Study of the Impregnation of Power-Transformer Cellulosic Materials With Dielectric Ester Oils

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ABSTRACT The application of alternative dielectric oils as esters in power transformers is hindered by the lack of knowledge regarding their properties and respecting which are the best techniques to ensure their proper performance. In this sense one of the fields needing an impulse is the impregnation processes of transformers cellulosic materials with these alternative oils, currently impregnated in most of the cases with mineral oils. This paper studies the impregnation behavior of eight usual dielectric solids, with two esters and a traditional mineral oil. Empirical equations of the impregnation evolution with time have been obtained, from these the rigid cellulosic materials present in the transformers and the viscosity of the dielectric oils have been identified as the key materials and properties to consider during impregnation. An adaptation of the current impregnation processes to the alternative oils have been proposed by increasing their temperature from ambient temperature up to 61-74°C, depending on the viscosity of the oil used.

INDEX TERMS Dielectric, ester, impregnation, model, transformer, temperature.

I. INTRODUCTION

The impregnation step of transformer's solid insulators with dielectric oil during the manufacturing of these electric machines could condition their life expectancy. It is known the role of oils as boosters of the dielectric capacities of transformer solid insulators [1]–[3]. An incorrect impregnation procedure or an excessive haste in the commissioning of one of these machines may lead to the presence of air voids, reducing the insulating capacities of the dielectric papers and promoting the occurrence of failures potentially catastrophic [4], [5].

Consequently, the transformer manufacturers and network operators have been cautious in this sense, promoting techniques and methods to ensure a proper impregnation. Examples of this are the impregnation under vacuum or at elevated temperatures, that eases the complete entrance of oil in the solid without comprising the final properties [1], or the use of equipment specifically designed to ensure the

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contact between oil and solid [6]. This was based on a deeper knowledge of the phenomena that underlies this process: the existence of forces that supposes the entrance of fluid in the pores of a material and their dependence on several parameters to be considered [7].

In this sense, the evolution of the materials has also promoted the adaptation and improvement of impregnation of dielectrics. The appearance of safer and more ecologic alternative dielectric oils as esters [8] has compromised the methods in use, thought for traditional mineral oils and, additionally, it has put the focus on the lack of knowledge and experience regarding the behavior of these fluids [9].

Thus, many researches have been dedicated to this alternative fluids, studying mainly their capacities [10]–[12], their compatibility with other transformer construction materials [13]–[15] or their evolution under working conditions [16], [17]. Scarce studies have been still focused on improving the impregnation state-of-art respecting alternative dielectric oils. Comparisons between the impregnation capacity of different oils have been performed with samples of dielectric papers. Lu *et al.* [8] focused on the characterization

of the impregnation speed of a mineral and an alternative oil in pressboards. They found that the natural alternative oil, more viscous, can impregnate at 60°C similarly than the mineral one at 20°C. Additionally, they noticed that the impregnation worsened from single-layered to multi-layered pressboards. A similar situation was found by Dai and Wang et al. [5], again with pressboard, between a mineral oil and a natural ester. In this case, moreover, the mineral oil at 40°C behave like a synthetic ester at 60°C. The oil viscosity conditions the impregnation speed. The relative impregnation capacities of this kind of fluids and their opposite tendency regarding their viscosity were confirmed by *Pawel Rozga*, with the addition of a low viscosity ester, more similar to the mineral oil [9].

In the case of the studies of Jariyanurat et al. [3] they compared the dielectric properties of pressboard samples impregnated with a mineral oil and a natural ester during three different time laps. They noticed that the benefits of oil impregnation on the pressboard dielectric strength, more intense as more lasted the impregnation, were more pronounced in those with natural ester. The dependence of the improvement of the dielectric properties of solid insulation on the impregnation time was also noticed by Indarto et al. [4].

In view of this need to deepen in the impregnation of dielectric solid insulators this work proposes the study of impregnation considering the large variety of solid insulating materials present in transformer, with representatives from the main dielectric fluids found in literature. The intention is to characterize the impregnation process of these materials and thus make an advance in the applicability of dielectric esters, being a significant progress over previously published articles.

II. IMPREGNATION THEORETICAL BASIS

To simplify the explanation of the physics under the impregnation of the pores of a dielectric solid these are studied as capillary cylinders of radius r, as this shown in Fig. 1. The incoming of fluids in capillary is ruled by the Hagen-Poiseuille Law (1) [5], [8].

$$\frac{dV}{dt} = \frac{\pi}{8\eta} \cdot \frac{r^4}{L} \Delta P \tag{1}$$

where V is the volume of fluid, t is the time, η is the dynamic viscosity, r is the capillary radius, L is the length of the capillary submerged in the fluid and ΔP is the gradient of pressure inside the pore. The pressure gradient can be expressed as the difference between the pressure forces for the introduction of the fluid and those against this event. Among the first category they are the external pressure P_E and the pressure created by capillary effect (or capillary attraction) P_S. Against the entrance of fluid is the inner pressure of the pore P_I, generated by the air encapsulated inside the pore. The existence of this encapsulated air supposes the impregnation processes of this kind to be dynamic, as the magnitude of the inner pressure increases as the fluid rises and the available volume

declines, reducing the impregnation velocity as larger is the impregnated length [8]. In this sense, for impregnation purposes, the shorter the pores of a material the better [5].

Fluids as oils in touch with porous materials as papers tend to get into the pores, as it is represented in Fig.1. This is due to the prevalence of the external pressure and the capillary effect over the inner pressure. A way to enhance this prevalence is by removing the inner pressure by the application of vacuum in the solid samples prior the impregnation [7], a widespread technique in impregnation studies [5], [8]. Another technique is to increase the external pressure once the solid samples are completely submerged and the pores are isolated from the atmosphere by the oil [7].
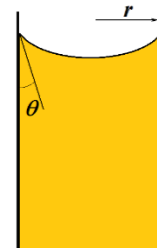

FIGURE 1. Example of the equilibrium reached by a fluid in a capillary tube when the solid-liquid adhesive forces overcome the fluid's cohesive forces.

