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Experimental Study on the Thermal Conductivity and Viscosity of a Transformer Oil-based Nanofluid Containing ZnO Nanoparticles

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ABSTRACT

This study investigates the effect of ZnO nanoparticles of the transformer oil on thermal conductivity and dynamic viscosity characteristics. For this purpose, the consequence of temperature and nanofluid concentration variations as important parameters affecting thermal conductivity and viscosity of the samples, have been explored. The results indicated that the thermal conductivity of the nanofluid was higher than that of the pure transformer oil at the temperature of 25°C. Also, a rise in the concentration of the nanoparticles of the transformer oil increased the thermal conductivity of the nanofluid. Besides, the thermal conductivity at the volume fractions of 0.05% and 1% increased by approximately 4.61% and 11.53%, respectively. The dynamic viscosity reached the highest level at maximum volume fraction in all temperatures. In addition, an increase in the temperature reduced the dynamic viscosity of both the pure transformer oil and the nano-oil. At a given temperature, a rise in the volume fraction of ZnO nanoparticles enhanced the dynamic viscosity. Moreover, to predict the dynamic viscosity of the nanofluid, a new correlation was presented as a function of temperature and volume fraction with R-Sq=0.9913.

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1. Introduction

A nanofluid is composed of a base fluid in addition to solid particles with a small volume fraction of 1-10% and sizes of below 100 nm which are called nanoparticles [1]. The idea of nanofluids was introduced by Choi to improve the heat transfer characteristics of fluids [2]. Nanofluids were also employed as a coolants in micro-electronics and micro-channels [3-4], solar collectors [5-7], photovoltaic thermal system [8], vertical plate [9], and heat exchangers [10-12]. In the last two decades, many studies have focused on thermal conductivity [13-18], and dynamic viscosity of nanofluids [19-23].

On the other hand, a transformer (electrical transformer) is a static electrical device used in electric industries. In addition, transformer oil is a dielectric liquid used as an insulator and cooling liquid in transformers. It is known that, a rise in the thermal conduction of transformer oil increases the lifecycle, charge capacity, and cooling capacity of transformers. The thermal properties of transformer oils can be enhanced by adding solid nanoparticles with higher thermal conductivity than the base fluid [24-26].

In this regard, Choi et al. [27] prepared three nanofluids by dispersing Al_2O_3 and AlN nanoparticles in the transformer oil. They studied three nanofluids at volume fractions of up to 4% consisting of spherical Al_2O_3 powder with the particle diameter of 13 nm, bar-shaped Al_2O_3 powder with the dimensions of 2×20×200 nm, and spherical AlN powder with a diameter of 50 nm in the transformer oil. They employed an ultrasonic bath and a ball mill to stabilize the nanofluids. They also used the transient hot-wire method to measure thermal conductivity. Their tests indicated that the three nanofluids had higher thermal conductivity than pure oil. Moreover, it was found that the thermal conductivity of the AlN nanofluid was considerably higher than that of the Al_2O_3

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nanofluid at the same volume fraction. For the AlN nanofluid at the volume fraction of 0.5%, the thermal conductivity and overal heat transfer coefficient increased by approximately 8% and 20%, respectively. Also, the viscosity of their nanofluids increased as the nanoparticle concentration increased.

In another study by Beheshti et al. [28], they prepared two nanofluids with different weight concentrations by adding oxidized multi-wall carbon nanotubes to the transformer oil. The oxidized carbon nanotubes had the diameter, length, and purity of 10-20 nm, 30 μm, and >95%, respectively. The particles were added to the transformer and directly dispersed for two hours by an ultrasonic bath at room temperature. The nanofluids were prepared at two weight concentrations of 0.001% and 0.01%. They employed the KD2 Pro thermal analyzer to measure the fluid's thermal conductivity at different temperatures ranging from 20°C to 80°C. Their observations demonstrated that the thermal conductivity of the nanofluids was dependent on some parameters, including the thermal conductivity of the solid particles and base fluid, the particle concentration, size, and temperature. They also found that the thermal conductivity of the transformer oil was reduced as the temperature increased. However, the thermal conductivity of the nanofluids was enhanced as the concentration increased. Furthermore, the results revealed that the thermal conductivity continued to increase until reaching 60°C and then began to decline. The reduction was induced by the deposition of nanoparticles in the fluid at above 60°C. Moreover, the thermal conduction of the 0.001 and 0.01 weight percentages increased by approximately 5.7% and 7.7%, respectively.

