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Assessing the use of natural esters for transformer field drying

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Abstract—In recent years great attention has been paid to ester fluids as an alternative to mineral oil. At the present the use of these liquids is becoming a common practice in distribution transformers and even some experiences have been published reporting their application to power transformers. One of the main differences between ester fluid and mineral oil is the much greater capability of absorbing water by esters.

In this paper the possibility of using this kind of liquids in transformer field drying is assessed.

Hot oil (HO) drying with mineral oil is one of the most widely used methods to dry transformers in field, as it is a relatively simple and well known process and it is less aggressive for the insulation than other drying methods. Moreover, drying the oil, while it is preferably hot, is the only method available to dry transformers online. However the water extraction rate of the process is very poor because of the highly hydrophobic character of mineral oil, and in consequence large drying times are needed to achieve a significant reduction in the water content of the insulation. A first theoretical analysis seems to indicate that the use of a less hydrophobic liquid would significantly reduce the drying times involved in the process.

This paper aims to quantify the improvement of the HO drying process that is achieved by using ester fluids instead of mineral oil. Both drying agents were compared by means of theoretical simulations as well as laboratory tests.

Index Terms—moisture dynamics; natural esters; diffusion coefficient; transformer load

I. INTRODUCTION

The presence of water in transformer insulation affects the equipment reliability in addition to its loading capability. On one hand, excessive water content increases the presence of partial discharges and decreases the dielectric strength of the insulation. Moreover water promotes the hydrolysis reactions, that are the predominant ageing processes of the transformer insulation at working temperatures. Transformers are subjected to drying processes after manufacturing. However, as cellulosic insulation is a highly hydrophilic material, some amount of water will still be present after that.

The amount of water present in transformer insulation increases through the years of service due to several underlying causes. In free breathing transformers the rate of water contamination could be up to 0.2% per year of service while in membrane-sealed preservation systems it increases in about 0.03 to 0.06% per year [1]. Water contamination may also happen in presence of poor gaskets or in case of

field repairs involving oil draining that expose active parts to air. Additionally the aging process of the cellulose generates water, so that the water content of the transformer will increase through the years.

Because of the hydrophobic nature of oil and the hydrophilic character of paper, water is absorbed in the paper in a proportion of 1% in oil vs. 99% in cellulose, a greater amount of water is usually concentrated in the thick insulation [1]. According to the IEEE standard C57.91-2011 [2] a transformer with a moisture content in its insulation greater than 4% is too wet to be operated safely. When high water contents are found in units with a significant remaining service-life, it is common to schedule drying treatments that are usually performed in the field.

Different drying methods are available to dry power transformers in the field [3], but all of them involve two basic steps:

- 1) Forcing the water to travel through the insulation thickness until reaching its surface where it is removed by the drying agent.
- 2) Extracting the water away from the transformer usually by a treatment of the drying agent.

The first step is the one that requires more time to be completed. As it is well known, the diffusion of water inside the insulation can be accelerated by increasing the temperature of the system. In some cases, the circulation of a hot drying agent (i.e air or oil) is used to heat the insulation. Sometimes additional heating is applied to get higher drying temperatures and to reduce the drying times. Some commonly used heating methods are Low Frequency Heating (LFH), based on forcing circulation of current in the transformer windings, or Hot Oil Spray (HOS), that is usually applied in combination with vacuum.

To remove water from the insulation surface, a dry environment must be created around it. This is usually achieved by the application of vacuum inside the tank, or by forcing the circulation of hot and dry oil or air through the transformer active parts. The main differences between the available drying methods lies in the agents that are used to remove the surface moisture, and in how the solid insulation is heated to force the exit of water from its inner part to the surface. Table I summarizes the most relevant methods used at the present. Some advantages and disadvantages of each of these methods can be seen in Table II.

In an authors' previous work [4], [5], [6], the HO drying method was theoretically studied; the main finding was that the drying times involved in the process are large and, in consequence, this kind of drying processes is sometimes less

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Table I: Main methods used to dry transformers in the field.

