International Journal of Electrical and Computer Engineering (IJECE)
Vol. 7, No. 3, June 2017, pp. 1530~1537
ISSN: 2088-8708, DOI: 10.11591/ijece.v7i3.pp1530-1537

Characteristics of Mineral Oil-based Nanofluids for Power Transformer Application

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Article Info

Article history:

Received Feb 7, 2017
Revised Apr 5, 2017
Accepted Apr 29, 2017

Keyword:

Mineral oil
Nanofluids
Nanoparticles
Plasma treatment

ABSTRACT

Trends in the field of nanomaterial-based transformer oil show most of the conducted works have focused only on the transformer oil-based nanofluids but limited studies on the stability of transformer oil-based nanofluids. Since mineral oil-based nanofluids still can produce the sedimentation, thus the cold-atmospheric pressure plasma method is proposed to functionally modify the Silicon Dioxide (SiO_2) nanofiller in order to enhance the electrical properties of the mineral oil-based nanofluids. The AC breakdown strength oil samples before and after modification were measured. It was found that the plasma treated nanofluids have higher AC breakdown voltage compared to pure oil and untreated nanofluids. Also, Fourier Transform Infrared (FTIR) Spectroscopy has been used in this study to analyse the physical changes of oil samples. It is envisaged that the added silica nanofiller has significant effect on electrical properties of the transformer oil-based nanofluids which would enable to the development of an improved class of liquid dielectric for the application of power transformer.

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1. INTRODUCTION

Maintaining continuous power supply is a major responsibility of power engineers in the world. Power transformer is one of the crucial equipment which requires condition monitoring and diagnostic to sustain uninterrupted power supply. Insulation in transformer involved solid and liquid dielectrics which play major role in determining the equipment lifetime. The world's energy requirement has been dominated by petroleum oil for centuries in many areas, including transportation, household, and electricity. Nowadays, mineral oil has been used as main source of insulation material for equipment such as power transformer. In 1892, General Electric had introduced the mineral oil as a dielectric coolant [1]. Mineral oil which is refined from petroleum is a good insulating material because of its good electrical properties, aging behaviour, low relative permittivity, low dissipation power factor (power factor) and low viscosity. Mineral oil has much better heat transfer rate than comparable solid insulating material and it has also better self-healing after a breakdown occurrence thus making it suitable for the use in high voltage transformers [2].

The principle chemical components of mineral oil are complex mixtures of hydrocarbons. For a long term application, it is essential to improve both the electrical and the thermal properties of the mineral oil [3]. Recently, great progress has been made in improving the electrical breakdown strength and heat transfer of mineral oils by introducing nanoparticles thereby producing a liquid namely nanofluid.The term “nanofluids” was introduced by the researchers at the Argonne National Laboratory and refers to a two-phase mixture [4], containing a liquid phase which is the host, and dispersed nanoparticles in suspension. A nanofluid is a heat transfer fluid, in which a small amount of nano-sized materials (nanoparticle, nanofibers, nanotubes, nanowires, nanorods or nanosheets) are stably suspended in a traditional heat transfer fluid (such as mineral oil, water or ethylene glycol) [2]. Huifei et al. studied the properties of mineral oil-based silica nanofluids. The results show that the addition of SiO_2 nanoparticles improved the AC breakdown voltage of the mineral oil [5].

The sedimentation or sludge is a major problem occurs in nanofluids. Improper dispersion of nanoparticles in transformer oil would result in sedimentation which eventually leading to nonstability of the nanofluids. Generally, the long term stability of nanoparticle dispersion is one of the basic requirements of the nanofluid application. Previous researchers found that the usage of surfactants or dispersants can mitigate the sediment issue in nanofluids. Adding dispersants to enhance the compatibility of two different materials is an easy and economical method but the functionality of the surfactants under high temperature is also a big concern, especially for high-temperature application. The surfactants can avoid early sedimentation, however the exact amount of surfactants added to particle for a specific case is remained a question. Also, it is considerable as a major challenge to select suitable surfactants [6]-[7]. Using a surfactant to modify the surface of nanoparticles has improved the nanoparticles dispersion but low surface reactivity of nanofillers may result in unsatisfactory improvement of the nanofluids. Mostly surfactants are acid based therefore it can affect the nanofluids if an ageing happens. Therefore, ageing rate would become much faster and the acidity would increase thereby affecting the insulating paper in the transformer.