In another study by Du et al., four nano-oils with different concentrations were prepared by dispersing BN nanoparticles with a mean diameter of 50 nm [29]. The density of BN nanoparticles was 0.11 g/cm^3, which was lower than the density of the transformer oil. The BN nanoparticles were dispersed in the filtered oil by a magnetic mixer at the mass fractions of 0.01%, 0.03%, 0.5%, and 0.1%. The suspending oil was homogenized by an ultrasonic homogenizer for 40 minutes at 25°C to reduce possible aggregations. The results indicated that an increase in the BN nanoparticle concentration, improved the heat transfer considerably.

Aberoumand and Jafarimoghaddam [30] prepared a hybrid nanofluid consisting of WO_3 and Ag_2O particles and a transformer oil via the electric explosion of the wire (EEW) method at weight concentrations of 1%, 2%, and 4%. They employed Zeta potential measurements to evaluate the stability of the nanofluids. It was observed that the thermal conductivity increased by up to 41% at a concentration of 4% and temperature of 100°C.

Considering the importance of thermal conductivity of a transformer oil, Amiri et al. [31] added amine graphene quantum dots (AGQD) to a transformer oil to improve its properties. Their results revealed that by raising the temperature, thermal conductivity of the base transformer oil in the measured temperature range (30 to 70 °C) was decreased, while for the transformer oil with graphene this demonstrated an upward trend. Also, their observations showed that the dynamic viscosity of the transformer oil and nanofluid decreased with increasing temperature. The maximum increase in dynamic viscosity due to the addition of AGQD was 1.1%.

In another study, four different concentrations of diamond nanoparticles ranging from 0.1% to 0.15% were investigated [32]. The results demonstrated that an increase in the concentration led to a rise thermal conductivity of the nanofluid. Also, a rise in the temperature increased the thermal conductivity of both the nanofluid and the base oil. In addition, experimental data revealed that the viscosity decreased as the temperature rose. This was due to the reduction in adhesion force by the rise in temperature. Furthermore, an increase in the concentration of nanoparticles led to an elevation of the kinematic viscosity of the nanofluid. In fact, a rise in the concentration of diamond nanoparticles increased the Van Der Waals force and nanofluid viscosity.

The current study investigates the thermal and rheological properties of the ZnO-transformer oil nanofluid. Nanofluids were prepared using a two-step method in five volume fractions within 0.05% to 1%. As can be reviewed in the last studies, only a few researches have been performed on the thermal conductivity and viscosity of transformer oil-based nanofluids. Hence, this experimental study on thermophysical properties of ZnO-transformer oil could be a practical guideline in developing the application of nanoparticles in the transformer oil and production of a new generation of transformer oils.

2. Preparation and stability methods

The ZnO nanoparticles were obtained from the US Research Nanomaterials, Inc. The properties of the Zinc oxide nanomaterials were provided by the company and are present in table 1. The transformer oil was made by the Iranol company. Tables 2 presents the specifications of the transformer oil (as the base fluid).

The nanoparticles were physically dispersed in the transformer oil by a magnetic stirrer and an ultrasonic homogenizer with volume fraction percentages of 0.05, 0.125, 0.25, 0.5, 1. The samples were placed on the magnetic stirrer for 2 hours. Then, the suspentions were placed in the 400W ultrasonic homogenizer for 15 minute to break down the agglomerations. Finally, the stability of the prepared nanofluids was investigated by observation after 48 hours in which no sedimentation was observed in the nanofluids.