To able tracing the impregnation evolution based on the appearance, the solid samples to impregnate should not be submerged in the fluid. This supposes that, under vacuum, the pressure gradient is only created by the capillary effect, changing the Hagen-Poiseuille Law as it is showed in (2).

$$\frac{dV}{dt} = \frac{\pi}{8\eta} \cdot \frac{r^4}{L} P_S \tag{2}$$

By transforming the capillary volume impregnated in function of the radius and length, and by integration, this law can be formulated as in (3).

$$L = \frac{1}{2} r \sqrt{\frac{P_S}{\eta}} \sqrt{t} \tag{3}$$

The capillary effect rises from the equilibrium between the adhesive forces between the solid and the fluid, the gravitational forces and the cohesive forces between fluid molecules (whose magnitude is represented by the fluid's surface tension γ). This equilibrium is at the same time represented by the value of the contact angle θ, between the solid surface and the tangent to the surface of the fluid in contact to the solid (Fig. 1) and depends on the capillary radius. Thus, the capillary effect pressure is as in (4).

$$P_S = \frac{2\gamma \cos\theta}{r} \tag{4}$$

From the combination of (3) and (4) it rises an expression of the length reached by a fluid in the pores of a material in function of the radius of these pores, the viscosity of the fluid, the relationship between solid and fluid and the time elapsed,

TABLE 1. Main characteristics of the oils and esters used for impregnation purposes.

Parameter	Mineral Oil	Natural Ester	Synthetic Ester
Density (293K) (kg/m^3)	842	910	969
Kinematic viscosity (313K) (m^2/s)	$1.03 \cdot 10^{-5}$	$3.92 \cdot 10^{-5}$	$2.74 \cdot 10^{-5}$
Moisture content (ppm)	15	150	22
Flash point (K)	443	603	523
Acidity (mg KOH/g)	0.01	0.05	0.05
AC Breakdown voltage (kV)	30	65	77
Biodegradability (28 days) (%)	---	85	72

under vacuum (5). An analysis of (5) reflects that it exists a linear relationship between the length reached by the oil and the time squared root, represented by the slope λ, known as impregnation rate [5]. Also, it can be seen that, after a defined time, the impregnated length would be larger as wider is the capillary, as lower is the viscosity of the oil, as higher is the surface tension of the oil or as smaller is the contact angle [5]. Nevertheless, among different dielectric oils, their capillary effect pressures, from their surface tension and contact angle, do not differ too much [8].

$$L = \sqrt{\frac{r\gamma cos\theta}{2\eta}} \sqrt{t} = \lambda\sqrt{t} \qquad (5)$$

As oil's viscosity and surface tension depend differently on temperature, an enhancement of the impregnation rate of a fluid-solid combination could come from the control of this variable. Although both the viscosity and the surface tension of the fluid get reduced by increases of temperature, this reduction is more pronounced in case of viscosity [5], [8]. Thus, it can be said that oil viscosity is the main parameter to condition the impregnation of a determined solid material under vacuum [8] and, also, that it is the main parameter to be managed to improve this impregnation, in example by heating the oil. If heat is applied to accelerate any impregnation the execution of vacuum is even more important as, on the contrary, the pores inner pressure would be higher due to the larger water vapor pressure [7].

III. MATERIALS AND METHODS

The experimental impregnation studies of this research have been developed with three different oils. Two alternative dielectric esters, with natural and synthetic origin (N.E. and S.E. respectively), and a traditional mineral oil for transformers (M.O.), as reference for comparison purpose. Regarding the solid insulators, four different dielectric papers (crepe, Diamond Dotted Paper or DDP, Kraft and Presspaper or PSP) and other four rigid dielectrics, made of pressboard and wood (Laminated pressboard T-IV blocks, Laminated pressboard T-IV bushing insulation, Laminated pressboard T-IV sticks and Phenolic wood blocks), have been tested. The specifications of these liquid and solid materials are available in Table 1 and Table 2, respectively. Examples of each cellulosic are shown in Fig. 2.

As can be seen in Table 1, the density and kinematic viscosity of the esters are larger than those in the mineral oil. Then, slower impregnations with these esters are expected. The advantages of these dielectric oils come from other properties as their higher flash points or breakdown voltages, that improve the safety of the transformers, or their biodegradability, ensuring a low impact in the environment in case of spills. Also, by comparing Table 2 paper's dielectric strengths, it is noticeable the positive effect of impregnating dielectric paper with oil, mentioned in the introduction.

These materials were subjected to drying processes. For this, the solid insulators were previously cut. The dielectric papers were conformed in stripes of 30 cm x 2 cm and set in the test support (Fig. 3 (a)). In the case of the rigid materials there were used pieces of 10 cm of length.
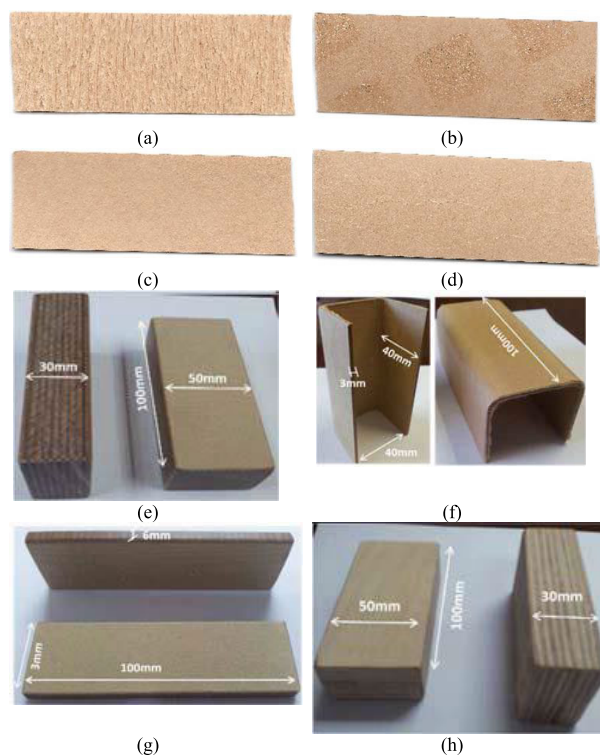

FIGURE 2. Appearance of the dielectric papers (Crepe paper (a), DDP (b), Kraft paper (c) and PSP (d)) and rigid cellulosic materials (Laminated pressboard T-IV blocks (e), Laminated pressboard T-IV bushing isolation (f), Laminated pressboard T-IV sticks (g) and Phenolic wood blocks (h)).

