Journal of Heat and Mass Transfer Research 6 (2019) 85-93

Semnan University

Journal of Heat and Mass Transfer Research

Journal homepage: http://jhmtr.journals.semnan.ac.ir

Experimental Investigation of the Alumina/Paraffin Thermal Conductivity Nanofluids with a New Correlated Equation on Effective Thermal Conductivity

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PAPER INFO

Paper history:
Received: 2018-04-12
Received: 2018-12-09
Accepted: 2018-12-09

Keywords:
Experimental correlation;
Alumina;
Liquid Paraffin;
Nanofluid.

ABSTRACT

Liquid paraffin as a coolant fluid can be applied in electronic devices as a result to its suitable capabilities such as electrical insulating, high heat capacity, chemical and thermal stability, and high boiling point. However, the poor thermal conductivity of paraffin has been confined its thermal cooling application. Addition of high conductor nanoparticles to paraffin can fix this drawback properly. In this article, the influence of the nanoparticles on the thermal conductivity of base material was assessed. Temperature (20-50°C) and volume fractions (0-3%) effect on the thermal conductivity of paraffin/alumina nanofluids have been considered. Nanofluid samples were prepared applying the two-step method. The thermal conductivity was measured by a KD2 pro instrument. The results indicated the thermal conductivity augments smoothly with an increase in volume fraction of nanoparticles as well as temperature. Moreover, it observed that for nanofluids with more volume-fraction the temperature affection is more remarkable. Thermal conductivity enhancement (TCE) and effective thermal conductivity (ETC) of the nanofluid was calculated and new correlations were reported to predict the values of them based on the volume fraction of nanoparticles and temperature of nanofluid accurately.

DOI: 10.22075/jhmtr.2018.14041.1203

1. Introduction

Traditionally, water, oil, and ethylene glycol have been considered as coolant and heat removing fluids in electrical components [1]. Water has a large heat capacity and consequently considered as a good conductor of heat. However, it has some drawbacks as an electrical coolant. It boils easily, promotes rusting of machine parts, and does not lubricate well. It conducts electrical current and is not suitable in electrical systems as well [2-4]. Moreover, recent developments in high-tech systems, which generate a higher rate of heat, increase the need for more efficient cooling processing and coolant with more desirable thermal properties. Consequently, other materials are necess-ary to create an optimal cutting and coolant fluid [5].

Liquid paraffin is applied as a coolant because of its high heat capacity (2130 $Jkg^{-1}K^{-1}$). It also considered as a good coolant for electrical devices because of being an electrical insulator with the proper specifications like chemical and thermal stability [6].Nontheless, The main drawback of paraffin as a coolant fluid is its low thermal conductivity [7].

The past decade has experienced the rapid development of nanotechnology, so new scales of heat transfer rates were introduced by "nanofluids". Previous studies have reported that these fluids take a higher thermal conductivity in comparison with the base fluids [8, 9]. A considerable number of researches have reported nanofluids including various kind of nanoparticles like Al_2O_3, CuO, TiO_2, Fe_3O_4, MgO to achieve an enhanced thermal conductivity [10-15]. Gupta Munish et al. [16] accomplished a review investigation of the effects of important parameters like volume fractions, particles' size and shape on thermal characteristics of varrious kind of materials.

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Alumina nano-particles are applied in the wide variety of nanofluids because forms nanofluids with a higher thermal conductivity as well as lower viscosity compared to other metal oxide nanoparticles. Fuethermore, alumina particles are cheap, nontoxic and easily available [17].

Umer et al. investigated the heat transfer characteristic of thermal oil/Al_2O_3 nanofluid including various mass fraction in range of 0.5–3 wt.%. Thermal properties of the nanofluid were studied for using in cooling systems. A considerable enhancement of the nanofluid thermal conductivity was observed.