To ensure the stability of these samples, dynamic light scattering (DLS) was utilized with the HORIBA SZ-100 series instrument at a 90° scattering angle and a 25°C ambient temperature. The results of the analysis showed that the average size of the sample was 37.9, indicating that the nanoparticles were not clogged in the base fluid and

Table 1. The characteristics of Zinc Oxide nanoparticles.

Compound Formula	ZnO
True density	5606 kg/m^3
Purity %	99.8
Particle size	20 nm
SSA	80-120 m^2/g
Color	white

Table 2. The specifications of the transformer oil

Characteristics	Specification	Test Method
Kinematic Viscosity at 40 °C	16 cSt	ASTM-D445
Natural Pour Point	-30 °C	ASTM- D97
Flash Point	140 °C	ASTM- D93
Density at 15 °C	860 kg/m^3	ASTM- D1298
Breakdown Voltage	30 kV	IEC- 156 II
Dielectric Dissipation factor	< 0.005	IEC- 247
Acidity	0.03 mg KOH/g	ASTM- D664

their stability was adequate. Fig. 1 indicates the suspended nanoparticles at different volume fractions.

Fig.2 shows a result of the stability test of transformer oil-zinc oxide nanofluid at a concentration of 0.25% by using DLS analysis.

3. Equipment and measurement methods

The thermal conductivity of the nanofluids was measured by the KD2 Pro device with a Ks1 sensor, which specifically measures liquid thermal conduction. The KD2 Pro thermal analyzer was manufactured by Decagon Devices, Inc. that functions based on the transient hot-wire method. The EN55022:1987 standard was also utilized for this purpose. To ensure the functionality of the device, the thermal conductivity of the calibrated liquid was measured and compared to the reported value. Fig. 3 shows the thermal analyzer device and its sensor.

The Brookfield CAP 2000+ cone and plate viscometer was used to measure the viscosity of the nanofluids. A volume of 0.5 cm^3 of the sample was required for measurement, and the temperature was adjusted by a thermoelectric module up to 75°C. Moreover, the viscometer allowed for adjusting the shear rate up to 1000 rpm. Fig. 4 represents the low torque CAP 2000+ device.

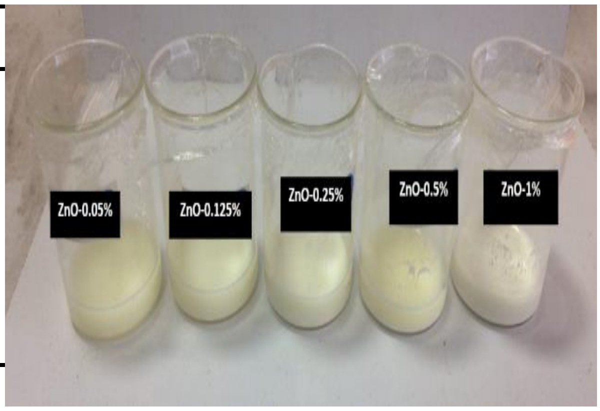

Figure 1. The suspensions at different volume fractions.

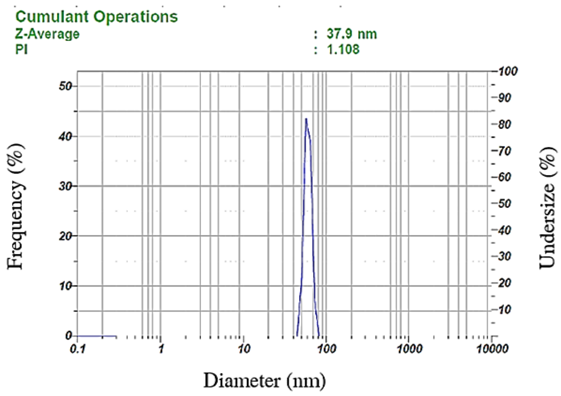

Figure 2. DLS analysis of the nanofluid in a volume fraction of 0.25%.

