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Review

A Brief Review of the Impregnation Process with Dielectric Fluids of Cellulosic Materials Used in Electric Power Transformers

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Abstract: In the manufacturing of power transformers, the impregnation of the solid electric insulation systems (cellulosic materials) with a dielectric liquid is a key issue for increasing the breakdown voltage of the insulation, and this prevents the apparition of partial discharges that deteriorate the insulation system. After introducing the problem, this article presents the theory of impregnation and later carries out a bibliographical review. Traditionally, mineral oils have been used as the dielectric liquid in electrical transformers, but for environmental (low biodegradability) and safety (low ignition temperature) reasons, since the mid-1980s, their substitution with other ester-type fluids has been studied. However, these liquids have some drawbacks, including their higher viscosity (especially at low temperatures). This property, among other aspects, makes the impregnation of cellulosic materials, which is part of the transformer manufacturing process, difficult, and therefore this tends to lengthen the manufacturing times of these machines.

Keywords: power transformer; solid insulation; dielectric fluid; impregnation

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1. Introduction

Electricity is a form of energy that has become a fundamental support of modern society. Today the industrial, commercial, and residential sectors cannot be understood without it, since it is employed for very diverse uses, such as motor drives, fluid heating, lighting, etc.

According to the data offered by the International Energy Agency (IEA) [1], in 2020 there was a global demand equivalent of final energy of 9571 million tons of oil, of which 1958 were in the form of electricity, which represents approximately 20% of the total.

A great part of this energy is generated, transported, distributed, and consumed in large electrical power systems. In these systems, electricity is generated in power plants. In conventional plants, it is produced at voltages of 10 to 30 kV, while in other plants, such as wind power plants, this generation is carried out at a lower voltage, which normally does not exceed 1 kV.

In the transport of electricity, from the generation to the proximity of the points of consumption, it is required to carry out at least three voltage changes, for which electrical transformers are used [2].

Electrical transformers [3] constitute one of the fundamental elements in electrical power systems. They are responsible for making changes in the voltage/intensity of electricity, which are produced to reduce losses in transport and distribution (when carried out at high voltage) and to make consumption safer (when produced at low voltage). The stability of the electrical network depends to a large extent on its operation.

They are static machines, so in general, they are robust and highly reliable [4]; however, sometimes they suffer breakdowns, which may be derived from a defective design, a bad operation, or the excessive aging of components.

By producing changes in the voltage level of electricity, transformers have parts subjected to two different voltages, so they have to be equipped with an appropriate electrical insulation system. The materials used to build this system have dielectric, mechanical, and thermal properties, and those typically used in the manufacture of electrical power transformers are [5]:

- Paper, which is used to insulate the conductors that make up the high- and low-voltage electrical windings of the machine.
- Wood, cardboard, or presspaper (rigid), which are used to create small separations in the electrical windings and thus form channels through which the liquid that cools the windings circulates (Figure 1 [6]).
- Liquid, which, in addition to fulfilling its function as a coolant, must contribute to maintaining electrical insulation inside the machine.

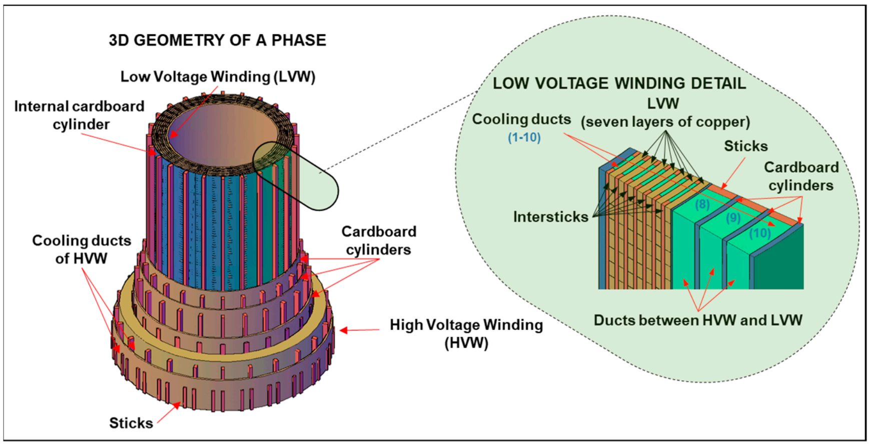


Figure 1. 3D geometry of one phase and details of the LVW of a power transformer, adapted from [6].

It should be noted that, while an aged or deteriorated liquid can be regenerated or replaced, changing the solid insulation (both paper and rigid) is practically impossible since it implies that the transformer must be completely disassembled, which is economically unfeasible. This means that, in practice, it is the good condition of the solid insulation that limits the useful life of the transformer.

To date, due to the combination of their dielectric and cooling properties, price, and availability in the market, oils of mineral origin have been widely used in electric power transformers. However, this does not imply that their use does not present some drawbacks.

From a purely technical point of view, the main problem with mineral oils is their relatively low flash point, which is around 150 °C [7,8]. Although this temperature is higher than that which these machines typically work at (it is usually less than 100 °C), it implies a potential fire hazard when an overload occurs in the transformer, and therefore the working temperature of some points of the transformer can reach the critical value. In this way, and especially in areas where fire can be a serious risk to people and equipment, such as transformers located inside urban centers, it is important to limit this risk.

From an ecological point of view, in the event of an accidental spill, mineral oils have a great impact due to their low biodegradability [8,9]; this aspect is especially relevant in areas where an accidental spillage of the liquid could generate a great environmental impact, such as near rivers and lakes.

To try to solve these two effects, in the 1980s the transformer industry was forced to look for biodegradable dielectric fluids with flash points higher than 250 °C, and in some of them this can exceed 300 °C [10]. These new liquids were synthetic esters. These fluids are synthesized organic compounds, and therefore, in addition to good biodegradability, they have been endowed with properties such as high dielectric strength, relatively low viscosity, high combustion point, and thermal and chemical stability.

In the following decade, and due to strict environmental regulations, vegetable oils and natural esters began to be studied. Examples of these regulations are Directive 96/59/EEC on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT) (2000/2112(INI)) and the EU Ecolabel regulation. Between 1999 and 2001, three commercial products based on different plant sources (sunflower, canola, and soybean) were patented for use in transformers [8]. Figure 2 graphically represents the historical evolution that dielectric liquids have undergone since the beginning of electrical transformer technology to the current state [8].

