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Behavior of Nanoparticles in Service Transformer Oils and their Performance on Laboratory Ageing

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Abstract

The transformer is the most critical apparatus in the electric power network. Reliable operation of it is of foremost concern for a proficient power supply. Therefore, it is vital to safeguard the transformer so that it functions at its highest capacity. In order to achieve it, an improvement in the insulation system is necessary, as the majority of faults in transformers are due to the malfunctioning of the insulation system. Petroleum-based oils are extensively used as insulating liquids in transformers. The latterly evolved field of nanotechnology has encouraged studies on Nanofluids (NFs), which are suitable as liquid insulators. In spite of the advantages of NFs in electrical and thermal behavior compared to their base fluids, further studies are needed to establish their long-standing performances as liquid insulators. In this study, three mineral oil samples, new, mid-aged, and extensively aged, were taken. Nanofluids of 0.02% Al_2O_3 and 0.02% SiO_2 of these oils were prepared. The base fluids and nanofluids were characterized by interfacial tension, acidity, dielectric dissipation factor, resistivity, and electric strength. The nanofluids prepared were subjected to laboratory thermal ageing in the presence of copper and kraft paper for 64 hours at 150 °C. The unaged and laboratory-aged nanofluids were characterized for acidity, Interfacial Tension (IFT), Specific Resistance (SR), Tan Delta (TD), and Dielectric Strength (BDV). It was found through this work that the addition of nanoparticles upgraded the properties of oil samples. The long-term applicability and permanence of nanofluids might depend on catalytic effects. These catalytic effects are derived from the internal assembly materials of the transformer.

Keywords: Ageing, Mineral Oil, Nanofluids, Transformer Oil

1. Introduction

A power transformer is one of the most expensive components in the electric power network. Transformer operation efficiency and dependability are dependent on the quality of its insulation. Transformer oil serves as an insulator, coolant, agent to preserve internal components from damage, and diagnostic medium[1]. Mineral oil has been used extensively as a transformer insulator for more than a century because of its inexpensive cost, excellent cooling and insulating qualities, and compatibility with paper insulators[2]. Worldwide increases in demand for electricity necessitate the development of transformers with higher voltages. It is reported that the inferior thermal and dielectric properties of transformer oil may reduce the life of the transformer to half of its expected life span of 35 to 40 years[3]. Thus, there is a requirement for obtaining suitable transformer oil with improved cooling and insulating properties to meet ultra-high voltage applications. One of the efforts includes using nanotechnology to improve the thermal and electrical capabilities of liquid insulation. In 1959, Feynman indicated the applications of nanotechnology in physics, chemistry, biology, electronics, etc[4]. The term nanofluid was proposed by Choi and Eastman in 1995 for a liquid that contains nanosized particles[5]. A substance with nanoscale dimensions, with sizes ranging from roughly 1 to 100 nm, is called a nanomaterial[6]. The nanomaterials used in transformer oil are broadly classified as (i) insulating nanoparticles such as Al_2O_3, SiO_2, and BN; (ii) semiconducting materials like TiO2, CuO, and Cu_2O; and (iii) conducting materials like Fe_2O_3, ZnO, and SiC. Various other materials, such as magnetite, polymetallic ferrites, bimetallic oxides, carbon nanotubes, fullerene, graphite, graphene, and diamond, are studied[7]. The distinctive features exhibited by nanomaterials are due to their critical sizes. They have a substantially higher surface-to-volume ratio than bulk materials due to their size. As a result, more atoms are available on the surface for interactions with neighbouring materials, giving them these superior features. This is the reason that during the past two decades, numerous researchers have worked on the study of insulating nanofluids. The nanoparticles present in fluids can create shallow traps that have an electron tapping and de-tapping action, which reduces the breakdown procedure by polarizing internally under space charge[8,9].