TABLE 2. Main characteristics of dielectric solid materials in this research.

Material	Thickness (mm)	Moisture Content (%)	Tensile Strength Machine Direction (MPa)	Apparent density (kg/m³)	Dielectric Strength in air (kV/mm)	Dielectric Strength in oil (kV/mm)
Crepe Paper	0.55	< 8	73	800	≥ 5	≥ 30
DDP	0.15	< 8	75	935	≥ 1.1	≥ 50
Kraft Paper	0.15	< 8	75	1100	≥ 9	≥ 40
PSP	0.15	< 8	115	1153	≥ 10	≥ 70
Laminated pressboard T-IV blocks	30	< 6	124	1200	---	52
Laminated pressboard T-IV bushing insulation	3	< 8	115	1000	---	50
Laminated pressboard T-IV sticks	6	< 3.5	130	1300	---	13.5
Phenolic wood blocks	30	< 4	130	1000	---	15.5

Regarding the oil samples, 40 ml of each fluid were set in identical laboratory crystallizers. The solid insulators were firstly introduced in an oven at 105°C for 24 h. The drying processes continues introducing both the solid and liquid test samples, separately, in a vacuum chamber at 50°C under cyclic pressure variations during 63 h. Each cycle consisted in 6 hours under a 200mbar-N2 atmosphere, followed for 3 hours under vacuum (5 mbar). The moisture content of liquid and solid dielectrics is analyzed by Karl-Fischer titration (IEC 60814). This treatment removed the 75-80% of the moisture content in the solid samples, and between 75-85% in the oils, without the appearance of thermal degradation in the samples. The samples were conditioned to test temperature during the last cycle.

Once finished the drying process, inside the same vacuum chamber, the dry solid samples were partially introduced in the dry oil samples and, once again, the vacuum inside the chamber was done, while maintaining the test temperature. A camera recorded the evolution of the sample's impregnation process since the closure of the chamber, taking as reference a border between the dry and impregnated sample, denoted by a change in the color of the material, visible in Fig. 3 (b). The evolution of impregnation in each sample combination would allow knowing the impregnation rates. In those materials with an irregular frontier between dry and impregnated areas, a mean impregnated height is calculated.

In the case of paper samples, 6 different temperatures were set during the test series (ambient temperature, 40, 50, 60, 70 and 80°C). Regarding those samples based on pressboard and wood (Fig. 3 (c)), issues in the availability of these materials derived in a smaller number of impregnation temperatures tested, three per sample combination. These were chosen in base of the results obtained with paper samples, in function of the dielectric oil in application.

IV. IMPREGNATION RESULTS
From the recorded evolution of the impregnation on every sample combination at different temperatures there were
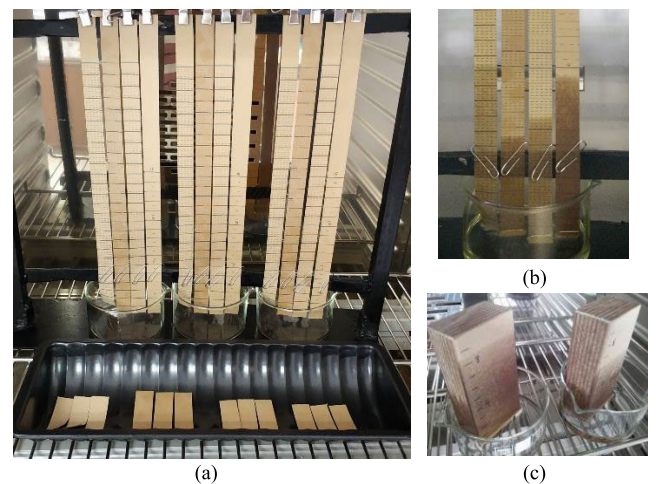

FIGURE 3. Disposal of the paper stripes on the test support inside the drying oven, with those paper samples for moisture control (a). Snapshot of the papers impregnation process with one of the oils under vacuum (b). Snapshot of the impregnation process of a rigid sample with two of the oils under vacuum (c).

periodically chosen images, for the measurement and registration of the relative positions of the impregnation borders in the materials regarding the starting points. As the impregnation rate slows down, the rhythm of registrations is slower as the tests progress.

A. IMPREGNATION OF PAPER SAMPLES
In first place the results obtained with the paper samples, impregnated with the three oils, are shown. In Fig. 4 it is summarized the evolution of the height of the impregnation border in the four papers with time, at 70°C. It is noticeable that the papers more easily to impregnate are the PSP and the crepe paper, while the DDP has the worst impregnation speed, regardless the oil used. Regarding how the test fluid affects these evolutions, the comparison of the three figures reflects that the fastest impregnation is reached with the mineral oil. On the contrary, the natural ester presents more difficulties

during impregnation, whatever the paper used. These situations are the same in the other 5 test temperatures, as it occurred in similar works [5], [8], [9].

According to that explained in Section 1, these height evolution results may be represented against the root square of time, in order to check the existence of a linear relationship between these two parameters, as expected and observed in other works [5], [8]. This is also fulfilled in this research, as it is shown in Fig. 5.