Kole and Dey [18] reported that an engine oil containing a 0.035 volume fraction of alumina produces the enhancement of 10.41% in the thermal conductivity in comparison with the one of the base fluid. They also manifested that thermal conductivity of the nanofluid varied linearly with the volume fraction of the nanoparticles.

Xie et al. [19] assessed the effect of alumina nanoparticles morphology on the enhancement of thermal conductivity of different base fluids. The interesting finding was that for various compounds including same nanoparticles, the thermal conductivity ratios were reduced as the thermal conductivity of the base fluid increases.

Fan et al. [20] assessed the effect of carbon nanomaterials addition on the liquid paraffin thermal conductivity. The nanofluids thermal conductivity was measured applying the transient hot-wire method at a constant temperature. It was concluded that the enhancement of nanofluid thermal conductivity strongly depends on the nanoparticles' size and shape. Other studies were coducted on the providing correlations to predict the thermal conductivity behaviour related to temperature and volume fraction of nanoparticles [21-26].

Zheng and Wang [27] presented a prediction model for the nanofluids effective thermal conductivity such as water/alumina, water/CuO, gear oil/CuO ,and EG/Cu nanofluids, considering the agglomeration affection. Their models contemplate both the agglomeration affection and the radial distribution function of nanoparticles. The results perusaded these models predict thermal conductivity more appropriately than other models, based on the comparisons with experimental datasets. Some other classical models and their remarks are tabulated in Tab.1.

Reviewing the previous researches reveals that the prediction of the enhanced thermal conductivity using the conventional models causes a significant deviation from experimental data [28, 29]. Accordingly, the thermal specifications of each nanofluid would rather investigate seperately [30]. Moreover, the thermal conductivity of liquid paraffin seems to be examined rather comprehensively because of its beneficial characteristics as a coolant fluid. Consequently, in this study, at first, a preparation method of liquid paraffin/alumina nanofluids is explained. Second, the thermal conductivity measured and its behaviour against the various temperatures (20-50℃) and volume fractions (0-3%) of the nanofluids are indicated and discussed. Finally, two equations are proposed to calculate (Relative Thermal Conductivity) RTC and (Thermal Conductivity Enhancement) TCE of the nanofluids, which are computed by the equations of (k_{nf} /k_{bf}) and (k_{nf} /k_{bf})-1) ×100, respectively.

2. Experimental section

2.1. Materials

- Liquid paraffin (Iran paraffin co., Iran) was used as base fluid.
- Commercial spherical-shaped alumina (Al_2O_3) powders (Alfa Aesar, Ward Hill, MA, USA) with an average diameter of 20nm as nanoparticles.
- Oleic acid as surfactant (Merck, Germany).

The specifications of the liquid paraffin and nanoparticles are presented in Tables 2 and 3, respectively [31].

2.2. Preparation method

In this experiment, the two-step method was applied for the preparation of nanofluid. In this method, nanoparticles powder are first synthesized and then suspended in the base fluid with or without the usage of surfactants [32]. This process is very suitable for preparing nanofluids containing oxide nanoparticles.

First, the nanoparticles were weighted and combined with the surfactant of 1 to 3 of their mass fraction, respectively, using an ultra-balance scale (RADWAG, Poland, see Fig. 1). Second, the compound was put on a magnet stirrer device at temperature of 70 ℃ for 30 minutes. Kole and Dey [18] reported that the engine oil/alumina nanofluid preparing with the oleic acid as surfactant remained stable for more than 80 days recognized as a good record of suspending. Wang et al.[33]also displayed that oleic acid could properly disperse $CaCO_3$ nanoparticles in paraffin. Subsequently, a computed weight of liquid paraffin according to Eq.1 was added to the compound. Finally, to assure a good nanoparticles dispersing in the base fluid and make homogenous nanofluids, an ultrasonic disruptor bath at a constant temperature of 50℃ and medium frequency was applied for at least 3 hours.

$$\phi\% = \frac{\left(w/\rho\right)_{np}}{\left(w/\rho\right)_{np} + \left(w/\rho\right)_{paraffin}} \tag{1}$$