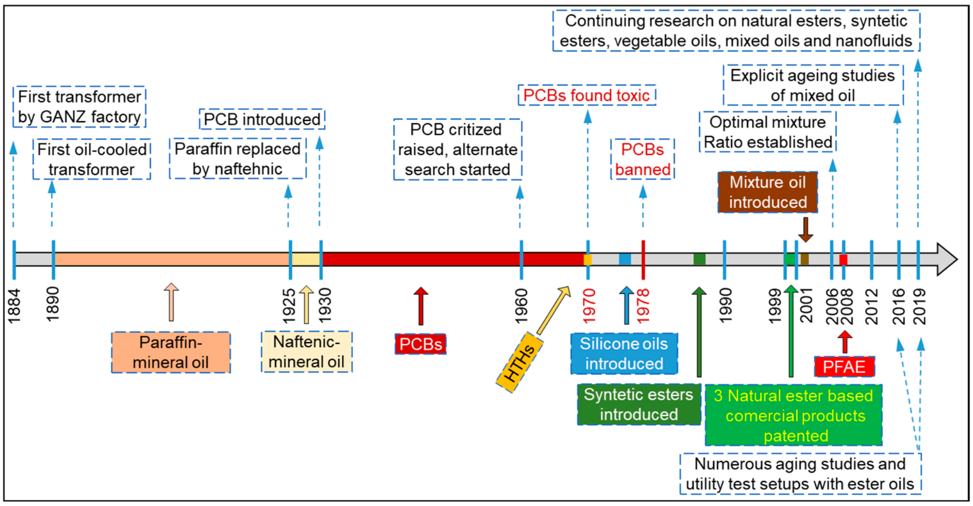


Figure 2. Timeline: Development of transformer insulating fluids, adapted from [8].

The interest in these liquids since the early years of this century is demonstrated by the fact that in 2013 a review work was published in which the evolution of the different insulating liquids, as well as their blends, was exposed. In the work, their fields of application and their main properties were presented [11].

There are currently a few ester-type fluids on the market, especially esters of plant origin, which can have many different sources (typically sunflower, rapeseed, soybean or palm). Each manufacturer purposefully adds different additives to their product to improve their behavior with respect to acidity, and sometimes their products are not "pure", since they have a mixture of different fluids. Table 1 includes typical values of the properties of different dielectric liquids [12].

Table 1. Typical values of dielectrics fluids properties [12].

Property	Mineral	Sunflower	Rapeseed	Soybean	Palm	Synthetic
Density 20 °C [g/cm^3]	0.839	0.91	0.92	0.92	–	0.97
Kinematic viscosity 40 °C [mm^2/s]	9.89	39.2	37	32–34	5.062	29
Flash point [°C]	176	330	>315	320–330	188	260
Fire point [°C]	–	362	>350	350–360	206	316
Pour point [°C]	−48	−25	−31	−18 to −21	−37.5	−56
Acidity [mg KOH/g]	<0.01	0.05	≤0.04	0.01–0.05	<0.01	<0.03
Water content [mg/kg]	15	150	50	4–50	52	50
Dissipation factor 90 °C	0.001984	0.03	<0.03	0.01–0.03	0.0029	<0.008
Dielectric Breakdown [kV]	46	65	>75	≥55	85	>75
Biodegradability [%]	–	85	98	>99	77	89

However, the use of these new dielectric fluids for transformers also has some drawbacks, among which two stand out:

- Higher viscosity, which makes their flow through the internal channels of the windings worse; therefore, they have worse characteristics as a cooling fluid. When a mineral oil is replaced by an ester liquid in a transformer in use, this problem can be solved, at least in part, with the inclusion of a pump that increases the speed of the new fluid. For a new transformer, it is possible to design cooling channels that are adapted to the higher viscosity of the fluid [8,13].
- The impregnation that ester liquids carry out with solid dielectrics is worse; this impregnation process is important since when the solids are soaked in the dielectric liquid, the possible air pockets that could be contained inside are eliminated. This, in addition to improving the dielectric properties, makes the solid insulation more homogeneous. To solve this inconvenience, the solution adopted is to increase the time that elapses between the liquid filling of the machines and their start-up [14]. However, in a competitive environment, reducing manufacturing times for a transformer can be a decisive aspect when purchasing equipment. In this sense, for manufacturers it could be important to reduce this time.

Cellulosic materials are polymers whose molecules make up microfibers and fibers with intra- and inter-fiber pores. These materials are composed of long and short fibers, and between them there are holes in the form of capillaries and air pockets, which initially are filled with air [15]. When impregnated by a dielectric liquid, it rises through the capillaries, displacing the air and filling both the capillaries and the bags, which gives the solid better dielectric properties (Figure 3).

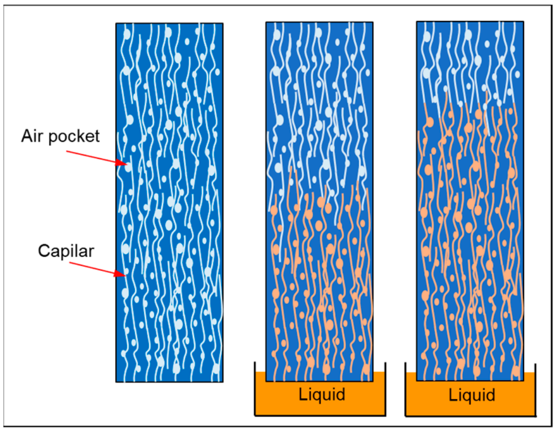


Figure 3. Diagram of the structure and impregnation process of a cellulosic material.

Before beginning to develop the theory of impregnation, it should be noted that in [16], the author, in addition to discussing the reasons why cellulosic dielectrics in electrical equipment are impregnated, presented different techniques of impregnation used in the manufacture of electrical machines, analyzing their advantages and disadvantages.

The impregnation of a solid material with a liquid consists of filling its internal cavities, or pores, which are initially filled with air, with the fluid. In this way, the impregnating liquid gradually replaces the air that is retained inside the solid.

The simplification of the physics of this impregnation process means that it can be considered to be carried out by capillarity through the pores of the material, and therefore it is carried out according to the Hagen–Poiseuille Law [14,17–19]; this implies that it is subject to both the adhesion forces between the solid and the liquid, as well as the cohesion forces of the fluid.

In this way, impregnation can be studied as the phenomenon of capillarity through a pore of a solid material that is partially submerged in a liquid. If it is considered that the pore is circular, it can be assumed that it happens as represented in the scheme of Figure 4. In the figure the liquid level (point E), the same level inside the capillary (point 2) and the level reached by the liquid inside the capillary (point 1) are marked.

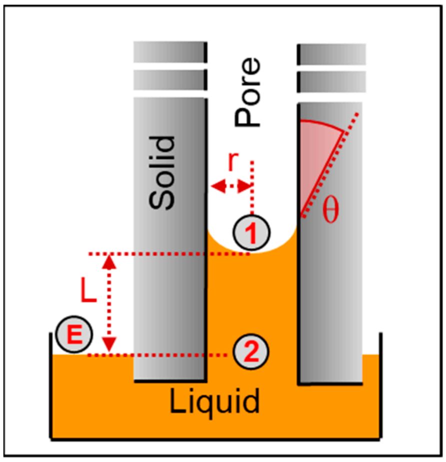


Figure 4. Schematic of the capillary process in a tube by a rising fluid.