In view of foregoing, this paper introduces atmospheric pressure plasma treatment which modifies the surface of the nanoparticles. Nowadays, atmospheric-pressure plasmas have a wide variety of potential industrial applications [8]. Yan et al. [9] resolved agglomerate issues in nanomixtures by using thermally non-equilibrium atmospheric-pressure plasma to modify the nanosilica surface. Meanwhile, Kim et al. claimed that plasma treated nanoparticles with desired surface functionalities can strongly interact with liquid molecules with better dispersed into the base fluid to form a stable suspension. Therefore, the application of cold atmospheric pressure plasma can modify the surface of the silica nanoparticles to enhance their compatibility with mineral oil and reliable to provide stronger interaction between the nanoparticles and the transformer oil. Besides, the usage of surfactants can be eliminated thus improving one of the important properties of transformer oil-based nanofluids. Hence, this work was carried out to enhance the electrical and dielectric performances of mineral oil-based nanofluids by using the plasma treatment [10].

2. RESEARCH METHOD

2.1. Materials

Hyrax Hypertrans transformer oil is a premium uninhibited mineral insulating oil made from a severely hydro-treated wax-free naphthenic oil which is good as a dielectric and a coolant. This type of mineral oil was used as base oil in this work. The silica (SiO_2) nanofillers were purchased from Sigma Aldrich with mean dry particle size of 12 nm. The nanofluid samples with 0.05 wt% and 0.1 wt% were prepared for the viscosity and AC breakdown tests.

2.2. Nanofluids Preparation

Two-step method is the most economic method to produce nanofluids in large scale, because nanopowder synthesis techniques have already been scaled up to industrial production levels [11]. In this experiment, as shown in Figure 1, the two-step method was used for preparing mineral oil-based nanofluid where the nanoparticles have been firstly weighed. Nanoparticles were initially dispersed in the transformer oil. The mixture was stirred with a magnetic stirrer for within 30 minutes and then sonicated to ensure a good dispersion of the mixtures. The silica nanofiller with different concentrations of 0.1% and 0.05% mass fraction were added to the 100% by weight of base fluid to study the effect of nanoparticles concentration. To achieve low humidity of transformer oil, the samples were dried for at least 24 hours in a vacuum oven at 60ºC [12]. Figure 2 shows the nanofluids condition between untreated and treated silica nanofluids. After 14 days, the sedimentations were observed in untreated nanofluid samples while no sedimentation was observed in the plasma treated nanofluid samples.

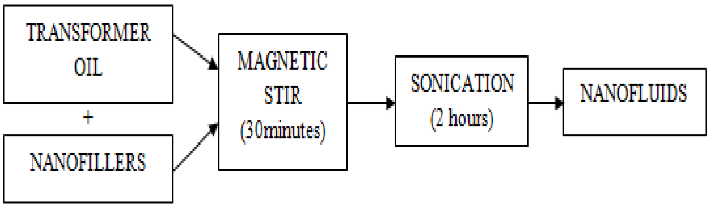
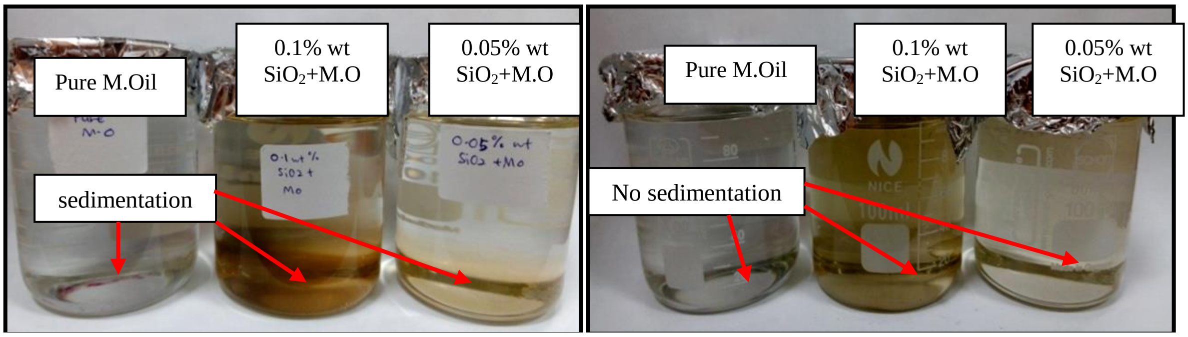