Method	Drying agent	Heating agent
Hot oil drying (HO)	Hot dry oil	Hot oil LFH
Vacuum drying (VD)	Vacuum	Hot oil cycles LFH Hot oil spray
Hot air drying (HA)	Hot dry air	Hot air

Table II: Advantages and drawbacks of the different drying methods.

Drying method	Advantages	Disadvantages and risks
HO	Well known No deimpregnation	Long drying times
VD	Fast removal of surface water Shorter times if heating is proper	Deimpregnation of oil Risk of tank collapse
HA	Lower drying times	Oxidation of oil Deimpregnation of solid insulation

effective. Also experimental studies showed much shorter drying times in the case of Hot Air (HA) drying although, in this case, there is an increased risk of oil-deimpregnation, as well as cellulose oxidation. The improvement in the drying time achieved with HA drying is due to the greater affinity of air for water in comparison to that of oil. This seems to indicate that the use of a more hygroscopic fluid than mineral oil would be a way to increase the efficiency of the HO drying diminishing drying times and obtaining lower moisture contents in the solid insulation at the end of the process.

In recent years the use of natural and synthetic esters is becoming common in distribution transformers [7]. One of the properties of these fluids is that they are able to absorb much greater amounts of water than mineral oils [8]. Some authors have suggested that the use of this kind of fluid would be useful to reduce the drying times making the drying process more efficient [8], [9], [10]. In [10], a drying method based on the use of ester fluids is proposed as an alternative to HO drying. The method consists of using vegetable oil only for drying purposes, afterwards the transformer should be refilled with mineral oil for operation, as the transformer was designed to be operated with mineral oil. In that work, qualitative analysis is presented that compares the equilibrium condition between paper and oil in both cases and also reports some preliminary experiments.

In this paper the improvement obtained by the use of ester fluids is quantified. To this aim a theoretical model is used that simulates drying processes at different temperatures considering drying with mineral oil and drying with natural esters. Drying experiments were also performed using both drying agents in the laboratory at different drying conditions. Finally, performances of different ester fluids were compared.

II. THEORETICAL ANALYSIS OF THE PROCESS

A. Theoretical model

In [4], a model to simulate the HO drying process of a transformer was presented. The model, based on Fick's second law, is used to study the mass transport problem in the transformer insulation. Because of typical dimensions of the transformer insulation the process was considered to be one-dimensional.

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2} \quad (1)$$

where D is the moisture diffusion coefficient of the solid insulation and C is the moisture concentration.

The boundary condition to solve 1 can be obtained from Fessler's approach [11]:

$$C_{equil} = 2.173 \cdot 10^{-7} \cdot p_v^{0.6685} \cdot \exp\left(\frac{4725.6}{T}\right) \quad (2)$$

where p_v is the moisture partial pressure that can be calculated from oil relative humidity (HR) as

$$p_v = HR \cdot p_{v,sat} = \frac{ppm}{ppm_{sat}} \cdot p_{v,sat} \quad (3)$$

where ppm , is moisture concentration in oil expressed in parts per million and ppm_{sat} and $p_{v,sat}$ are moisture concentration and partial pressure when saturated [11] respectively. The partial pressure of the saturated oil can be obtained by Antoine equation [12], and the oil moisture concentration in saturation condition can be obtained from the following expression [13]:

$$\log(ppm_{sat}) = A - \frac{B}{T} \quad (4)$$

The parameters A and B are constants with depend on the oil properties. If mineral oil is used as a drying agent, the parameters A and B could be taken as $A = 7.09$ and $B = 1567$ [11], [13]. In case of using a different drying agent the parameters A and B corresponding to that fluid must be considered.

IEEE Std C57.147-2008 [14] provides two sets of values for A and B obtained on two different ester fluids (Table III). The standard concludes that the properties of both of them regarding to the moisture solubility are very similar at the temperatures of interest.

Table III: Parameters A and B for different insulating fluids provided by IEEE Std C57.147-2008.

