Adaptation of the impregnation conditions of cellulosic transformer solids to the use of natural esters.

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***Abstract*- Transformers' operation and end of life mainly depend on its solid insulation. It is subjected to different stresses that cause the cellulose degradation. The ageing process is highly dependent on the moisture content and the correct impregnation. In the impregnation process, the dielectric coolant fluid is absorbed by the rest of the transformer porous materials, especially the insulating cellulosic materials, conditioning their properties. Due to the transition to a more sustainable energy system, new lines of research that explore alternatives to traditional mineral oils, as esters, are being developed. However, it is necessary to study their behaviour in the different manufacturing processes and during the operating life of the transformers for their future application. In this paper, the changes to be made in the impregnation process to include a soya-based liquid, taking the place of mineral oil, and considering as solid dielectrics Crepe Paper, Diamond Dotted Paper (DDP), Kraft and Presspaper (PSP) are studied.**

I. INTRODUCTION

Current environmental concern has led to the search to reduce the impacts present in the different components of the electrical system. From the point of view of electrical power transformers, their environmental weakness lies in the use of mineral oils as a coolant and electrical insulator. Their low flash point increases the chances of fire, generating toxic and harmful gases that promote global pollution. In addition, in the event of a leak, local contamination of soils and runoff water produced would be severe.

This situation has led to the need to develop new lines of research that study alternatives to this type of oil, focusing on those of vegetable origin. Their incorporation into the machine increases the safety of the installation in case of fire and, due to their biodegradable nature, in the event of leakage, reduces their impact on the environment. However, its cooling capacity decreases due to its higher viscosity.

In view of the future incorporation of these alternative oils as cooling and insulating medium, studies are required to know the behavior of these liquids during the phases to which current transformers are exposed during their manufacture. In this, the pores of the insulating materials during the impregnation process are filled by the fluid giving to the whole a higher dielectric strength. This reduces the probability of partial discharges that compromise the cellulose degradation, which would reduce the operating life of the transformer [1].

The aim of this work is to identify the necessary changes to be made in the impregnation process to include esters, taking the place of mineral oil, to match the times and quality usually achieved during impregnation with traditional oils. For this purpose, experimental tests are made to simulate the real impregnation process carried out in the industry, varying the temperature conditions. The influence of temperature on the characteristics of the dielectric liquids, such as viscosity and surface tension, as well as that which dominates the process are studied. In addition, the ease of impregnation shown by the solid materials studied is considered.

II. THEORETICAL PRINCIPLES OF IMPREGNATION

A. Viscous flow of oil in the capillary.

The pores of the insulating materials, which initially contain air, during the impregnation process are filled by the fluid. The amount of liquid per unit of time flowing into the capillaries, assuming a parallel distribution of these, follows the Hagen-Poiseulle law (1) [2].

$$\frac{dV}{dt} = \frac{\pi}{8 \cdot \mu} \cdot \frac{r^4}{L} \cdot (P_0 - P_1) \tag{1}$$

where,

L = Depth or length of impregnation that increases with time.

$P_0 = P_E + P_S$, where P_0 is the pressure in the liquid equal to the sum of P_E, external pressure and P_S, the pressure in the capillary created by the liquid.

P_1 = Internal pressure.

r = Average equivalent radius of the capillary.

t = Time.

V = Volume of oil inside the capillary.

μ = Dynamic viscosity of the insulating oil.

Assuming that the volume of the capillary is cylindrical and integrating (1) as a function of time, the impregnation length is expressed according to (2).

$$L = \frac{1}{2} \cdot r \cdot \sqrt{\frac{P_E + P_S - P_1}{\mu}} \cdot \sqrt{t} \quad (2)$$

Equation (2) shows that the length, and hence the impregnation speed, are inversely proportional to the viscosity of the fluid. Furthermore, due to the radical nature of the equation, as the impregnation time increases, the impregnation speed slows down.

B. *Capillary action*

Within a liquid, its molecules are under internal cohesive forces that hold the substance together, that are responsible for the creation of the surface tension. However, when the liquid comes into contact with a solid surface, adhesion forces appear between both. Depending on the solid and the type of fluid studied, the adhesion forces can achieve a greater magnitude than the cohesion ones. This cause that liquid forms a concave surface with a contact angle θ with the solid, wetting the solid surface and allowing the liquid to flow into the capillary, even in opposition to external forces such as gravity.

The pressure created by the surface tension that pushes the liquid upward is defined in (3).

$$P_s = \frac{2 \cdot \gamma \cdot \cos\theta}{r} \quad (3)$$

where,

P_s = capillary pressure.

γ = surface tension of the dielectric liquid.

θ = contact angle between the oil and the cellulosic solid.