This relation, called impregnation rate, is estimated from the experimental results for all the set of tests done with the sample combinations at the different temperatures by linear regression. The impregnation rate meets the slope of the tendency lines, as those available in Fig. 5. Later, the mean value of the different impregnation rates at each temperature has been obtained. These mean values are represented in Fig. 6.

Here, it is again noticeable the dependence of impregnation speed on the fluid and paper types, already mentioned, but also how an increase of the impregnation temperature improves the impregnation speed. The mean relative increase of the impregnation rate with temperature has been up to 63% with the mineral oil, 89% with the synthetic ester and 91% with the natural ester. The creation of tendency lines from the experimental data shows that the variation of the impregnation rate with temperature fits with a linear expression in the temperature gap studied, according to the coefficients of determination obtained, also summarized in Fig 6.

Thus, mathematical equations to represent this relationship between these parameters have been obtained. These are available in Table 3 and are useful to infer how one of these oils would behave in a determined temperature, or which temperature is needed to ensure a desired impregnation speed. Although the relative increases of impregnation rates with temperature were larger in the esters, from the slopes of the linear regressions it can be seen that the impregnation speed is more affected by temperature when mineral oil is used, followed once more by synthetic ester.

TABLE 3. Parameters of the linear equations representing the variation of the impregnation rates of the tested papers with the temperature, for the three dielectric oils under study.

$\lambda = a \cdot T(°C) + b$	Mineral Oil		Synthetic Ester		Natural Ester	
	a	b	a	b	a	b
Crepe	0.0415	2.6476	0.0346	1.1834	0.0285	1.1880
DDP	0.0278	1.4339	0.0207	0.5792	0.0184	0.6054
Kraft	0.0305	1.8916	0.0243	0.8039	0.0219	0.7453
PSP	0.0409	2.7106	0.0311	1.3145	0.0272	1.1141

In Fig. 7 the mathematical equations for DDP (dotted lines) and PSP (dashed lines) have been represented with the three types of fluids (for clarity of the figure, the other two types of paper have not been represented). It can be observed that, for all three fluids, PSP is better impregnated than DDP. Moreover, one can notice how the mineral oil (brown) impregnates faster than the synthetic ester (green), being the natural ester (blue) the one with the slowest impregnation speed,
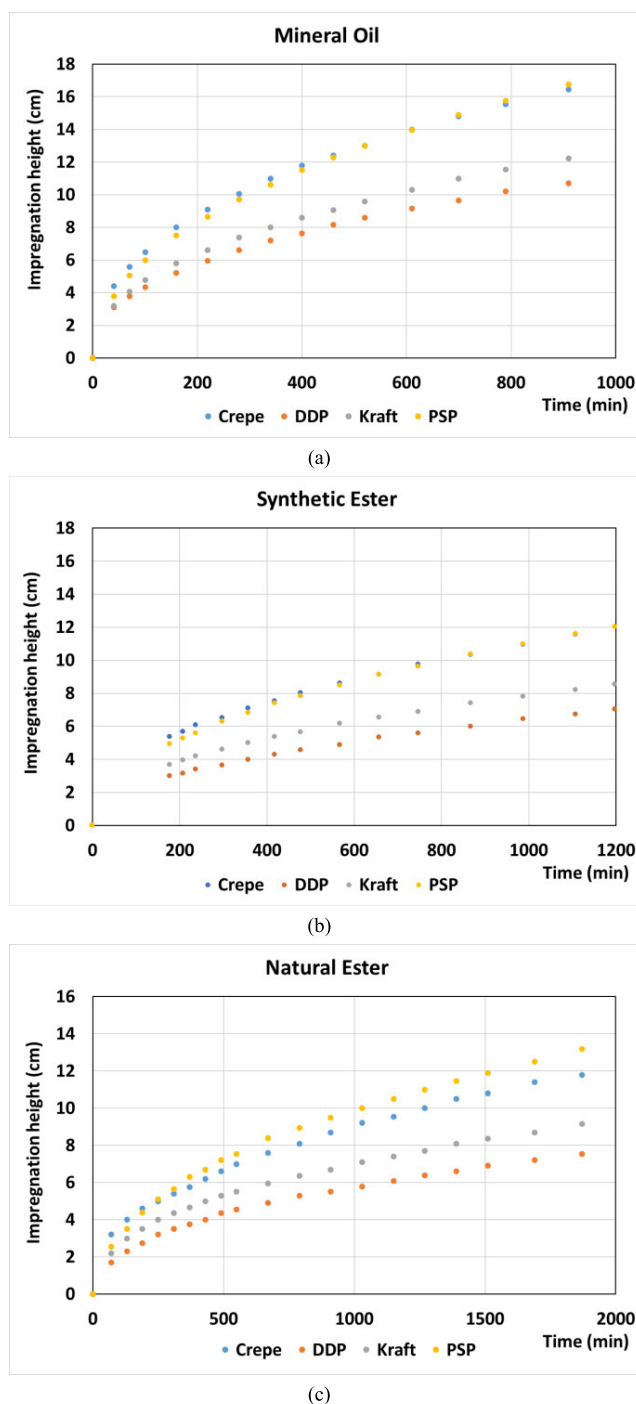

FIGURE 4. Time evolution of the impregnation height in the different paper samples at 70°C with mineral oil for the three types of fluids.

