Effect of maghemite nanoparticles on insulation and cooling behaviour of a natural ester used in power transformers

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***Abstract*— In this paper, an experimental research was conducted to study the effect of the presence of Fe_2O_3 nanoparticles over cooling and dielectric performance of a natural ester used in power transformers. Different concentration samples of nanofluid have been characterized to find an optimal one, focusing on viscosity, thermal conductivity and dielectric strength. A monitored experimental platform has been used to observe the temperature increases during operation while being cooled. This includes a single-phase distribution transformer, working at three different load levels, C=0.7, C=1 and C=1.3. Both natural ester base fluid and optimal nanofluid have been used as cooling fluid. At first sight, the nanoparticles seem not to affect neither thermal conductivity nor viscosity at the concentrations used. On the contrary, breakdown voltage of base fluid experiments an enhancement at some of them. The cooling capacity of the nanofluid has also shown an improved behavior.**

Keywords—nanofluid, transformer, cooling, breakdown voltage, experimental platform.

I. Introduction

During power transformer operation a significant amount of heat due to power loss from the core and windings, is generated. The temperature control of windings is critical to increase lifespan of these kind of machines and it is carried out through transformer oil. Additionally, this fluid is utilized as insulation medium. Therefore, the quality of the oil in a transformer plays an important role in performing both functions (insulating and cooling). Recent advances in nanofluids have enhanced the capabilities and usage of such liquids in a wide range of applications which include heat dissipation and electric insulation.

Chiesa et al. [1], *Choi et al.* [2] and *Xie et al.* [3] demonstrated the effect of concentrations of Al_2O_3 between 0.25 and 1 %v, 0.5 and 4%v and 5 %v respectively over oil thermal conductivity (k). In these studies improvements of base fluid thermal conductivity between 2 and 38% were found. These increases were bigger the higher was the concentration of the solid fraction. Among those concentrations similar enough, the variation of k was also equivalent.

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This is not the case with other nanoparticles whose bulk material thermal conductivity is lower, as SiO_2, also investigated by Chiesa [1], or TiO_2, taken in consideration by *Jin et al.* [4] and *Lv et al.* [5]. The first one, with the same concentrations of nanoparticles presented approximately half large k variance. TiO_2 nanofluids have been prepared with concentrations around 0.1% in volume, reaching variations up to 1.2%. Regarding iron species investigations (Fe_2O_3 and Fe_3O_4), better improvements of the thermal conductivity have been shown according to *Nkurikiyimifura et al.* [6], as concentrations between 1 and 5% in volume got enhancements of k in the range 10-60%.

Mansour et al. [7] focused on the heat transfer coefficient (h) of Al_2O_3 nanofluids. Concentrations between 0.1 and 0.6 g/l showed variations around 15% respecting base fluid coefficient. *Peppas et al*. [8] also studied h in nanofluids that combine Fe_2O_3 and vegetal base oil, with similar results, as the cooling was improved up to 45% with concentrations several times less than those used by Nkurikiyimifura. These results seem to point to a more pronounced effect of nanoparticles over h than over k.

Respecting dielectric properties, several studies have also demonstrated the beneficial effect of nanoparticles on breakdown voltage (BDV) of base fluids at low concentrations of nanoparticles. *Hanai et al.* [9] discovered that after improvements close to 25 % of BDV in samples of 0.05% in volume of TiO_2, at higher concentrations this parameter decreases. *Peppas et al.* [8], *Irwanto et al*. [10], and *Rafiq et al.* [11] obtained similar tendencies with Fe_2O_3 and Fe_3O_4 nanofluids at different concentrations between 0.1 and 0.4 g/l. Therefore, the viability of high concentration nanofluids is constrained by their dielectric properties, and according to [2] also due to increases in the viscosity.

Based on the above, this paper presents a novel approach to experimental investigation of the cooling capacity of a dielectric nanofluid, as including the testing of this property in an experimental platform. A combination between maghemite nanoparticles and a commercial natural ester for transformers has been selected for this task. Temperature variations between the nanofluid and the base fluid as coolants in an experimental transformer are obtained. The concentration of applied nanofluid is selected regarding the results from the characterization of the thermal and dielectric properties of samples at different concentrations.