Before measuring thermal conductivity, the characteristics and stability behaviour of nanofluid were inspected. Two Prepared samples of paraffin/alumina nanofluids, one with oleic acid and second with propanamine-triethoxysilyl as the surfactants were made and evaluated after 72 hours. Fig. 1B indicates the samples, once they made and Fig.1C depcited those after the elapsed time of 72 hours, respectively. As it can be observed, the nanofluid with oleic acid shows up a homogenous compound while the other has sediment. Fig.1D illustrates

Table 1. Some classical models for predicting thermal conductivity of nanofluids used in literatures

Maxwell[21]	$k_{nf}/k_{bf}=1+\frac{3(k_p/k_{bf}-1)\varphi}{(k_p/k_{bf}+2)-(k_p/k_{bf}-1)\varphi}$	Spherical nanoparticles
Hamilton-Crosser[22]	$k_{nf}/k_{bf}=1+\frac{k_p/k_{bf}+(n-1)-(n-1)(1-k_p/k_{bf})\varphi}{k_p/k_{bf}+(n-1)+1-(k_p/k_{bf})\varphi}$	n=3 for Spherical and n=6 for Cylindrical nanoparticles
Jeffrey[23]	$k_{nf}/k_{bf}=1+3\left(\frac{k_p/k_{bf}-1}{k_p/k_{bf}+2}\right)\varphi+\left(3\left(\frac{k_p/k_{bf}-1}{k_p/k_{bf}+2}\right)^2+\frac{3}{4}\left(\frac{k_p/k_{bf}-1}{k_p/k_{bf}+2}\right)^2+\frac{9}{16}\left(\frac{k_p/k_{bf}-1}{k_p/k_{bf}+2}\right)^3\left(\frac{k_p/k_{bf}+2}{2k_p/k_{bf}+3}\right)...\right)\varphi^2$	Spherical nanoparticles
Davis[24]	$k_{nf}/k_{bf}=1+\frac{3(k_p/k_{bf}-1)}{\left(k_p/k_{bf}+2\right)-\left(k_p/k_{bf}-1\right)\varphi}(\varphi+f(k_p/k_{bf})\varphi^2+O(\varphi^3))$	High order expressions represent interaction of particles
Lu and Lin[25]	$k_{nf}/k_{bf}=1+(k_p/k_{bf})\varphi+b\varphi^2$	Spherical and non-spherical

Table 2. Properties of liquid paraffin [31].

Items	Results
Dynamic viscosity at 20 (40)°C	25-80 (12.5-16.5)mPa.s
Melting point	-12°C
Flash point	190 -200 °C
Specific gravity	0.800-0.860
Carbon residue wt %	0.001-0.005
Color saybolt	28-30
Aromatic mass %	0.1-0.5
Initial boiling point	390 °C
Final boiling point	470 °C

Table 3. Physicochemical properties of alumina (Al_2O_3) nanoparticle.

Parameter	Value
Color	White
Purity	99.5%
True density	3.6 gr/cm3
Diameter	20nm
Appearance	Powder

the prepared samples of nanofluids with the volume fraction of 0, 1, 2, and 3% just before the experiment.

Furthermore, the Laser Particle Analyzer (ORDUAN TECHNOLOGIES, France) was applied to test the stability and average dispersed size of nanoparticles in the base fluid which integrated by the Dynamic Light Scattering (DLS) approach. The results are given in Fig. 2. As it was reported by the figure, the mean value of the diameters of the coated nanoparticles were distinguish equal to 28.86nm with the intensity of 98.95%. If the particles are stuck together, cracked or deposited, the measured sizes by this spectrum are much larger than the initial size of the base nanoparticles. As it's shown in this figure, the highest frequency of particles is in the range of temperature as well as volume fraction of nanoparticles contained in the basefluid. The thermal conductivity measurements were accomplished by the Decagon devises KD2 thermal analyzer with ±5% standard deviation. Each measurement was repeated five times to ensure that the data are dependable and the given data is the average of the measurements.

