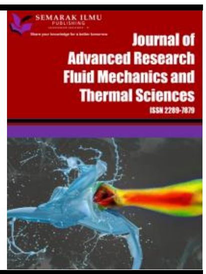
SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Experimental Investigation on Thermal Conductivity of Palm Oil and Zinc Oxide PFAE-based Nanofluids

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ARTICLE INFO

Article history:
Received 5 May 2023
Received in revised form 7 July 2023
Accepted 13 July 2023
Available online 27 July 2023

Keywords:
Transformer oil; nanofluids; thermal conductivity; insulation liquid; viscosity; Zinc oxide nanoparticle; palm oil; PFAE

ABSTRACT

Vegetable oil (VO) have been constantly researched as an alternative to the conventional mineral oil (MO) in the application of transformer insulation liquid. VO is deemed as a suitable replacement for MO as they are a renewable source, cheaper in price, and have a high thermal conductivity, high flashpoint, and high breakdown voltage value. In addition, the trending interest in nanofluids has made it possible to further improved the insulating properties of VOs. This paper reports the experimental results of thermal conductivity test of Palm oil-based nanofluids and Palm fatty acid ester (PFAE)-based nanofluids. The nanoparticles used in this work is Zinc Oxide (ZnO) <50nm nano powder and the nanofluid (NF) samples are varied by low, medium and high concentrations. The test was conducted at 9 different temperatures from 25°C to 65°C with 5°C gap. The result shows that a low and medium concentration nanofluid has an improvement in thermal conductivity value, up to 42.6% and 59.5% respectively for palm oil-based nanofluid. Meanwhile, the high concentration palm oil-based nanofluid has lower enhancement in thermal conductivity value at certain temperatures. As for PFAE-based nanofluids, the thermal conductivity value has improved by up to 27% and 14.4% for medium and high concentration respectively. Nanofluids with medium concentration of ZnO, has the highest enhancement in insulating and cooling properties for both palm oil and PFAE-based nanofluids. This observation is supported by the kinematic viscosity value of the mentioned nanofluid.

1. Introduction

The urgency to replace the non-renewable source MO with alternatives VO as liquid insulators has been increasing in trend ever since decades ago. There are various options of VOs that has been further researched to be implemented as transformer liquid insulator, in which the common used by researchers are palm oil, soybean oil, rapeseed oil, sunflower oil, coconut oil, groundnut oil, olive oil, mustard oil and natural esters derived from the VOs [1–8].

Often, in Malaysia palm oil is chosen as the test subject over other VOs in studying the alternative to transformer oil. This is due to its availability in the country and its cheaper price compared to other

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https://doi.org/10.37934/arfmts.108.1.93102

VOs. Palm oil is also a good insulating liquid since it has a high flash point and fairly high breakdown voltage as shown in Table 1 below.

Table 1
Properties of VOs used is research works on transformer oil [1, 7–9]

Properties	Coconut oil	Rapeseed oil	Soybean oil	Palm oil	PFAE
Dielectric strength (kV)	60	49.9	39	38.09	81
Density (g/cm^3)	0.917	0.9	0.9	0.9	0.86
Pour point (°C)	23	-18	-1	15	-
Flash point (°C)	225	325	234	242	186

The consistent invention of nanofluids has made the future of applying the VOs as liquid insulators brighter as the demand increased. This is because many researchers found that mixing NP in a substance can improve the properties of its function. The adding of certain amount of nanoparticles into transformer oil has been reported to enhance its breakdown voltage (BDV) and thermal conductivity value [7, 10–17]. Based on a brief literature review shows in Table 2, it is reported that the adding of certain percentage of nanoparticles into the base oils has increased the thermal conductivity of the base oil. Research in this scope is still lacking and need to be further explored due to broad selection of nanoparticles and concentration that may affect differently on the liquid dielectric performance.

Table 2
Summary from other research works on the enhancement of thermal conductivity of nanofluids compared to the base oil

