Ageing of crepe paper in mineral oil and natural ester

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***Abstract* – Several billion liters of transformer oil are used in oil filled transformers worldwide. These machines are voltage transformation devices in which during their operation the heat of windings and iron core firstly is transferred to the insulation oil and then to the cooling medium. Currently, this type of transformers mainly utilizes mineral oils due to their proven good service performance. However, mineral oil has certain limitations such as their low flashpoint and biodegradability which conditions its use in indoor environments, and it may cause a high environmental impact during its use. The development of biodegradable liquids (synthetic and natural esters) has provided an alternative. Nevertheless, a question arises when natural esters are used in power transformers, are they compatible with the rest of materials used in their design. Nowadays, although several studies of accelerated thermal ageing have been undertaken there are few works that study the impact of insulation liquid and temperature on the degradation rate of other cellulosic materials such as crepe paper. This paper can take different shapes of the surface being insulated and has greater surface area which allows to retain more oil reducing the working temperature of the transformer. For this reason, this work has compared the impact of the type of insulation oil (a mineral oil and a natural ester) and the temperature (150ºC, 130ºC and 110ºC) on lifetime of this insulation paper. Degree of polymerization has been measured to quantify the effects. Additionally, the degradation suffered by insulation oils has been evaluated through the measurement of acidity, dissipation factor and DC resistivity. It has been found that the degradation suffered by natural ester is higher than mineral oil, however, the biodegradable liquid extends the life of crepe paper.**

Keywords: crepe paper, natural ester, ageing, degree of polymerization, dissipation factor

I. Introduction

Transformers are devices of critical importance in current electric power transmission and distribution, so their importance in current energy distribution systems is enormous [1]. Oil-immersed transformers are currently used in large-scale and high-voltage transformers and their insulation is usually a combination of liquid and solid dielectric materials [2]. The insulating fluid widely used in this kind of transformers is mineral oil which serves as dielectric insulator and coolant [3, 4]. However, this insulation fluid has relatively low flash and fire points, it is also toxic in nature, and hazardous in the soil and in the water, being its biodegradability not more than 30% [5]. Consequently, mineral oil has started to be substituted for alternative liquids such as natural and synthetic esters due to its biodegradability and fire safety properties [6-8]. Natural and synthetic esters in comparison with mineral oil possesses physical and chemical differences that make compulsory the assessment of both alternative oils in comparison with mineral oil before they are widely applied [9]. For this reason, there is a great deal of works which have analyzed different issues related with the use of new insulation liquids in power transformers. Some authors have studied ageing behavior of natural and synthetic esters through the analysis of different properties [3, 6, 10-14]. For instance, Rao et al. [3] monitored degradation rate using ultraviolet spectroscopy. Furthermore, they analyzed the variations in cellulose crystal parameters of Kraft paper using X-ray diffraction (XRD). This paper was aged in mineral oil, natural ester, synthetic ester and a mixture of mineral oil and synthetic ester at different temperatures (110°C, 150°C, 170°C and 200°C). Matharage et al. [12] carried out a study of the evolution in time of 2-FAL and methanol concentration, oil acidity, tensile index and degree of polymerization (DP) of Kraft paper. These properties were also analyzed by Fernández et al. [13], although they also aged thermally upgraded insulator paper and studied the water content in oil. On the other hand, Bandara et al. [6] not only evaluated DP of pressboard, but they also measured AC breakdown strength, 2-FAL, acidity and dissolved gases of mineral and synthetic esters aged with pressboard insulation. These studies and others have found that thermal ageing rates of insulation solids immersed in natural esters are reduced compared to those in mineral oil.

The insulation solids usually studied include papers such as Kraft paper [10, 15-18], thermally upgraded papers [19], aramid paper [1, 20], pressboard [11, 21] and their degradation during thermal aging has been evaluated through the degree of polymerization [15, 16, 19, 22], the tensile strength [10, 17, 18, 21-23], Fourier transform infrared spectroscopy (FTIR) or energy dispersive X-ray [16], being the DP and the tensile strength the most commonly used methods.

Even though, the degradation suffered by different insulation papers immersed in biodegradable oils during thermal ageing tests has been studied, there are few works that have analyzed the effect of insulation liquids on the deterioration of other cellulosic materials such as crepe paper, used to insulate irregular shapes and surfaces inside power transformers in which suitable insulation cannot be achieved with flat papers. Considering the importance that degradation suffered by insulation materials such as crepe can have in the performance of power transformers, this work attempts to investigate the influence of a commercial natural ester and the temperature on lifetime of this kind of paper. Degree of polymerization is used to quantify the effects. Additionally, the degradation suffered by insulation oil is evaluated through acidity, dissipation factor and resistivity.