3. Results and discussion

3.1. Measured thermal conductivity

First, temperatures in the range of 20 to 50°C and volume fractions of nanoparticles from 0 to 3% were changed and the thermal conductivity of the paraffin were measured. Then the data was presented to evaluate the trend of thermal conductivity against the temperature and volume fraction of nanoparticles.

In order to assess the reliability of the measurements, the thermal conductivity of n-paraffins was obtained from various references and a comparison was made between them and the measurements. The results were prostrayed in Fig. 3. The maximum deviations between the present measurements and associated values of n-tetradecane from the study of Wada et al. [34] is 4.11% .

The experimental data of thermal conductivity of nanofluid as a function of temperature and volume fraction of nanoparticles is presented in Fig.4. Generally, it can be observed that the ETC increases smoothly with increase of both ϕ and T. However, an increase in volume fraction has a greater effect on thermal conductivity than temperature. Wei Yu et al. [36] also confirmed that the temperature had a very small effect on the effective thermal conductivity of LP/Cu nanofluids.

Nevertheless ETC seems to be affected slightly with the temperature changes, the effect of temperature is more significant for concentrated nanofluids. These results seem to be consistent with the previous researches [30]. The more the volume fraction of nanoparticles in the base fluid, the more intensify of the interaction of nanoparticles and the base fluid. This is because of the Brownian motion magnifies in higher temperature.

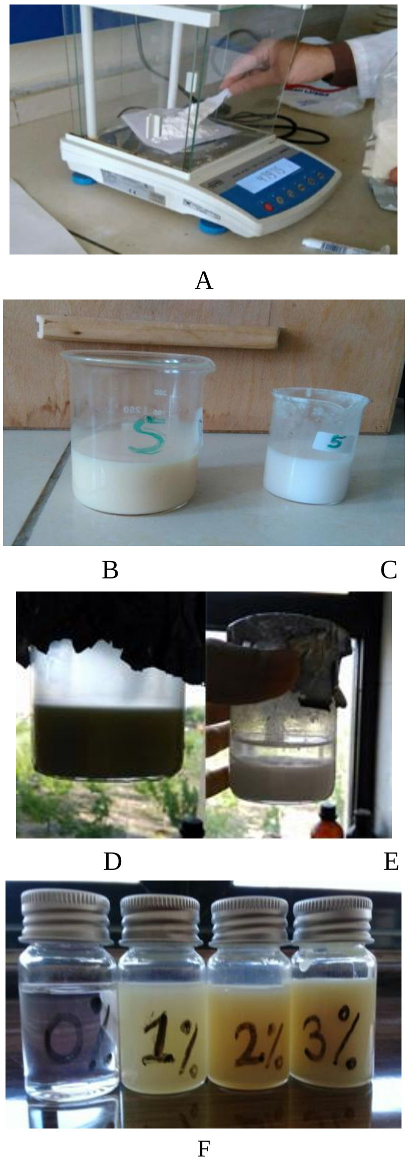

Figure 1. A: Photographs of ultra-balance scale and alumina nanoparticles, B: Sample of nanofluid (2%) with oleic acid, C: Sample of nanofluid (2%) with propanamine-triethoxysilyl, D: The sample with oleic acid after 72 hours, E: the sample with propanamine-triethoxysilyl after 72 hours, F: The prepared nanofluids with volume fraction of 0, 1, 2, and 3%.

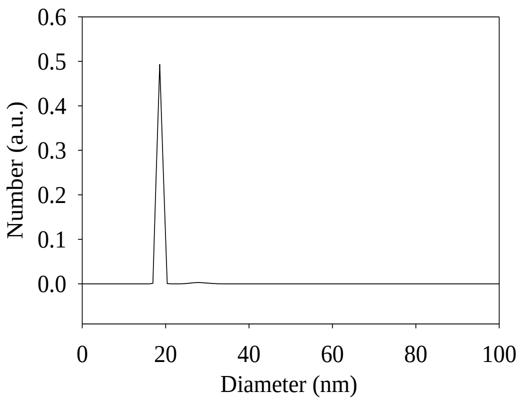

Figure 2. Particle size distribution of alumina nanoparticles in paraffin.

