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

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ABSTRACT

Liquid paraffin as a coolant fluid can be used in electronic devices due 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 confirmed in its thermal cooling application. Addition of high conductor nanoparticles to paraffin can fix this drawback properly. In this study, the influence of the nanoparticles on the thermal conductivity of base material was assessed. The effects of temperature (20 °C ≤ T ≤ 50 °C) and volume fraction (0 ≤ ϕ ≤ 3%) on the thermal conductivity of paraffin/alumina nanofluids have been presented. Nanofluid samples were prepared by the two-step method and thermal conductivity measurements were done by a KD2 pro instrument. The results showed that the thermal conductivity increased uniformly with the increase of solid volume fraction and temperature. Moreover, it can be observed that for more concentrated samples, the effect of temperature was more tangible. 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.

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. But, it has some drawbacks as an electrical coolant. It boils easily, promotes rusting of machine parts, and does not lubricate well. It also conducts electrical current and is not suitable in electrical systems [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. Therefore, other materials are necessary to create an optimal cutting and coolant fluid [5].

Liquid paraffin is used as a coolant because of its high heat capacity (2130 Jkg⁻¹K⁻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]. However, 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 the new generation of heat transfer fluids called “nanofluids” has been developed. Previous studies have reported that these fluids offer higher thermal conductivity in comparison with the base fluids [8, 9]. A considerable number of researchers have reported nanofluids including various kind of nanoparticles like Al₂O₃, CuO, TiO₂, Fe₃O₄, 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 various kind of materials.

Alumina nanoparticles are used in the wide variety of nanofluids because the nanofluids formed with these particles have lower viscosity and higher thermal conductivity compared to other particles such as copper oxide. Moreover, alumina particles are cheap, safe and readily available [17].

Umer Ilyas et al. [18] investigated the heat transfer characteristic of thermal oil/Al₂O₃ nanofluid with various mass fraction of 0.5–3% wt. to enhance thermal properties of oil for advanced cooling systems. Considerable enhancement of the thermal conductivity of oil was observed. Kole and Dey [19] reported an enhancement of 10.41% in the thermal conductivity of engine oil/Al₂O₃ nanofluid containing only 0.035 volume fraction of nanoparticles. They also showed that the thermal conductivity of the nanofluid varied linearly with the volume fraction of the nanoparticles.
Xie et al. [20] assessed the effect of alumina nanoparticles morphology on the enhancement of thermal conductivity of different base fluids. The interesting finding was that among the various suspensions using the same nanoparticles, the enhanced thermal conductivity ratio was reduced with increasing thermal conductivity of the base fluid.

Fan et al. [21] assessed the effect of carbon nanomaterials addition on the thermal conductivity of liquid paraffin based suspensions. The thermal conductivity of the suspensions was measured using the transient hot-wire method at a constant temperature. It was shown that the thermal conductivity of the suspensions increased with the increase of carbon additives loading and the rate of relative increase was depended strongly on their size and shape.

A lot of comprehensive studies were conducted on the providing correlations to predict the thermal conductivity behaviour related to temperature and volume fraction of nanoparticles which are tabulated at Tab.1 [22-26]. Zheng and Wang [27] presented a prediction model for the effective thermal conductivity of some popular nanofluids such as water/alumina, water/CuO, gear oil/CuO , and EG/Cu nanofluids, considering the agglomeration effect on enhancement thermal conductivity. Their models considering both the agglomeration effect and the radial distribution function of nanoparticles. The results showed the models including the effect of agglomeration phenomenon are more appropriate than other models based on comparisons with experimental datasets.

Reviewing the previous researches shows that the prediction of the enhancement thermal conductivity based on the conventional models results in a significant deviation from experimental data [28]. So, the thermal specifications of each nanofluid would rather investigate separately [29]. Moreover, the thermal conductivity of liquid paraffin needs to be investigated more comprehensively because of its beneficial characteristics as a coolant fluid. Therefore, in this study, at first, a preparation method of liquid paraffin/alumina nanofluids is explained. Second, the thermal conductivity measured and its distribution function of nanoparticles. Finally, two equations are proposed to predict the (Relative Thermal Conductivity) RTC and (Thermal Conductivity Enhancement) TCE of the nanofluids, which are calculated by the equations of (kat /kso) and (kat /kso)-1)x100, respectively.

