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Multiple Nanoparticles for Enhancing Breakdown Strength and Heat Transfer Coefficient of Oil Nanofluids

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***Abstract*—The improvement of oil transformer performance is related to several factors. The most important factors are dielectric and thermal capability. Nanotechnology is an effective science used for enhancing the dielectric and thermal properties of the transformer oil. In this work, barium titanate (BT) nanoparticles were dispersed into the pure transformer oil by 0.005 g/L volume fraction (vf%). From the obtained results, it is noticed that BT enhances the thermal properties of the transformer oil by about 33%, although, the dielectric properties were decreased by about 10%. To improve the dielectric properties also, 0.01 vf% titanium dioxide (TiO_2) nanoparticles with 0.005 vf% BT was dispersed into the base oil. The hybrid nanofluid sample achieves about 33% and 45% enhancement for the thermal and dielectric properties, respectively.**

Keywords– Transformer oil, Nanofluids, Hybrid nanoparticles, Dielectric properties and Thermal properties.

I. Introduction

In the framework of improving the power grid performance, it is necessary to pay attention to improving the performance of the power transformer because it is one of the most important equipment of the electrical power system. Transformer oil is the most critical insulating material in power transformers, where it has been used as cooling and insulating medium. So, the enhancement of its thermal and dielectric properties affects positively the power transformer performance.

Recently, some searchers were oriented to study the influence of nanoparticles addition to the base transformer oil on its thermal and dielectric properties under the name of nanooil or nanofluid. Regarding the thermal properties of the transformer oil, Timofeeva et al. presented 10% thermal conductivity enhancement by the mixing of synthetic oil with 5% volume fraction of silica nanoparticles where the increasing of volume fraction achieved an increasing of thermal conductivity [1]. In [2], Al_2O_3 nanoparticles were dispersed with surfactant into the pure transformer oil. It is concluded that, the heat transfer coefficient was affected by not only nanoparticles concentration but also weight percent of the surfactant. Abd-elhady et al. concluded that, transformer oil with semiconductive cadmium sulfide quantum dots has higher thermal properties than the base transformer oil [3]. Shukla et al. loaded up to 0.12% volume fraction of ND into naphthenic transformer base oil. The thermal conductivity of oil was enhanced by 14.5% at 40^o C which was increased further with the increase in temperature [4]. An enhancement in thermal conductivity up to 70% is reported for nanodiamond based thermal fluids in [5].

On the other hand, regarding the dielectric properties of the transformer oil, Jin et al. achieved up to 79% enhancement of breakdown voltage at 0.1% probability by the dispersion of SiO_2 nanoparticles at 20-30 ppm humidity level [6]. Segal et al. could improve the dielectric properties of transformer oil

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with adding Fe_3O_4 nanoparticles [7]. The DC breakdown strength of the transformer oil is increased over 20% with the use of 0.0004 g/L Fe_3O_4 nanoparticles as reported in [8]. Two types of nanofillers (Al_2O_3 and TiO_2) with different band gap structure have been dispersed with pure oil. For all types of these nanoparticles, breakdown voltage increases above that of the base oil with increasing the weight percent until a certain point [9].

The aim of this work is the improving of the thermal and dielectric properties of transformer oil at the same time. One of the effective nanoparticles that improve the dielectric properties of the transformer oil is titanium dioxide (TiO_2) nanoparticles [10]. Although, TiO_2 nanoparticles achieved an improving in the dielectric properties of the transformer oil, but they did not achieve satisfactory results of the transformer oil thermal properties. In this work, barium titanate nanoparticles (BT) were dispersed into transformer oil with a certain weight percent to form a nanofluid sample. Breakdown strength and heat transfer coefficient were measured for this sample to excogitate the transformer oil dielectric and thermal properties, respectively. On the other hand, another nanofluid sample was prepared by the dispersion of BT and TiO_2 nanoparticles into the pure transformer oil under the name of hybrid nanofluid. The same measurements were repeated to investigate the influence of the hybrid nanoparticles on the thermal and dielectric properties of transformer oil.

II. Experimental Proceeding

A. Nanofluids Preparation

The nanofluid was prepared by dispersing nanoparticles into the pure transformer oil with a certain weight percent. In this work, two nanofluid samples were prepared. The first sample consisted of a concentration of 0.005 g/L (BT/transformer oil). To prepare this sample, a quantity of base transformer oil was put in a graduated beaker and the required weight of BT nanoparticles (average size 50 nm) was detected using a sensitive electronic balance. The BT nanoparticles were added to the base transformer oil, and then, the beaker was put on a magnetic stirrer at 1500 rpm for 15 minutes. For good dispersing of BT nanoparticles into transformer oil, ultrasonic disruptor was used for 60 minutes after stirring with an interval of 5 minutes after each 30 minutes. The obtained sample was dried by putting it in a vacuum oven at 45 °C for 24 hours to remove gas bubbles and moisture content composed during ultrasonic process. Before testing the obtained sample, the sample was cooled down in air for 20 minutes.