Author/ year	Base oil	Nanoparticles used	Volume/ mass fraction of nanoparticles	Range of temperature (°C)	Maximum enhancement of thermal conductivity
[18]	Vegetable oil	Boron nitride (BN)	0.05wt% and 0.1wt%	30-80	3.5%
[7]	Soybean oil (SO), coconut oil (CO), and palm oil (PO)	Hybrid aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2)	0.2wt%, 0.4wt% and 0.6wt%	30-60	125.3% for PO 23.3 % for SO 14.1% for CO
[19]	Transformer oil (did not state type of oil)	Diamond nanoparticles	0.1 wt% 0.12wt% 0.2 wt% 0.6 wt%	20 and 30	73%
[20]	transformer oil TRANSOL by Savita	Amorphous graphene (a-GS)	0.0012wt% 0.0025wt% 0.005wt% 0.01wt%	35-55	30%
[16]	Purified aged transformer oil (Shell Diala)	Silicon dioxide (SiO_2), Al_2O_3, and TiO_2	0.1vol%	30-70	20.83%
[21]	Transformer oil	Hexagonal boron nitride nanosheets (BNNS)	0.01wt% 0.025wt% 0.05wt%	Room temperature	45.09%

2. Methodology

This section presented the flow of the experimental study from the start of the experiment by selecting the nanoparticles weight in the base fluid or nanofluid concentration to nanofluid sample preparation, until the thermal conductivity test done on the nanofluid sample.

2.1 Nanofluids Sample Preparation

This experimental work uses ZnO <50 nm nanoparticles in the form of powder to mixed in the base oils to produce VO-based nanofluids. The nanofluid is prepared by dispersing the ZnO nanoparticles in the base oil respectively, which are palm olein oil (PO) and palm fatty acid ester (PFAE) abbreviated in this experiment as PEO. To further study the effect of ZnO nanoparticles on the base oils, this study experiment on preparing nanofluids with several distinct concentration which are low, medium and high concentration, as shown in Table 3.

The preparation of nanofluid samples in this work were performed by using two-step method, which is a common method used in other research work, where the nanoparticle is first mixed in the base oil with or without the use of surfactant, and then being dispersed by using ultrasonic waves to get a fully dispersed nanofluid [7, 20, 22].

In this experimental study, the nanofluid samples are prepared by weighing the nanoparticles using analytical beam balance to get the desired concentration following the concentration in Table 3. Then, it is mixed into the base fluid and stirred manually using a stirring rod for 2 minutes or until the nanoparticle can be seen to scattered evenly in the base oil.

The process of dispersing the nanoparticles in the base oil is done using ultrasonic device, which projects ultrasonic waves to the mixture of nanoparticles and the base oil, breaking their molecules and make it easier for the nanoparticles to be fully dispersed in the base oil and becomes a nanofluid. Figure 1 shows the preparation process of nanofluids in this study.

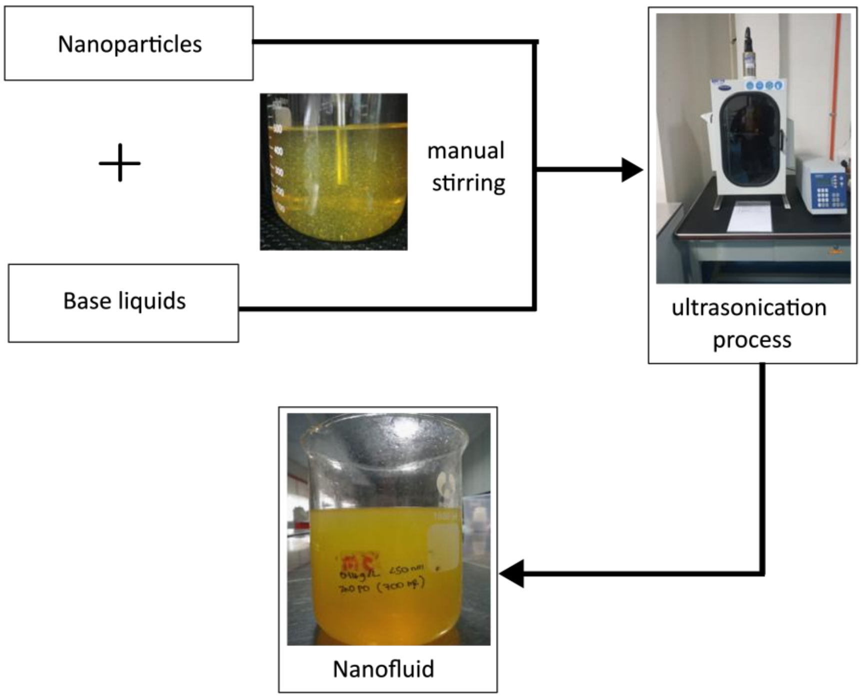


Fig. 1. Preparation of Nanofluid sample (Palm oil-based Zinc Oxide nanofluid)

Table 3
The concentration category of PO and POE-based nanofluids tested

ZnO nanoparticles concentration in base fluid	Low	Medium	High
	0.0025 g/L	0.04 g/L	0.14 g/L

2.2 Thermal Conductivity Test

Thermal conductivity indicates the ability of material to conduct heat [16] and for an insulating liquid, this value is an rather important as it is related to the rate of temperature rise of the liquid to serve as a good cooling medium[23].

