Effect of Magnetic and Non-magnetic Nanoparticles on Insulation and Cooling Behaviour of a Natural Ester for Power Transformers

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***Abstract* –This paper analyses and compares the impact that maghemite and titania nanoparticles have in the electrical and thermal performance of a commercial natural ester used in power transformers. Vegetal-oil-based nanofluids have been prepared at different concentrations. Once the nanofluids were obtained, the breakdown voltage of the oil samples with and without nanoparticles was measured. It was found that the concentration of nanoparticles influences the breakdown voltage of natural ester. The existence of optimal concentrations has been noticed, and these nanofluids were selected for the upcoming tests.**

The cooling capacity of these liquids and the base fluid was measured through a thermal analysis in an experimental platform. The experiment developed is based on a 1-phase transformer (800 VA, 230/115 V) immersed in a stainless-steel fulfilled with insulating liquid. The temperatures inside the tank were monitored at the bottom and at the top of the tub to measure the oil temperature. Other sensor measured the hotspot winding temperature, defined as the hottest temperature of winding conductors in contact with solid insulation or insulating liquid. This sensor was located at the top of the winding as the most probable hot-spot location. Ambient temperature was also measured as a reference. A microcontroller (Arduino) and an Integrated Development Environment (IDE) was utilized to record the measurements of the sensors.

The results of the thermal study showed that only maghemite based nanofluids exhibited improved heat transfer characteristics in comparison with the natural ester oil.

Keywords: nanofluid, transformer, cooling, dielectric, vegetal oil.

I. INTRODUCTION

Power transformers are key elements of electrical energy transmission and distribution systems since they operate as nodes between the different lines. During their operation, heat is produced due to power loss. High temperatures inside the transformer could damage some critical components, reducing its lifespan. In order to control the temperature, the machines are immersed in transformer oil. This fluid has a double function: heat dissipation and electrical insulation. Traditionally, mineral oil has been used. With the aim of increasing the power and efficiency of power transformers, dielectric nanofluids have been developed.

Depending on the base fluid and the nanoparticles added, different nanofluids have been studied. Some authors have found that the addition of nanoparticles enhance the cooling capacity of the base fluid, since the thermal conductivity (k) is increased. *Jin et al.* [1] and *Lv et al.* [2] found that k of the base oil was increased up to 1.2% with the addition of TiO_2 nanoparticles with a 0.1% volume concentration.

Other nanoparticles showed higher increasements. *Chiesa et al.* [3], *Choi et al.* [4] and *Xie et al.* [5] studied the effect of Al_2O_3 nanoparticles using concentrations between 0.25 and 5%v. The results showed that k was improved between 2 and 38% and the increases were greater the higher the concentration of nanoparticles. Even better results were found by *Nkurikiyimifura et al.* [6] and *Peppas et al.* [7] when using iron nanoparticles. The first one studied concentrations between 1 and 5% in volume and he obtained k enhancements in the range 10-60%. The second one also found that k was increased up to 45% but using concentrations lower than those used by *Nkurikiyimifura.*

Magnetic effects of iron nanoparticles have also been studied. Some authors have prepared magnetic nanofluids, known as ferrofluids, to study the effect of thermomagnetic convection on the cooling capacity of the ferrofluid. *Pislaru et al.* [8] and *Patel et al.* [9] found that the temperature reached in the transformer was lower when using the ferrofluid than the base oil The decrease of temperature could not be related to k enhancement and numerical simulations also showed the appearance of thermo-magnetic forces.

As it was explained, transformer fluids also must have good dielectric properties. Thus, some authors have studied the effect of nanoparticles on the breakdown voltage (BDV) of base fluid. *Muangpratoom et al.* [10] found that BDV of base fluid was increased up to 25% when using 0.03%v TiO_2 nanoparticles. *Peppas et al.* [7], *Irwanto et al.* [11] and *Rafiq et al.* [12] obtained similar results with Fe_2O_3 and Fe_3O_4 nanofluids at different concentrations between 0.1 and 0.4 g/l.

Based on the above, this paper presents the study of dielectric and thermal behaviour of two different nanofluids. Non-magnetic TiO_2 and magnetic Fe_2O_3 nanofluids have been prepared at concentrations between 0.1 and 1 kg/m^3. A natural ester is used as base fluid. Breakdown voltage of nanofluids are compared with each other and with the base fluid. Thermal conductivity is also analyzed. Based on the results obtained, optimal concentrations of each nanofluid and the base fluid are tested in an experimental platform. Temperatures reached with each fluid are compared.

II. PREPARATION OF NANOFLUIDS

The properties of the base fluid chosen are shown in Table 1. It has not been noticed any effect of nanoparticles on thermal

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conductivity. The nanoparticles are high purity maghemite and titania, with a mean diameter in the gap 10-20 nm and spherical shape.