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Expression</th>
<th>Nanofluids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell [22]</td>
<td>( k_{nf}/k_{bf} = 1 + \frac{3(k_f/k_{bf} - 1)\varphi}{(k_f/k_{bf} + 2) - (k_f/k_{bf} - 1)\varphi} )</td>
<td>Spherical nanoparticles</td>
</tr>
<tr>
<td>Hamilton-Crosser [23]</td>
<td>( k_{nf}/k_{bf} = 1 + \frac{k_f/k_{bf} + (n-1)-(n-1)(1-k_f/k_{bf})\varphi}{k_f/k_{bf} + (n-1) + 1-(k_f/k_{bf})\varphi} )</td>
<td>n=3 for spherical and n=6 for cylindrical nanofluids</td>
</tr>
<tr>
<td>Jeffrey [24]</td>
<td>( k_{nf}/k_{bf} = 1 + \frac{3(k_f/k_{bf} - 1)\varphi}{(k_f/k_{bf} + 2)^2} - \frac{3}{16}\frac{9(k_f/k_{bf} - 1)^2}{(k_f/k_{bf} + 2)^2} + \frac{2k_f/k_{bf} + 3}{2k_f/k_{bf} + 2} )</td>
<td>Spherical nanoparticles</td>
</tr>
<tr>
<td>Davis [25]</td>
<td>( k_{nf}/k_{bf} = 1 + \frac{3(k_f/k_{bf} - 1)\varphi}{(k_f/k_{bf} + 2)^2} - (k_f/k_{bf} - 1)\varphi} ) ((\varphi + f(k_f/k_{bf})\varphi^2 + O(\varphi^3)))</td>
<td>High order expressions represent the interaction of particles</td>
</tr>
<tr>
<td>Lu and Lin [26]</td>
<td>( k_{nf}/k_{bf} = 1 + (k_f/k_{bf})\varphi + \beta\varphi^2 )</td>
<td>Spherical and non-spherical</td>
</tr>
</tbody>
</table>

### Table 2. Properties of liquid paraffin [30].

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

### 2. Materials

- Liquid paraffin (Iran paraffin co., Iran) was used as the base fluid.
- Commercial spherical-shaped alumina (Al2O3) powders (Alfa Aesar, Ward Hill, MA, USA) with an average diameter of 20nm as nanoparticles.
- Oleic acid as the surfactant (Merck, Germany).

The specifications of the liquid paraffin and nanoparticles are shown in Tables 2 and 3, respectively [30].

### 2.2. Preparation method

In this experiment, the two-step method was used for the preparation of nanofluid. In this method, nanoparticles powder are first synthesized and then suspended in the base fluid with or without the use of surfactants [31]. 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-balanced scale (RADWAG, Poland, see Fig. 1A). Second, the compound was put on a magnetic stirrer device at the temperature of 70°C for 30 minutes. Kole and Dey [19] reported that the engine oil/alumina nanofluid preparing with the calculated amount of oleic acid as the surfactant was tested to be stable for more than 80 days. Wang et al. [32] also showed that oleic acid could properly disperse CaCO3 nanoparticles in paraffin. Then, a calculated weight of liquid paraffin according to Eq.1 was added to the compound. Finally, to disperse the nanofluids in the base fluid and make homogenous nanofluids, an ultrasonic disruptor at 50°C constant temperature bath and medium frequency were used for about 3 hours.
Table 3. Physicochemical properties of alumina (Al₂O₃) nanoparticle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>White</td>
</tr>
<tr>
<td>Purity</td>
<td>99.5%</td>
</tr>
<tr>
<td>True density</td>
<td>3.6 gr/cm³</td>
</tr>
<tr>
<td>Diameter</td>
<td>20nm</td>
</tr>
<tr>
<td>Appearance</td>
<td>Powder</td>
</tr>
</tbody>
</table>

\[ \phi = \frac{\left(\frac{w}{\rho}\right)_{np}}{\left(\frac{w}{\rho}\right)_{np} + \left(\frac{w}{\rho}\right)_{paraffin}} \] (1)

Before measuring the thermal conductivity, the characteristics and stability behaviour of nanofluid were examined. 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 and C indicate the samples, once they made and Fig.1D and E 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.1F shows 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 used to test the stability and average dispersed size of nanoparticles in the base fluid which integrated by the Dynamic Light Scattering (DLS) approach. The particle size distribution of alumina nanoparticles in paraffin and the measured size distributions by the volume occupied by nanoparticles are shown in the Fig. 2A and B, respectively. As it is observed in the Fig. 2A, the highest frequency of particles is in the range of 20 nm which is equal to the initial diameter of nanoparticles. 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. Fig. 2B depicts that the mean value of the diameters of the coated nanoparticles were distinguished equal to 28.86nm with the intensity of 98.95% of all alumina nanoparticles. It means that 98.95% of reflecting nanoparticles are in the range that is near to the size of 28.86nm. This shows that nanoparticles are neither agglomerated nor sedimented, indicating the level of stability.

