispersed water based nanofluids prepared by chemical precipitation technique, Journal of colloid and interface science, 349 (2010) 434-437.

[21] Q. Li, Y. Xuan, Measurement of thermal conductivities of nanofluids, JOURNAL OF CHEMICAL INDUSTRY AND ENGINEERING-CHINA-, 54 (2003) 42-114.

[22] H.U. Kang, S.H. Kim, J.M. Oh, Estimation of thermal conductivity of nanofluid using experimental effective particle volume, Experimental Heat Transfer, 19 (2006) 181-191.

[23] Q. Li, Y. Xuan, J. Wang, Experimental investigations on transport properties of magnetic fluids, Experimental Thermal and Fluid Science, 30 (2005) 109-116.

[24] D. Wen, Y. Ding, Natural convective heat transfer of suspensions of titanium dioxide nanoparticles (nanofluids), IEEE Transactions on Nanotechnology, 5 (2006) 220-227.

[25] W. Duangthongsuk, S. Wongwises, Measurement of temperature-dependent thermal conductivity and viscosity of TiO2-water nanofluids, Experimental Thermal and Fluid Science, 33 (2009) 706-714.

[26] A.A. Nadooshan, An experimental correlation approach for predicting thermal conductivity of water-EG based nanofluids of zinc oxide, Physica E: Low-dimensional Systems and Nanostructures, 87 (2017) 15-19.

[27] D. Singh, E. Timofeeva, W. Yu, J. Routbort, D. France, D. Smith, J. Lopez-Cepero, An investigation of silicon carbide-water nanofluid for heat transfer applications, Journal of Applied Physics, 105 (2009) 064306.

[28] A. Huminic, G. Huminic, C. Fleaca, F. Dumitrache, I. Morjan, Thermal conductivity, viscosity and surface tension of nanofluids based on FeC nanoparticles, Powder Technology, 284 (2015) 78-84.

[29] R. Adhami Dehkordi, M. Hemmat Esfe, M. Afrand, Effects of functionalized single walled carbon nanotubes on thermal performance of antifreeze: An experimental study on thermal conductivity, Applied Thermal Engineering, 120 (2017) 358-366.

[30] M. Shamaeil, M. Firouzi, A. Fakhar, The effects of temperature and volume fraction on the thermal conductivity of functionalized DWCNTs/ethylene glycol nanofluid, Journal of Thermal Analysis and Calorimetry, 126 (2016) 1455-1462.

[31] M. Soltanimehr, M. Afrand, Thermal conductivity enhancement of COOH-functionalized MWCNTs/ethylene glycol–water nanofluid for application in heating and cooling systems, Applied Thermal Engineering, 105 (2016) 716-723.

[32] W. Yu, H. Xie, X. Wang, X. Wang, Significant thermal conductivity enhancement for nanofluids containing graphene nanosheets, Physics Letters A, 375 (2011) 1323-1328.

[33] L.S. Sundar, M.K. Singh, A.C.M. Sousa, Enhanced heat transfer and friction factor of MWCNT–Fe3O4/water hybrid nanofluids, International Communications in Heat and Mass Transfer, 52 (2014) 73-83.

[34] S. Suresh, K.P. Venkitaraj, P. Selvakumar, M. Chandrasekar, Synthesis of Al2O3–Cu/water hybrid nanofluids using two step method and its thermo physical properties, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 388 (2011) 41-48.

[35] S. Sarbolookzadeh Harandi, A. Karimipour, M. Afrand, M. Akbari, A. D'Orazio, An experimental study on thermal conductivity of F-MWCNTs–Fe3O4/EG hybrid nanofluid: Effects of temperature and concentration, International Communications in Heat and Mass Transfer, 76 (2016) 171-177.

[36] M. Afrand, Experimental study on thermal conductivity of ethylene glycol containing hybrid nano-additives and development of a new correlation, Applied Thermal Engineering, 110 (2017) 1111-1119.

[37] N.N. Esfahani, D. Toghraie, M. Afrand, A new correlation for predicting the thermal conductivity of ZnO–Ag (50%–50%)/water hybrid nanofluid: An experimental study, Powder Technology, 323 (2018) 367-373.

[38] M.H. Esfe, S. Esfande, S.H. Rostamian, Experimental evaluation, new correlation proposing and ANN modeling of thermal conductivity of ZnO-DWCNT/EG hybrid nanofluid for internal combustion engines applications, Applied Thermal Engineering, (2017).

[39] A. Shahsavar, M. Bahiraei, Experimental investigation and modeling of thermal conductivity and viscosity for non-Newtonian hybrid nanofluid containing coated CNT/Fe3O4 nanoparticles, Powder Technology, 318 (2017) 441-450.

[40] M.S. Kumar, V. Vasu, A.V. Gopal, Thermal conductivity and rheological studies for Cu–Zn hybrid nanofluids with various basefluids, Journal of the Taiwan Institute of Chemical Engineers, 66 (2016) 321-327.

[41] M. Hemmat Esfe, A. Alirezaie, M. Rejvani, An applicable study on the thermal conductivity of SWCNT-MgO hybrid nanofluid and price-performance analysis for energy management, Applied Thermal Engineering, 111 (2017) 1202-1210.

[42] Afrand, M., Abedini, E., Teimouri, H., "How the dispersion of magnesium oxide nanoparticles effects on the viscosity of water-ethylene glycol mixture: experimental evaluation and correlation development", Physica E: Low-dimensional Systems and Nanostructures, vol. 87, pp. 273-280, 2017.