	A	B
Ester fluid 1	5.7080	802
Ester fluid 2	5.3318	684

B. Simulation of the drying process

The drying process of transformer insulation has been simulated using the model explained before. Simulations were carried out considering a conventional HO drying process performed with mineral oil as well as a HO drying using an

ester fluid. The parameters A and B corresponding to ester fluid 1 in Table III have been considered.

It is important to note that the only difference introduced to simulate the drying process with mineral oil and with a natural ester fluid was just the change in the boundary condition (i.e. (4)). The expression of the diffusion coefficient considered in all simulations was (5). This equation was experimentally obtained by the authors in a previous work on samples of Kraft paper impregnated with mineral oil [15].

$$D = 0.5 \cdot e^{0.5 \cdot C - \frac{10057 - 133.7 \cdot l}{T}} \quad (5)$$

where C is moisture concentration of paper in %, l is the insulation thickness in mm and T is the insulation temperature in Kelvin.

At present, experiments are being conducted to calculate the moisture diffusion coefficient in cellulosic insulations impregnated with natural esters. This coefficient may differ from that obtained for mineral-oil-impregnated materials, so the simulated values shown in this section should be taken as approximate results. However, it may be noted, that, in case of drying a transformer immersed in mineral oil with a natural ester fluid, the results of the simulation would be pretty realistic as, in this case, the fluid adsorbed in the insulation would be mineral oil.

Firstly simulations were done to determine the influence of the drying fluid in deciding the rate of water removal at different temperatures. Drying processes were simulated at temperatures 60 and 80°C. The analyzed specimen was a piece of cellulosic insulation 5 mm thick, with homogeneous initial moisture content of 3%. Diffusion in just one face of the insulation was considered, as it happens in the insulation of transformer windings or in the bushing leads. The moisture content of the oil during the drying process was assumed to be 10 ppm, which is a typical value when a transformer is being dried with HO in the field.

As can be seen in Figs. 1 and 2 the use of natural esters improves the rate of drying at both temperatures, although in the case of drying at 80°C the improvement is not so significant. More important is the acceleration in water removal in case of drying at 60°C (Fig. 2).

It is also interesting to note that the improvement obtained by the use of an ester fluid notably increases when the moisture content of the oil is not so low during the drying process. This may happen during the drying process of large transformers with great amounts of oil, so that the filter is not able to keep moisture at low enough values. In Fig. 3 the drying curves at 70°C when drying with mineral and vegetable oil are shown for moisture contents in oil of 5 and 20 ppm. As can be seen, when the moisture content of oil is very low, little improvement is achieved by substituting the mineral oil by an ester, whereas in case of drying process in which moisture content in oil was 20 ppm an increase in the drying rate is observed while using an ester fluid.

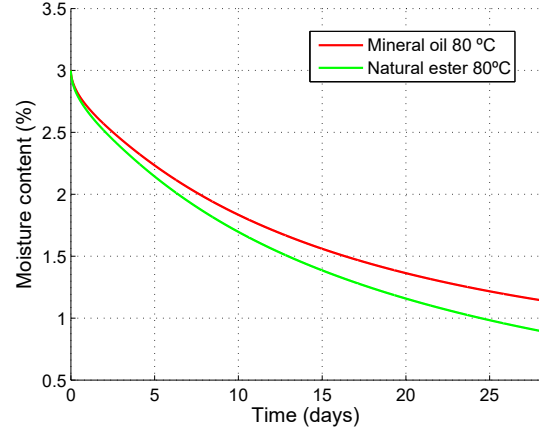


Figure 1: Calculated drying curves of a 5 mm insulation considering HO drying at 80°C with mineral oil and with a natural ester fluid with a moisture content of 10 ppm.

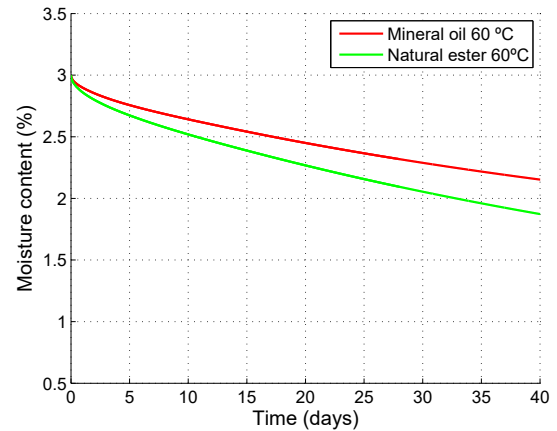


Figure 2: Calculated drying curves of a 5 mm insulation considering HO drying at 60°C with mineral oil and with a natural ester fluid with a moisture content of 10 ppm.