II. Experimental

This work has analyzed the behavior of crepe paper 67/100 (Table I), when it is thermally aged in two different commercial oils (a naphthenic oil and a natural ester, Table II). The vegetable oil is a rapeseed-based fluid.

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TABLE I. CREPE PAPER PROPERTIES

Property		Unit	Values
Grammage		g/m^2	104
Thickness / 5 sheets		µm	198
Hill count		cm^{-1}	12
Extended tensile index	machine direction	Nm/g	69
	cross machine direction		33
Tensile strength	machine direction	kN/m	4.7
	cross machine direction		3.3
Elongation at break	machine direction	%	52
	cross machine direction		4.3
Dissipation factor in air/oil	20°C		0.0035
	90°C		0.0040
Ash content		%	0.3
Aqueous extract conductivity		mS/m	2
pH of aqueous extract			6.8

TABLE II. TRANSFORMER OILS' PROPERTIES

Property	Unit	Mineral oil (MO)	Natural ester (NE)
Viscosity, 40ºC	(mm^2/s)	7.6	39.2
Density, 20ºC	kg/dm^3	0.877	0.91
Pour point	ºC	-63	-25
Flash point	ºC	154	330
Water content	mg/kg	<20	150
Breakdown voltage	kV	40-60	65
Acidity	mg KOH/g	<0.01	0.05
Dielectric dissipation factor (90ºC)		<0.001	0.03

A. *Ageing procedure*

The aging experiments were performed on paper strips (260x15 mm) cut from Crepe paper. The strips were dried in vacuum (2 mbar), at 100ºC (24 hours). Portions (25 g) were enclosed with transformer oil (0.75 l) in stainless steel vessels (1 L), with a nitrogen headspace of 25% by volume, so the study of crepe degradation will only take into account the effect of temperature and insulation liquid on the paper ageing without considering oxygen effect. Thus, it will be needed in future works to carry out an assessment about the impact that high levels of moisture and oxygen might have in the deterioration rate of insulating paper, which will modify the kinetics. The vessels were kept in ovens, at 110, 130 and 150ºC, and both paper and oil were sampled throughout the aging period. After each aging time (Table III) was reached, the vessels were cooled at room temperature (25ºC) for five hours and then the oil and paper samples were extracted for analysis.

TABLE III. AGEING TIME

Property	Ageing time (h)						
Temperature	*Samples*						
	1	2	3	4	5	6	7
150ºC	0	143	265	452	592	818	1004
130ºC	0	207	630	1273	1756	2491	3186
110ºC	0	284	1116	1949	3454	7383	17305

B. *Insulation ageing assessment*

The method most used for characterizing paper degradation involves the determination of the chain scission number as a function of the degree of polymerization (DP). The degree of polymerization was determined according to ASTM D4243 by measuring the kinematic viscosity of the paper in solution. Regarding insulation oil (mineral and natural ester), their ageing was analyzed through acidity (ASTM D 664), dissipation factor (IEC 60247) and DC resistivity (IEC 60247).

III. RESULTS

This section shows the degradation suffered by insulation system (crepe paper/mineral oil, crepe paper/natural ester) aged at three different temperatures.

A. *Dielectric dissipation factor*

Dielectric dissipation factor testing is a measure of the dielectric losses in an insulation system. The Figs. 1 and 2 illustrate the change suffered by this property during the aging carried out in this work.

This property is widely utilized by users of transformers to assess the quality (or uniformity) of the insulation liquid. The dielectric dissipation factor as it can be observed in the Figs. 1 and 2, is strongly affected by thermal ageing especially for high periods. The value of dissipation factor at the end of thermal ageing at 110ºC is quite high in both oils in comparison with the tests carried out at 130ºC and 150ºC. Additionally, it can be observed that this property has values quite superior in the natural ester.

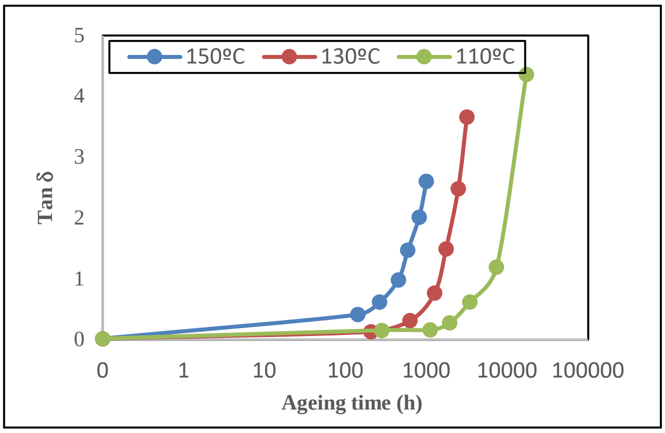

Figure 1. Dielectric dissipation factor of natural ester during ageing.