Figure 1. Flowchart for the preparation of mineral oil-based nanofluid



(a) (b)

Figure 2. Mineral oil-based SiO_2 nanofluids after 14 days of preparation: (a) untreated silica/mineral oil nanofluids, (b) treated silica/mineral oil nanofluids

2.3. Plasma Treatment of the Nanofillers

The silica nanofillers were treated using atmospheric pressure plasma treatment. The plasma discharges were applied on the nanofillers surface to avoid early sedimentation occur in the oil. The cold atmospheric air pressure plasma was generated by 50 Hz power supply with maximum 10kVrms applied voltage and the output power consumed was 9-10W. The plasma setup consists of two glass plates and the nanofillers was placed in between the plates. A tin coated copper coil electrode was placed 2 mm above the top of nanoparticle layer. Air was used as the working gas for discharge. Treatment time was carried out in time 30 minutes. The nanoparticles were stirred for 30 seconds at every 5 minutes of surface treatment to obtain homogenous plasma treatment [9]. The set-up of the treatment is shown in Figure 3. After the treatment, the treated nanofillers were mixed with the base oil according to two step method.

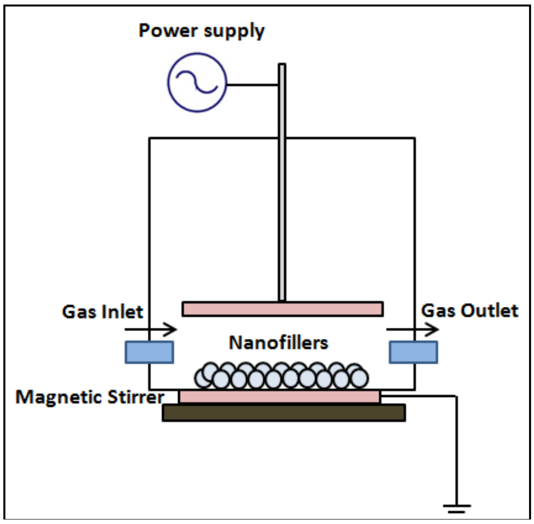


Figure 3. Schematic diagram of the cold atmospheric-pressure plasma reactor

3. RESULTS AND ANALYSIS

3.1. AC Breakdown Voltage Test

The breakdown voltage test was carried out according to IEC 60156 standard. Figure 4 shows a test cell for breakdown voltage and digital measuring instrument (Haefely, DMI 551) with operating terminal (Haefely, OT 276). The electrode configuration consists of two spherical brass electrodes with 2.5 mm gap distance. The rate of voltage rise was 2 kV/s. Figure 5 shows the comparison of AC breakdown voltages of treated and untreated nanofluids. It can be clearly seen that the AC breakdown voltage has increased with the increase in nanoparticle concentration for both treated and untreated nanofluids. The treated 0.1wt% silica nanofluid yields highest result compared to other samples.

(a) (b)

Figure 4. (a) Test cell for breakdown voltage test, (b) Digital measuring instrument (DMI 551) with operating terminal (OT 276)

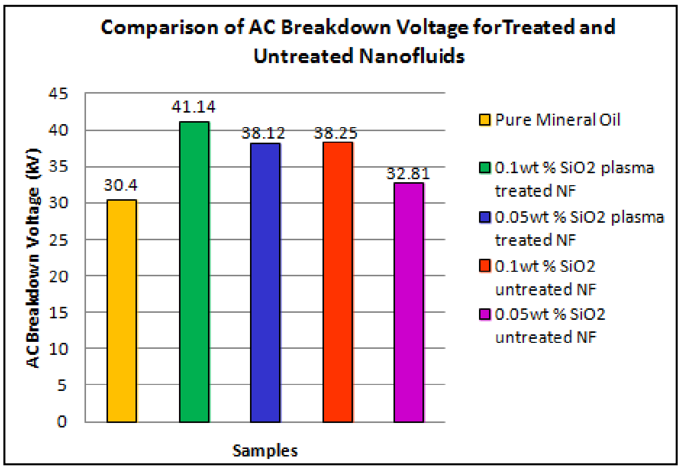


Figure 5. Comparison of AC breakdown voltage for treated and untreated nanofluids