II. Preparation of Nanofluids

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

Table 1. The nanoparticles are high purity maghemite, 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 Fe_2O_3 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 four samples with concentrations between 0 and 0.5 g/l 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. Experimental Determination of Samples Properties

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.

Starting with the thermal conductivity, it is measured at different temperatures with a Hot Transient Wire equipment. With the samples inside vials, and these last partially immersed in hot water, the analyser takes every 15 minutes a thermal conductivity measurement while the system gets cold, until ambient temperature. From the registered results, represented in Fig. 2, tendency lines have been obtained. It has not been noticed any effect of nanoparticles on thermal conductivity.

Table 1. Characteristics of natural ester base fluid.

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

(a) Natural ester (b) 0.5 g/l Ferrofluid

Fig. 1. Prepared samples appearance.

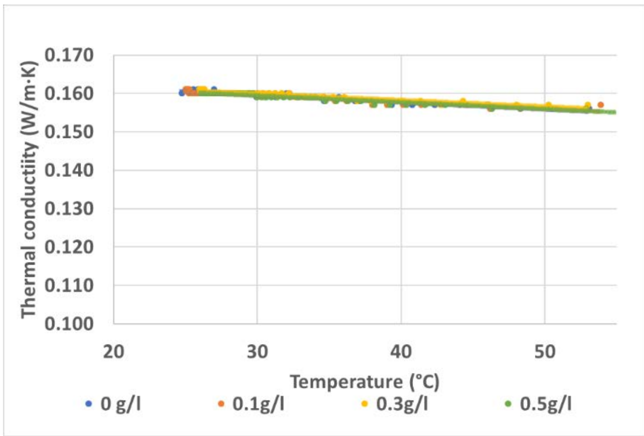


Fig. 2. Tested samples thermal conductivity evolution vs temperature.

A similar situation is found in dynamic viscosity measured with a rotatory viscosimeter. The results of this property (Fig. 3), at different temperatures, does not reveal any influence of nanoparticles at the studied concentrations.

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, due to its influence over dielectric properties, by Karl-Fischer Titration (IEC 60814) in a coulombmeter.

Fig. 4 shows how the mean BDV of base fluid is improved at lower concentrations, with a maximum of 8% at 0.1 and 0.3 g/l. This effect is lost with higher concentrations, as 0.5 g/l nanofluid sample shows lower voltage than base fluid one.

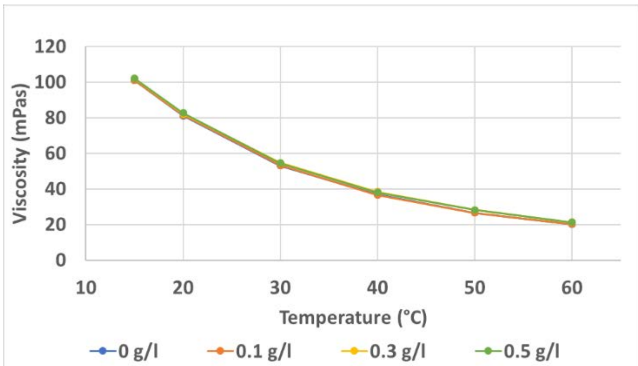


Fig. 3. Tested samples viscosity evolution with temperature.

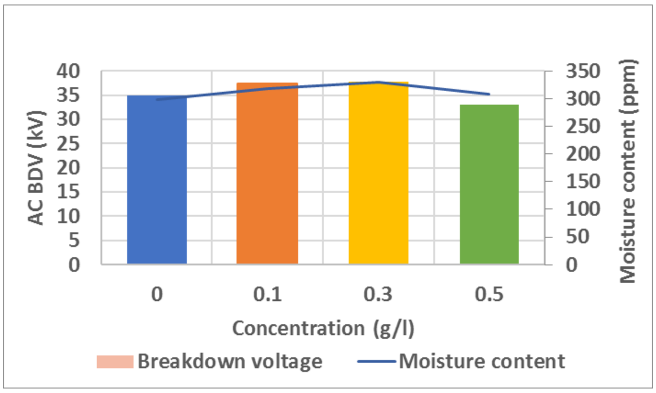
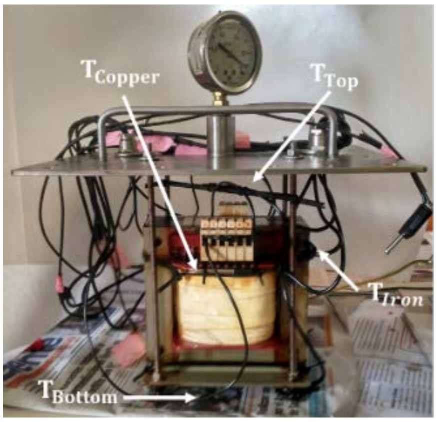


Fig. 4. Dielectric strength and moisture content of tested samples.