This results revealed that the stability of samples is reliable before tests accomplishment. Therefore, the thermal conductivity was measured as a function of temperature as well as the volume fraction of nanoparticles contained in the base fluid. The thermal conductivity measurements were accomplished by the Decagon devises KD2 thermal analyzer with a standard deviation of ±5%. Each measurement was repeated five times to ensure that the data are dependable and the given data is the average of the measurements.
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 uniformly with increase of both \( \phi \) and \( T \). However, an increase in volume fraction has a greater effect on thermal conductivity than temperature. Wei Yu et al. [35] 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 by the temperature changes, the effect of temperature is more significant for concentrated nanofluids. These results seem to be consistent with the previous researches [29]. The more the volume fraction of nanoparticles in the base fluid, the more intensifying the interaction of nanoparticles and the base fluid. This is because of the Brownian motion magnifies in higher temperature.

Figure 2. A: Particle size distribution of alumina nanoparticles in paraffin, B: Measured size distributions of the volume occupied by nanoparticles.

3. Results and discussion

3.1. Measured thermal conductivity

In this section, the effects of temperature (20°C ≤ \( T \) ≤ 50°C) and volume fraction of nanoparticles (0 ≤ \( \phi \) ≤ 3%) on the thermal conductivity of the nanofluids are presented. Moreover, the findings are discussed comprehensively to evaluate the trend of thermal conductivity in relation to temperature and volume fraction of nanoparticles.

In order to assess the reliability of the measurements, the thermal conductivity data of n-paraffins was obtained from various references and a comparison was made between them and the measurements of the base fluid. The results were shown in Fig. 3. The maximum deviations between the present measurements and associated values of n-tetradecane from the study of Wada et al. [33] is 4.11%.

Regarding the effect of volume fraction and temperature simultaneously, it is difficult to explain precisely the reasons of the ETC augmentation. However, in accordance with the earlier findings, the increase in the conduction heat transfer is associated with the following events [36, 37]:

1. Brownian motion that causes nanoparticles to collide with each other.
2. The liquid layering of the base fluid at the liquid-solid interface and interaction with basefluid molecules.
3. Collisions between the base fluid molecules.

However, the main reason of TCE increase with temperature can be recognized to Brownian motion and larger interactions between nanoparticles as well as larger collisions between the basefluid molecules. Studies also show that nanoparticles conduct heat ballistically or in the fast diffusive manner [38]. However, Keblinski et al. [39] speculated that Brownian motion is unlikely to have a direct role in the enhancement of thermal conductivity. Wen and Ding [40] suggested that a possible explanation for this is that it facilitates avenues for faster diffusion and potential ballistic transport of energy carriers. There are, however, still some other possible and unknown influences of nanoparticles in combination with temperature on the thermal conductivity that should be investigated more.

TCE of the nanofluids which is the ratio of thermal conductivity of the nanofluid to the base fluid versus \( \phi \) for various temperatures is depicted in Fig. 5. Generally, the figure shows that the TCE increases with the increase of nanoparticles volume fraction in the base fluid. It also reveals that TCE changes more...
significantly with $\phi$ in the range of 1–3% than in the range of 0–1%. In other words, for more concentrated samples (2 and 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 nanoparticles which enhances the heat conduction and consequently the thermal conductivity.

![Image](image1.png)

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

Fig.6 indicates the changes of TCE versus temperature for various volume fractions. The result shows that there is a similar trend in TCE with the increase of temperature for all mentioned volume fractions. As it was mentioned before, several possible mechanisms and phenomena have been postulated that can influence the thermal behaviour of nanofluids. First, there are some evidence that the 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 [41]. Second, based on the recent study by Alawi et al.[42] Brownian motion of nanoparticles was reported as a potential mechanism for the increase in thermal conductivity of nanofluids at elevated temperatures. Third, it was suggested that as temperature increase, the viscosity of base fluids decreases and the Brownian motion of nanoparticles consequently increases. Finally, it has been confirmed that convection-like effects inducing by Brownian motion result in the increase of apparent thermal conductivities. All in all, in spite of the above elaboration, it is difficult to reach an agreement on a single mechanism causing this treatment.