Under conditions where during impregnation there is no difference between the external and internal capillary pressure, the pressure in the liquid is due to the pressure caused by surface tension. Combining equation (2) and (3), the impregnation length can be expressed as shown in (4).

$$\mathrm{L} = \sqrt{\frac{\mathrm{r} \cdot \gamma \cdot \cos\theta}{2 \cdot \mu}} \cdot \sqrt{\mathrm{t}} = \lambda \cdot \sqrt{\mathrm{t}} \quad (4)$$

As shown in (4), the impregnation length maintains a linear relationship with the square root of time, known as the impregnation rate λ [3]. The impregnated length over time in this situation is dependent on the properties of the liquid, such as the surface tension, its viscosity and the contact angle between the liquid and the solid, as well as the average equivalent radius of the capillary. For two given materials under the same conditions, these values are constant, giving rise to the impregnation rate λ.

C. *Inner Pressure*

By changing the pressure values at which the impregnation is carried out, the speed of the process can be increased. Before the impregnation process vacuum is applied in order to remove the internal pressure of the capillary. However, there is usually a remaining pressure in the capillary, because the vacuum never becomes complete and due to the effect of the water evaporation pressure.

When a solid is impregnated by a liquid, as the impregnation length increases, so does the internal pore pressure because the available free volume relative to the initial is reduced.

The relationship between the internal pressure (P_1) and the impregnated length at a certain instant (L) is expressed according to (5).

$$P_1 = P_A \cdot \frac{L_0}{L_0 - L} \quad (5)$$

Where P_A is the initial pressure in the capillaries of the solid, L_0 its total length and L the impregnated length at an instant of time.

III. Methodology

The cellulosic insulating materials studied are Diamond Dotted Paper (DDP), Kraft, Presspaper (PSP) and Crepe. The main property that takes part in the impregnation process is their density, as it shows a direct relationship with the defined capillary mean radius (4). On the dielectric liquids side, the physical-chemical properties, such as surface tension and viscosity, of a soya-based ester and a mineral oil, in the temperature range studied are compared, as well as that one which dominates the process. The vegetable oil, according to the values provided by the manufacturers at 40ºC, has a kinematic viscosity value higher than the mineral one by 400% higher. Then, higher impregnation speeds of traditional oil are expected in relation to the ester under the same process conditions (4).

The dimensions of the cellulosic papers were 1.5 x 30 cm. These were subjected to a drying process. The starting moisture percentage of the cellulosic materials, according to the conditions of the laboratory was 7-8.5%. After several tests it was concluded that, when the drying temperature is 105ºC, the cellulosic paper after the first 3 hours of drying, reduces its water content below 0.75%. For the drying process of dielectric liquids, good results were obtained by performing vacuum cycles of 15 mbar and introducing dry nitrogen at a pressure of 500 mbar, at a temperature of 50ºC. These cycles were 2 h in vacuum, followed by half an hour in nitrogen atmosphere, for a total time of 12 h. Humidity values of about 35 and 70 ppm were obtained for mineral and vegetable oil respectively.

After drying process, the solid and liquid samples are conditioned under vacuum at the test temperature. At this time, the dry dielectric fluid is introduced into the impregnation containers with the cellulosic samples already placed in them, leading to the beginning of impregnation.

Impregnation is carried out in the vacuum chamber at 15 mbar in a temperature range between 31ºC (ambient) and 80ºC. The aim is recording the temperature at which the natural ester impregnates the cellulosic material as fast as the mineral oil does. This will be the equivalent temperature. This process was recorded with a controlled camera that took photographs every thirty minutes. These photographs were analyzed on a computer using software that allows to measure the impregnation lengths at the recorded moments. The advance of this variable is visible because as the impregnation progresses, the cellulosic material obtains a darker colour due to the presence of the oil in its pores, as shown in Fig. 1.

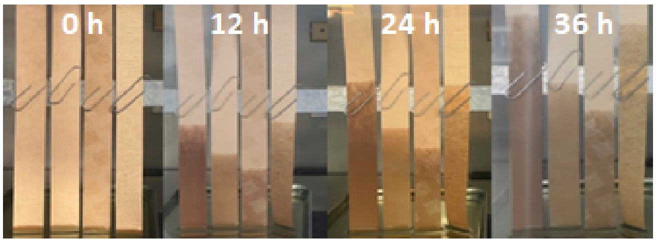

Fig. 1: Advance of impregnation length over time for cellulosic papers; PSP, Kraft, DDP and Crepe, from left to right.

IV. Results and Discussion

An example of recorded data on the progress of impregnation over time in dielectric materials is depicted in Fig. 2. It is evident that the impregnation speed experienced by the sample over time slows down as it progresses. In addition, the papers that impregnate faster can be already seen. Those that show a greater ease of impregnation are PSP and Crepe, while the slowest of the studied set are Kraft and DDP. The order of the papers' impregnation rate analyzed in this situation is maintained independently of the dielectric fluid used and the temperature, since the changes in fluid characteristics due to temperature variation affect all cellulosic samples equally.