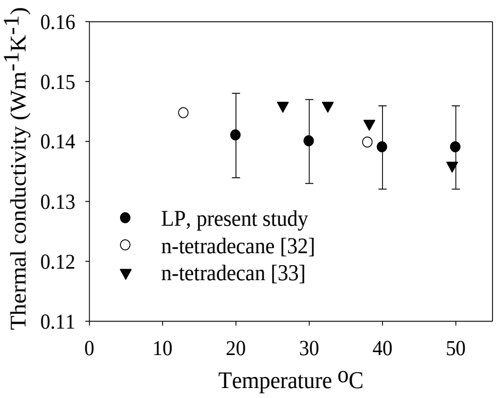

Figure 3. Comparison between present measurements of liquid paraffin and previous studies [34, 35].

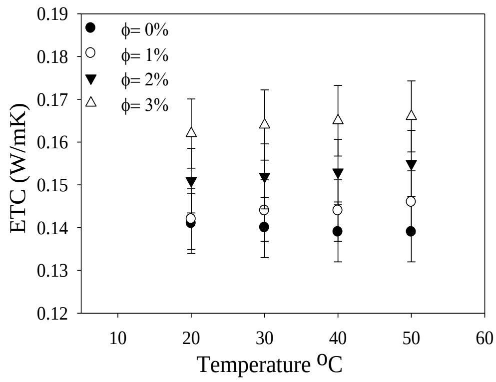

Figure 4. ETC of nanofluids versus temperature for different solid volume fractions

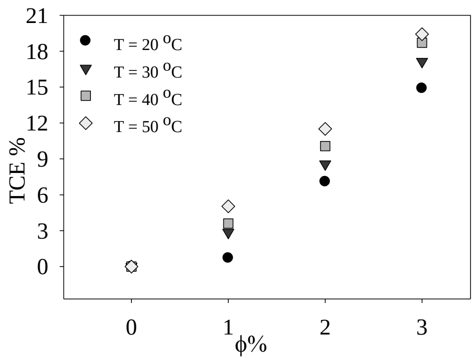

Figure 5. TCE of nanofluids versus solid volume fraction for different temperatures.

Regarding the effect of volume fraction and temperature simultaneously, it is difficult to explain precisely the reasons of the ETC augmentation. Despite that, in accordance with the earlier findings, the increasing in the conduction heat transfer is associated with the following events[37, 38]:

1. Brownian motion of that causes nanoparticles to collide with each other.

2. Liquid layering of the base fluid at the liquid-solid interface and interaction with basefluid molecules.

3. Collision between the base fluid molecules.

4. Heat diffusion within suspended nanoparticles in basefluid.

However, the main reason of TCE augmentation with an increase in temperature would elemtally associate with Brownian motion and larger interactions between nanoparticles as well as larger collisions between the basefluid molecules. Studies also indicate that nanoparticles conduct heat applying diffusive manner and via convention [39]. Nonetheless, Keblinski et al. [40] speculated that Brownian motion play indirect role in the enhancement of thermal conductivity. Wen and Ding [41] suggested that a anoparticles might play as a bridge to convey of energy through the fluid. There are, however, still some other possible and unknown influences of nanoparticles in associated with temperature on the thermal conductivity that should be investigated in the future.

Nanofluids thermal conductivity enhancement (TCE) versus volume fractions for various temperatures are depicted in Figs. 5. The figure illustrates that the TCE increases with the increase of nanoparticles volume fraction in the base fluid. It also reveals that TCE changes more significantly with the volume fraction increase in the range of 1–3% than in the range of 0–1%. In other words, for more concentrated samples (1–3%), the effect of adding nanoparticles on the thermal conductivity is more significant. The probable reason is that, adding more nanoparticles causes more interaction between them which enhances the heat conduction and consequently the thermal conductivity.