The volume of liquid that rises through the solid, Vol_{liq} (m^3), can be expressed according to Equation (1):

$$Vol_{liq} = \pi \cdot r^2 \cdot L\left(m^3\right) \quad (1)$$

Being:
r—the equivalent radius of the pore considered circular (m);
L—the length of impregnation (m).
Considering that the flow rate of the impregnating liquid can be expressed according to Equation (2):

$$Q_{liq} = \frac{Vol_{liq}}{t}\left(m^3/s\right) \quad (2)$$

Being:
t—the time (s)
Equation (2) can be expressed in a differential mode so that the flow rate with the liquid impregnating the solid in a time interval can be expressed as the product of the cross-sectional area of the pore, [$\pi.\ r^2$] (m^2), by the impregnation speed, [dL/dt] (m/s), Equation (3).

$$dQ_{liq} = \frac{dVol_{liq}}{dt} = \frac{d\left(\pi \cdot r^2 \cdot L\right)}{dt} = \pi \cdot r^2 \cdot \frac{dL}{dt}\left(m^3/s\right) \quad (3)$$

Taking into account the pressure loss equation, H, in a circular duct, Equation (4), is expressed by the Darcy Equation.

$$H = \frac{P}{\gamma} = f \cdot \frac{L}{D} \cdot \frac{v^2}{2 \cdot g}(m) \quad (4)$$

Being:
P—the pressure (Pa);
γ—the specific weight of the fluid (N/m^3);
f—the friction factor (dimensionless);
D—the equivalent diameter of the pore considered circular (m);
v—the impregnation speed (m/s);
g—the acceleration due to gravity (m/s^2).

As the impregnation speed is small, it can be considered that the laminar flow condition is fulfilled, Re < 2000, and therefore the friction factor can be calculated with Equation (5).

$$f = \frac{64}{Re} \tag{5}$$

Reynolds (Re) is calculated according to Equation (6).

$$Re = \frac{v \cdot L_c}{n} = \frac{v \cdot D}{n} \tag{6}$$

Being:
L_c—the characteristic length; for a circular pore it is the diameter (m);
ν—the kinematic viscosity of the fluid (m^2/s).
In this way, we consider that the relationship between the dynamic and kinematic viscosities is Equation (7).

$$n = \frac{\mu}{\rho} = \frac{\mu}{\gamma/g} = \frac{\mu \cdot g}{\gamma}\left(m^2/s\right) \tag{7}$$

Being:
μ—the dynamic viscosity of the fluid (Pa.s);
ρ—the fluid density (kg/m^3).
The flow rate of absorbed liquid can also be expressed according to Equation (8), which is the Hagen–Poiseuille Law.

$$dQ_{liq} = \frac{dVol_{liq}}{dt} = \frac{\pi}{8 \cdot \mu} \cdot \frac{r^4}{L} \cdot \Delta P\left(m^3/s\right) \tag{8}$$

Being:
Vol_{liq}—the volume of liquid absorbed (m^3);
ΔP—the pressure difference in the capillary (Pa).
In this case, the ΔP in the capillary can be expressed according to Equation (9).

$$\Delta P = P_2 - P_1 (Pa) \tag{9}$$

Being:
P_2—the pressure on the surface of the liquid inside the capillary (Pa), point 2 in Figure 3;
P_1—the air pressure inside the capillary pore at length L (Pa), point 1 in Figure 3
Thus, Equation (8) can be expressed as Equation (10).

$$dQ_{liq} = \frac{dVol_{liq}}{dt} = \frac{\pi}{8 \cdot \mu} \cdot \frac{r^4}{L} \cdot (P_2 - P_1)\left(m^3/s\right) \tag{10}$$

From which it follows that:

- The rate of impregnation decreases as the liquid is introduced into the pore since the pressure inside the pore increases [19];
- The shorter the pore length, the higher the impregnation rate [18].

Therefore, when porous materials, such as solid dielectrics, come into contact with a liquid, a phenomenon of solid impregnation occurs because the effect of capillarity is stronger than that of internal pressure. One way to increase the impregnation rate is by modifying the ΔP, which can be performed in two ways:

- Producing a vacuum on solid samples before impregnating them [18,19];
- Increasing the pressure of the gas located on the dielectric liquid once the solid is submerged and has been isolated from the external pressure [20].

Combining Equations (3) and (8), Equation (11) is obtained.

$$\pi \cdot r^2 \cdot \frac{dL}{dt} = \frac{\pi}{8 \cdot m} \cdot \frac{r^4}{L} \cdot \Delta P \left(m^3/s \right) \tag{11}$$

Eliminating the pore area ($\pi . r^2$) from both sides of the equation—Equation (12), ordering it—Equation (13), integrating it—Equation (14), and taking the square root—Equation (15), results in the impregnation length at a given time—Equation (16).

$$\frac{dL}{dt} = \frac{1}{8 \cdot m} \cdot \frac{r^2}{L} \cdot \Delta P (m/s) \tag{12}$$

$$L \cdot dL = \frac{r^2}{8 \cdot m} \cdot \Delta P \cdot dt \cdot t \tag{13}$$

$$\frac{L^2}{2} = \frac{r^2}{8 \cdot m} \cdot \Delta P \cdot t (m) \tag{14}$$

$$\frac{L}{\sqrt{2}} = \frac{r}{2 \cdot \sqrt{2}} \cdot \sqrt{\frac{\Delta P \cdot t}{m}} (m) \tag{15}$$

$$L = \frac{r}{2} \cdot \sqrt{\frac{\Delta P \cdot t}{m}} (m) \tag{16}$$

Studying the balance of forces that appears in a liquid that rises through a capillary, (Figure 5, Equation (17)), it is possible to determine the present contact angle θ (Equation (18)).

$$2 \cdot \pi \cdot r \cdot \sigma \cdot \cos\theta + P_2 \cdot \pi \cdot r^2 = P_1 \cdot \pi \cdot r^2 (N) \tag{17}$$

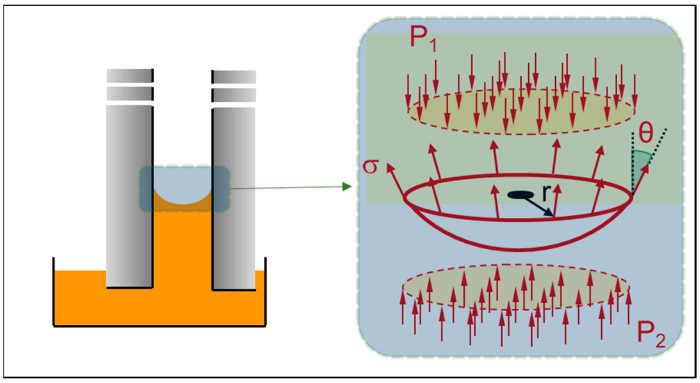


Figure 5. Balance of forces in a liquid that ascends through a capillary.