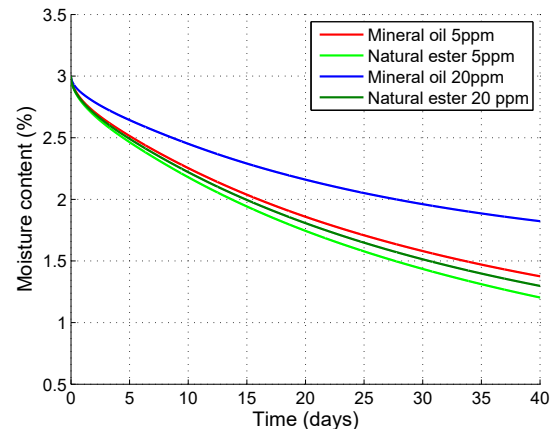


Figure 3: Calculated drying curves of a 5 mm insulation at 70°C considering different moisture contents in oil

III. EXPERIMENTAL STUDY

A. Test plant

The drying plant (Fig. 4) was designed to reproduce the conditions of a real hot oil drying process. The specimen to

be dried is introduced into a tank that is filled with oil (Fig. 5). Oil is continuously forced to circulate through a drying filter by means of a pump. The filter dries the oil, extracting the water that is released from the paper during the drying process. Oil also passes through a heater where it is heated to a specified value.

The plant is provided with optical sensors to measure the temperatures of the paper and the oil, and it also incorporates a capacitive sensor to register oil moisture evolution. The moisture sensor was installed in a pipe at the bottom of the plant that connects the deposit and the drying filter and was recalibrated to determine the ppm in the different fluids using Karl Fischer measurements. All the variables are registered and controlled by means of an acquisition system allowing control of the oil temperature.



Figure 4: Drying plant

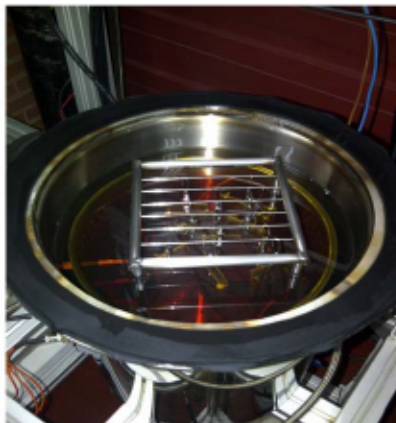


Figure 5: Disposition of pressboard samples in the deposit of the test plant

B. Sample preparation

Dynamics experiments were performed on pressboard samples prepared with a high initial moisture level. The specifications of the evaluated pressboard were according to the international standard IEC 641-3-1, being all of type B.3.1.

The test specimens were obtained from one layer of pressboard sheet. Pieces of thicknesses 0.5, 1, 2 and 3 mm were evaluated during the experimental stage of the work. The four edges of each specimen were coated with epoxy resin to prevent desorption of moisture through these sides during the drying processes and to ensure a unidirectional desorption only through the upper and lower surfaces (Fig. 6).

Before impregnating with oil, samples were humidified by placing them in a climatic chamber under temperature of 35°C and relative humidity of 70%. Wetting conditions were established according to Jeffries's curves [16] to get an equilibrium moisture of about 9%. After that, the test specimens were impregnated by submerging them in mineral oil or natural ester at room temperature and atmospheric pressure for a period no less than one week. Finally, the oil-impregnated test specimens were introduced again in the climatic chamber to re-wet them until the beginning of the drying experiment.