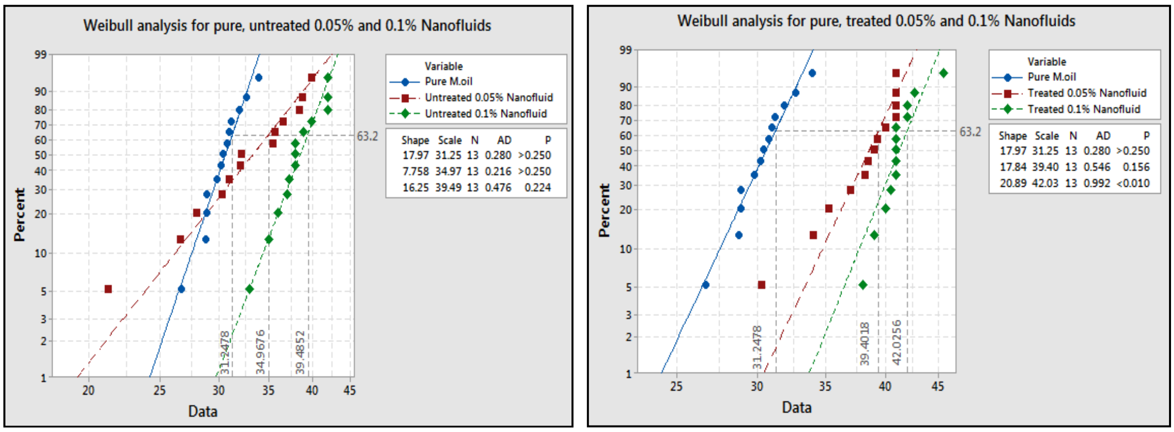
Table 1 shows the AC breakdown voltage enhancement of mineral oil due to the addition of treated and untreated SiO_2 nanoparticles. As consequences, the plasma surface modication treatment of silica nanoparticles has contributed to higher AC breakdown strength. The 0.1wt% and 0.05wt% plasma treated nanofluids have enhanced in about 35.33% and 25.4% respectively compared to pure mineral oil. Whilst, the 0.1wt% and 0.05wt% untreated nanofluids has enhanced in about 25.82% and 7.92% respectively compared to pure mineral oil. These obvious breakdown strength enhancement based on addition of nanoparticles has suggested a significant solution to improve the breakdown voltage of mineral oil which has been reported tends to reduce after certain years of service [13].

Table 1. AC breakdown voltage enhancement in nanofluids

Samples	Enhancement (%)
0.1wt % SiO_2 plasma treated NF	35.33
0.05wt % SiO_2 plasma treated NF	25.4
0.1wt % SiO_2 untreated NF	25.82
0.05wt % SiO_2 untreated NF	7.92

3.2. Weibull Analysis of AC breakdown tests

Figure 6(a) shows the 2-parameter Weibull analysis of the AC breakdown voltage of mineral oil, untreated 0.05wt% and 0.1wt% SiO_2 nanofluids with 95% confidence intervals. The parameters of the Weibull plot are shown the graph. The weibull analysis of AC breakdown voltage for treated samples compared with base oil shows in Figure 6(b). All the results and the enhancement of the pure oil, treated and untreated nanofluids were compiled in Table 2.



(a) (b)

Figure 6. Weibull analysis at 63.2% breakdown probability for (a) pure oil, untreated 0.05wt% and 0.1wt% nanofluids, (b) for pure oil, treated 0.05wt% and 0.1wt% nanofluids

Table 2. AC breakdown at 63.2% breakdown probability of mineral oil, treated and untreated SiO_2 nanofluids using 2-parameter Weibull analysis

Samples	Breakdown Voltage (kV)	Enhancement (%)
Pure Mineral Oil	31.25	-
0.1wt % SiO_2 plasma treated NF	42.03	34.50
0.05wt % SiO_2 plasma treated NF	39.40	26.08
0.1wt % SiO_2 untreated NF	39.49	26.37
0.05wt % SiO_2 untreated NF	34.97	11.90