Being:
σ—the surface tension of the liquid (N/m);
θ—the contact angle between the solid and the liquid.

$$\cos\theta = r \cdot \frac{P_1 - P_2}{2 \cdot \sigma} = r \cdot \frac{\Delta P}{2 \cdot \sigma} \tag{18}$$

In this way, the effect of the pressure in the capillary can be expressed according to Equation (19).

$$\Delta P = \frac{2 \cdot \sigma \cdot \cos\theta}{r} (Pa) \tag{19}$$

As introduced in Equation (16), the equation that determines the impregnation height reached by a fluid in a porous material is obtained as a function of the pore radius, the dynamic viscosity of the fluid, the surface tension of the liquid, and the contact angle, all under certain pressure conditions (Equation (20)).

$$L = \sqrt{\frac{r \cdot \sigma \cdot \cos\theta}{2 \cdot \mu}} \cdot \sqrt{t}(m) \tag{20}$$

If the impregnation ratio, λ, is defined according to the expression of Equation (21), Equation (22) is finally obtained, which offers the relationship between the time and the height of impregnation under the conditions determined λ.

$$\lambda = \sqrt{\frac{r \cdot \sigma \cdot \cos\theta}{2 \cdot \mu}} (m/\sqrt{s}) \tag{21}$$

$$L = \lambda \cdot \sqrt{t}(m) \tag{22}$$

Analyzing Equation (20), it is observed that the impregnation length increases with [16]:

- Decreasing the radius (as long as the effect of capillarity is maintained);
- Decreasing the kinematic viscosity; in this sense, it must be considered that a hotter fluid is less viscous;
- Increasing the surface tension of the liquid;
- Decreasing the contact angle (cos θ).

From a practical point of view, between the different dielectric oils, their capillary effect pressures, their surface tension, and their contact angle do not differ too much [19].

As both the dynamic viscosity and the surface tension of liquids depend on temperature, an improvement in the impregnation speed of a fluid–solid combination must consider the control of this last variable.

Although both the dynamic viscosity and the surface tension of the liquid decrease with increasing temperature, this reduction is more pronounced in the case of viscosity [18,19]. Therefore, it can be said that viscosity is the parameter that has the bigger influence when it comes to conditioning the impregnation of a certain solid material [19], so its management—for example, heating the liquid—is the main activity that can be performed to speed up the impregnation process.

On the other hand, the internal pressure in the pores (vacuum) is also a parameter that has a certain influence, which is increased in the case of increasing the temperature, since it would increase the internal pressure of the water vapor retained in the pores [20].

If heat is applied to accelerate the impregnation, the execution of the vacuum is even more important since, on the contrary, the internal pressure of the pores would be higher due to the higher pressure of the water vapor contained in them [20].

2. Impregnation of Solid Dielectrics

Regarding the impregnation of solid insulators used in electric power transformers, this is a topic that has aroused interest in the industry for many years. In 1965, L. E. Feather, from the Materials and Processes Development Department of the Power Transformer Division of Westinghouse Electric Corporation, published a paper [21] in which he analyzed the method and times of the drying and impregnation processes necessary to manufacture a power transformer. He commented that the modification of these methods can reduce the time from one day to one week, which undoubtedly helps the manufacturer in meeting delivery dates. Figure 6 shows the diagram of the vapotherm processing equipment [21].

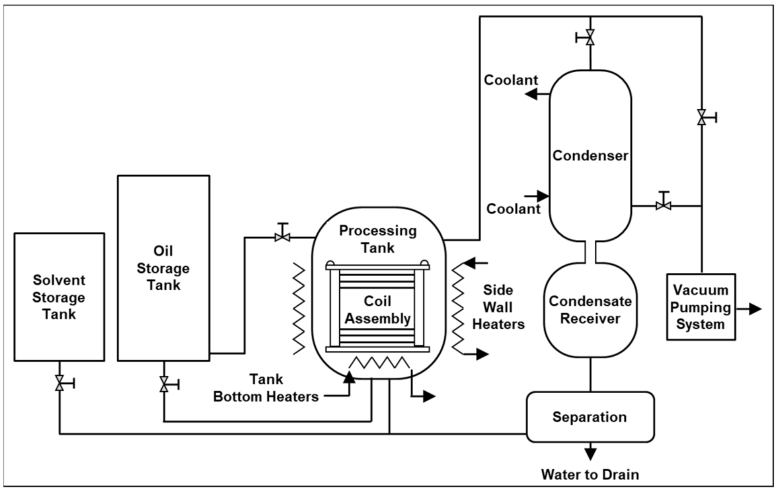


Figure 6. Vapotherm processing equipment schematic diagram, adapted from [21].

A few years later, in 1975, an article [22] was published in which, in addition to offering the equations that model the phenomenon of impregnation, the authors analyzed how the breakdown voltage evolved in the pressboard with impregnation time. They tested five samples, and the results obtained (Table 2) evidenced the significant improvement of this property with the impregnation time increase.

Table 2. Breakdown voltage obtained during impregnation, from [22].

Time Elapsed from the Beginning of the Impregnation	0	13 min	1 h	2 h	4 h 20 min	6 h 40 min	11 h 45 min	48 h	48 h 15 min	48 h 30 min
Breakdown voltage (kV)	32.8 [a]	69.5	69.5	78.5	89.5	90.5	93.5	90.5 [b]	89.5 [b]	95.2
	33.6 [a]	70.5	72.8	80	89.5	96.1 [b]	92	92.8	90.5 [b]	93.5 [b]
	34.5 [a]	70.5 [b]	73	80	89.5	92.1	93.5	92 [b]	90.5	89.5 [b]
	35.2 [a]	71	73.5	85	94	90.5 [b]	93.5	93.5	93.5 [b]	90.5 [b]
	34.5 [a]	71 [b]	77	89.5	92 [b]	90.5	91.5	91.5	97	92.5 [b]

[a] Test on untreated and unimpregnated samples. [b] Tests with breakdown spot outside the uniform field area.

In 1984, researchers from the Toshiba Corporation published an article [20] in which the effects of both temperature and pressure on impregnation were taken into account. They carried out the impregnation of the transformer board with mineral oil and included in the work graphs with results of how the temperature and the applied pressure influenced the evolution of the pressure inside the transformer board and the impregnation height achieved (Figure 7). These results indicate that the internal pressure increases significantly more by increasing temperature from 20 °C to 50 °C than by increasing vacuum pressure to 0.1 MPa; these increases also occur with the impregnation height, but although the changes in applied pressure have a similar influence on both measurements, the temperature has more influence on the height than on the internal pressure.

These authors published a second part of the article [17], in which, in addition to engaging in a theoretical study of the equations that govern the phenomenon, they estimated the coefficients of said equations by adjusting them with the experimental results.

