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Research Paper

The aging impact on the cooling capacity of a natural ester used in power transformers

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HIGHLIGHTS

- The paper presents an experimental-numerical study on cooling capacity of a ester.
- The numerical model was validated with nine experimental tests and simulations.
- The results indicate that cooling capacity of the natural ester worsens with aging.
- The higher the temperature, the lower the impact of aging on the cooling capacity.
- This will serve to know how the hot-spot temperature is affected by degradation.

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ABSTRACT

In this paper, an experimental and numerical research was conducted to study the aging effect on the cooling performance of a natural ester habitually used in power transformers. A monitored experimental platform has been used to observe the temperature increases with the aging of the ester. Three samples with three aging levels (fresh oil, aged oil and aged oil with paper) were tested at three load levels, C = 0.72, C = 1 and C = 1.3 (9 tests). The two aged samples (6 liters each) were aged in an accelerated way within an oven: 1 week at 150 °C. Also, some physicochemical properties of the insulation system were determined. In the case of the liquid, viscosity, moisture, acidity, dissipation factor (90 °C) were measured. The degree of polymerization and the moisture were measured in paper samples. A 2D numerical model has been developed with COMSOL Multiphysics to replicate the thermal-hydraulic behavior of the samples in the platform. That is, the idea is to determine the temperature and velocity distributions of the different samples in order to analyze their differences and to compare their cooling capacity. At first sight, the aging affects negatively to the cooling capacity of the new alternative liquid based on natural esters.

1. Introduction

Currently, mineral oil is commonly used as a dielectric and coolant liquid in power transformers worldwide. In these devices, Joule losses heat the windings and the fluid cools them circulating through channels arranged among conductors. The main goal of the cooling is to prevent excessive temperatures in these conductors, i.e. to avoid the appearance of hot-spots (hottest temperature areas in the conductors in contact with solid insulation, mainly paper or cardboard) since the aging of the paper is sensible to temperature. In fact, according to IEC 60076-7 standard, an increase of 6 °C doubles the insulation ageing rate, reducing the lifespan of the device [1]. For this reason, several theoretical and experimental techniques have been traditionally used by manufacturers and customers to determine the oil flow pattern, temperatures distribution and the location and value of the hot-spots in the windings [2]. Among the former, Computational Fluid Dynamics (CFD) modelling is relatively recent in comparison with other such as Thermal-Hydraulic Network Modelling (THNM). CFD characterizes in fine detail the flow and temperature distributions at the expense of being more demanding in computational requirements and more time consuming than THNM.

Despite its disadvantages, CFD technique has been used since the beginning of the twenty-first century to model the thermal-fluid behaviour of mineral oil flowing through the windings. For instance, Mufuta et al. and El Wakil et al. modelled two windings using this technique in first decade of the millennium. The former characterizes the oil flow through an array of discs with different spaces between discs and different inlet conditions [3]. The latter employed a 2D axisymmetric

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model of a power transformer with six different geometries and six different inlet velocities in order to study the heat transfer and oil flow through the windings [4]. In the current decade, other authors have contributed to this labour. For instance, Torriano performed 2D and 3D simulations of a Low Voltage Winding (LVW) of a power transformer with zigzag cooling to determine the effects of several elements, such as sticks and inter-sticks, in the temperature distribution [5,6]. In 2011, Gastelurrutia et al. carried out a study where they developed a 3D and a 2D-model of an Oil Natural-Air Natural (ONAN) distribution transformer. They demonstrated the good capacity of the simplified 2D model to represent the thermal behaviour of the whole transformer [7]. In 2012, Tsili et al. established a methodology to develop a 3D-model and to predict hot-spot temperature [8]. In this year, Skillen et al. carried out a CFD simulation of a 2D non-isothermal flow axisymmetric model in order to characterize the oil flow in a transformer winding with zigzag cooling [9]. In 2014, Yatsevsky carried out a 2D-axisymmetric simulation of an oil-immersed transformer with natural convection, including the core, the tank and the radiator, in order to predict hot-spots. The developed model showed a good adequacy verified by experiments [10]. Recently, Torriano et al. has developed a 3D-Conjugate Heat Transfer model of an ON disc-type power transformer winding scale model. An underestimation of the average and hot-spot temperatures was obtained in this model in comparison with the experimental setup when the entire cooling loop was considered. This is the reason why the authors chose to reduce the computational domain to the winding, setting the inlet boundary conditions. This way, the model accuracy was improved significantly [11].