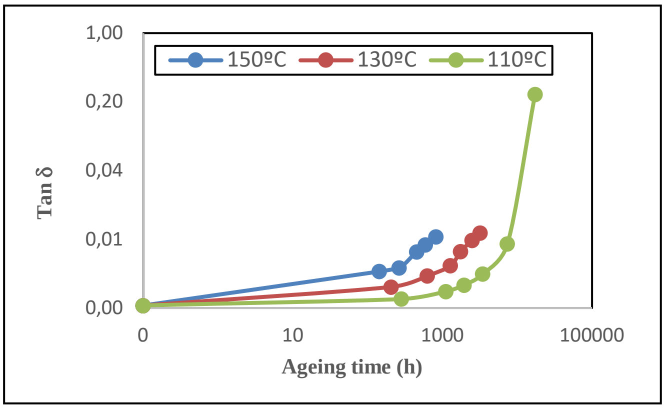

Figure 2. Dielectric dissipation factor of mineral oil during ageing.

B. DC resistivity

This property indicates the leakage current when a DC voltage is applied to the insulation system. Figs. 3 and 4 gathers the DC resistance of samples measured during aging tests. It is shown that mineral oil has the highest resistance. Furthermore, mineral oil showed more stable resistance at the highest temperatures when the aging period is shorter in comparison with thermal test carried out at 110ºC. The results indicated that mineral oil has superior resistance stability.

C. Acidity

Figs. 5 and 6 show the variation of acidity of natural ester and mineral oil respectively, during thermal aging. It can be observed that the acidity increases over ageing level of both liquids. However, this effect is much more significant in natural ester which increases its acidity by several orders in comparison with mineral oil, especially at 150ºC.

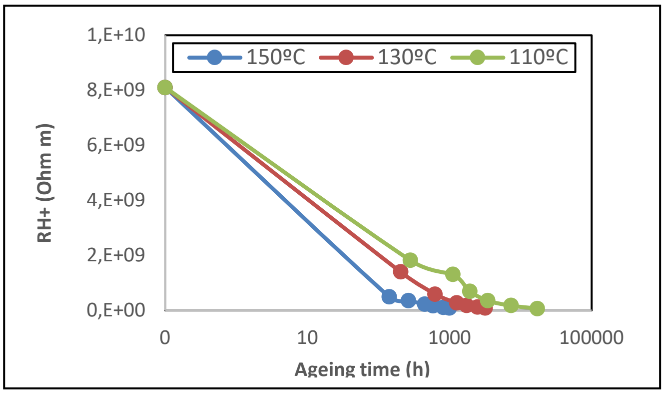

Figure 3. DC resistivity of natural ester during ageing.

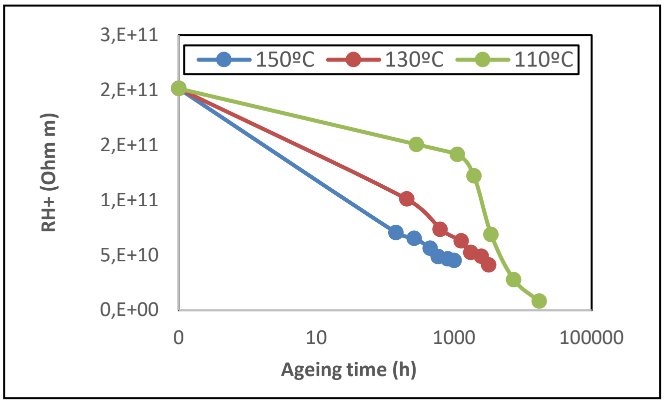

Figure 4. DC resistivity of mineral oil during ageing.

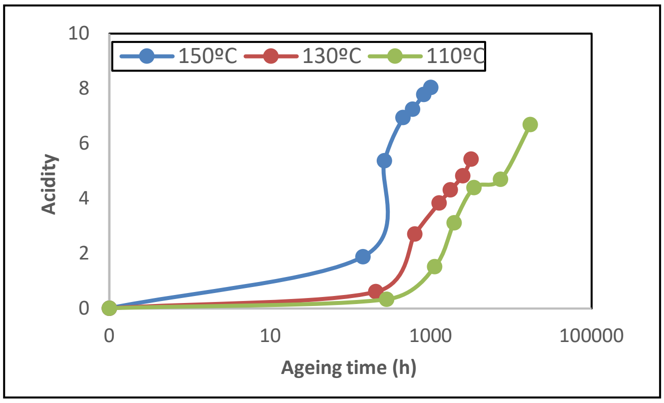

Figure 5. Acidity of natural ester during ageing.