Figure 3. KD2 Pro device

The accuracy of the KD2 Pro device was ±5% and for the viscometer it was ±2%. The uncertainty of the measured data was calculated from the following equation:

$$U = \frac{S}{\sqrt{N}} \tag{1}$$

where U was the standard uncertainty, N was the number of measurements, and S was the standard deviation that was calculated from equation 2.

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \bar{X})^2} \tag{2}$$

Figure 4. The Cap 2000 viscometer

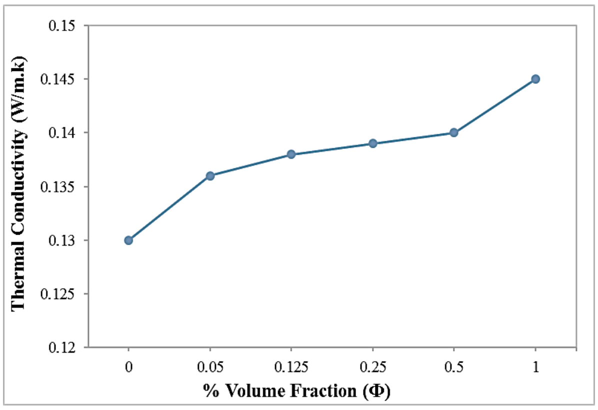

Figure 5. The variation of the nanofluid thermal conductivity considering volume fraction at temperature of 25°C.

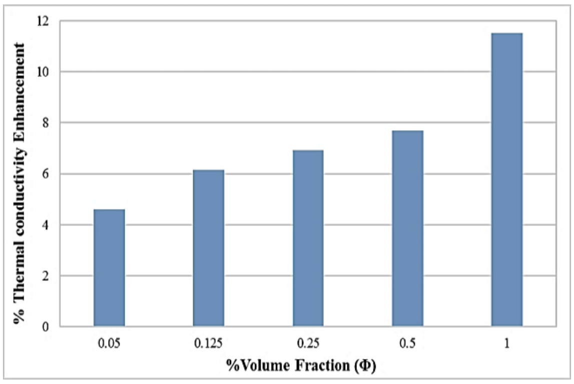

Figure 6. Nanofluid thermal conductivity enhancement at different volume fractions.

Based on this equation, for instance, the uncertainty of thermal conductivity at 25° C and 1% volume fraction was obtained as 5.024%. Also, the uncertainty of dynamic viscosity at 25° C and 1% volume fraction and shear rate of 2666 1/Sec was acquired to be 2.00016%.

4. Results and discussion

Fig. 5 indicates the variation of the thermal conductivity of ZnO-transformer oil nanofluid considering the volume fraction at 25°C. As can be seen, all five nanofluid samples had higher thermal conductivity than the pure transformer oil. Furthermore, a rise in the volume fraction increased the thermal conductivity. Fig. 6 indicates nanofluid thermal conductivity enhancement percentage at different volume fractions. As can be observed, the highest thermal conductivity enhancement was obtained at the highest volume fraction. Moreover, the results revealed that the thermal conductivity was enhanced up to 11.5% at the volume fraction of 1%.

Table 3. The strength index and power index of the nanofluids at the temperature of 25°C.

φ	k	n
0	0.1949	0.9625
0.05	0.1944	0.9641
0.125	0.2346	0.9446
0.25	0.2334	0.9463
0.5	0.2352	0.9486
1	0.2502	0.9479

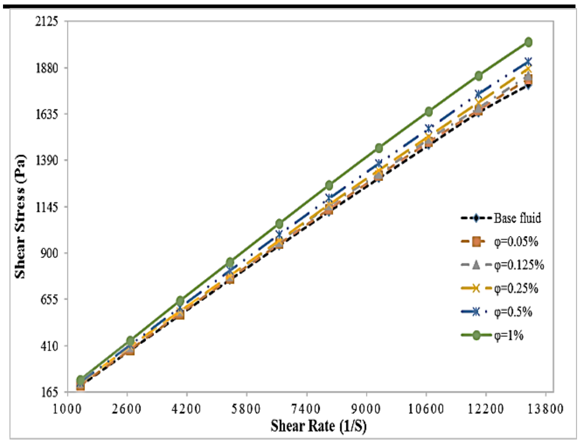

Figure 7. The shear stress versus shear rate for different volume fractions at 25°C.