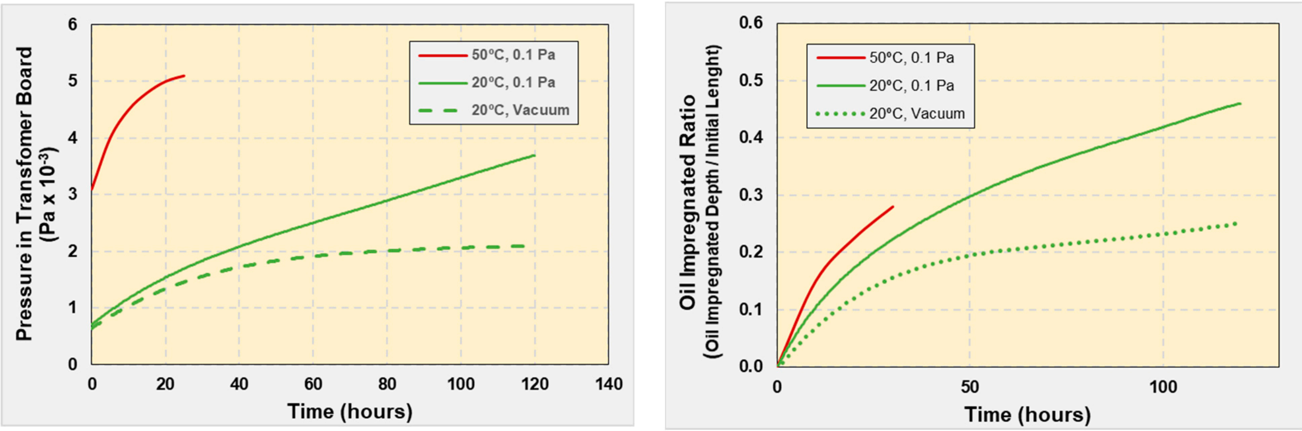


Figure 7. Pressure change in transformer board and changes in oil impregnation depth. Data from [20].

An article [23] was published in 1985 in which the author analyzed the impregnation of a kraft pressboard under different pressure conditions; although the results of the impregnation length on the substrate (L2) measurement offered a good approximation with the theoretical prediction, the results of the impregnation length on the filter cake (L1) did not have a good fit (Figure 8). Unfortunately, the poor quality of the photograph in the article does not clearly show the impregnated sample.

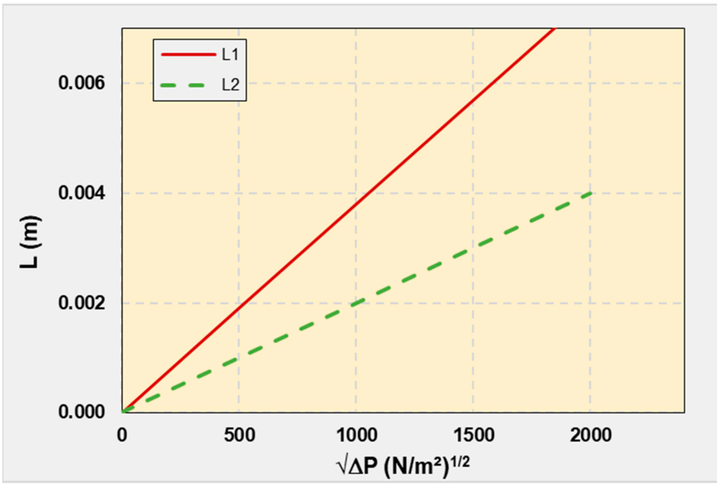


Figure 8. Measure values of L1 and L2. Data from [23].

In 1988 [24], a paper was presented in which the dielectric properties (dielectric constant and dissipation factor) acquired by kraft paper and polypropylene film were analyzed after different impregnation periods (1 and 5 h) and under different temperatures (23 °C, 45 °C, and 70 °C). Regarding the dielectric constant, the results showed that in the two materials, it is of the same order of magnitude and increases with impregnation time, but it is barely influenced by temperature. However, regarding the dissipation factor, in polypropylene film, it is increased by both time and temperature, while in kraft paper it is increased by time but shows a somewhat erratic behavior concerning temperature, although the value is much higher in magnitude than in polypropylene film (Figure 9).

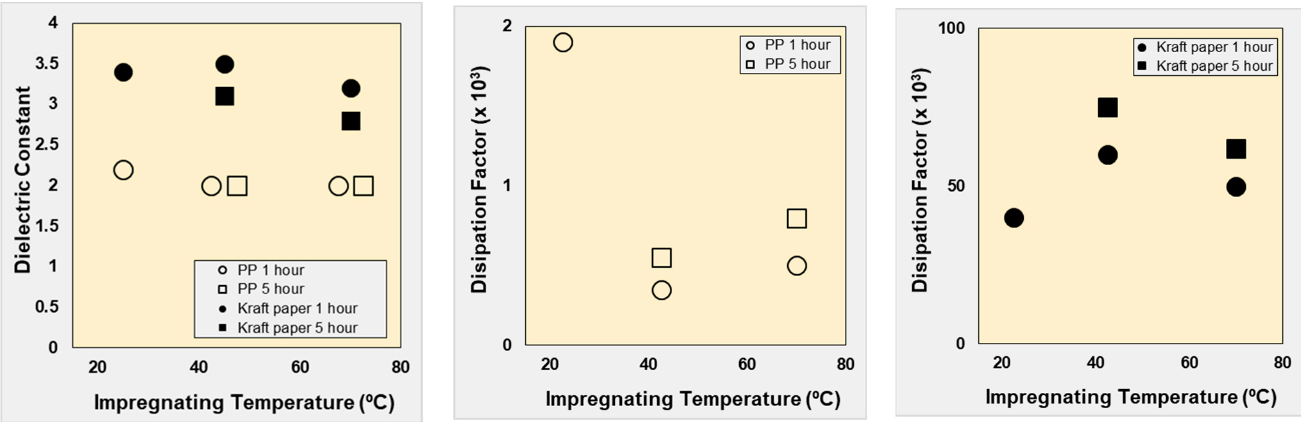


Figure 9. Dielectrics constant and dissipation factor vs. impregnating temperature for polypropylene film and kraft paper. Data from [24].

A few years later, in 2001, a paper was presented in which aspects related to the manufacture of transformers were also commented on [25]. In the work, an analysis of the cost of the energy necessary to produce the drying and accelerate the impregnation process of the machine was carried out. The author studied the use of three different systems to carry out the heating that favors these processes: a convective system that uses gas to produce heat, a convective system that heats based on electricity, and a heating system based on electric induction. The results showed that the induction system was considerably cheaper (Table 3).

Table 3. Heat loads, from [25].