The results of impregnation length, due to its radical evolution, can be represented as a function of the square root of time, as shown in Fig. 3. A linear relationship between both variables can be verified (4). The slopes of these graphs are known as the impregnation ratio (cm/√min), which is representative of the impregnation speed of the samples [3]. These trends coincide with the views in Fig. 2.

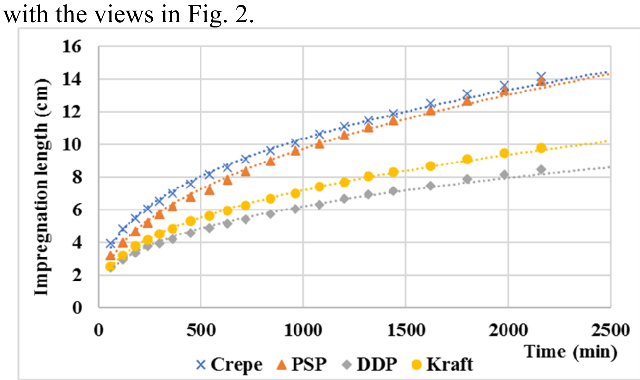

Fig. 2: Variation of the impregnation length over time for natural ester at 50ºC.

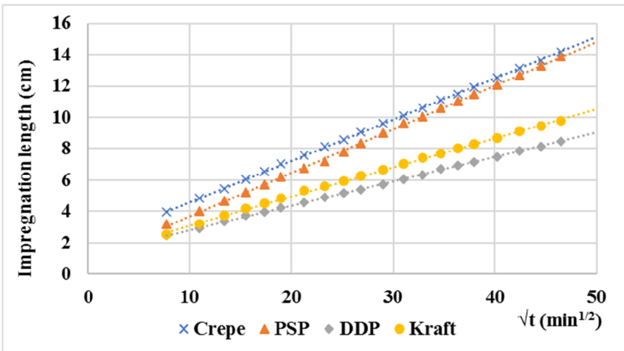

Fig. 3: Variation of impregnation length with square root of time for natural ester at 50ºC.

Fig. 4 shows the length of impregnation as a function of the time of the Kraft paper with the two oils studied at 50ºC. It is observed that the mineral is the one that reaches the longest impregnation lengths. This is because of the low viscosity value in the temperature range studied compared to the natural ester, which favors the impregnation process (4).

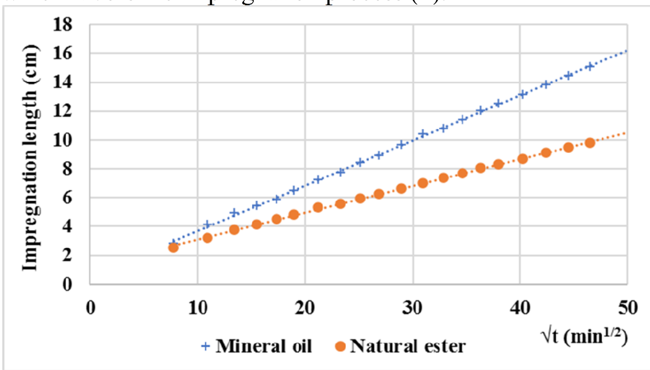

Fig. 4: Variation of impregnation length with the square root of time for Kraft paper with a natural ester and a mineral oil at 50ºC.

The impregnation slopes of all possible combinations of paper and oil, for a temperature range between 31ºC (ambient) and 80ºC, are represented in Fig. 5.

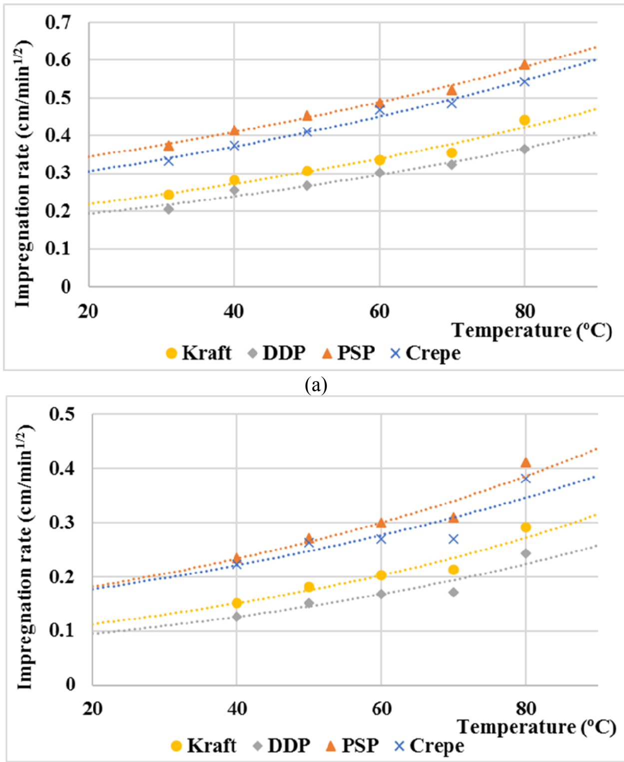

Fig. 5: Variation of impregnation ratio with temperature for (a) mineral oil and (b) natural ester.