The preparation of the samples follows the two-step method. The commercial nanoparticles are added to fresh natural ester and homogenized by mechanic stirring and ultrasounds. A rest period follows the preparation for the elimination of bubbles. No additional treatment is applied. Fig. 1 shows the appearance of the base fluid and one of the nanofluids prepared.

Under this method six samples with concentrations between 0 and 1 kg/m^3 have been prepared to be characterized. The selection of this gap is based on the optimal concentrations found in bibliography regarding the dielectric properties.

III. CHARACTERIZATION OF NANOFLUIDS

In a first stage it has been tried to find an optimal concentration of nanofluid regarding its dielectric and thermal properties, characterized by standard methods:

A. *Thermal Conductivity*

Starting with the thermal conductivity measurements, this property is measured at different temperatures with a Hot Transient Wire equipment. With the samples inside vials, and these inside an oven at increasing temperature, the analyser takes every 15 minutes a thermal conductivity measurement while the system gets hot, from ambient temperature. From the registered results, represented in Fig. 2 and Fig. 3, tendency lines have been obtained. It has not been noticed any effect of the Fe_2O_3 or the TiO_2 nanoparticles on thermal conductivity, as the results of the different samples meet each other.

TABLE I. PROPERTIES OF THE VEGETAL BASE FLUID

Density (20ºC) (g/ml)	0.91
Viscosity (40ºC) (cSt)	<50
Thermal conductivity (25°C) (W/K·m)	0.1691
Tan δ	<0.05
AC BDV (kV)	>35

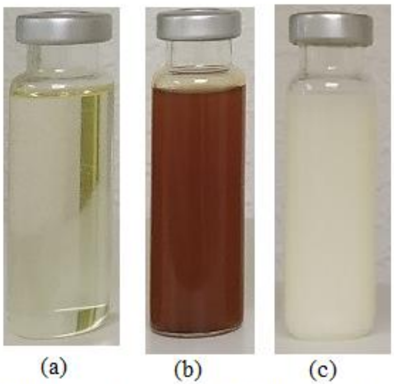
(a) (b) (c)

Figure 1. Appearance of the three kind of fluids tested: a) base fluid, b) ferrofluid, c) TiO_2 nanofluid.

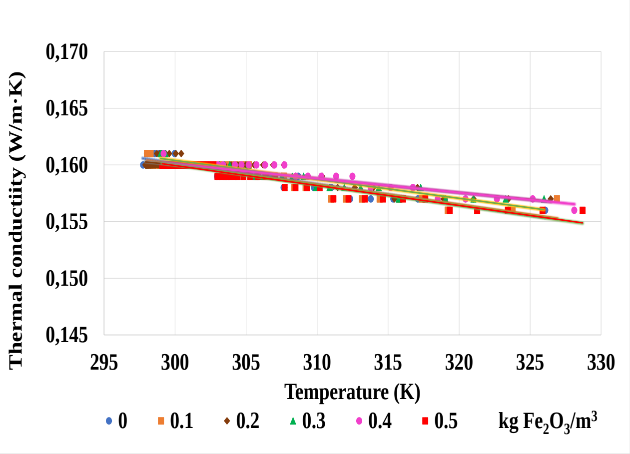

Figure 2. Thermal conductivities of the base fluid and the Fe_2O_3 nanofluids characterised at different temperatures.

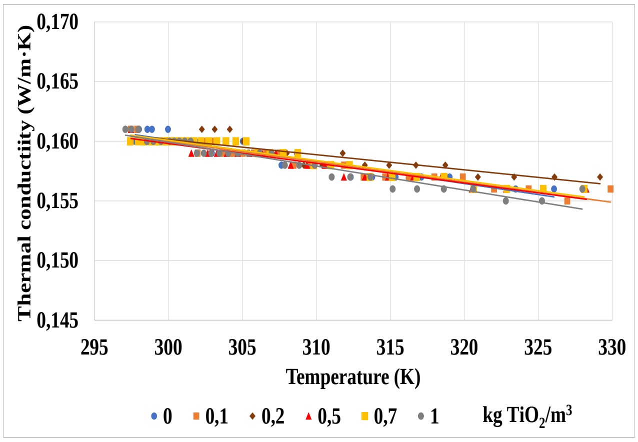

Figure 3. Thermal conductivities of the base fluid and the TiO_2 nanofluids characterised at different temperatures.

B. *AC Breakdown Voltage*

The AC breakdown voltage (BDV) is determined by a dielectric oil tester at rated temperature, according to IEC 60156 methodology. The moisture content is also controlled, with all the samples around 250 ppm, by Karl-Fischer Titration (IEC 60814) in a coulombmeter.