A lot of studies are being conducted on nanofluids in dielectric applications to better understand the mechanism for their superior performance over the base fluid[10–12]. However, extensive oxidative thermal ageing studies are to be executed in order to understand the degradation behavior, and this is one of the active research areas. These studies are essential to confirm the usefulness and workability from the practical standpoint of applying nanofluid-based insulating oil[13].

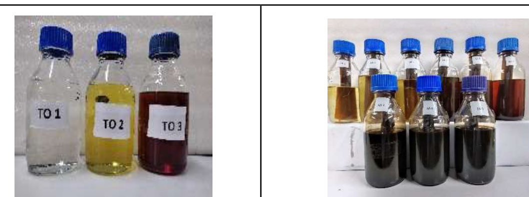
This work aims to study the performance of mineral oil-based Al_2O_3 and SiO_2 nanofluids and their oxidative thermal ageing behavior. The oxidative ageing of insulation is influenced not only by the catalytic effects of copper and kraft paper but also by other materials used for fabricating a transformer, which come into contact with the oil. In order to consider these catalytic factors and approach practicability more effectively, along with a new oil sample, one service oil of mid-age and another one extensively deteriorated were selected in this work. Nanofluids of 0.02% Al_2O_3 and 0.02% SiO_2 of these mineral oils were prepared for performance evaluation. The nanofluids prepared were subjected to laboratory thermal ageing in the presence of copper and kraft paper for 64 hours at 150 °C. The unaged and laboratory-aged nanofluids were characterized for acidity, Interfacial Tension (IFT), Specific Resistance (SR), Tan Delta (TD), and Dielectric Strength (BDV).

2. Experimental Methods

Mineral oil-based new transformer oil conforming to IEC 60296[14] was taken as fresh oil (TO1). Two other oils, one a service oil of mid-age (TO2) and another one extensively deteriorated (TO3), both conforming to IEC 60422[15], were selected. These oil samples were considered base oils in this work. Al_2O_3 with a primary particle size of 13 nm and SiO_2 with a particle size of 10–20 nm were procured from Sigma Aldrich. These nanoparticles were put into the base oil to get 0.02% w/v NFs. The two-step method was followed for the preparation of nanofluids. The samples were mechanically stirred and sonicated. These procedures were performed to achieve adequate dispersion and enhanced stability. The sample details are shown in Table 1. The samples were subjected to thermal ageing at 150 °C for 64 hours in the presence of Kraft paper (1:20) and copper catalyst (3 g/l). The unaged and laboratory-aged nanofluids were characterized for acidity, Interfacial Tension (IFT), Specific Resistance (SR), Tan delta (TD), and Dielectric Strength (BDV) as per IEC 60422. Figure 1 shows the appearance of three oil samples taken for the study (a) and nanofluids after laboratory thermal ageing (b).

Table 1. Sample details

Sample	Composition
SA1	TO1
SA2	TO2
SA3	TO3
SA4	TO1 + 0.02% Al2O3
SA5	TO1 + 0.02% SiO2
SA6	TO2 + 0.02% Al2O3
SA7	TO2 + 0.02% SiO2
SA8	TO3 + 0.02% Al2O3
SA9	TO3 + 0.02% SiO2



(a) Selected oil samples. **(b)** After ageing.

Figure 1. **(a)** Appearance of three oil samples taken for the study. **(b)** Nanofluids after laboratory thermal ageing.

3. Results and Discussions

The transformer oil samples under study show a significant difference in their appearance, as shown in Figure 1. This indicates substantial differences in their physicochemical properties. A change in appearance was observed for laboratory thermally aged nanofluids, which indicated the degradation of oil samples. However, it is a qualitative analysis. The Interfacial Tension (IFT) of transformer oil is the measure of the force required to break the molecular attraction working between the layers of oil and water. The IFT value is dependent on the polar contaminants present in the oil. The higher values of IFT indicate a better quality of the oil. Figure 2(a) depicts the IFT of three base fluids and their nanofluids. A huge difference in IFT was observed among the based fluids, indicating significant variation in oil qualities. Both the Al_2O_3 and SiO_2 nanofluids of the three base fluids exhibited increases in IFT. It is observed from Figure 2(b) that the nanofluids maintained their superior quality after laboratory ageing. In the case of aged service oils, the effect of the addition of nanoparticles was minimal compared to fresh oil. Therefore, IFT analysis indicated an increase in oil quality through nanoparticle addition and that this effect was prominent in the nanofluids of fresh oil.