It can be seen how as temperature increases, so do the impregnation ratios. This is because the effect of temperature on viscosity is much higher than the effect on surface tension, as shown in Fig. 6. Moreover, this last variable shows an opposite trend with the process since lower surface tension values would slow the impregnation (4). Based on this, it can be asserted that viscosity variation predominates over surface tension when deciding impregnation temperatures. Previously, other authors [4] have already stated that the capillary effect, formed by the surface tension and the contact angle between the liquid and the dielectric insulator, hardly suffer any variation between the different combinations of materials.

On the other hand, it is seen that vegetable oil undergoes a greater increase in the impregnation ratio, as a result of the reduction of viscosity in natural esters is greater than that suffered by mineral oil (Fig. 6). However, it is the mineral oil that has the highest impregnation speeds in the temperature range studied.

Due to the exponential variation of viscosity with temperature, being also the main property that conditions the impregnation, in Fig. 6 an exponential adjustment of the variation of the impregnation ratio as a function of temperature has been made. Table I shows the model parameters according to this setting. From these, the temperatures at which a certain impregnation ratio value is reached for any of the combinations of materials studied are deducted.

With the data of the impregnation ratios in mineral oil at room temperature, and the model equations collected in Table I, it is possible to estimate the temperatures at which a material is impregnated, with an alternative liquid, at the same rate as with mineral oil at room temperature. The average temperature at which dielectric materials must be heated when using a natural ester based in soya is about 77 ºC.

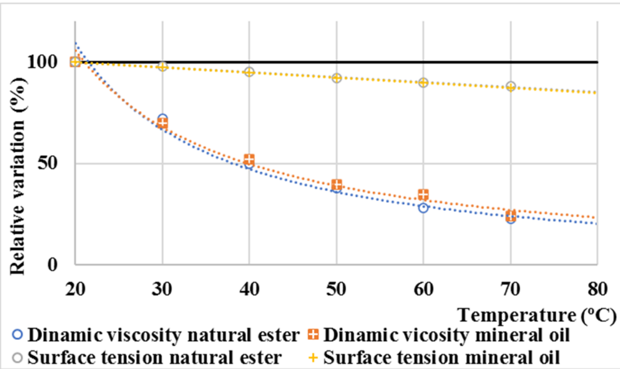

Fig. 6: Representation of the variation of surface tension and relative viscosity at 20ºC with temperature for the dielectric liquids studied.

TABLE I
EXPONENTIAL MATHEMATICAL MODEL OF THE IMPREGNATION RATIO VARIATION WITH THE TEMPERATURE

$\lambda(T) = ce^{dT}$	Natural ester			Mineral oil		
	c	d	R^2	c	d	R^2
Kraft	0.0840	0.0147	0.926	0.1760	0.0110	0.957
DDP	0.0712	0.0143	0.951	0.1561	0.0107	0.908
PSP	0.1412	0.0126	0.975	0.2886	0.0088	0.961
Crepe	0.1418	0.0112	0.964	0.2518	0.0097	0.926

V. CONCLUSIONS

The application of alternative dielectric liquids, instead of conventional ones, as insulators and transformer coolants, requires an adaptation in the impregnation methods traditionally used for this purpose. The analysis of surface tension and viscosity with the effect of temperature, for a natural soya ester and a mineral oil, has shown that viscosity is the property of dielectric liquids that most influences the impregnation process, since, unlike surface tension, it presents large variations in the temperature range studied, regardless of the combination of materials analyzed.

The use of the ester as a dielectric and coolant liquid is conditioned by its higher viscosities, compared to those of mineral oils, which slow the impregnation processes, and therefore the manufacture of transformers. This disadvantage can be avoided without extending production times taking advantage of the evolution of viscosity with temperature. The increase of this variable means the acceleration of the impregnation process with both oils, due to the decrease in their viscosity. This acceleration is more pronounced as higher is the viscosity of the oil, i.e., in the ester. However, esters do not reach the impregnation levels seen with mineral oil in the temperature range studied under the same process conditions.

On the cellulosic paper side, those that obtain higher impregnation rates, reducing impregnation times for a defined length, in descending order are PSP, Crepe, Kraft and DDP.

The heating of the ester allows to achieve impregnation speeds similar to those shown by the mineral oil at room temperature in each solid material. In the case of the soya-based ester studied, the average temperature at which it equals the traditional impregnation process is 77ºC.

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