The other sample consisted of a concentration of 0.005 g/L (BT/transformer oil) and 0.01 g/L (TiO_2/transformer oil). To prepare this sample, a quantity of base transformer oil was put in a graduated beaker and the required weight of BT nanoparticles (average size 50 nm) was detected using a sensitive electronic balance. The BT nanoparticles were added to the base transformer oil, and then, the beaker was put on a magnetic stirrer at 1500 rpm for 5 minutes before processing under ultrasonic disruptor for 5 minutes. During these 10 minutes, the required weight of TiO_2 nanoparticles (average size 21 nm) was detected using the sensitive electronic balance. TiO_2 nanoparticles were added to the mixture of BT and transformer oil. The obtained sample was re-stirred for another 5 minutes at the same rpm and re-put under ultrasonic disruptor for 60 minutes after stirring with an interval of 5 minutes after each 30 minutes. The following process to prepare this sample was completely as same as the first sample.

B. Heat Transfer Coefficient of Nanofluids

Transformer oil plays an important role as a cooling medium for power transformers. Highly heat transfer coefficient indicates highly cooling effect of the transformer oil. To evaluate the heat transfer coefficient for each prepared sample, the following equation is used [2]:

$$H = \frac{Q}{T_i - T_o} \quad (1)$$

Where:

- Q = amount of heat transferred (heat flux), W/m^2.
- H = heat transfer coefficient, W.m^{-2}.K^{-1}.
- $T_i - T_o$ = difference in temperature between the solid surface and surrounding fluid area.

Fig. 1 shows the experimental setup used for heat transfer coefficient test. The heater was connected to a controlled power supply. The inlet temperature (T_i) and the outlet temperature (T_o) were measured at the heater surface and at the opposite side, respectively. Both temperatures were recorded every 5 minutes until thermal steady state condition has been attained. After that, the heat transfer coefficient (H) could be evaluated. The heat transfer coefficient for the base oil was determined after the thermal steady state condition as an average value of 304 W.m^{-2}.K^{-1}.

C. Dielectric Strength of Nanofluids

Highly dielectric strength of transformer oil provides reliable operation of power transformers. Low values of breakdown (BD) voltage indicate presence of high moisture content and conducting impurities in the oil and adversely affect the transformer performance. So, the most important property of the transformer oil is its breakdown voltage. An oil breakdown tester is used in this study to carry out the AC breakdown voltage of each prepared sample at room temperature. The voltage ramp rate and test electrodes were selected as per IEC-60156 standard. The separation between electrodes was adjusted to 2.5 mm. The voltage ramp rate was set at 2 kV/s. Ten measurements were performed for each sample, and their average is taken as the obtained result for each sample. Weibull distribution was presented to evaluate

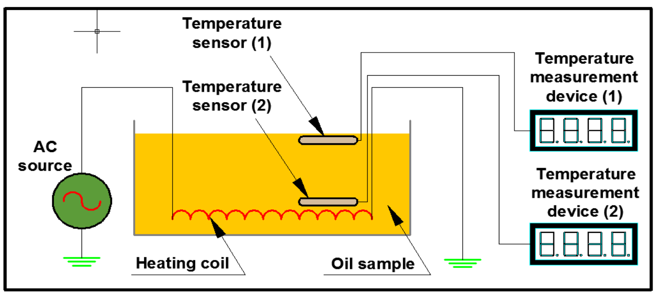

Figure 1. Experimental setup for heat transfer coefficient test.

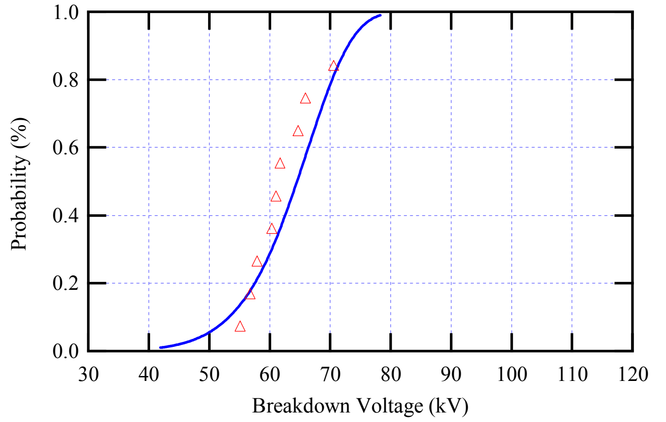

Figure 2. Cumulative probability versus breakdown voltage for pure transformer oil.