![Image](image2.png)

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

Fig.6 also shows 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°C. This effect can be explained by the discussed influence of nanoparticles and temperature on the thermal conductivity as well as a possible agglomeration of bundled nanoparticles and alignment in the direction of the heat transfer path, especially at the volume fraction of 3% [43].

3.2. A new correlation for RTC

In this section, a new correlation is proposed and verified for predicting the thermal conductivity of the nanofluids. This correlation estimates the RTC of the nanofluids as a function of $\phi$ and $T$ and is expressed as in Eq.2.

$$RTC = \frac{b + a\phi}{b - 2a\phi} + c\phi$$  \hspace{1cm} (2)

In which $\phi$ is the volume fraction in volume%. One of the physical reasons for selecting this kind of correlation is its similarity to the traditional Maxwell model and its modified model suggested widely by many researchers [44-46]. 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 shows the values of the coefficients of Eq.2 at various temperatures.

![Image](image3.png)

Figure 7. Correlated equation of RTC as well as the measured data. Furthermore, it obviously shows the effects of temperature and solid volume fraction on the RTC of the nanofluid. To assess the precision of the suggested correlation, the experimental values, the equation results, and the calculated error are tabulated in Tab.5. The values of errors (%Error <1.92) confirm the accuracy of the recommended equation.

![Image](image4.png)

Figure 8. TCE of nanofluids versus temperature for various solid volume fractions.

**Table 4: The coefficient values of correlated equation**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>a</td>
<td>0.14</td>
</tr>
<tr>
<td>b</td>
<td>-1.97</td>
</tr>
<tr>
<td>c</td>
<td>0.2031</td>
</tr>
</tbody>
</table>

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

$$b = -2.7106 + 0.072T - 0.0017T^2$$  \hspace{1cm} (3)

$$c = 0.2251 - 0.0011T$$  \hspace{1cm} (4)

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

To evaluate the precision of the suggested correlation, the correlation is given again in Eq.4 for the percentage of TCE and illustrated in Fig.8.

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

Fig.8. shows the equation (5) related curves and the points obtained by experiments. As it can be observed from the results, the proposed equation fit to the experimental data in some cases, showing that the recommended experiential equation has an acceptable accuracy and is practical.

4. Conclusion

An experimental study on the thermal conductivity of liquid paraffin based nanofluids with alumina nanoparticles was performed. Measurements were accomplished in the temperature range of 20–50 °C for samples with the solid volume fractions of 0, 1, 2, and 3%. Measurements showed that the thermal conductivity of nanofluids increased uniformly with the increase of \( \phi \) and \( T \). It was concluded from experimental data that the increase of TCE is more significant for nanofluids with more volume fraction of nanoparticles. Moreover, the findings indicated that the TCE of paraffin/alumina nanofluid was 19.42%, which was related to the temperature of 30 °C and the solid volume fraction of 3%. A new experimental correlation was proposed and elaborated to estimate the RTC and TCE of the nanofluids. Comparisons indicated that the correlation has the maximum deviation of 1.92% and is suitable and accurate for engineering applications.

### Nomenclature

- **k**: Thermal conductivity (Wm\(^{-1}\)K\(^{-1}\))
- **T**: Temperature (°C)
- **w**: Weight (gr)

### Abbreviation

- LP: Liquid Paraffin
- TCE: Thermal conductivity enhancement, \( (k_{nf}/k_{bf}) - 1 \) \times 100
- ETC: Effective thermal conductivity, \( k_{ef} \)
- EG: Expanded graphite
- RTC: Relative thermal conductivity, \( (k_{nf}/k_{bf}) \)

### Greeks symbols

- \( \phi \): Nanoparticle volume fraction
- \( \rho \): Density (gr/cm\(^3\))

### Subscripts

- nf: Nanofluid
- bf: Base fluid

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

<table>
<thead>
<tr>
<th>( \phi % )</th>
<th>Temperature °C</th>
<th>Curve fit equation</th>
<th>Error%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>0</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1</td>
<td>1.007</td>
<td>1.029</td>
<td>1.036</td>
</tr>
<tr>
<td>2</td>
<td>1.071</td>
<td>1.086</td>
<td>1.101</td>
</tr>
<tr>
<td>3</td>
<td>1.149</td>
<td>1.171</td>
<td>1.187</td>
</tr>
</tbody>
</table>

Figure 7. Comparison between the predicted RTC by the correlation and the experimental data versus \( \phi \) at different temperatures.

Figure 8. Passing curves through the points of TCE obtained by experiments at different temperatures.

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**unreviewed proof**
References