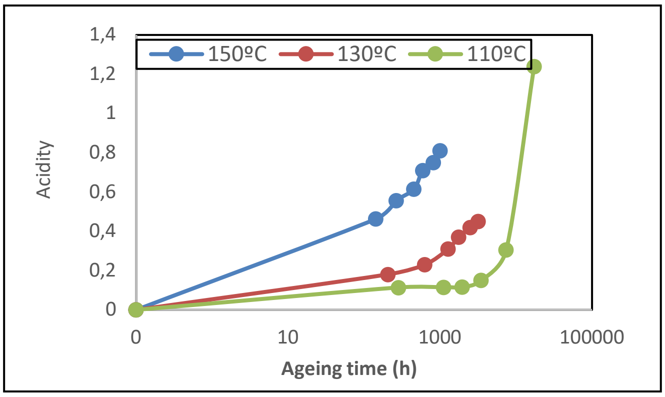

Figure 6. Acidity of mineral oil during ageing.

As Bandara and Ekanayake established in their work [24], the behavior of acidity in the natural ester can be explained due to hydrolytic degradation of vegetable oil. As at high temperature moisture migrates from insulation solid to oil, and it enhances the hydrolysis reaction in the oil. Thus, the value of acidity in the biodegradable oil was about 30% higher than the one at 100ºC.

D. Degree of polymerization

Figs. 7 and 8 display the evolution of DP, as a function of the aging time and the temperature at which thermal aging took place.

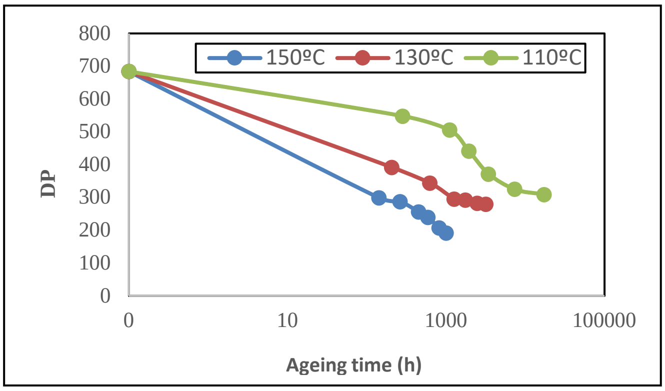

Figure 7. DP of crepe paper immersed in natural ester during ageing.

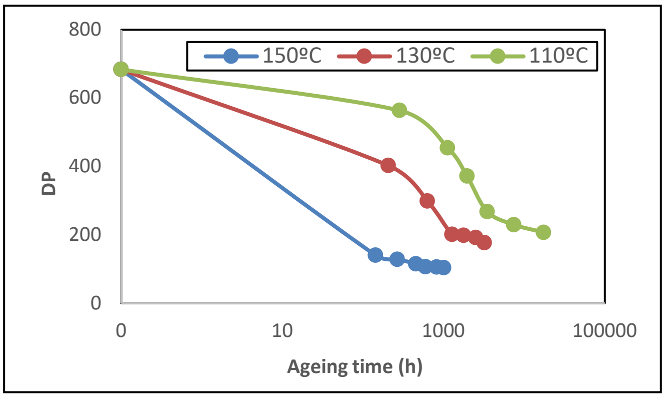

Figure 8. DP of crepe paper immersed in mineral oil during ageing.

It can be observed for both commercial oils that the DP decreases over time and this decrease becomes faster when the ageing temperature increases. However, if the degradation rates suffered by crepe paper are compared, it is found that natural ester extends insulation solid life. As shown in these figures, average DP of crepe paper decreases rapidly in the first 100 h of ageing when this is immersed in mineral oil at 150ºC, whereas in natural ester are needed around 1000 h. When aging temperature is reduced the difference diminishes.

IV. Conclusions

The assessment of the DP loss has showed the critical effect of the type of oil on the ageing of this insulation paper, finding a higher degradation when mineral oil is used as insulation liquid.

It has also been analyzed the impact that thermal ageing can have in a natural ester in comparison with mineral oil through the measurement of acidity, dissipation factor and DC resistivity. It has been found that the degradation suffered by natural ester is higher than mineral oil, however, the biodegradable liquid extends the life of crepe paper as it has been concluded for other insulation papers.

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