Fig. 4 and Fig 5. show how the mean BDV of base fluid is improved at lower concentrations, with a maximum of 15.1% at 0.2 Fe_2O_3 kg/m^3 and a maximum of 33.2% at 0.5 TiO_2 kg/m^3. This effect is lost with higher concentrations, as these nanofluid samples show lower voltages.

According to these results only the dielectric characterization provides information about the nanoparticle concentration able to be considered as optimal, respectively 0.2 kg/m^3 of Fe_2O_3 and 0.5 kg/m^3 of TiO_2. Among them, the titania nanofluid seem to be the best option as solid fraction, as the variation of the base fluid BDV is larger.

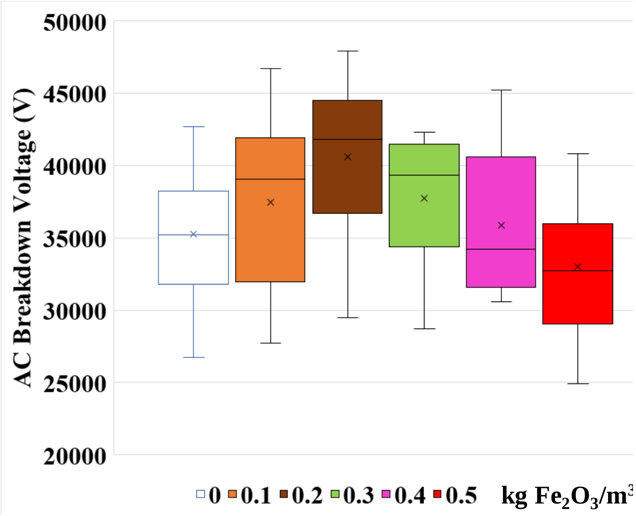

Figure 4. Distribution of the breakdown voltage values obtained during the characterization of the base fluid and the Fe_2O_3 nanofluids.

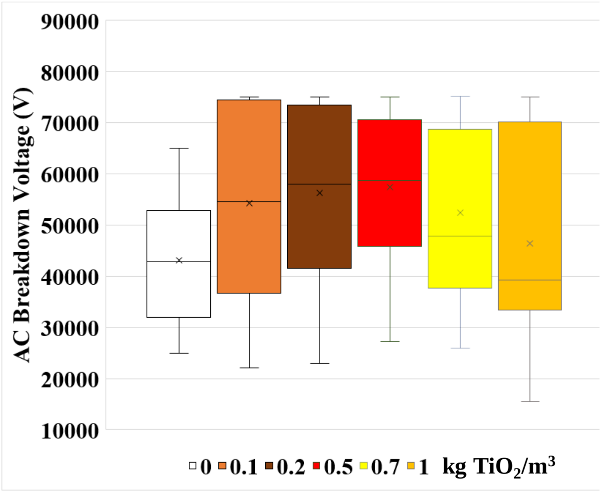

Figure 5. Distribution of the breakdown voltage values obtained during the characterization of the base fluid and the TiO_2 nanofluids.

IV. EXPERIMENTAL SETUP

Following the experiment used by *Patel et al.* [9], an experimental setup was developed to study the cooling performance of the base fluid and the optimal nanofluids found during characterization in a prototype distribution transformer. This experimental platform has been built with a small single-phase transformer (800 VA, 115/230V), shown in Fig. 6, immersed in a tank. The cooling fluid movement inside the tank is driven only by natural convection cycles due to the heat generated during operation.

The platform and ambient temperatures are monitored by five probes located in representative places. The Fig. 6 shows, approximately, the location of the four probes inside the equipment. The ambient temperature is taken as reference. The capture and saving of the temperature measurements are made by a microcontroller and an Integrated Development Environment (IDE). The load is controlled by adjusting three variable resistors, as shown in Fig. 7.

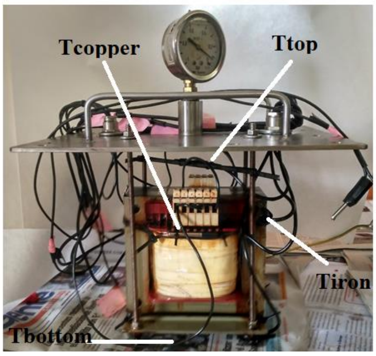

Figure 6. Transformer of the experimental setup and location of the probes.

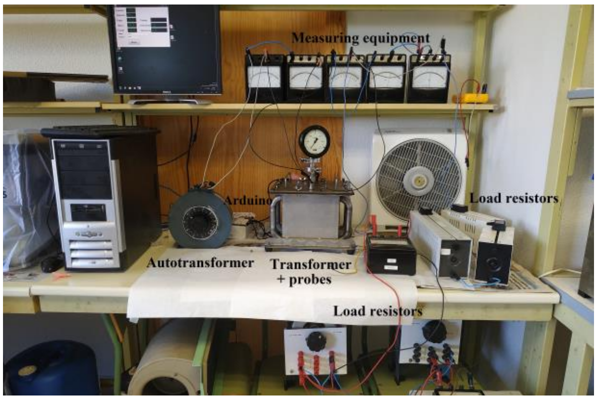

Figure 7. Experimental setup picture.