with slightly lower values than the synthetic ester. In order to achieve the same impregnation speed with the synthetic ester as mineral oil at room temperature (25°C), according to the equations, it is necessary to reach around 77°C. And, to achieve a similar speed with the natural ester, it is necessary to exceed 95°C. These equivalent temperatures have resulted higher than in other researches taken as reference (60°C for natural esters [5], [8]) but still bearable by the dielectric materials.
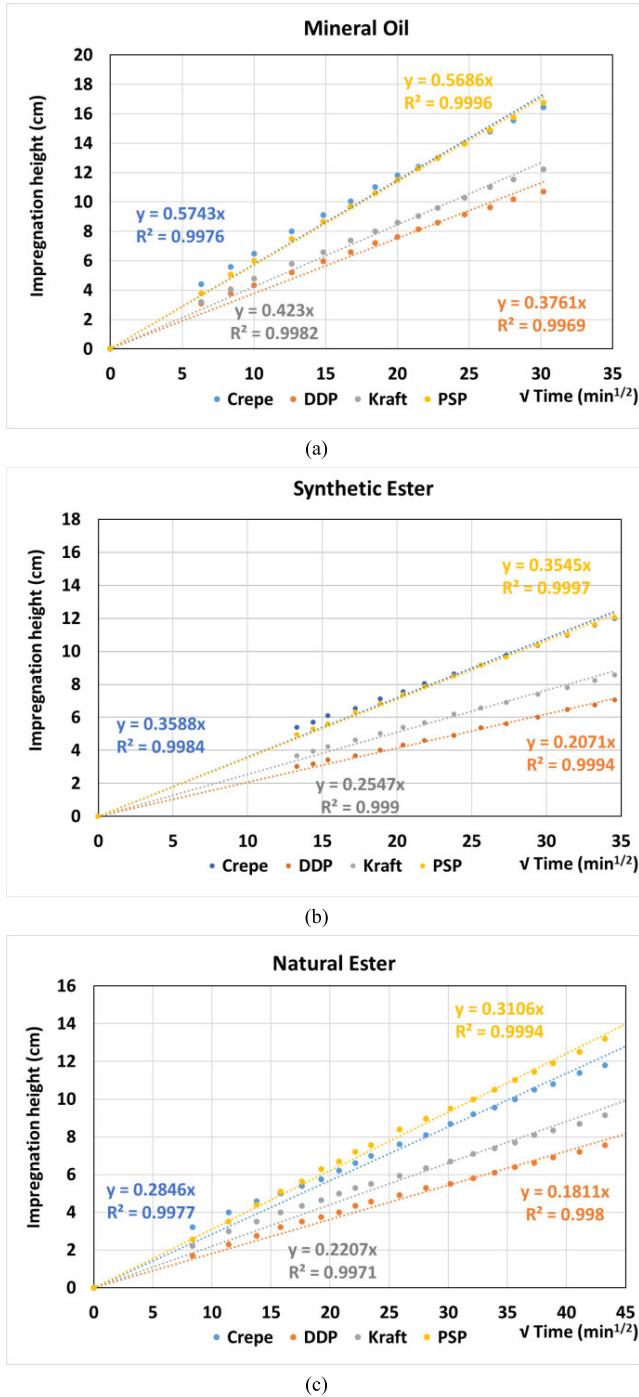
(a)

(b)

(c)

FIGURE 5. Relationship between time square root and the impregnation height in the different paper samples at 70°C for the three types of fluids.

B. IMPREGNATION OF RIGID CELLULOSICS

With the impregnation results of papers as starting point and considering the restrictions in the availability of rigid cellulosic samples, the test temperature gaps for rigid cellulosic materials impregnation were chosen in function of the dielectric oil to be used. Thus, those samples impregnated with mineral oil were heated between ambient temperature and 60°C. Ranges between 40 and 70°C and from
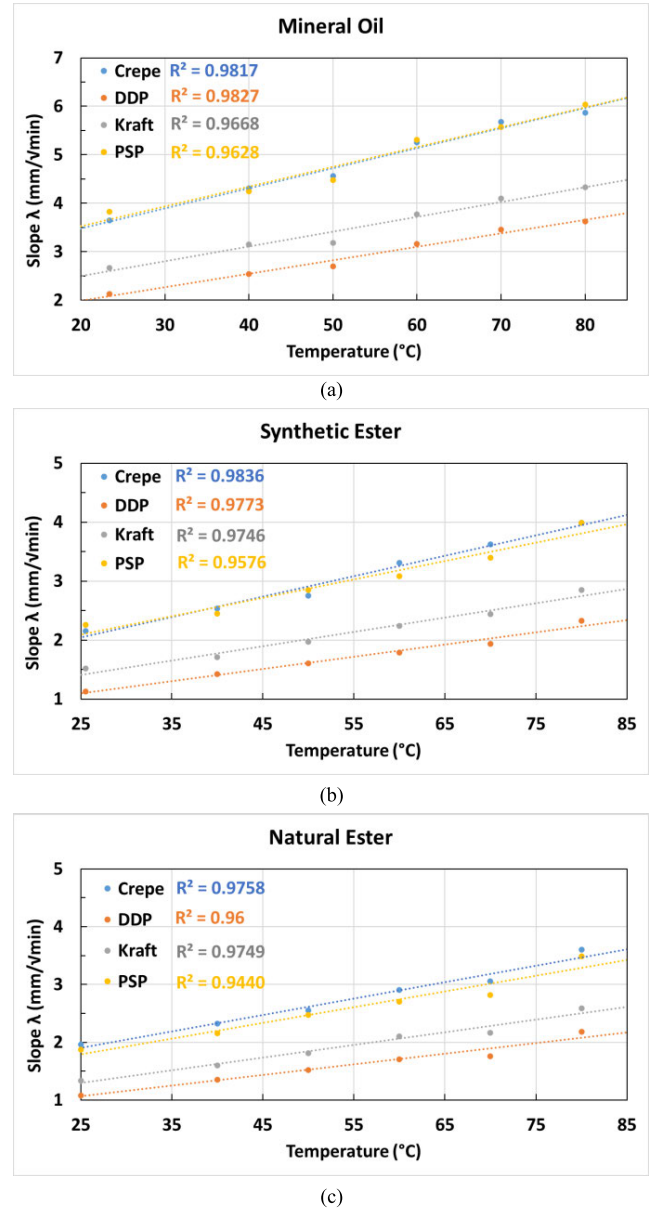

(a)

(b)

(c)

FIGURE 6. Mean impregnation ratios λ of the tested papers, at different temperatures, with mineral oil (a), synthetic (b) and natural ester (c).