AC breakdown strength at all probabilities and to provide dielectric failure analysis and failure auspice with small number of tests. Fig. 2 shows the cumulative probability function of Weibull distribution for pure transformer oil that given by [10]:

$$F(v) = 1 - e^{-(\frac{v}{\lambda})^{\xi}} \quad (2)$$

Where:

- v = Breakdown voltage, kV.
- λ = Scale parameter, kV.
- ξ = Shape parameter.

III. Single Nanofluid Sample

A. Thermal Properties

Due to the dispersion of 0.005 g/L BT nanoparticles into pure transformer oil, the heat transfer coefficient was determined as shown in Fig. 3. This sample provided a significantly improvement in heat transfer coefficient, where it attained 404 $W.m^{-2}.K^{-1}$ corresponding to about 33% above that of the base transformer oil.

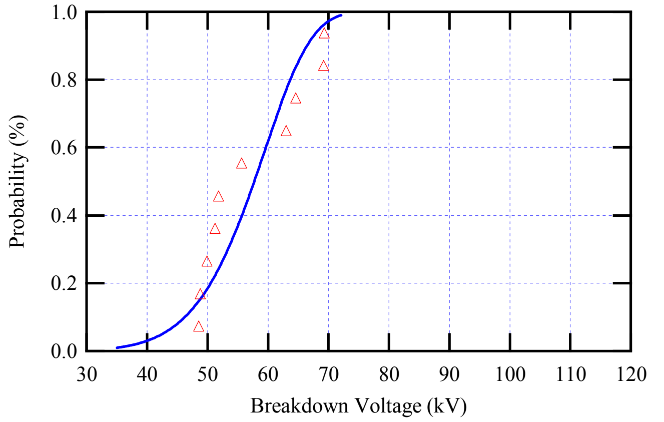

Figure 4. Cumulative probability versus breakdown voltage for 0.005 g/L BT nanofluid sample.

Table I. Weibull analysis for base oil and single nanofluid sample.

$BaTiO_3$ (g/L)	0	0.005
Scale parameter (kV)	67	60.24
Shape parameter	9.8	8.5
v at 50% probability (kV)	64.5	57.7
v at 10% probability (kV)	53.3	46.3

B. Dielectric Properties

Fig. 4 shows the cumulative probability function for 0.005 g/L BT nanofluid sample. Shape parameter, scale parameter, breakdown voltage at 50% probability and breakdown voltage at 10% probability are presented in Table I. Due to the dispersion of 0.005 g/L BT nanoparticles into pure transformer oil, the breakdown voltage at 50% probability and 10% probability decreased by about 11% and 13%, respectively, compared to the base transformer oil.

IV. Hybrid Nanofluid Sample

A. Thermal Properties

Regarding hybrid nanofluid sample, 0.005 g/L of BT nanoparticles with 0.01 g/L TiO_2 nanoparticles were dispersed

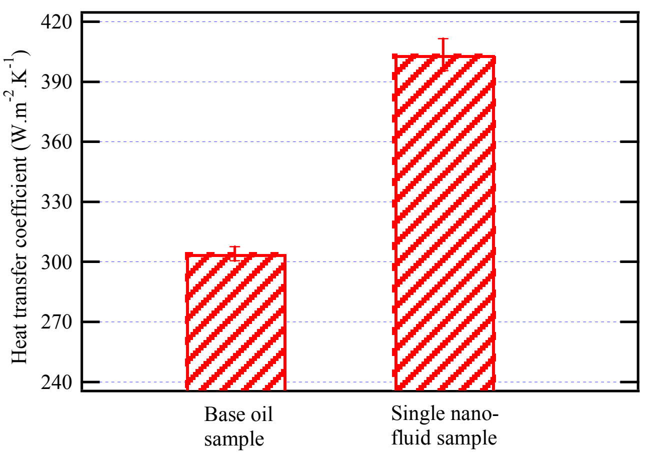

Figure 3. Heat transfer coefficient for single nanofluid sample compared to base oil.