	Gas Convection	Electric Convection	Induction
	Btu/Hr	Btu/Hr	Btu/Hr
Product Load	36,900	36,900	36,900
Conveyor Load	92,250	92,250	0
Wall Losses	26,875	26,875	0
Opening Losses	9600	9600	0
Exhaust Losses	42,509	20,368	0
Total Heat	208,134	185,993	36,900

A year later, in 2002, a paper was presented [26] in which a study of the effect of drying, impregnation, and temperature cycles on the clamping pressure of the transformer windings was carried out. The tests were performed on five radial spacers (from milled transformer board TIV, 2 mm thickness) separated by bundles of paper-insulated copper conductors. This pressure is adjusted for the initial moment of the life of the transformer, but with its operation, it can change substantially due to effects such as changes in temperature or the presence of humidity, which can seriously damage the insulation of the windings. The study concluded by establishing that the impregnation itself does not influence the clamping stress (Figure 10, but temperature increases do have important effects (Figure 11) since the clamping forces can deviate easily by far more than 10 percent from the theoretical value (for hot windings above and very cold windings below the designated initial force). This is an aspect to consider when wanting to speed up the impregnation rate by raising the temperature. The latter is especially relevant when biodegradable oils are used, which are more viscous than mineral oils and require higher temperatures to reduce impregnation times.

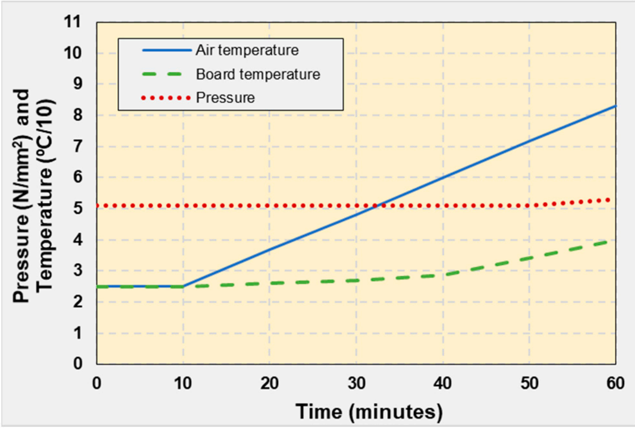


Figure 10. Change in clamping pressure during impregnation. The clamping pressure did not alter due to oil impregnation; it remained exactly as before impregnation. Data from [26].

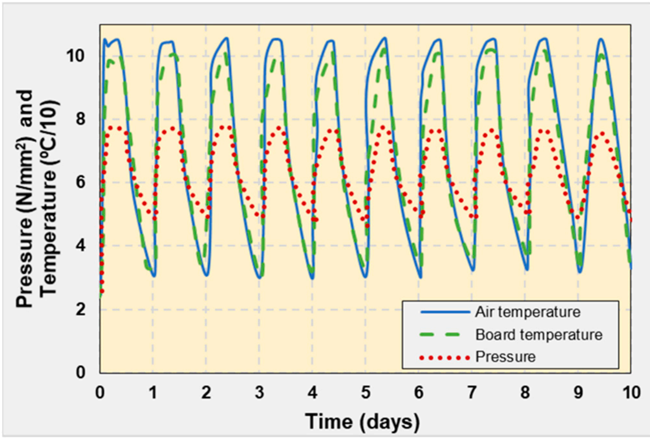
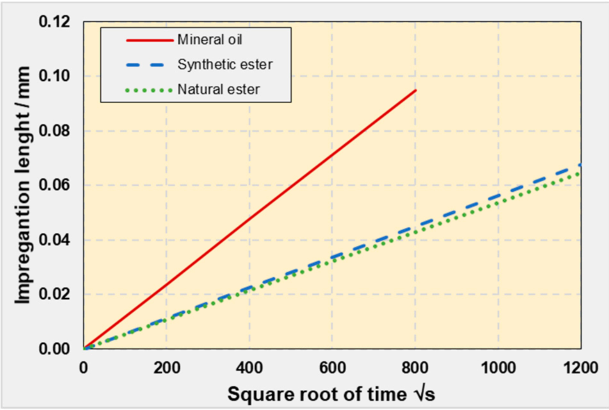


Figure 11. Change in clamping pressure during impregnation due to thermal cycles. The daily thermal cycles caused an oscillation of the clamping force between 5 and 8 N/mm2. The early morning pressure value (at 30 °C) fluctuated slightly according to the change in the ambient temperature. Data from [26].

In 2007, a group from the University of Manchester published a paper [27] in which they offered data from an impregnation study. They studied the impregnation of cellulosic insulation for transformers (pressboard and laminated pressboard blocks) with mineral oil and two biodegradable liquids. The pressboard results (Figure 12) showed that if the temperature of mineral oil is increased from ambient to 60 °C, the same impregnation height is achieved 70% of the time. If a synthetic ester is used at 60 °C, the same impregnation height is achieved as in the previous case 90% of the time, while if the ester is vegetable, at 60 °C the same impregnation height is achieved at 110% of the impregnation time. Regarding the laminated pressboard blocks, the tests concluded that at 60 °C, a similar impregnation height is achieved with the esters to that achieved with mineral oil at room temperature (Figure 13).

The following year, continuing with the work of the previous year, the same group published a paper [18] in which, in addition to including the equations that model the impregnation process, they compared the impregnation of both synthetic ester and vegetable ester with the which performs a mineral oil. In this case, samples of pressboard strips (3 mm thick and 2 cm wide) and two types of pressboard blocks (33 × 70 × 110 mm and 33 × 115 × 115 mm) were impregnated (Figure 14). They found that temperature has a great influence on impregnation since it is a factor that affects both viscosity and surface tension. The results showed that in the impregnation of the pressboard strips at 20 °C, 40 °C and 60 °C, there is a linear relationship between the impregnation height and the square root of the time, the temperature activates the impregnation process, and the mineral oil impregnates better than the synthetic ester—the latter better than the vegetable ester (Figure 15 and Table 4). The results of the impregnation of the two types of pressboard blocks showed that if the temperature of the esters is increased to around 60 °C, they could achieve impregnations similar to those achieved with mineral oils at 20 °C (Figure 16). Although temperature contributes to increasing the degradation of cellulosic materials, this thermal level is not significant.



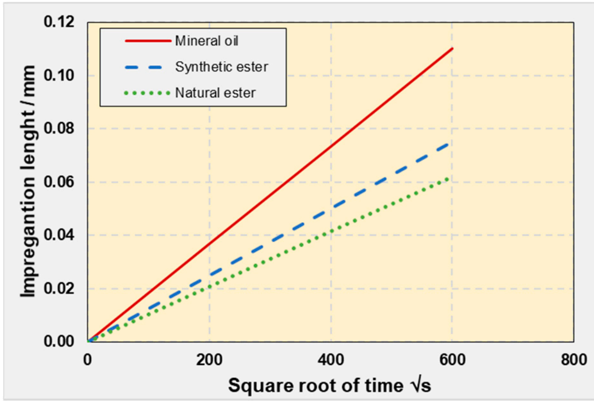


Figure 12. Changes of fluid height movement with time at 20 °C and 60 °C in pressboard. Data from [27].