[43] Ahmad Hajatzadeh Pordanjani, A.J., Afshin Ahmadi Nadooshan, Masoud Afrand, "Effect of two isothermal obstacles on the natural convection of nanofluid in the presence of magnetic field inside an enclosure with sinusoidal wall temperature distribution", INT J HEAT MASS TRAN, vol. 121, pp. 565–578, 2018.

[44] Akbari, M., Afrand, M., Arshi, A., Karimipour, A., "An experimental study on rheological behavior of ethylene glycol based nanofluid: proposing a new correlation as a function of silica concentration and temperature", Journal of Molecular Liquids, vol. 233, pp. 352-357, 2017.

[45] Ali Karimi, M.A., "Numerical study on thermal performance of an air-cooled heat exchanger: Effects of hybrid nanofluid, pipe arrangement and cross section", Energy Conversion and Management, vol. 164, pp. 615–628, 2018.

[46] Cheraghian, G., Wu, Q., Mostofi, M., Li, M.-C., Afrand, M., Sangwai, J.S., "Effect of a novel clay/silica nanocomposite on water-based drilling fluids: Improvements in rheological and filtration properties", Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 555, pp. 339-350, 2018.

[47] Esfe, M.H., Esfandeh, S., Afrand, M., Rejvani, M., Rostamian, S.H., "Experimental evaluation, new correlation proposing and ANN modeling of thermal properties of EG based hybrid nanofluid containing ZnO-DWCNT nanoparticles for internal combustion engines applications", Applied Thermal Engineering, vol. 133, pp. 452-463, 2018.

[48] Esfe, M.H., Motahari, K., Sanatizadeh, E., Afrand, M., Rostamian, H., Ahangar, M.R.H., "Estimation of thermal conductivity of CNTs-water in low temperature by artificial neural network and correlation", INT COMMUN HEAT MASS, vol. 76, pp. 376-381, 2016.

[49] Izadi, F., Ranjbarzadeh, R., Kalbasi, R., Afrand, M., "A new experimental correlation for non-Newtonian behavior of COOH-DWCNTs/antifreeze nanofluid", Physica E: Low-dimensional Systems and Nanostructures, vol. 98, pp. 83-89, 2018.

[50] Keyvani, M., Afrand, M., Toghraie, D., Reiszadeh, M., "An experimental study on the thermal conductivity of cerium oxide/ethylene glycol nanofluid: developing a new correlation", Journal of Molecular Liquids, vol. 266, pp. 211-217, 2018.

[51] Khodadadi, H., Aghakhani, S., Majd, H., Kalbasi, R., Wongwises, S., Afrand, M., "A comprehensive review on rheological behavior of mono and hybrid nanofluids: Effective parameters and predictive correlations", INT J HEAT MASS TRAN, vol. 127, pp. 997-1012, 2018.

[52] Nadooshan, A.A., Esfe, M.H., Afrand, M., "Evaluation of rheological behavior of 10W40 lubricant containing hybrid nano-material by measuring dynamic viscosity", Physica E: Low-dimensional Systems and Nanostructures, vol. 92, pp. 47-54, 2017.

[53] Nadooshan, A.A., Esfe, M.H., Afrand, M., "Prediction of rheological behavior of SiO 2-MWCNTs/10W40 hybrid nanolubricant by designing neural network", Journal of Thermal Analysis and Calorimetry, vol. 131, pp. 2741-2748, 2018.

[54] Nadooshan, A.A., Eshgarf, H., Afrand, M., "Measuring the viscosity of Fe3O4-MWCNTs/EG hybrid nanofluid for evaluation of thermal efficiency: Newtonian and non-Newtonian behavior", Journal of Molecular Liquids, vol. 253, pp. 169-177, 2018.

[55] Ranjbarzadeh, R., Akhgar, A., Musivand, S., Afrand, M., "Effects of graphene oxide‑silicon oxide hybrid nanomaterials on rheological behavior of water at various time durations and temperatures: Synthesis, preparation and stability", Powder technology, vol. 335, pp. 375-387, 2018.

[56] Sepyani, K., Afrand, M., Esfe, M.H., "An experimental evaluation of the effect of ZnO nanoparticles on the rheological behavior of engine oil", Journal of Molecular Liquids, vol. 236, pp. 198-204, 2017.

[57] Shahsavani, E., Afrand, M., Kalbasi, R., "Experimental study on rheological behavior of water–ethylene glycol mixture in the presence of functionalized multi-walled carbon nanotubes", Journal of Thermal Analysis and Calorimetry, vol. 131, pp. 1177-1185, 2018.

[58] W. Liu, J. Alsarraf, A. Shahsavar, M. Rostamzadeh, M. Afrand, T.K. Nguyen, Impact of oscillating magnetic field on the thermal-conductivity of water-Fe3O4 and water-Fe3O4/CNT ferro-fluids: Experimental study, Journal of Magnetism and Magnetic Materials, (2019).

[59] A. Handbook-Fundamentals, American society of Heating, Refrigerating and Air-Conditioning Engineers, (2009)

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[68] Highlights

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- Using curve-fitting to propose a correlation for predicting thermal conductivity
- Preparing homogeneous and stable samples of GO-TiO_2/water hybrid nanofluid
- Presenting effects of temperature and GO-TiO_2 concentration on thermal conductivity
- 32.8% improvement in thermal conductivity of the hybrid nanofluid compared to water

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