The power law model was used to identify the behavior of the samples. The power law model represents the relationship between the shear stress and shear rate as follows:

$$\tau = k\gamma^n \quad (3)$$

where k is the strength index and n is the power index. At this point, n=1 represents Newtonian behavior. On the other hand, n>1 and n<1 illustrate non-Newtonian behaviors. If n>1, the fluid is a dilatant (shear-thickening) fluid, while n>1 indicates a pseudoplastic (shear thinning) fluid. This method has been used in several previous studies [33-34]. Table 3 provides the strength index and power index of the fluids at different volume fractions at 25°C. As can be observed, the fluid was a shear-thinning fluid at the entire volume fractions, and the lowest strength index was obtained to be 0.1949% for the base fluid.

Fig. 7 indicates the shear stress versus the wide range of shear rates in different volume fractions at the temperature of 25°C. As can be seen, the highest shear stress was obtained in the volume fraction of 1%, while the lowest shear stress was gained in the pure transformer oil. Moreover, a rise in the shear rate increased the difference between the shear stress values of different concentrations.

Trend evaluation of viscosity diagram versus the shear rate is another method to detect whether a fluid is

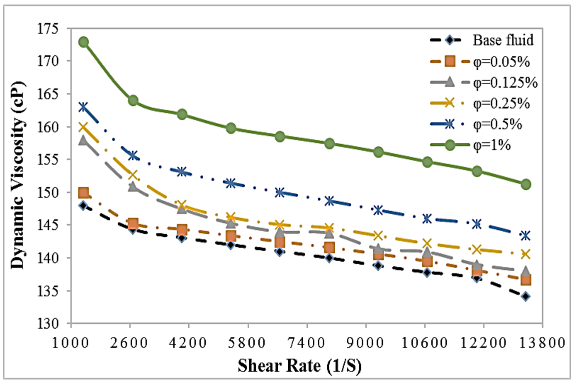

Figure 8. The dynamic viscosity respect to shear rate in different volume fractions at 25°C.

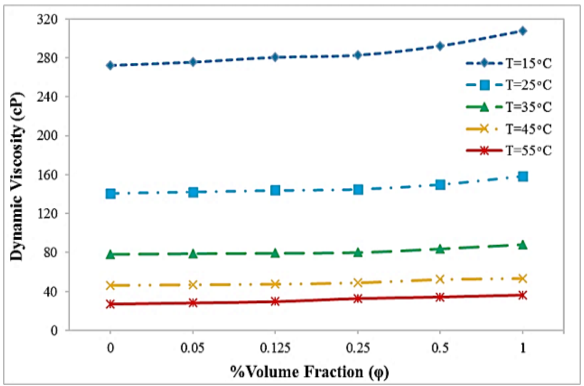

Figure 9. The dynamic viscosity versus volume fraction at different temperatures in the shear rate of 6665 s-1.

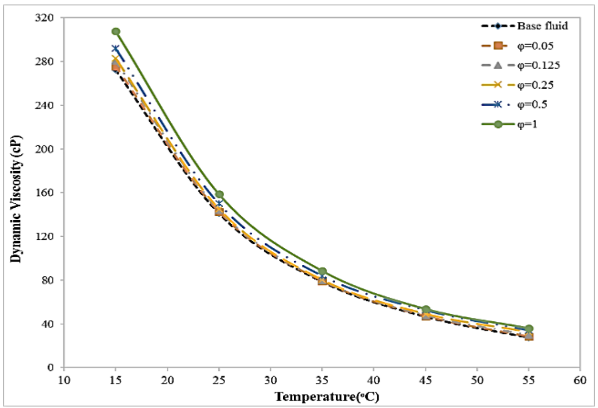

Figure 10. The dynamic viscosity versus temperature at different volume fractions in the shear rate of 6665 s-1.