The presence of acids has a strong impact on insulating materials. So, acidity is considered the most significant chemical parameter. Numerous types of acids are formed through the hydrolysis reaction of the oil-paper insulation. These acid molecules can have low or high hydrocarbon chains. Inorganic acids may be present as contaminants. The presence of acids accelerates the degradation of insulation and metallic corrosion. The acidity of base fluids and corresponding nanofluids are illustrated in Figure 3. The acid numbers of base fluids TO1, TO2, and TO3 were 0.281, 0.0059, and 0.242 mg KOH/g, respectively. The acid numbers of base fluids after ageing were 0.005573, 0.0499, and 0.32 mg KOH/g, respectively. The acid numbers of the corresponding Al_2O_3 nanofluids were 0.342, 0.156, and 0.368, respectively. The acid numbers of the corresponding SiO_2 nanofluids were 0.322, 0.0895, and 0.322, respectively. Therefore, the addition of nanoparticles did not show a positive impact on controlling the acid number during the thermal ageing of TO1 and its nanofluids. In the case of TO2, the formation of acid was less compared to TO1 and its nanofluids. There was no significant difference in the acid value of TO3 and its nanofluids. Therefore, further studies are needed to understand the reason for the variation in observations between TO1 and TO2.

The occurrence of degradation products such as ionic and polar molecules, water, carbon particles, etc. in the oil-paper system increases the dielectric dissipation factor of the tan delta value. An increase in tan delta is associated with dielectric losses. Charge carriers are formed in oils with a high tan delta, which initiates local breakdown.

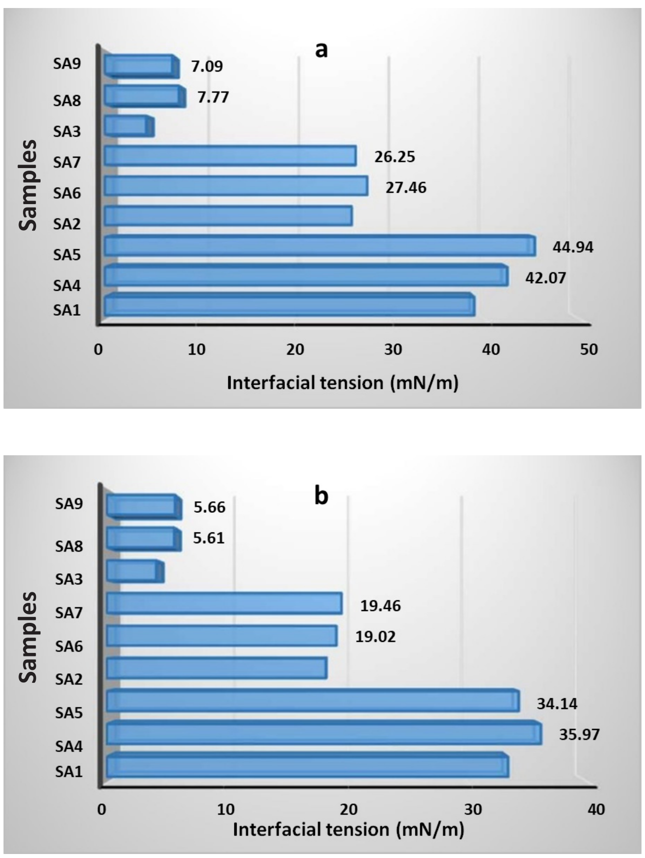


Figure 2. **(a)** Interfacial Tension (IFT) of samples, unaged. **(b)** Aged at 1500C for 64 hours.