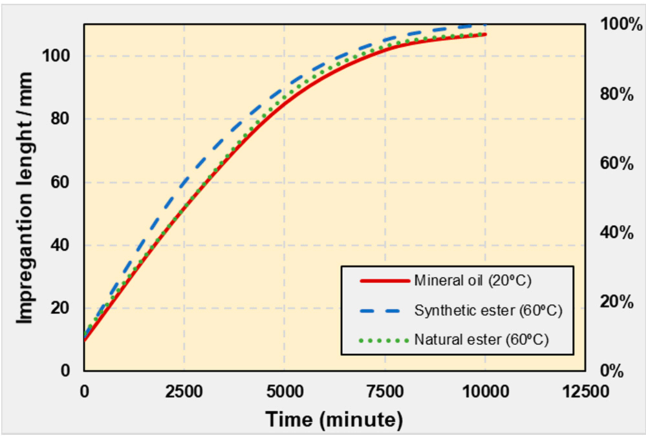


Figure 13. Impregnation results of laminated pressboard blocks. Data from [27].

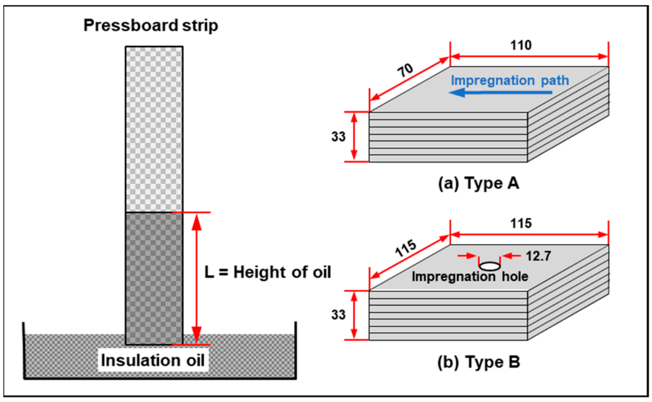


Figure 14. Pressboard stick and pressboard blocks (dimensions in mm), adapted from [18].

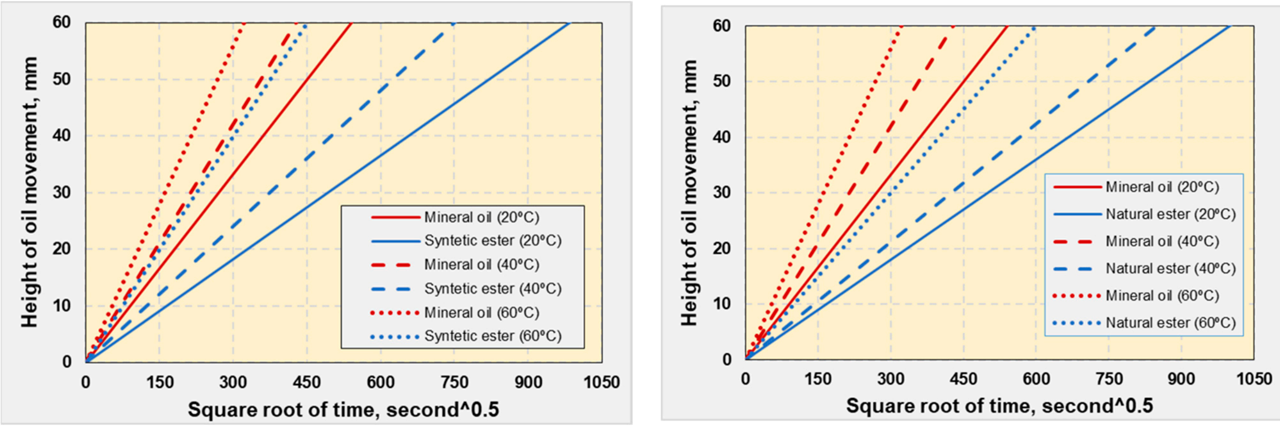


Figure 15. Capillary actions of synthetic and natural ester compared with mineral oil in pressboard stick. Data from [18].

Table 4. Slopes of oil height against the square root of time in pressboard stick, from [18].

Type of Oil		Mineral Oil	Synthetic Ester	Natural Ester
Slope λ (m/$\sqrt{t}$)	20 °C	1.13×10^{-4}	0.64×10^{-4}	0.63×10^{-4}
	40 °C	1.41×10^{-4}	0.96×10^{-4}	0.86×10^{-4}
	60 °C	1.81×10^{-4}	1.40×10^{-4}	1.10×10^{-4}

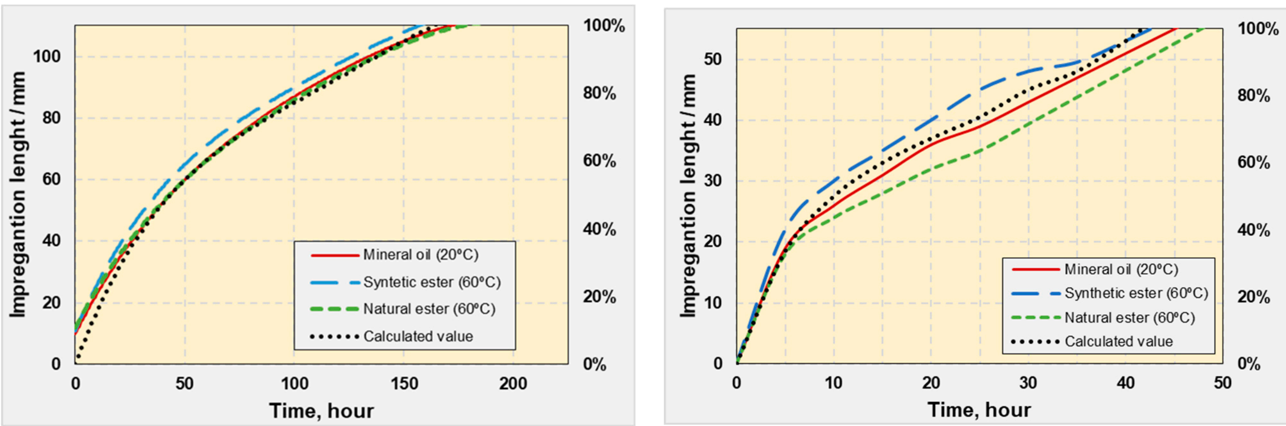


Figure 16. Impregnation results of type A and B blocks. Data from [18].

More recently, in 2014, another work similar to the previous one [19] was presented in which impregnation was carried out, in this case with single-layer pressboard (2 mm thick and 1.5 cm wide) and multi-layer pressboard (150 × 35 × 10 mm) and using vegetable oil (rapeseed), and the researchers compared it with impregnation using mineral oil. The results, shown in Figures 17 and 18, showed that the impregnation is governed by phenomena such as the viscosity of the oil, the capillarity, and the internal pressure of the oil in the material; as a direct consequence, impregnation with vegetable oil is worse than that carried out with mineral oil. However, they carried out impregnations at different temperatures, demonstrating that if the temperature of the vegetable oil is increased to around 60 °C, an impregnation similar to that carried out by mineral oil at 20 °C is achieved, which corroborates the results obtained by other authors in previous works [18,27].