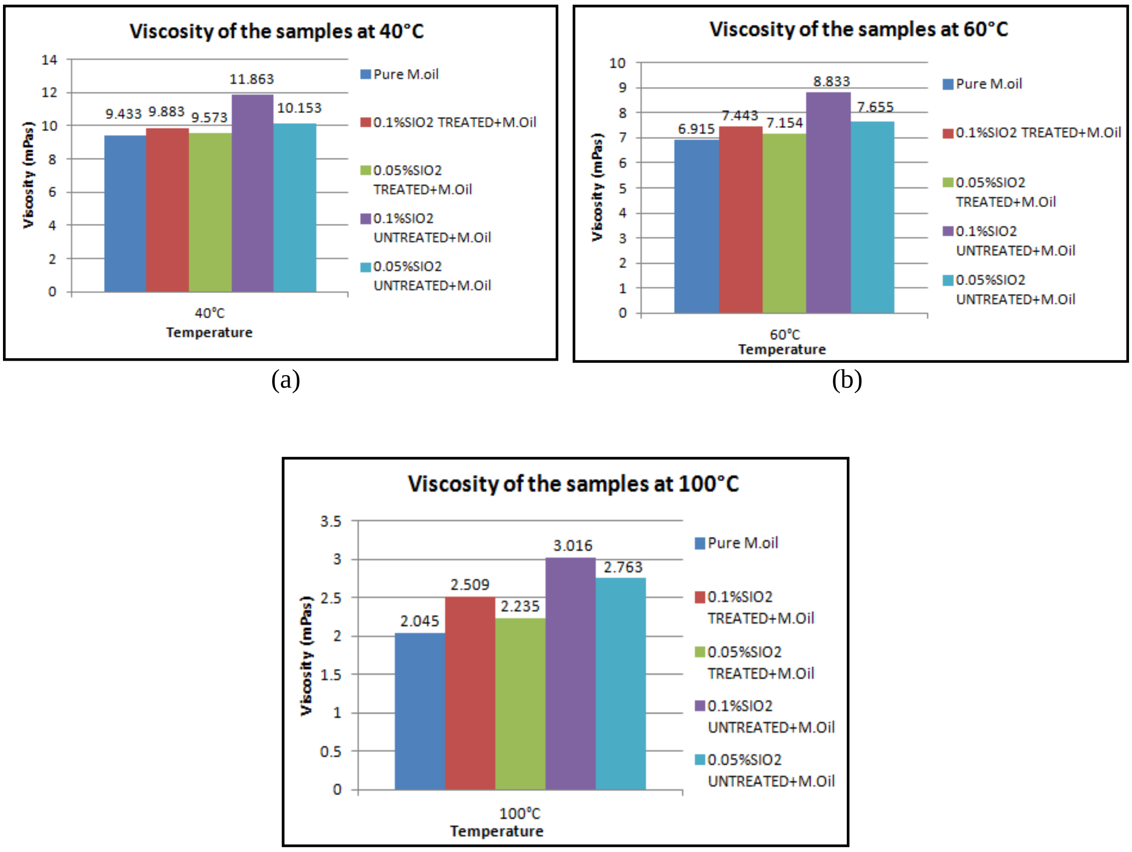
For AC breakdown voltage tests, SiO_2 nanoparticles can enhance the breakdown voltage of mineral oil significantly at higher probabilities with addition of 0.05 wt% and 0.1 wt% nanoparticles. The enhancement of the breakdown voltage at 0.1 wt% nanoparticles concentration is remarkable. The AC breakdown voltage of SiO_2 nanofluids increases with the increase in particle concentration.

3.3. Viscosity

Viscosity is one of the important parameters to be studied in because it can affect both heat treansfer and electical properties of the nanofluid [5]. Viscosity test on the oil samples was performed using Brookfield DV-II + Pro Automated viscometer as shown in Figure 7 with CP-42 spindle based on ISO 3104 standard. In this paper, the rheometer has measured the viscosity at the temperatures of 40°C, 60°C and 100°C.

Based on the graphs shown in Figure 7, it can be elucidated that the viscosity of treated nanofluids is lower than untreated nanofluids but a bit higher compared to pure mineral oil. The viscosity decreased with an increasing temperature. At 40°C, it is clearly seen that the samples increased about 4.77% for treated 0.1wt%, 1.48% for treated 0.05wt%, 25.76% for untreated 0.1wt% and 7.63% for untreated 0.05wt%

compared to base oil. However at 60°C, the viscosity of treated samples was increased about 7.63% for 0.1wt% and 3.86% for 0.05wt% while for untreated samples, the viscosity increased about 27.74% for 0.1wt% and 10.70% for 0.05wt% compared to base oil. The viscosity of all samples have decreased significantly at 100°C. The treated samples have resulted in 22.7% higher for 0.1wt% and 9.3% higher for 0.05wt% compared to base oil whereas 47.5% and 35.11% higher for untreated 0.1wt% and 0.05wt% respectively compared to base oil.