Figure 6: Pressboard samples 100 x 40 each

C. Test conditions

A first set of drying experiments were performed on pressboard samples of different thicknesses impregnated with mineral oil. After that the experiments were repeated using a commercial natural ester fluid, Bioelectra®. Temperatures and insulation thickness used in tests are summarized in Table IV.

Table IV: Experimental testing conditions

Fluid	Temperature (°C)	Pressboard thickness (mm)
Mineral oil	60, 70, 80	0.5, 1, 2, 3
Ester	60, 70, 80	0.5, 1, 2, 3

The samples were dried by hot oil circulation in the test plant (Figs. 4 and 5) and during the whole process pressboard samples were periodically extracted and analyzed with Karl Fischer method [17]. The experiments were stopped when the moisture determined on all the samples was less than 1% in weight.

In the case of the experiments carried out with natural ester, nitrogen atmosphere was used during the extraction

process with the aim of avoiding oxidation of oil. Dielectric measurements were also carried out daily on oil samples extracted from the tank to monitor its condition.

IV. RESULTS

As explained in the previous section, drying experiments were performed on pressboard samples of different thickness subjected to different temperatures (Table IV). The same experimental conditions were applied to the HO drying process carried out with mineral oil and to that using Bioelectra[®] natural ester as drying agent.

Figs. 7 and 8 show the drying curves obtained on the samples of different thickness dried with mineral and vegetable oil at 70°C. As expected, the drying times are greater for the thicker samples. If the drying times are compared for samples of the same thickness, it is found that they are significantly shorter in case of drying with natural ester that those when they are dried with mineral oil.

Additionally it must be remarked that, although the procedure of sample preparation was exactly the same for all the samples, the resultant initial moisture contents were slightly different in both cases (i.e. about 10% in weight for the samples impregnated with natural ester and about 9% in those impregnated with mineral oil). The explanation to these differences can be found in the re-wetting process the samples were subjected to once impregnated with oil. During this part of the preparation process the mineral oil avoided adsorption of moisture, but the natural ester absorbed some moisture increasing the total moisture content of the sample.

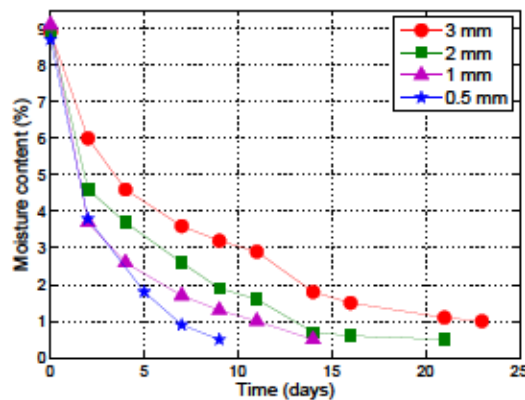


Figure 7: Drying curves of pressboard at 70°C in presence of mineral oil

To quantify the improvement achieved in the drying times with the change of drying agent, the number of days required to dry the different samples to a level below 1% in weight were calculated as shown in Table V. As can be seen, the drying times diminish in between 20% and 70% when drying with the natural ester. Although these data should be taken as an estimation, as they are affected by slight differences in the initial moisture of the samples and because of the fact that the drying curve is discrete, it is important to note that the greater improvements appear in the case of the drying processes carried out at lower temperatures, as was observed in the simulation stage. The experimental data obtained at 60

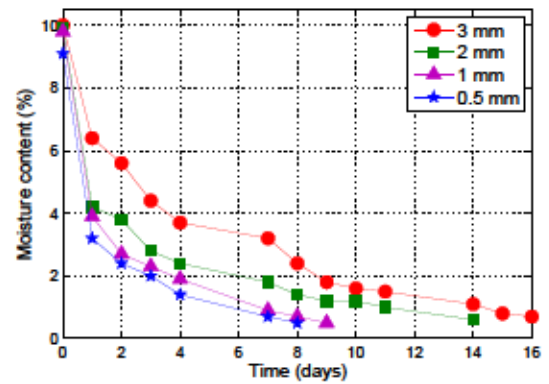


Figure 8: Drying curves of pressboard at 70°C in presence of the natural ester Bioelectra[®]