In spite of all the research that is being carried out about the mineral oil as a coolant and also as a dielectric liquid, there is an increasing interest in its substitution by new biodegradable fluids with higher ignition points. Natural esters are one type of these alternative liquids. Nonetheless, tests have to be done to ensure the performance of these fluids from all points of view. For instance, as in the case of mineral oil, their cooling capacity (i.d. measure of a cooling system's ability to remove heat) have to be verified. In fact, several authors have carried out this labor comparing different types of alternative liquids with mineral oil in different cooling systems. For instance, in 2015, Park and Han compared the temperatures distribution and the hot-spots values and their location of three dielectric liquids (a natural and a synthetic esters and a mineral oil) in a 2D numerical model of a zigzag cooling system [12]. In the same year, Lecuna et al. performed the same work using a 3D numerical model of an axial cooling system with three types of alternative dielectrics liquids. Two cooling indexes (convective heat transfer coefficient (h) and the cooling criterion (P)) were also calculated [13]. These works concluded that alternative liquids produce higher temperatures in the transformer windings designed for mineral oil. More recently, Santisteban et al. evaluated the cooling performance of two alternative natural liquids with that of a typical mineral oil. This task was carried out using a 2D-axisymmetric model of a LVW with zigzag cooling in which temperature distributions, hot-spot temperatures and their locations, and hot-spot factors were determined. In contrast to the results of the previous works, this work shows that the hot-spot temperature is lower for the natural oils than that of mineral oil [14].

All the works mentioned in the two previous paragraphs consider thermal properties of fresh dielectric liquids. That is, the values of the thermal-fluid properties (viscosity, μ, density, ρ, heat capacity, C_p, and thermal conductivity, k) are those of the fresh oils and do not vary. However, in the operation of a power transformer, these properties are affected over time for different factors such as the aging or moisture content [15]. In fact, many experimental results of the variation of the viscosity with the aging can be found for several dielectric liquids in the literature [16–21]. These works compare the viscosity variation of different types of natural ester-based oils with a mineral oil during thermal aging. However, the influence of this variation on the cooling capacity of the liquid is not determined. The only work that studies this topic was published by Kassi et al. In 2016, they carried out an experimental and numerical analysis using mineral oil as a coolant. The results of a 2D axisymmetric numerical model of a 3-phase power transformer column comparing fresh with aged oil showed the worsening of the cooling capacity with aging, thus resulting in an increase of the hot-spot temperature [22]. Nevertheless, the effect of the thermal aging on cooling capacity of the natural esters it has not been evaluated yet.

Based on the above, this paper presents a numerical and experimental study of the cooling capacity of a commercial natural ester with three levels of aging. Temperature variations with the degradation of the oil are obtained in an experimental platform. Also, a 2D numerical study of this experimental setup has been developed to determine its temperature and velocity distributions.

First sections of this paper present the experimental work: thermal-aging of the samples and determination of their physicochemical properties are described in Section 2; the experimental setup is shown in Section 3. Then, the numerical model developed is presented in Section 4. Model validation and its results are presented in Sections 5 and 6, respectively. Finally, in Section 7, some conclusions are drawn from the experimental and numerical results obtained.

2. Thermal aging and physicochemical properties measurement

The aging procedure followed in this paper is described in Section 2.1. The methodology applied to determine the properties of the liquids and the paper, used both as insulation system, and the values obtained are presented in Section 2.2.

2.1. Aging method

The assessment of the evolution of thermal, electrical or mechanical properties in electrical insulating materials requires long periods of time, which are not feasible under the point of view of time and costs. For this reason, accelerated ageing tests in laboratory are needed to obtain useful information. Currently, ageing procedures and evaluation of test results of electrical insulating materials are described in the standard IEC 60216-1:2013 [23].

In order to evaluate the effect of thermal aging on the cooling capacity of a commercial natural ester, the temperature distribution in a stainless-steel casing containing insulating oil with different degree of aging and a 1-phase transformer was assessed. During these tests three types of aged oil samples were studied. The first one was a fresh oil which has not suffered any kind of thermal stress. The second sample of oil was obtained through an accelerated thermal aging test in which the natural ester was thermally aged without any additional material. Finally, the last type of oil was obtained by thermal aging of the natural ester based oil and pressboard 3055 (PSP 3055) strips, see Fig. 1.

Six vessels for each sample of aged oil were prepared by inserting 1000 ml of natural ester with a nitrogen headspace of 25% by volume, and 150 g of PSP 3055 in the case of the third sample of oil. The thermal ageing was then carried out at 150 °C for 168 h, see Fig. 2. After aging time, the vessels were cooled at room temperature (25 °C) for five hours.

Regarding the oil aged with PSP 3055, this insulating solid was previously dried under vacuum at 100 °C for one day in the steel vessels, obtaining solid samples with a moisture content of 2.5%.

2.2. Experimental determination of the physicochemical properties of samples

Small quantities of the oil samples are taken to evaluate their dynamic viscosity since the heat carrier capacity of these fluids strongly depends on this property. In fact, the variation of the property with the temperature is determined. Other properties related with the thermal performance of samples (density, heat capacity and thermal