V. SETUP RESULTS

The tests have been carried out at three different load levels (C); rated current (C=1), -30% underload (C=0.7) and +30% overload (C=1.3), starting at the rated temperature. The increasing temperatures of the probes were caught every five minutes until the steady-state is reached. IEC 60076-2 defines this state as when the variations of the top oil's temperature rise below 1 ºC·h-1 over a consecutive period of 3 hours.

Samples of base fluid, 0.5 kg/m^3 TiO_2 and 0.2 kg/m^3 Fe_2O_3 nanofluids have been tested, those with the largest dielectric strength.

The results obtained from the platform are shown in Fig. 8 and Fig. 9, as temperature gradients relative to the ambient temperature of both fluids in each probe once temperature stability criteria were fulfilled. It is noticeable the lower increase of temperature when ferrofluid is used as cooling fluid, while the TiO_2 nanofluid behave a little worse than the base fluid. This better behavior of the ferrofluid is clearer as the heat to dissipate is larger (C=1.3), with a gradient against the room temperature up to a 11% lower in some of the probes.

An explanation of this situation, in view of the general absence of variation in the thermal conductivity, and the results from the experimental setup with the titania nanofluid could come from the magnetic nature of the maghemite nanoparticles. The appearance of thermal-magnetic interactions between the magnetic nanoparticles and the magnetic field of electric devices, able to improve the cooling of these devices, has already been considered in previous researches [9]. Respecting the TiO_2 nanofluid results, its worse performance could be due to the increasing of viscosity caused by nanoparticles presence.

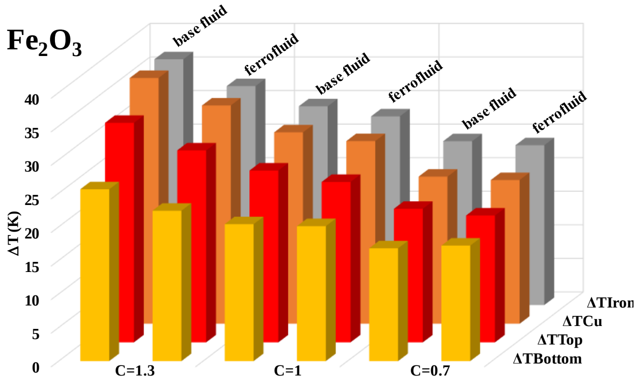

Figure 8. Temperature grandients of the different locations of the experimental setup against the ambient temperature, at the different load ranges while cooled with base fluid and Fe_2O_3 optimal nanofluid.

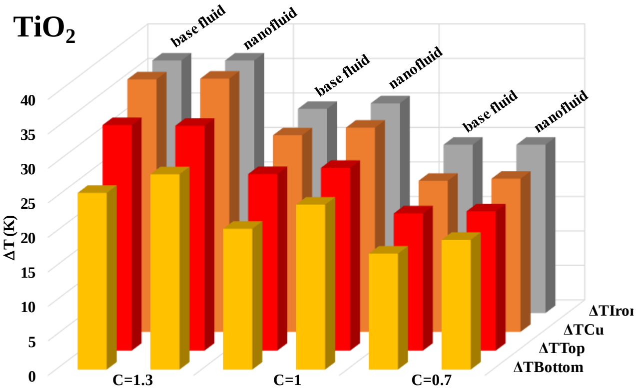

Figure 9. Temperature grandients of the different locations of the experimental setup against the ambient temperature, at the different load ranges while cooled with base fluid and TiO_2 optimal nanofluid.

VI. CONCLUSIONS

Six different concentrations of Fe_2O_3 (0 - 0.5 kg/m^3) and TiO_2 (0 - 1 kg/m^3) vegetal-based nanofluids for transformers have been submitted to characterization regarding different thermal and dielectric properties (thermal conductivity, dielectric strength and moisture content). While no influence on the thermal conductivity was noticed, probably due to the low concentrations of nanoparticles, optimal improvements of natural ester AC BDV of 15.1% was found with 0.2 kg/m^3 of Fe_2O_3 and 33.2% with 0.5 kg/m^3 of TiO_2 nanoparticles.

Both optimal nanofluids and base fluid have been tested as cooling fluids of a single-phase distribution transformer while working at three different load levels. Five temperature probes placed strategically in different points have registered the temperature evolution. The results show a better behavior of the ferrofluid, with lower gradients of temperature against the environmental one, up to 11%.

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