In the present study, thermal conductivity test was done using a single needle thermal property analyzer KD2 Pro by Decagon Devices Inc., Pullman, WA, USA. The thermal conductivity of PO and PEO-based nanofluids was tested at 9 different temperatures in a range of 25 °C to 65°C. The 5°C interval at each temperature was set so that the effect of increasing temperature to the thermal conductivity value of prepared nanofluid samples can be seen clearly. The thermal conductivity readings was repeated 3 times at each temperature, then the average value is calculated, which is similar to the procedure performed by Gaurav *et al.,* in their studies [24].

The set-up of thermal conductivity test is shown in Figure 2. KD2 Pro works following the transient hot-wire method, in which the needle is rest into the liquid sample to take the measurement of thermal conductivity and thermal resistivity value. A water bath is used in this test to vary the temperature of samples. Hence, the thermal conductivity is expected to be increases as the temperature increases, due to the Brownian motion of nanofluids is also temperature-dependent.

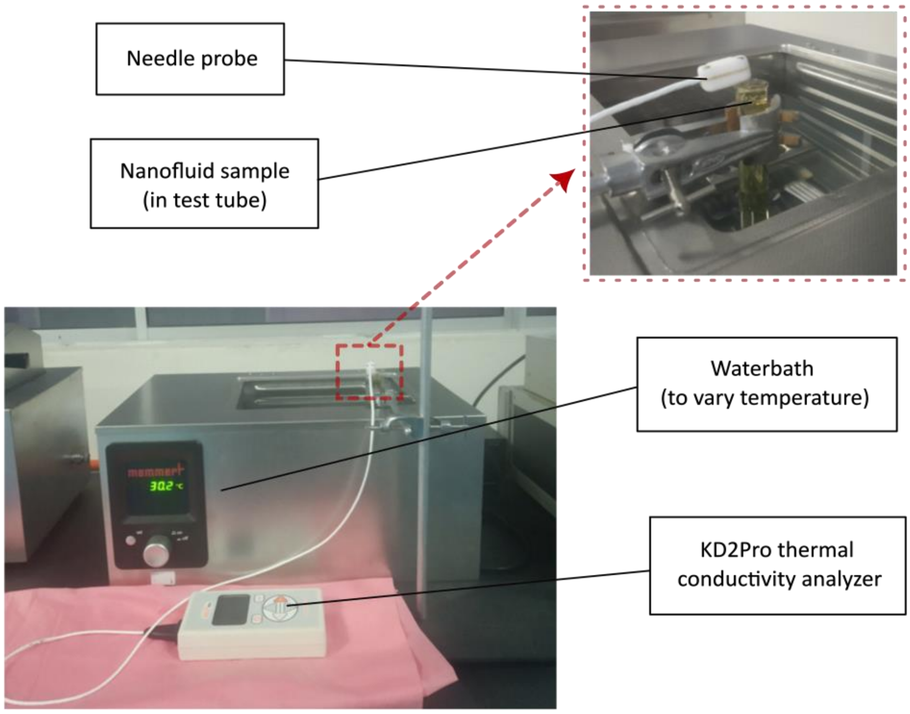


Fig. 2. Set-up of thermal conductivity test on the nanofluid samples

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 108, Issue 1 (2023) 93-102

3. Results

The results of thermal conductivity test of PO, PEO and their nanofluids are presented and discussed. The results obtained from experiment, among which are thermal conductivity value of the nanofluid samples at 25 °C to 65 °C, the percentage enhancement in thermal conductivity, and their relevance to the kinematic viscosity value.