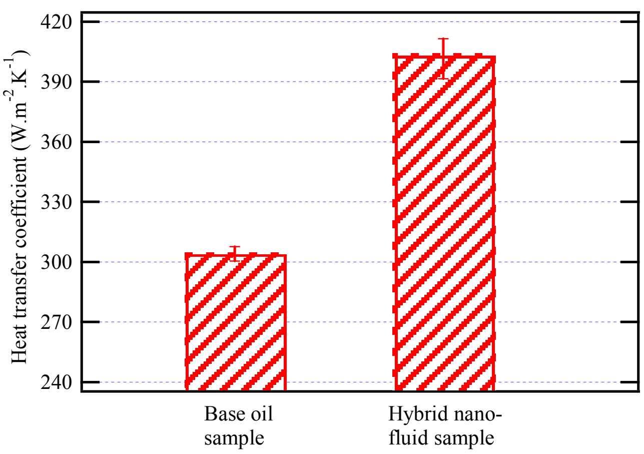

Figure 5. Heat transfer coefficient for hybrid nanofluid sample compared to base oil.

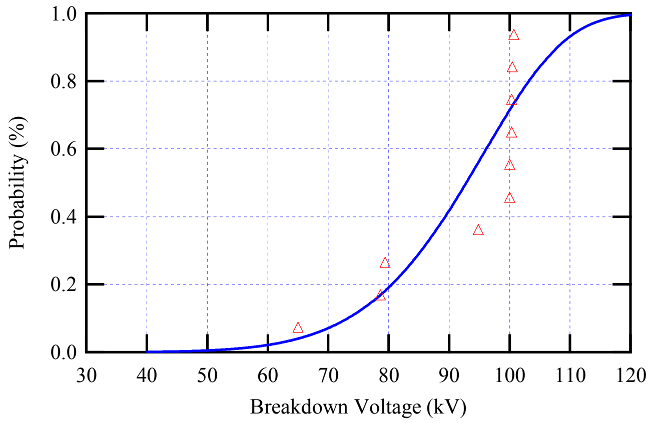

Figure 6. Cumulative probability versus breakdown voltage for hybrid nanofluid sample.

Table II. Weibull analysis for base oil and hybrid nanofluid sample.

$BaTiO_3$ (g/L)	0	0.005
Scale parameter (kV)	67	97.2
Shape parameter	9.8	8.0
v at 50% probability (kV)	64.5	92.9
v at 10% probability (kV)	53.3	73.3

into pure transformer oil. Fig. 5 shows that the heat transfer coefficient was significantly enhanced compared to the base transformer oil, but kept around the same value of single nanofluid sample. This indicates that TiO_2 nanoparticles didn't contribute to the enhancement in thermal properties.

B. Dielectric Properties

The cumulative probability function for the hybrid nanofluid sample is presented in Fig. 6. Table II presents shape parameter, scale parameter, breakdown voltage at 50% probability and the breakdown voltage at 10% probability. The breakdown voltage was improved by about 45% compared to the base transformer oil.

V. Discussion

Fig. 7 presents the heat transfer coefficient and the

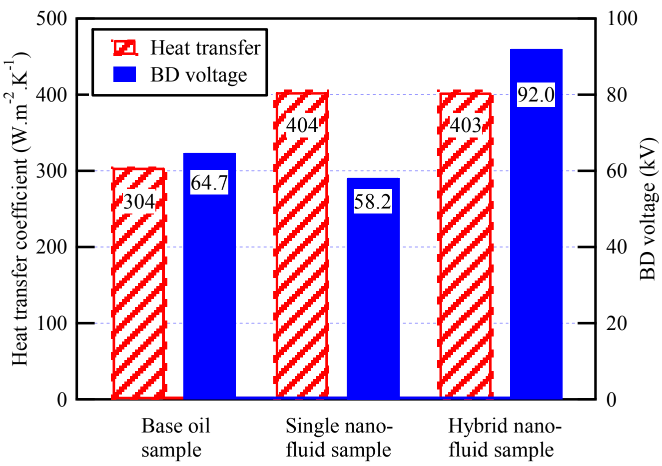

Figure 7. Heat transfer coefficient and BD voltage for the prepared samples.

breakdown voltage for base oil sample, single nanofluid sample and hybrid nanofluid sample. The specific heat capacity of BT nanoparticles (≈ 0.5 J/gK) is lower than that for the base oil (≈ 1.8 J/g.K). So, the presence of BT nanoparticles into the oil provides a more heat commute than the pure oil sample. Subsequently, the heat transfer coefficient of the prepared nanofluid samples was enhanced compared to the pure transformer oil. On the other hand, for the single nanofluid sample, a negative effect of BT on the dielectric strength of transformer oil has been observed. This is attributed to two reasons. The first reason is the agglomeration due to the attraction force that easily attracts the small volume of nanoparticles to each other with a subsequent sedimentation of BT due to its large density (6.02 g/cm^3). The second reason is the semi-conductivity of BT due to its positive temperature coefficient of resistivity [11]. So, TiO_2 nanoparticles were used to treat the problem of dielectric strength degradation. The selection of TiO_2 is returned to its significant electronegativity since titanium and oxygen have electronegativities of about 1.5 and 3.5, respectively [12]. Thence, the hybrid nanoparticles enhanced not only the heat transfer coefficient, but also the dielectric strength.