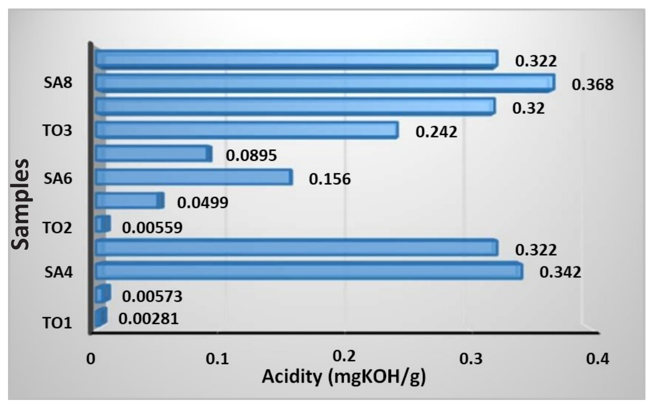


Figure 3. Acidity of samples, unaged (TO1, TO2, TO3), and aged at 150 0C for 64 hours (SA1 to SA9).

Figure 4(a) shows a significant reduction in the tan delta for all the nanofluids. TO1 exhibited a tan delta of 0.00051, whereas the tan delta observed for its Al_2O_3 and SiO_2 nanofluids was 0.00016 and 0.00011, indicating a significant reduction in tan delta. Similarly, for TO2, the tan delta of 0.0026 was reduced to 0.001 and 0.00146, respectively, for its Al_2O_3 and SiO_2 nanofluids. In the case of TO3, the tan delta of 0.10026 came down to 0.08147 and 0.07905, respectively, for its Al_2O_3 and SiO_2 nanofluids. Figure 4(b) illustrates the Tan Delta of thermally aged base fluids and nanofluids. On thermal ageing, the increase in Tan Delta was less in nanofluids compared to the base fluid, TO1. The values were 0.00496, 0.0009, and 0.0004 for the base fluid and its Al_2O_3

and SiO_2 nanofluids, respectively. In the case of TO2 and its nanofluids, the tan delta was found to be increased. The aged TO3 and its nanofluids exhibited almost the same tan delta. This indicates that the addition of nanoparticles is capable of reducing the tan delta in fresh oil and is able to control the tan delta in mid-aged oil and even oil of poor quality, i.e., TO3 and its nanofluids.

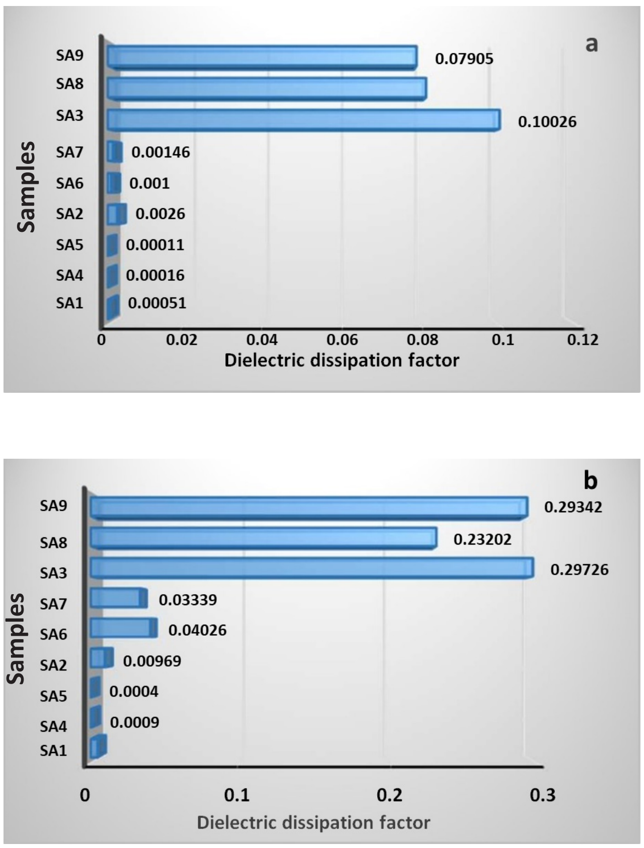


Figure 4. **(a)** Tan Delta of samples, unaged. **(b)** Aged at 1500C for 64 hours.