IV. EXPERIMENTAL SETUP

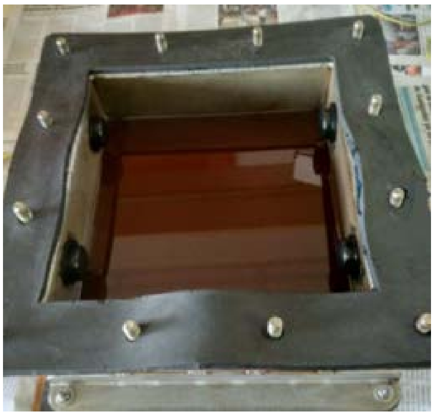
Following the experiment used by *Patel et al*. [12], an experimental setup was developed to study the cooling performance of the ferrofluid in a prototype distribution transformer. This experimental platform has been built with a small single-phase transformer (800 VA, 115/230V), shown in Fig. 5, immersed 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. 5 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 the scheme of Fig. 6.



(a) Transformer and probes

(b) Measuring and monitoring equipment



(c) Transformer tank

Fig. 5. Experimental platform.

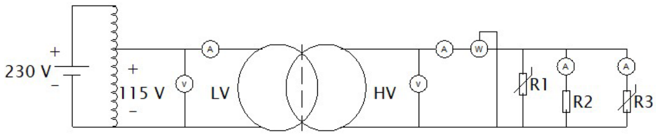


Fig. 6. Experimental platform electric circuit.

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.

Both samples of base fluid and 0.2 g/l Fe_2O_3 nanofluid have been tested. As the largest dielectric strength was found at 0.1 and 0.3 g/l, it is plausible that an intermediate concentration was the optimal one regarding this property.

The results obtained from the platform are shown in Fig. 7, 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. These differences are higher when the heat to dissipate is larger (C=1.3).

VI. CONCLUSIONS

Four different concentrations (0 - 0.5 g/l) of a Fe_2O_3 vegetal-based nanofluid for transformers have been submitted to characterization regarding different physical and dielectric properties (viscosity, thermal conductivity, dielectric strength and moisture content). While no influence on the two first were noticed, probably due to the low concentrations of nanoparticles, an optimal improvement of natural ester AC BDV of 8% was found at 0.1 and 0.3 g/l of Fe_2O_3.

Both 0.2 g/l nanofluid 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 nanofluid, with lower gradients of temperature against the environmental one, up to 11%.

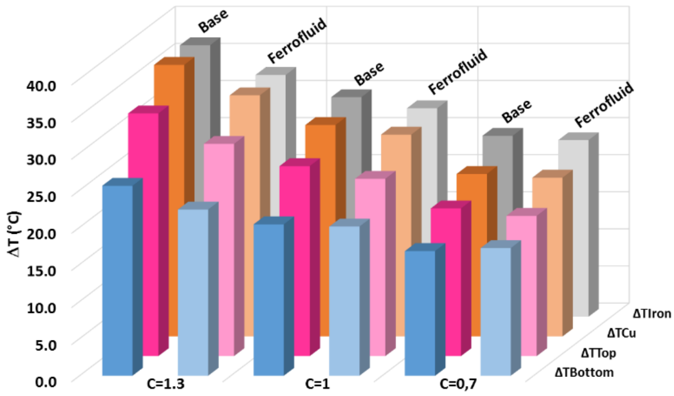


Fig. 7. Experimental gradients of temperature registered in the platform.

These nanofluids with enhanced cooling and dielectric capacities, if applied in actual transformers cooling circuits, would enhance the life span of this equipment, assuring their operation in safer conditions.

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