50 to 100°C were chosen for those with synthetic and natural ester, respectively. The main intention was to be close to those temperatures that allow these alternative oils to impregnate with a similar rate than the mineral oil at ambient temperature.

The test method was the same used for papers, obtaining the evolution of the impregnation in the pressboard and wood samples with mineral oil, synthetic ester and natural ester. As the impregnation frontier in these cases is more irregular (Fig. 8), a mean oil height was inferred, as in [7]. The evolution of oil height in these materials showed again a linear relationship with time squared root. From these results, the impregnation rates were calculated and averaged at three different temperatures. These have been plotted in Fig. 9.
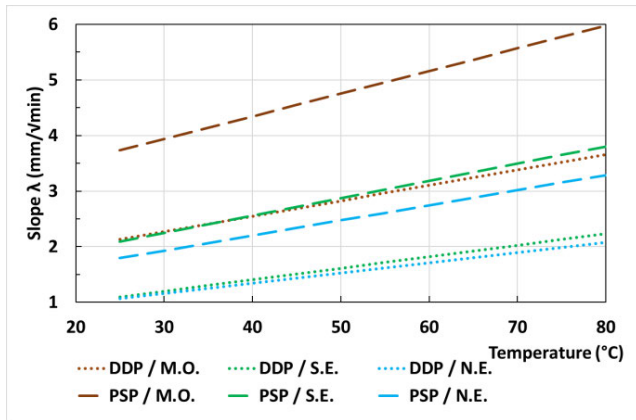
FIGURE 7. Plots of the mean impregnation ratio (λ) evolution-with-temperature equations for DDP and PSP papers.
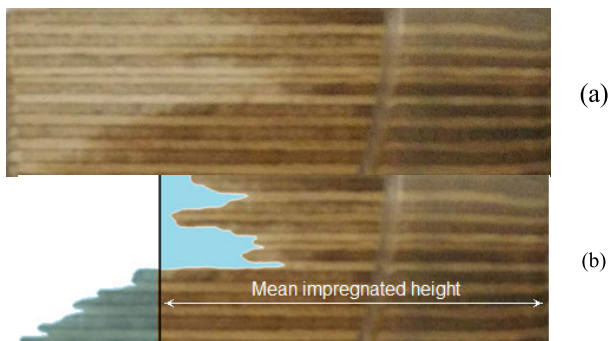

FIGURE 8. Appearance of an irregular impregnation border in a phenolic wood (a). Estimation of the mean impregnated height in case of irregular impregnation border (b).

The evolution with the temperature of the impregnation rates was similar to those saw with dielectric papers, with a worst adequation to a linear regression, probably due to the limited number of temperatures tested. It can be appreciated that, among the tested materials, the phenolic wood presents the larger impregnation speed, followed by the pressboard bushing isolators. The results are not clear regarding the pressboard sticks and blocks, showing in any case similar impregnation rates. Respecting the oils, by comparing at similar temperatures, the mineral oil shows a bigger impregnation capacity, followed by the synthetic ester, with the natural ester in the last position.

From the linear regressions more impregnation empirical equations were obtained, summarized in Table 4. In this case the effect of temperature on the impregnation of these materials is not that with papers. Although the relative effect of temperature on impregnation rate is still bigger in the esters, especially in the natural one, when speaking in absolute terms it is not clear which oil impregnation speed is most affected.
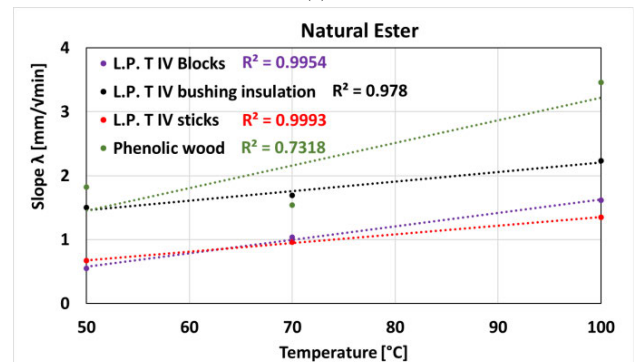
In Fig. 10, the impregnation models for Laminated pressboard T-IV bushing insulation (dotted lines) and Laminated pressboard T-IV sticks (dashed lines) with the three types of fluids are available (for clarity of the figure, the other two types of rigid insulators have not been included).
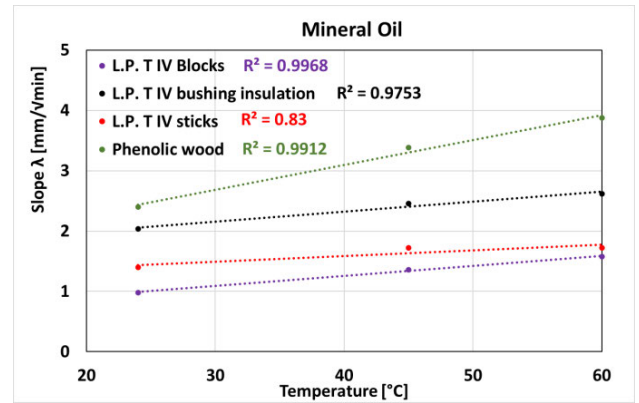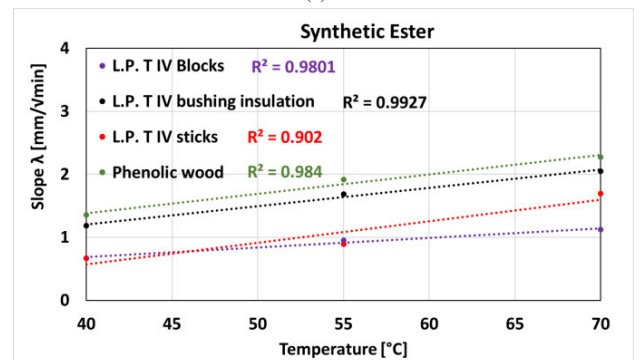
FIGURE 9. Mean impregnation ratios of the tested rigid cellulosic materials at different temperatures for the three fluids.