VI. Conclusions

This paper studied the effect of barium titanate nanoparticles dispersion inside the transformer oil. BT nanoparticles were inserted into the base transformer oil with weight percent of 0.005 g/L. Even though, this dispersion led to an improvement in the oil heat transfer coefficient by about 33%, this dispersion decreased the breakdown voltage by about 10%. To overcome this problem, another sample was prepared by the dispersion of 0.01 g/L TiO_2 nanoparticles with 0.005 g/L BT nanoparticles into transformer oil. This hybrid nanofluid enhanced the heat transfer coefficient as same as the single nanofluid sample and improved the breakdown voltage by about 45%. The improvement of heat transfer coefficient and breakdown voltage returns to the lowest specific heat capacity of BT nanoparticles and the significant electronegativity of TiO_2 nanoparticles, respectively.

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References

[1] E. V. Timofeeva, M. R. Moravek and D. Singh, "Improving the heat transfer efficiency of synthetic oil with silica nanoparticles," J. Colloid Interface Sci., vol. 364, pp. 71-79, 2011.

[2] D. A. Mansour and A. M. Elsaeed, "Heat transfer properties of transformer oil-based nanofluids filled with Al_2O_3 nanoparticles," IEEE Int'l. Conf. Power and Energy (PECON), Malaysia, pp. 123-127, 2014.

[3] A. M. Abd-Elhady, M. E. Ibrahim, T. A. Taha and M. A. Izzularab, "Dielectric and thermal properties of transformer oil modified by semiconductive CdS quantum dots," J. Electronic Materials, vol. 45, pp. 4755-4761, 2016.

[4] G. Shukla and H. Aiyer, "Thermal conductivity enhancement of transformer oil using functionalized nanodiamonds," IEEE Trans. Dielectr. Electr. Insul., vol. 22, pp. 2185-2190, 2015.

[5] J. J. Tijerina, T. N. Narayanan, C. S. Tiwary, K. Lozano, M. Chipara and P. M. Ajayan, "Nanodiamond-based thermal fluids", ACS Appl. Mater. Interfaces, vol. 6, pp. 4778-4785, 2014.

[6] H. Jin, T. Andritsch, P. H. F. Morshuis and J. J. Smit, "AC breakdown voltage and viscosity of mineral oil based SiO2 nanofluids," IEEE Conf. Electr. Insul. Dielectr. Phenom. (CEIDP), pp. 902-905, 2012.

[7] V. Segal, A. Hjortsberg, A. Rabinovich, D. Nattrass and K. Raj, "AC (60 Hz) and impulse breakdown strength of a colloidal fluid based on transformer oil and magnetite nanoparticles," IEEE International Symposium on Electrical Insulation, pp. 619-622, 1998.

[8] M. J. Given, M. P. Wilson, P. McGlone, I. V. Timoshkin, T. Wang, S. J. MacGregor, and J. M. Lehr, "The influence of magnetite nano particles on the behaviour of insulating oils for pulse power applications," IEEE Conf. Electr. Insul. Dielectr. Phenom. (CEIDP), pp. 40-43, 2011.

[9] D. A. Mansour, A. M. Elsaeed and M. A. Izzularab, "The role of interfacial zone in dielectric properties of transformer oil-based nanofluids," IEEE Trans. Dielectr. Electr. Insul., vol. 23, pp. 3364-3372, 2016.

[10] E. G. Atiya, D. A. Mansour, R. M. Khattab and A. M. Azmy, "Dispersion behavior and breakdown strength of transformer oil filled with TiO_2 nanoparticles," IEEE Trans. Dielectr. Electr. Insul., vol. 22, pp. 2463-2472, 2015.

[11] B. Ertuğ, "The overview of the electrical properties of barium titanate," American Journal of Engineering Research (AJER), vol. 2, no. 8, pp. 1-7, 2013.

[12] J. E. Huheey, E. A. Keiter, R. L. Keiter, *Inorganic chemistry: principles of structure and reactivity*, Fourth Edition, Harper Collins College Publishers, 1993.