Newtonian or non-Newtonian. It functions based on the dependence of viscosity on the shear rate. In a non-Newtonian fluid, if the viscosity declines as the shear rate increases, the fluid is pseudoplastic. On the other hand, if the viscosity rises as the shear rate rises and accordingly the fluid is dilatant.

Fig. 8 illustrates the dynamic viscosity in terms of shear rate in different volume fractions at 25°C. According to this Figure, the viscosity reduced as the shear rate increased in all concentrations. Therefore, the studied nanofluids behaved as a non-Newtonian shear thinning. It also shows that the viscosity sharply reduced to 2600 s^{-1} and then began to reduce on a moderate slope for the entire volume fractions.

Fig. 9 indicates the dynamic viscosity versus volume fraction at different temperatures in the shear rate of 6665 s^{-1}. According to this figure, a rise in the temperature at a given volume fraction, decreased the dynamic viscosity. Moreover, an increase in concentration, enhanced the dynamic viscosity at a fixed temperature. This phenomenon occured as the result of a joint between the nanoparticles which prevented the movement of the fluid layers in the higher solid volume fraction of nanoparticles. In fact, a rise in the concentration of ZnO particles increased the Van Der Waals force and consequently raised the nanofluid viscosity [35]. As can be observed, the highest dynamic viscosity was 32.35% at the volume fraction of 1%.

Fig. 10 shows the dynamic viscosity versus temperature at different volume fractions in the shear rate of 6665 s^{-1}. The results revealed that a rise in the temperature led to a decrease in the dynamic viscosity. This resulted from the reduction in adhesion due to increased temperatures. The dynamic viscosity was extremely sensitive to temperature. An increase in the temperature decreased the difference between dynamic viscosity values at different concentrations. The difference between the highest and lowest dynamic viscosity values was approximately 35.2 units at 15°C, while the difference was approximately 8.7 units at 55°C.

Fig. 11 illustrates the dynamic viscosity enhancement with respect to the temperature in different volume fractions at the shear rate of 6665 s^{-1}. According to Fig. 11, a rise in the volume fraction of ZnO nanoparticles increased the dynamic viscosity at a given temperature. The highest viscosity enhancement happened at the volume fraction of 1%, while the lowest took place at the volume fraction of 0.05%. Moreover, when the temperature rose above 35°C, the viscosity enhancement increased in all volume fractions.

In order to predict the dynamic viscosity of the ZnO-transformer oil nanofluid, a mathematical model based on experimental data was presented in the shear rate of 6665 1/s. It is noteworthy that this analysis was obtained by the Minitab 19 software, in which the dynamic viscosity was estimated as a function of two variables of temperature and volume fraction. In this equation, μ_{nf} was dynamic viscosity of nanofluid in centi Poise (cP), φ and T were the percentage of nanoparticle volume fraction (%) and sample temperature (°C), respectively.

$$\mu_{nf} = 518.4 - 19.525T + 42.4\varphi + 0.1953T^2 - 5.7\varphi^2 - 0.607\varphi * T \quad (4)$$

The values of adjusted R-sq, predicted R-sq and R-sq, were 98.95%, 98.55% and 99.13%, respectively. This indicates the high accuracy of the correlation in predicting the viscosity of nanofluids.

Analysis of variance for the model is presented in table 4. It should be noted that this analysis was provided by the aforementioned software. The P-value represents the effect of relationship dependent parameters. It should also be noted that the model terms were not significant for the P-value greater than 0.1 [36]. The F-value represents the role of the parameters in the model. Figure 12 shows the Pareto diagram. According to the Pareto diagram, the parameters