For the three fluids, the Laminated pressboard T-IV bushing insulation is better impregnated than the Laminated pressboard T-IV sticks. It can also be observed how the mineral oil (brown) impregnates faster than the synthetic ester (green), being again the natural ester (blue) the one with the slowest impregnation speed, with lower values than the synthetic ester.

The analysis of the equations in Table 4 reflects, once more, as in the Fig. 10, that the impregnation rates showed by mineral oil with the rigid components is achievable with the alternative oils by increasing the impregnation temperature. The synthetic oil showed a similar impregnation capacity at approximately 75°C. In the case of the natural esters, in this occasion, the temperature of equivalent impregnation is beyond 100°C.

TABLE 4. Parameters of the linear equations representing the variation of the impregnation rates of the tested rigid cellulosic materials with the temperature, for the three dielectric oils under study.

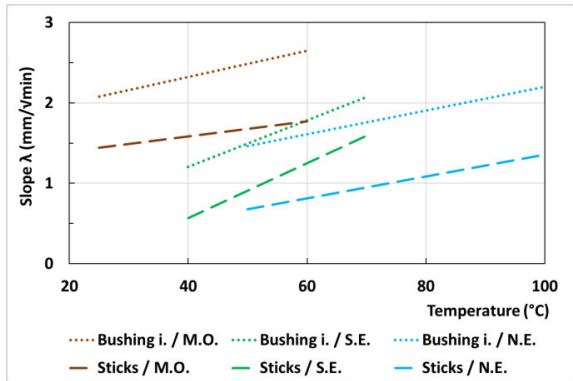| $\lambda = a \cdot T(°C) + b$	Mineral Oil		Synthetic Ester		Natural Ester	
	a	b	a	b	a	b
Pressboard T-IV blocks	0.0167	0.5880	0.0151	0.0859	0.0210	-0.4728
Pressboard T-IV bushing insulation	0.0164	1.6662	0.0289	0.0482	0.0148	0.7216
Pressboard T-IV sticks	0.0094	1.2092	0.0342	-0.7990	0.0136	-0.0025
Phenolic Wood	0.0412	1.4469	0.0308	0.1530	0.0353	-0.3114

FIGURE 10. Plots of the impregnation ratio (λ) mathematical equations derived from experimental results with Laminated Pressboard T-IV bushing insulation and Laminated Pressboard T-IV sticks and mineral oil (M.O.), synthetic ester (S.E.) and natural ester (N.E.) as fluids.

C. RESULTS DISCUSSION

A general view of the experimental results reflects in first place the dependence of impregnation speed on fluid viscosity, as it was seen in other works. Those fluids with a lower viscosity impregnate easily than others more viscous. These results follow this rule with all the cellulosic samples used, as it occurred in other works [9], [8]. With the results obtained it is also possible to check the information found about the scarce differences between the oils derived from their surface tension γ and contact angle θ. Once the impregnation ratio λ is known for these combinations of materials at different temperatures, it is possible to compare if the expression shown in (6), derived from (5), presents similar values, considering r is not a variable in each paper.

$$\frac{r \cdot \gamma \cdot \cos\theta}{2} = \lambda^2 \cdot \eta \tag{6}$$

This has been estimated at 40°C for the four papers used on the basis of the densities and kinematic viscosities available in Table 1 and the impregnation ratios. Although the density belongs for oils at 20°C the error is acceptable and similar to the three oils. The values found are summarized in Table 5.

As it can be seen there are not large differences between the three oils, more if they are compared with the different dynamic viscosities of the three oils at this temperature (from

TABLE 5. Product of the squared impregnation ratio and the estimated dynamic viscosity for each oil/paper combination at 40°C.

$\lambda^2 \cdot \eta$ (SI)	Mineral Oil	Natural Ester	Synthetic Ester
Crepe	$1.61 \cdot 10^{-5}$	$1.75 \cdot 10^{-5}$	$1.93 \cdot 10^{-5}$
DDP	$5.63 \cdot 10^{-8}$	$5.24 \cdot 10^{-8}$	$6.41 \cdot 10^{-8}$
Kraft	$8.39 \cdot 10^{-8}$	$8.36 \cdot 10^{-8}$	$9.39 \cdot 10^{-8}$
PSP	$1.64 \cdot 10^{-7}$	$1.74 \cdot 10^{-7}$	$1.73 \cdot 10^{-7}$

8.6 mPa·s in the mineral oil to 35.7 mPa·s the natural ester). This meets with the precedents about the similar capillary effect of the oils, being the viscosity and the radius the main variables in dielectric impregnation studies [8].

The variation of the impregnation rate with time was also linear as expected, as it seems to happen too with the evolution of this parameter with temperature in this case. Increases of temperature promote the impregnation speed due to decreases in oil's viscosities. Again, this is the most conditioning parameter considering the different evolution with the temperature of the surface tensions and dynamic viscosities shown in Fig. 11, as comparatively the surface tension scarcely varies. In this study, as in [9], the acceleration of impregnation has been also higher in esters. This leads to the existence of equivalent temperatures at which a more viscous oil, as synthetic or natural esters, could impregnate as a mineral oil, as in [5], [8].
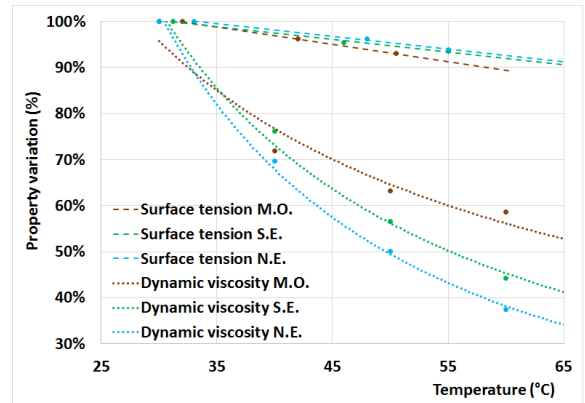

FIGURE 11. Evolution of the dynamic viscosity and the surface tension of the three oils with the temperature.