Fig.6 indicates the changes of TCE versus temperature for various volume fractions. The result indicates that there is a similar trend in TCE with the increase of temperature for all mentioned volume fractions. As it was mentioned before, several biophysical factors have been discussed that might influence on the thermal behaviour of nanofluids. First, there are some evidences that coating layer of a liquid has a potential governing mechanism in heat conduction from a solid wall to an adjacent liquid which is affected by temperature [42]. Second, based on the recent study of Alawi et al. [43] Brownian motion of nanoparticles was introduced to play an essential role in thermal conductivity augmentation of nanofluids at higher temperatures. Third, it was suggested that as temperature increase, the viscosity of base fluids decreases and the Brownian motion of nanoparticles increases again. Finally, it also is likely to be concluded that Brownian motion results in a convection phenomenon that increases the thermal conductivities. Overall, in spite of above elaboration, it is difficult to reach an agreement on a single mechanism causing this treatment.

Fig.6 also indicates this fact that the maximum enhancement in the thermal conductivity is equal to 19.42% which occurs at the volume fraction of 3% and the temperature of 50℃. This effect can be explained by the discussed influence of nanoparticles and temperature on the thermal conductivity as well as possible agglomeration

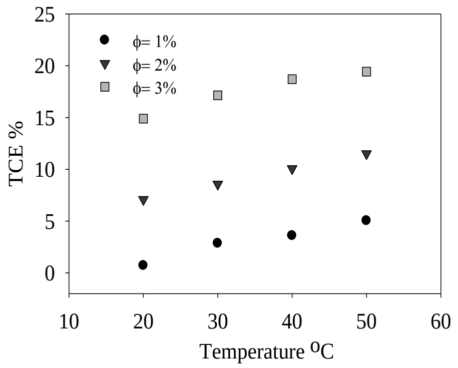

Figure 6. TCE of nanofluids versus temperature for various solid volume fractions.

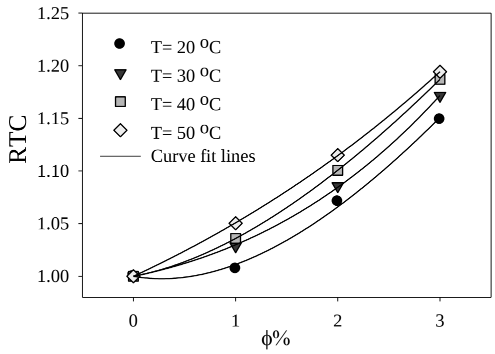

Figure 7. Calculated and experimental measured RTCs versus ϕ at different temperatures.

of bundled nanoparticles and alignment in the direction of the heat transfer path, especially at the volume fraction of 3% [44].

3.2. New correlation for RTC

In this section, a new correlation is proposed and verified for calculating the nanofluids thermal conductivity. This correlation estimates the RTC of the nanofluids as a function of volume fraction and temperature is presented in Eq.2:

$$\mathrm{RTC} = \frac{b + a\phi}{b - 2a\phi} + c\phi \tag{2}$$

Where ϕ is the volume fraction. One of the physical reasons of selecting this kind of correlation is its similarity to traditional Maxwell model as its modified model was suggested widely by many researchers [45-47]. In this correlation, the values of a takes the constant values of 0.14 (the thermal conductivity of base fluid) and b and c are dependent on the temperature. Tab.4 indicates the values of the coefficients of Eq.2 in various temperatures.

Fig.7 indicates the correlated equation of RTC as well as the measured data. Furthermore, it obviously demonstrates the effects solid volume fraction and temperature increases on the nanofluid thermal conductivity. To assess the accuracy of the given correlation, the experimental values, the equation results, and the calculated error are tabulated in Tab.5. The values

Table 4. The coefficient values of correlated equation.