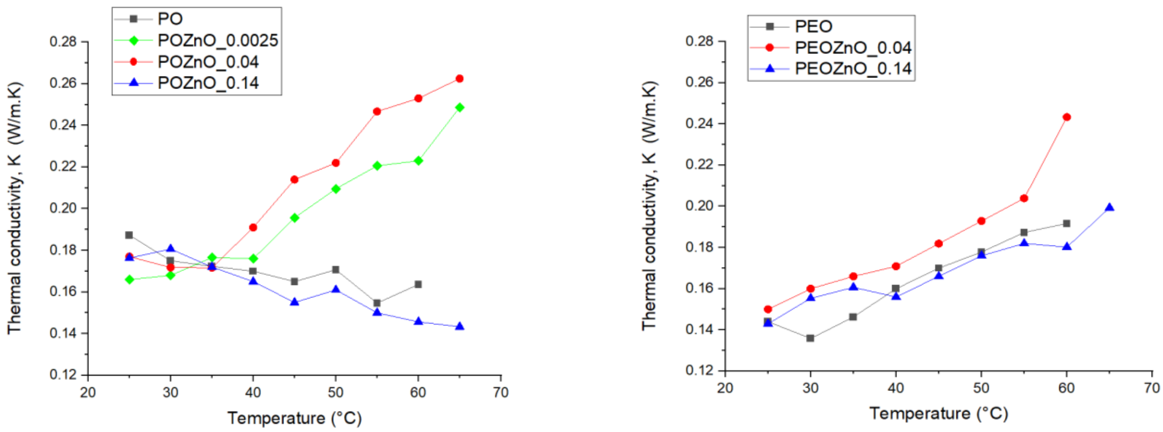
3.1 Thermal Conductivity of Nanofluids

As shown in Figure 3, for PO base oil, only POZnO_0.0025 and POZnO_0.04 have the thermal conductivity values higher than that of PO at 40°C to 65°C temperature. These low and medium concentrations also depict an increasing trend of thermal conductivity value as the temperature increased from 40 °C to 65 °C.

In this study, the increases of thermal conductivity value of nanofluid sample at higher temperatures is due to the increased intensity of Brownian motion effect, which is consistent with the findings reported by Wanatasanappan *et al.,* and M. Asefi *et al.,* in their studies [7, 19].

At 35 °C, PO and all its nanofluid samples have about the same thermal conductivity value. While at lower temperature, 25 °C and 30 °C , PO has the highest thermal conductivity compared to its nanofluids. At 40 °C to 65 °C as the temperature increases, the thermal conductivity value of PO and PO_0.14 decreases.

Meanwhile, for PEO base oil at lower temperature, from 20 °C to 35 °C all of the nanofluids has a higher thermal conductivity value compared to the base oil. Then, from 40 °C to 60 °C temperature, it can be seen that only PEOZnO_0.04 has higher thermal conductivity value compared to PEO. However, PEO and all its nanofluids has an increasing trend of the thermal conductivity value as the temperature increases.



(a) (b)

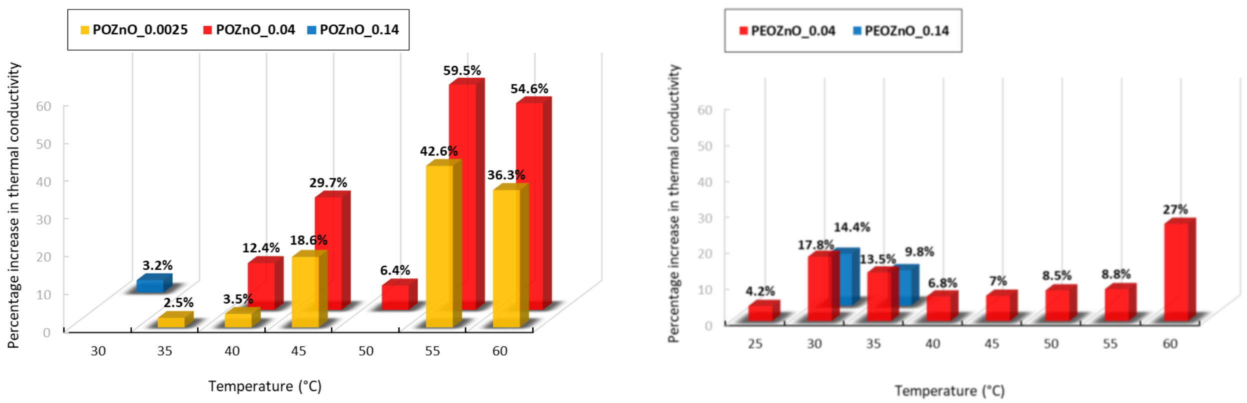
Fig. 3. Thermal conductivity varies by different temperatures of transformer oil samples. (a): Palm oil and nanofluids; (b)PFAE and nanofluids

In summary, the graph shows that at 40 °C to 60 °C, the low concentration (0.0025 g/L) and medium concentration (0.04 g/L) of PO-based nanofluids has increased in thermal conductivity value compared to its base oil. Meanwhile for PEO-based nanofluid, the medium concentration (0.04 g/L) also shows an increase in thermal conductivity value. Only the high concentration (0.14 g/L) has a lower thermal conductivity value compared to both PO and PEO base oil respectively at 40 °C to 60 °C temperature.