The equivalent temperatures found in this research have been quite similar to that found in the literature, especially speaking about the papers and pressboards. At the same time, also as in literature [8], the equivalent temperatures found were similar for papers, pressboards and rigid materials, but only in the case of the synthetic ester. This was not the situation with the natural ester. This could be due to the difficulties found by this last oil due to his higher viscosity, the larger section of rigid materials [5] and the presence of impermeable adhesive layers in the material matrix [8].

Regarding the differences found between solid samples for each impregnation liquid, an explication could come from the predominance of capillaries of different radius, that condition

also the densities of these materials, summarized in Table 2. According to [5] and [8], those less dense materials usually present higher impregnation rates, as they have wider pores than other denser materials. Among the papers here used, the crepe paper is the one with the lower density, and the one with the largest impregnation ratio. Nevertheless, this is followed by the PSP, the densest paper here used. This one has a similar density to the kraft paper, thus similar impregnation speeds in these papers where expected. Two possible scenarios rise at this point, considering a similar volume of holes in both materials Either the PSP has less, but wider capillaries of the same length than the kraft paper, or it has a larger number of capillaries of the same radius but shorter, as the length of pores is a variable that affects the impregnation speed, according to (1). Both scenarios, or a combination of them, could explain why the PSP is easier to impregnate despite is density.

The impregnation rates of the rigid materials present values according to their densities (Table 2), with the laminated pressboard sticks and blocks as the densest tested materials and as the cellulosics with the lowest impregnation velocities and rates with the three oils.

As the impregnation period of a transformer is based on the lower impregnation rate shown by the materials which it is composed [5], among the materials here tested the pressboard T-IV blocks are the constraining material, that with a larger impregnation rate at the ambient temperature, as can be seen in Fig. 12. Regarding the esters, the constraining materials are chosen in the range of temperature where the impregnation rates match those of the mineral oil at the rated temperature. These have been also the pressboard T-IV blocks for the synthetic ester, and the pressboard T-IV sticks for the natural ester.
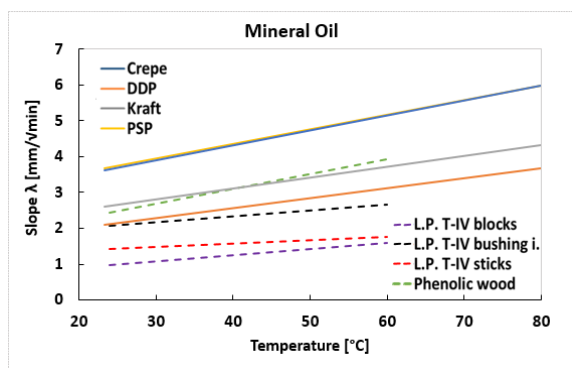

FIGURE 12. Mineral oil impregnation rates of the solid insulators tested.

Based on this, to have a similar impregnation time in a transformer with these cellulosic materials with the mineral oil at 25°C with the alternative oils 61°C (61.59°C) and 74°C (74.12°C) may be needed, with the synthetic and the natural esters, respectively. This can be checked in Table 6, that summarizes the impregnation ratios of each combination of cellulosic material and oil at these temperatures, according to the empirical equations. Just by ensuring these temperatures a proper level of impregnation may be reached applying

TABLE 6. Impregnation ratios of the dielectric materials at the equivalent temperatures pointed by the constraining materials.

λ	25°C - M.O.	61°C - S.E.	74°C- N.E.
Crepe	3.6848	3.2885	3.3015
DDP	2.1300	1.8372	1.9675
Kraft	2.6531	2.2817	2.3713
PSP	3.7321	2.2817	3.1293
T-IV Block	1.0055	1.0055	1.0837
T-IV Bus. Ins.	2.0762	1.8082	1.8185
T-IV Stick	1.4442	1.2838	1.0055
Phen. Wood	2.4769	2.0287	2.3050

the current impregnation methods with the alternative oils without extending the transformer manufacture times.

V. CONCLUSION

The substitution of the traditional mineral oils in transformer by alternative dielectric esters carries a lack of knowledge about how the existing impregnation techniques should be adapted. The main uncertainty comes from the higher viscosities of these esters, as the main external parameter to condition the impregnation of a material, and their effect on extending the impregnation times.

This research tries to bring light in this sense. The impregnation of eight different cellulosic dielectric materials (4 papers, pressboard, and rigid solids) with alternative and traditional transformer oils (two esters and a mineral oil) has been under study. The impregnation evolution with time of each combination at different temperatures have been characterized, between ambient temperature and 100°C.

From the results of this work, it first confirms the predominance of the dielectric oil viscosity as the most impregnation conditioning property, which supposes a drawback for the alternative oils, as it was set in the references studied. Comparatively, the contribution of the differences in surface tension and contact angle is limited. Secondly, it can be noticed that this drawback from dielectric esters could be saved by heating up the impregnation fluids up to a determined temperature at which the process is as fast as with mineral oil at ambient temperature. In fact, in the temperature range studied the impregnation ratios of the papers (Kraft paper, Crepe paper, DDP and PSP) were enhanced between 63 to 91% due to the decreases in viscosity.

The results reflect that between these materials, some belonging to the rigid solids category (different pressboard geometries and phenolic wood blocks) present the lower impregnation velocities. More precisely, the pressboard sticks and blocks showed the lowest impregnation speed, due to their higher density, and thus considered constraining materials, and taken as reference.

Considering these materials as the reference, it is possible to reach similar impregnation rates in a transformer with these materials and a synthetic ester or a natural ester at

temperatures of 61 and 74°C, respectively, regarding that was achieved with a mineral oil at ambient temperature (25°C), without increasing the impregnation time.

These temperatures are compatible with the preservation of the dielectrics integrity and properties and make the current impregnation methods compatible with dielectric esters.

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