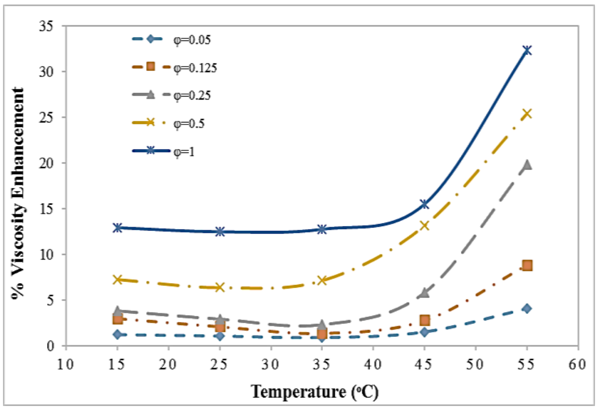

Figure 11. The viscosity enhancement versus the temperature in different volume fractions at the shear rate of 6665 s^{-1}.

Table 4. Analysis of Variance

Source	F-Value	P-Value
Regression	434.91	0.000
T	530.41	0.000
Φ	2.04	0.079
T^2	278.84	0.000
φ^2	0.04	0.763
φ*T	2.17	0.105

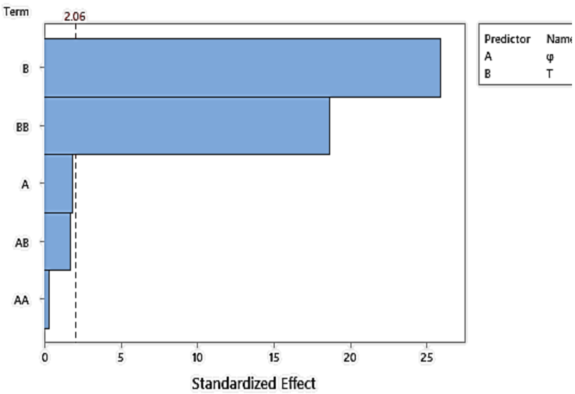

Figure 12. Pareto Chart of the standardized effects (response is μ, α= 0.05)

T and T^2 were influential parameters.

Conclusion

This study investigated the effect of temperature and concentration on the thermal conductivity and dynamic viscosity of ZnO-transformer oil nanofluids with the volume fractions of 0%, 0.05%, 0.125%, 0.25%, 0.5% and 1%. It was observed that the pure transformer oil and nanofluids were pseudoplastic non-Newtonian fluids. The results also demonstrated that the thermal conductivity of the nanofluids was higher than that of the pure transformer oil at the fixed temperature of 25°C. Moreover, at the same temperature, a rise in the nanoparticle concentration raised thermal conductivity. The thermal conductivity increased up to 11.5% at the volume fraction of 1%.

It was also revealed that an increment in the temperature at a specific volume fraction led to a reduction in dynamic viscosity. Furthermore, the viscosity followed an ascending trend as the concentration increased at a specific temperature. In all temperatures, the highest dynamic viscosity enhancement occurred at the 1% volume fraction, while the lowest viscosity enhancement took place at the 0.05% volume fraction of the nanofluid. Also, a correlation based on the viscosity data was presented by using the Minitab 19 software. This model, obtained the dynamic viscosity in centipoise as a function of temperature (°C) and volume fraction (%) at a constant shear rate of 6665 1/s.

It should be considered that the observed variation in dynamic viscosity was not desirable and besides the thermal performance of the transformer oil, it should have improved. In conclusion, the 0.05% volume fraction of nanoparticles appeared to be an appropriate choice to be used in transformers due to its higher thermal conductivity and a slightly elevated dynamic viscosity than pure transformer oil. However, further investigations are required to confirm the method for choosing the most desireable characteristics of transformer oil-based nanofluids, including breakdown voltage and flash point measurements.

Nomenclature

T	Temperature, (°C)
K_{nf}	Thermal conductivity, (W/m.k)
μ_{nf}	Dynamic viscosity of nanofluid, (cP)
φ	Volume fraction, (%)
k	Strength index
n	Behavior index
τ	Shear stress, (Pa)
γ	Shear rate, (1/S)
X_i	The measured value in each experiment
$\bar{x}$	Average measured data
N	Number of measurements
S	Standard deviation
U	Standard uncertainty

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