Figure 4 depicted the percentage increase of thermal conductivity for both PO and PEO-based nanofluids. For PO-based nanofluids, in average it shows that as the temperature increases from 35 °C to 60 °C, the enhancement in thermal conductivity also increases. It can be seen at 40 °C to 60 °C temperature, POZnO_0.0025 have an improvement in thermal conductivity for a minimum of 3.5 % up to 42.6 %, while the thermal conductivity enhancement in POZnO_0.04 starts from 12.4 % to maximum of 59.5 % increase. For PEOZnO_0.04, the thermal conductivity value increases from 6.8% to 27 % at temperature 40 °C to 60 °C.

In addition, both PO and PEO-based nanofluids with a high concentration (0.14 g/L) has an enhancement only at ambient temperature 30°C and 35 °C for 3.2 % and maximum of 14.4 % increase in thermal conductivity respectively. Thermal conductivity enhancement at lower ambient temperature is important since it can affect the lifespan of the transformer. According to a study conducted by Anshari *et al.,* on the effect of ambient temperature to the power transformer ageing, the ambient temperature of a transformer should be in the range of 20 °C to 35 °C for it to be operated more than 30 years [25].

From the graph, it can be observed that nanofluids with the medium concentration (0.04 g/L) has the highest enhancement percentage of thermal conductivity for both PO and PEO base oil which is 59.5 % and 27 % respectively. It is also gained from this experimental study, that the effect of ZnO nanoparticle on Palm oil is greater than its effect on PFAE in improving the thermal conductivity of a base oil.

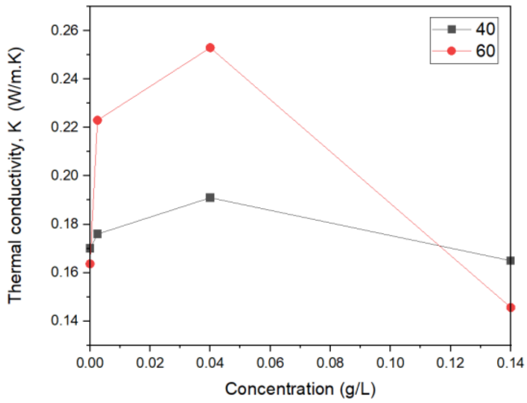


(a) (b)

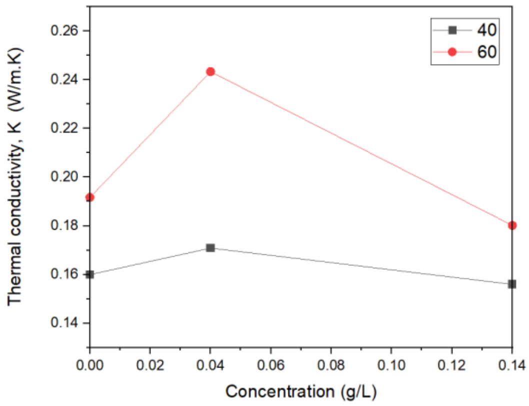
Fig. 4. Enhancement percentage in thermal conductivity of nanofluids at each temperature. (a): Palm oil-based nanofluids; (b)PFAE-based nanofluids

Figure 5 illustrates the thermal conductivity, K values corresponding to nanofluids concentration at 40 °C (the maximum ambient temperature of a transformer [26]) as well as at 60 °C (representing elevated temperature). Based on the figure, the thermal conductivity value does not always increase with nanofluids' concentration. By adding just small amount of nanoparticle into the base liquid increases the conductivity value and as shown in Figure 5, the increment is maximum at medium concentration. The 0.04 g/L concentration for both PO and PEO-based nanofluids has the highest thermal conductivity value at both temperatures. At high concentration, the K values get lower even below the K value of the base oil. This observation could be linked to the viscosity of the nanofluids.

Viscosity of oil is the resistance of that oil to flow, in which a high viscosity means high resistance to flow, while low viscosity implies a low resistance to flow. A good lubricating liquid has a low viscosity value, which cause it to have more fluidity and thus provides better cooling property [14]. In addition, Gaurav *et al.,* also stated in his paper that viscosity is a property that proves the ability of a liquid to lubricate [24]. Figure 6 shows the value of kinematic viscosity at 40°C for PO and its nanofluids.