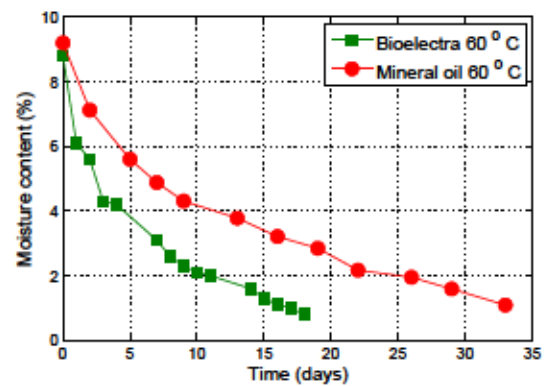


Figure 9: Comparison between drying a sample 3 mm thick with mineral oil and with natural ester at 60°C.

and 80°C on a 3 mm sample are shown in Figs. 9 and 10, where this aspects seems clear.

Table V: Approximate drying times required to achieve a moisture content lower than 1% when using natural ester (E) or mineral oil (M) as drying agents

	Time to $C < 1\%$ (days)					
	80°C		70°C		60°C	
	E	M	E	M	E	M
3 mm	10	14	15	23	17	33
2 mm	6	11	11	14	13	29
1 mm	6	12	7	11	8	26
0.5 mm	3	5	7	9	6	20

It is also interesting to compare the moisture content in the different oils during the drying processes. As can be seen, the water content in both fluids is low because of the action of the filter. The spikes in the curves correspond to the stops of the oil recirculation during the sample extraction operations. Anyhow, it must be noted that the ester fluid presented a higher moisture level, despite using the same kind of filter for water removal. This seems logical because of much higher solubility of water in these fluids and in consequence the appreciably different equilibrium conditions between paper and oil. Moreover it must be remarked that the efficiency of the filter may be lower due to the effect of the lower viscosity of ester fluids.

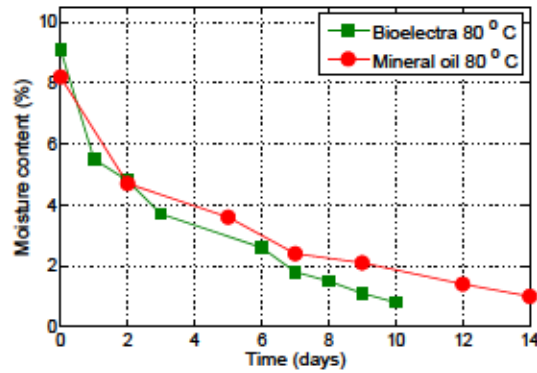


Figure 10: Comparison between drying a sample 3 mm thick with mineral oil and with natural ester at 80°C

Finally an additional drying process was carried out using the natural ester Biotemp® with the aim to compare the effectiveness of different ester fluids for drying purposes. This drying experiment was done at temperature 70°C, and for samples of thickness 0.5, 1, 2 and 3 mm. The results of the process are shown in Fig. 12. A comparison of the results obtained when drying a sample of 3 mm thick using both natural esters are plotted in Fig. 13.

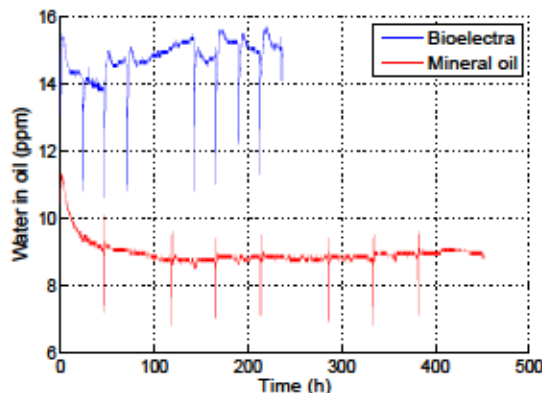


Figure 11: Moisture content in oil during the drying process at temperature 80°C

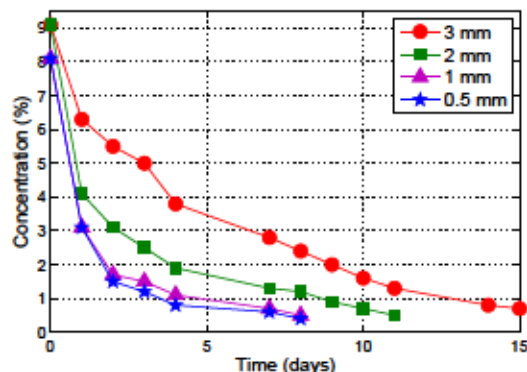


Figure 12: Drying curves obtained when drying with the natural ester Biotemp® at 70°C