Figure 5(a) describes a significant increase in resistivity for all the nanofluids. TO1 exhibited a resistivity of 1614 GΩm, whereas the resistivity observed for its Al_2O_3 and SiO_2 nanofluids was 11667 and 6737 GΩm respectively, indicating a significant increase in resistivity. Similarly, for TO2, the resistivity of 96.13 GΩm increased to 225.8 and 145.3 GΩm respectively, for its Al_2O_3 and SiO_2 nanofluids. In the case of TO3, the resistivity of 1.541 GΩm, remains almost the same. So, a significant improvement in resistivity was observed in nanofluids compared to the corresponding base fluids. Figure 5(b) shows the resistivity of thermally aged base fluids and nanofluids. On thermal ageing, the resistivity for all the samples was found to reduce compared to the unaged samples. The resistivity values were 190.7, 443.2, and 604.2 GΩm, respectively, for the base fluid, TO1, and its Al_2O_3 and SiO_2 nanofluids. In the case of TO2 and its nanofluids, the resistivity values were 23.3, 7.31, and 9.292 GΩm, respectively. The aged TO3 and its nanofluids exhibited almost the same resistivity. So, the resistivity of thermally aged nanofluids prepared from TO1 and TO2 was higher compared to their base fluids. There was no significant change in resistivity values for TO3 and its nanofluids.

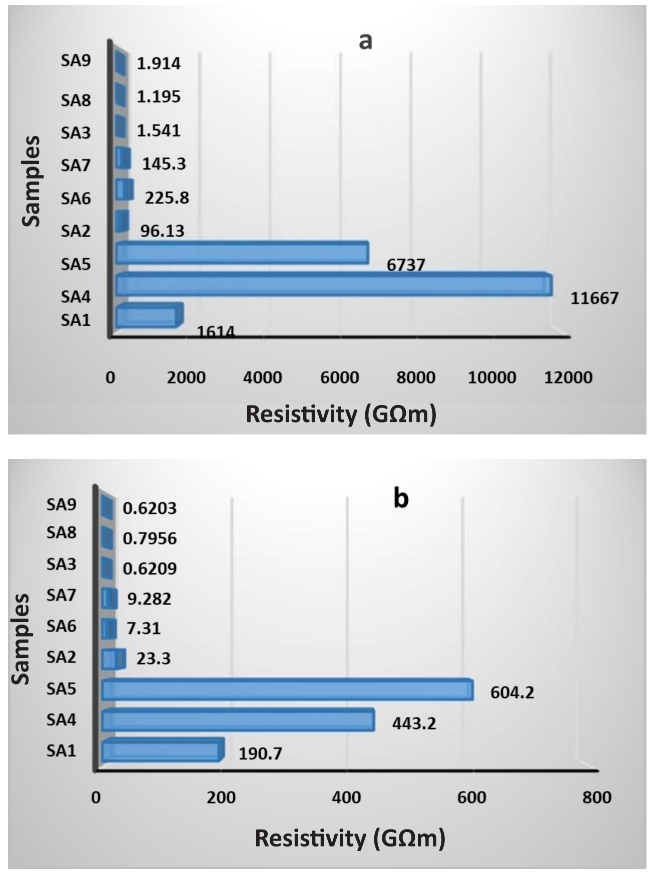


Figure 5. **(a)** Resistivity of samples, unaged. **(b)** Aged at 150 0C for 64 hours.