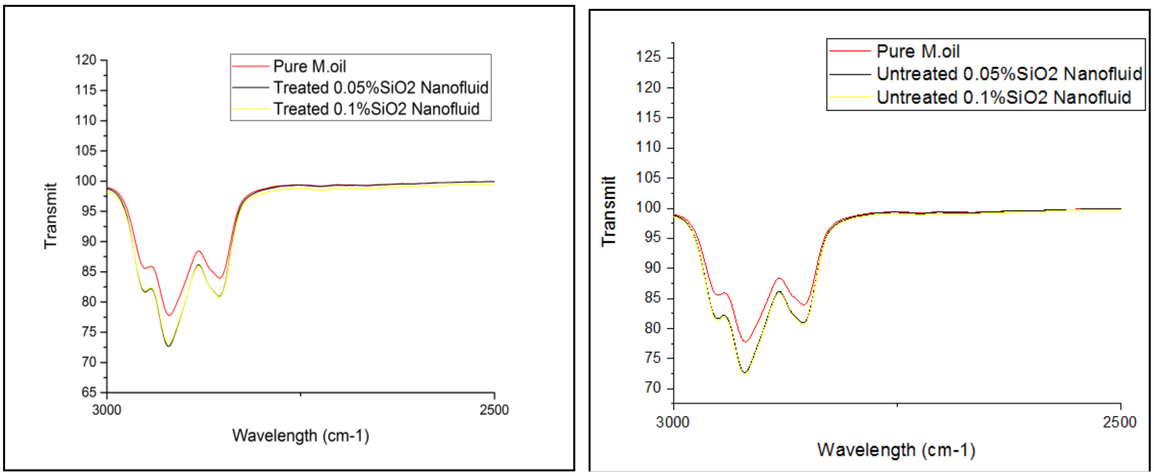
(a) (b)

(c)

Figure 7. Viscosity of pure mineral oil, treated and untreated 0.05wt% and 0.1wt% nanofluids at (a) 40°C, (b) 60°C and (c)100°C

3.4. FTIR Spectra

Infrared Spectroscopy (IR) provides mostly information about the presence or absence of certain functional groups [14]. The result of spectrum represents the molecular transmission. The graphs in Figure 8 show the regions of the spectrum where the bonds normally transmit and most stretching frequencies appear. A broad band around 2700–2850 cm-1 would indicate the possible presence of H–C=O bond, carbonyl compounds are those that contain the C=O functional group. In aldehydes functional group, it is at the end of a carbon chain. The carbon in the C=O bond of aldehydes is also bonded to another carbon and a hydrogen. This 2 graphs show the same spectrums shape because there are no chemical interaction happened. The pure oil sample show lower intensity compared to both treated and untreated samples.



(a) (b)

Figure 8. FTIR Spectra of (a) treated nanofluids and (b) untreated nanofluids at 2500-3000cm^{-1}

4. CONCLUSION

The addition of nanoparticles can improve the AC breakdown voltage of mineral oil. One approach to achieve the homogeneous dispersion and stable suspension of fine particles is by applying plasma treatment on the nanofillers. Instead of using surfactants, atmospheric pressure plasma treatment is an effective, simple, inexpensive and environmentally friendly method to improve the stability of nanofluids and enhance the characteristics of the nanofluids as well. Higher silica concentration, higher dielectric strength for both treated and untreated mineral oil-based nanofluids but the treated 0.1wt% sample shows the highest AC breakdown strength. The treated samples also show low viscosity than untreated samples with an increase in temperature thus summarizing the treated samples have also good heat transfer properties. The FTIR spectra captured the spectrum variations and classified as medium band. The graph shows the regions of the spectrum where the following types of bonds normally absorb. There are more parameters and analysis should be studied such as heat transfer properties and thermal conductivity to gain more comprehensive understanding on the mineral oil-based nanofluids.

ACKNOWLEDGEMENTS

The authors would like to thank Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (moHE) for financial supports through research grants vote 10J87, 4F599, 4F672, 13H98, and 11H21.

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