Coefficient	Temperature ºC 20	30	40	50
a	0.14	0.14	0.14	0.14
b	-1.97	-2.110	-2.590	-3.410
c	0.2031	0.192	0.181	0.170

of errors (%Error <1.92) confirm the accuracy of the recommended equation.

Consequently, based on the reported values, the coefficients of b and c are correlated with the Eq.3 and Eq.4.

$$b = -2.7106 + 0.072T - 0.0017T^{2} \quad (3)$$

$$c = 0.2251 - 0.0011T \quad (4)$$

Where T is the temperature in °C. These equations are valid for temperature range of 20–50 °C and solid volume fractions of 0 to 3%.

3.3. New correlation for the TCE

To evaluate the accuracy of the correlated equation, the correlation is calculated by Eq.4 and illustrated in Fig.8.

$$TCE\% = \left[\frac{b + a\phi}{b - 2a\phi} + c\phi - 1\right] \times 100 \quad (5)$$

Fig.8. illustrates the equation (5) related curves and the points obtained by experiments. As it can be observed from the results, the obtained equation approximately covers the experimental data. Therefore, the equation has a fine accuracy to be used to calculate the thermal conductivity.

4. Conclusion

The thermal conductivity of liquid paraffin based nanofluids with alumina nanoparticles was experimentally performed. Data was taken in the temperature range of 20–50°C and solid volume fractions of 0, 1, 2, and 3%. It was showed that the nanofluids thermal conductivity increases with an increase in volume fraction and temperature. It also was concluded that thermal conductivity variations are more significant for the higher volume fractions. Furthermore, the maximum increase (about 19.42%) in thermal conductivity associated with the temperature of 30°C and the solid volume fraction of 3%. A new experimental correlation was resulted and elaborated to calculate the RTC and TCE of the nanofluids. Comparisons indicated that the correlation has the maximum deviation of 1.92% that is suitable and accurate for engineering applications.

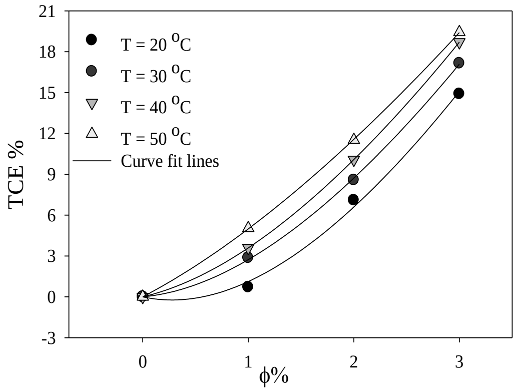

Figure 8. Correlated curves through the points of the experimental measured TCEs at different temperatures.

Table 5. Measured, curve fit, and error% values of RTC

ϕ%	Measured values 20 °C	30	40	50	Curve fit equation 20 °C	30	40	50	Error% 20 °C	30	40	50
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.00	0.00	0.00	0.00
1	1.007	1.029	1.036	1.050	1.016	1.016	1.035	1.056	0.92	1.20	0.12	0.55
2	1.071	1.086	1.101	1.115	1.074	1.069	1.096	1.128	0.29	1.50	0.47	1.19
3	1.149	1.171	1.187	1.194	1.161	1.149	1.176	1.214	1.02	1.92	0.93	1.61

0

Nomenclature

k Thermal conductivity($Wm^{-1}K^{-1}$)
T Temperature (˚C)
w Weight (gr)

Abbreviation

LP Liquid Paraffin
TCE Thermal conductivity enhancement, $((k_{nf}/k_{bf})-1)\times100$
ETC Effective thermal conductivity,(k_{nf})
EG Expanded graphite
RTC Relative thermal conductivity,(k_{nf}/k_{bf})

Greeks symbols

ϕ Nanoparticle volume fraction
ρ Density (gr/cm^3)

Subscripts

nf Nanofluid
bf Base fluid

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