(a)



(b)

Fig. 5. Thermal conductivity of ZnO nanofluids with increasing concentrations, at 40°C and 60°C. (a): Palm oil-based nanofluids; (b)PFAE-based nanofluids

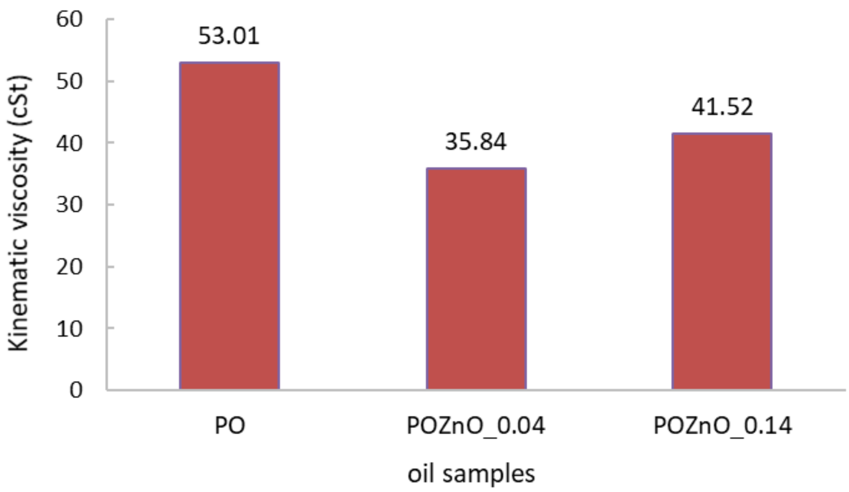


Fig. 6. Kinematic viscosity value at 40°C of PO and PO-based nanofluids medium and high concentration

In this study, the kinematic viscosity value for PO is 53.01 cSt. While for nanofluids, the kinematic viscosity value of POZnO_0.04 and POZnO_0.14 is 35.84 cSt and 41.52 cSt respectively. Both concentration of the PO-based nanofluids have a lower viscosity value compared to that of pure PO, which implies that the lubricating property of PO is increased with the adding of ZnO nanoparticle. As mentioned before, the lower the viscosity of the nanofluid, the better it will function as a cooling liquid. This is due to the bridge effect, where after the nanoparticle is added to the base oil, they settled down between oil layers which acting as bridges and then make the oil layers move on each other easily, thus reducing the viscosity of the fluid [14].

ZnO nanoparticles has successfully lowered the kinematic viscosity value. However, as the concentration gets higher, the nanofluids become thicker and as a result increases viscosity values. Thus, it can be said that the 0.04 g/L (medium concentration) is an optimum concentration of ZnO to be added to palm oil in order to improve its insulating and cooling property. This is consistent with the thermal conductivity result in this study, since POZnO_0.04 is the sample that has the highest percentage improvement in thermal conductivity, K value.

4. Conclusions

In brief, this experimental study reported the thermal conductivity of ZnO nanofluids for both palm oil and PFAE base oil respectively. In the beginning, process of preparing the nanofluid samples and the thermal conductivity test set-up are presented. As per discussed in the results section, it is concluded that this study has achieved results below;

i. The thermal conductivity value of PO and PFAE-based nanofluid samples increases along with the increases in temperature at 25°C to 65°C, except for sample PO-based nanofluids with high concentration 0.14 g/L which has decreases in thermal conductivity values as the temperature increases.
ii. PO-based nanofluids have the highest improvement in thermal conductivity value compared to that of PFAE-based nanofluids, meaning that the ZnO nanoparticles have more enhancement effect on PO compared to PFAE, in improving the insulating and cooling properties of VO.
iii. The thermal conductivity value of POZnO_0.0025 and POZnO_0.04 are higher than that of PO at 40°C and 60°C, while the thermal conductivity value of POZnO_0.14 is lower than that of PO at 40°C and 60°C temperature.
iv. Both of the PO and PFAE-based nanofluids with 0.04 g/L concentration has the highest thermal conductivity enhancement at 59.5 % and 27% respectively. Hence, the medium concentration is an optimum concentration of ZnO nanoparticle to improve the insulating properties of both the PO and PFAE base oil, compared to the low concentration (0.0025 g/L) and high concentration (0.14 g/L) nanofluids.

Acknowledgement
This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS/1/2019/TK05/UNIMAP/02/2). The authors would also like to acknowledge the support from the Faculty of Electrical Engineering & Technology (FKTE) and Faculty of Mechanical Engineering & Technology (FKTM), Universiti Malaysia Perlis (UniMAP) for providing the facilities for the research.

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