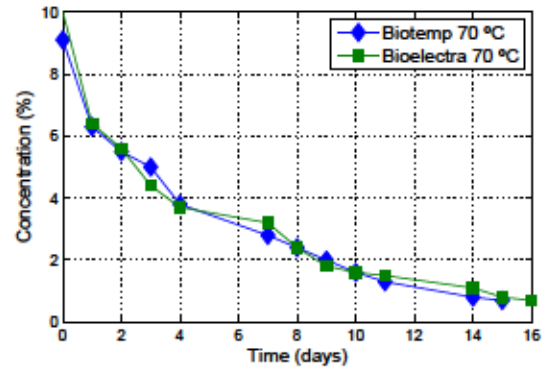


Figure 13: Comparison of the drying process with two different ester fluids

V. CONCLUSIONS

The use of natural esters has been proposed by several authors as a way to reduce the time involved in the drying processes of power transformers in the field. This paper quantifies the improvement achieved by this method. Simulations were done using a theoretical model solved by the Finite Element Method, and considering the solubility of each fluid as a function of temperature to state the equilibrium condition. Additionally, drying experiments were carried out with mineral oil and also using two different natural esters. The main conclusions of the study are summarized below:

- HO drying is a well known drying method that has been used for years to process transformers in the field. The main disadvantage of the method lies in the fact that mineral oil is very hydrophobic and, in consequence, the amount of water extracted in each oil circulation is low and the drying time required is very high. Some authors proposed to use ester fluids for drying purposes, as they absorb amounts of water of about 20 times greater than mineral oils.
- Currently, the price of ester fluids is high, therefore before using them for this application, it is necessary to determinate if the reduction of drying time that may be achieved compensates the investment that would be required. Moreover, the safety of the method should be guaranteed.
- As expected, the theoretical simulations and the laboratory experiments demonstrated that the use of esters makes the drying process more efficient allowing a reduction in the drying time. However, the improvement achieved is not equal for all the tested conditions. When the drying process is carried out at high temperature and low water content in oil the acceleration of the process seems not to be so significant to justify the application of alternative fluids. On the other hand, when the drying temperature is not so high, or the moisture content in oil cannot be kept within so low values, which sometimes happens when a large transformer is dried in the field, the improvement achieved turns out to be appreciable.
- Better results are also obtained on thinner insulations, where the effect of the boundary condition in the whole process is more significant. In the case of very thick

insulation, the largest part of the drying process is the removal of water from the inner part of the insulation to the surface of contact with oil where it is released. The duration of this period mainly depends on temperature and less on the drying agent.

- Different commercial natural esters were compared; very similar behaviors were observed between them.
- Natural esters are more oxidation susceptible than mineral oils. The drying procedures must be carefully revised in case of using these fluids to guarantee that the drying fluid is not degraded by contact with air or excess of temperature, as the presence of sludge and acid in oil could be harmful for solid insulation.
- This work should be completed to determine the effect of using different fluids in HO drying in the final condition of the insulation, and to guarantee that the procedure can be safely applied. The manufacturers of these kinds of liquids claim that they are compatible with mineral oil and that it would be safe even to operate with mixtures of both kinds of fluids. However esters have different physical properties (dielectric, viscosity, etc.) compared to mineral oil and the effect of the residual ester trapped in the winding after drying may alter the properties of the insulation. As a continuation of this work, tests are being developed to determine if the different drying processes performed at different temperatures and with the different fluids produce a significative degradation of the solid insulation.

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