The AC Breakdown Voltage (BDV) of aged and unaged base fluids and their nanofluids is shown in Figure 6. The measurement was carried out using spherical copper electrodes with a gap length of 2.5 mm. The BDV values were found to increase in both nanofluids of TO1. The heat-treated nanofluids of TO1 had also shown an increase in BDV values. The values were almost the same for aged and unaged nanofluids of TO1. The thermally treated nanofluids of TO2 had shown higher values of BDV compared to the unaged samples. There was no trend observed for samples of TO3. Moisture is an important contaminant that plays an important role in BDV measurements.

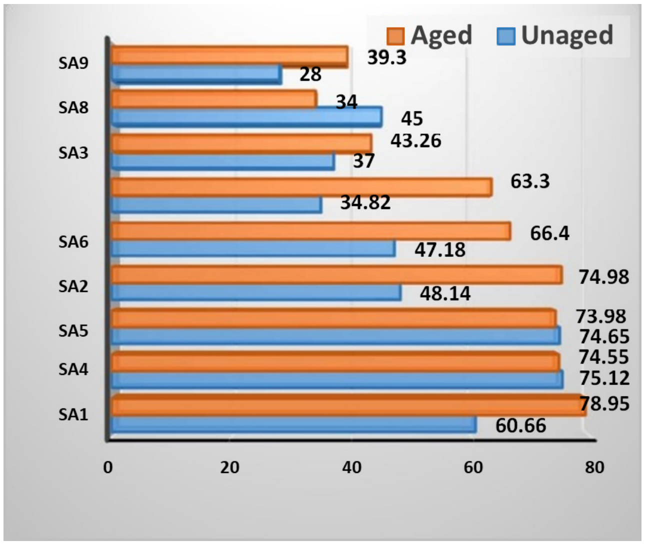


Figure 6. Breakdown voltage of unaged and samples aged at 150 0C for 64 hours.

4. Conclusions

The performance of mineral oil-based Al_2O_3 and SiO_2 nanofluids and their oxidative thermal ageing behavior was studied. The oxidative ageing of insulating materials in a power transformer is strongly governed by the catalytic nature of copper, kraft paper, and many other internal components of the transformer. In order to consider these aspects and approach practicability more effectively, along with a new oil sample, one service oil of mid-age and another one that had extensively deteriorated were selected in this work. The nanofluids prepared were subjected to laboratory thermal ageing in the presence of copper and kraft paper for 64 hours at 150 ^{0}C. The unaged and laboratory-aged nanofluids were characterized for acidity, Interfacial Tension (IFT), Specific Resistance (SR), Tan Delta (TD), and Dielectric Strength (BDV). The following conclusions are drawn:

A large difference in IFT was observed among the base fluids. It suggests a significant variation in oil qualities. An increase in IFT was observed in nanofluids. The nanofluids exhibited superior quality after laboratory ageing.

The Tan Delta was found to decrease in all the unaged nanofluids. This indicates an improvement in oil quality. In the case of thermal ageing, a lower Tan Delta was observed in nanofluids of fresh oil, whereas it was higher for service oil counterparts. Therefore, from the tan delta measurement, it is understood that the catalytic effect of materials other than copper and kraft paper might play a role in the oxidative degradation process of nanofluids.

Specific resistance values were higher in the nanofluids of fresh and mid-aged oil. No significant difference was observed in highly aged oil and its nanofluids. Laboratory thermally treated nanofluids of fresh oil were maintained to show higher specific resistance compared to their base fluid. However, it was found to be decreased in the nanofluids of heat-treated, mid-aged oil. Specific resistance was almost at the same level for heat-treated, highly aged samples.

It was observed from the study that the addition of nanoparticles improved oil quality. The long-term applicability and permanence of nanofluids might depend on catalytic effects. These catalytic effects might be derived from the internal assembly materials of the transformer.

5. Acknowledgment

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