In 2016, a paper was presented [28] in which the different dielectric properties that pressboard acquired when impregnated with a natural ester and mineral oil were analyzed. The authors offered data on breakdown voltage for different thicknesses (1.6 and 3.2 mm) after different impregnation periods (3, 6, and 9 h) and with different dielectric permittivity levels after 3 h of impregnation at different temperatures (35 °C to 90 °C). The breakdown voltage results showed that the value increases with increasing impregnation time and that it is higher when impregnating with the natural ester (Table 5), while the dielectric permittivity results show that this value decreases with temperature and is lower in the natural ester (Table 6).

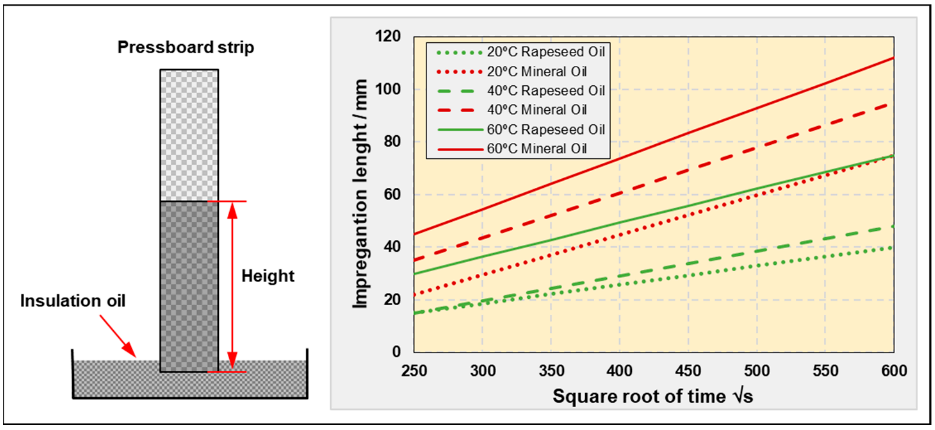


Figure 17. Experimental model of single-layer impregnated pressboard and the impregnation length versus the square root of impregnation time. Data from [19].

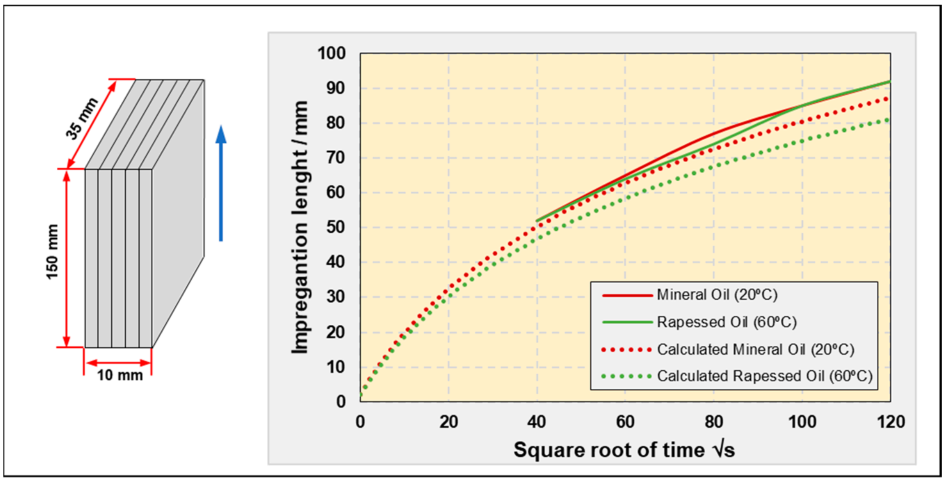


Figure 18. Multi-layer impregnated pressboard experimental model, theoretically calculated and measured values. Data from [19].

Table 5. Breakdown voltage of liquid impregnated pressboard, from [28].

Pressboard Thickness (mm)	Impregnated Time (h)	Breakdown Voltage (kV)	
		Natural Ester	Mineral Oil
1.6	3	43.9	41.2
	6	49.2	46.7
	9	57.2	51.7
3.2	3	65.7	62.3
	6	75.2	70.6
	9	85.6	77.5

Table 6. Dielectric permittivity of natural ester and mineral oil at different temperatures after using for 3 h impregnation of pressboard, from [28].

Temperature (°C)	Natural Ester	Mineral Oil
35	3.08	2.12
40	3.07	2.12
45	3.06	2.12
50	3.05	2.11
55	3.03	2.11
60	3.01	2.11
65	2.99	2.1
70	2.98	2.1
75	9.96	2.09
80	2.94	2.09
85	2.92	2.08
90	2.91	2.07

In 2017, a paper was presented in which the delta tangent was analyzed for flat pressboard (0.5 × 3 mm) and wraps with a layer thickness of 6.25 mm, which were made from kraft paper in cylinders with a thickness of 0.15 mm and an aluminum cylinder as a rack, when these materials were impregnated with two different liquids: a new oil, based on the gas-to-liquids process, and another mineral oil. The measurements were made with two different methods: FDS (frequency domain spectroscopy) and PDC (polarization and depolarization current) [29]. They obtained similar results with both oils (Figure 19), so they concluded that the two oils performed a similar impregnation process on both kraft paper and pressboard.

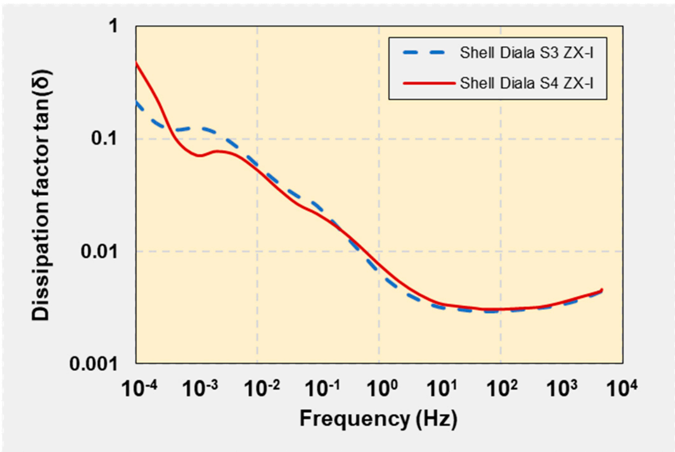


Figure 19. Dielectric dissipation factor of kraft paper impregnated with two different fluids over the frequency from 100 µHz to 5 kHz at 20 °C. Data from [29].

That same year, 2017, a paper [30] was presented in which, considering that the size of the capillaries of solids is a determining parameter for the impregnation process, the authors carried out a statistical treatment to determine the size of the capillaries present on pressboard. After analyzing 99 different samples (Figure 20), they determined that the average radius is 65.37 nm.

In the following year, 2018, the same group presented a work [31] in which the authors tried to measure the pore size and absorptive capacity of the pressboard. After saturating the material with mineral oil (Figure 21), the authors concluded that this material has a capillary diameter of approximately 25.6 nm and that it can absorb 25.6% of its volume.

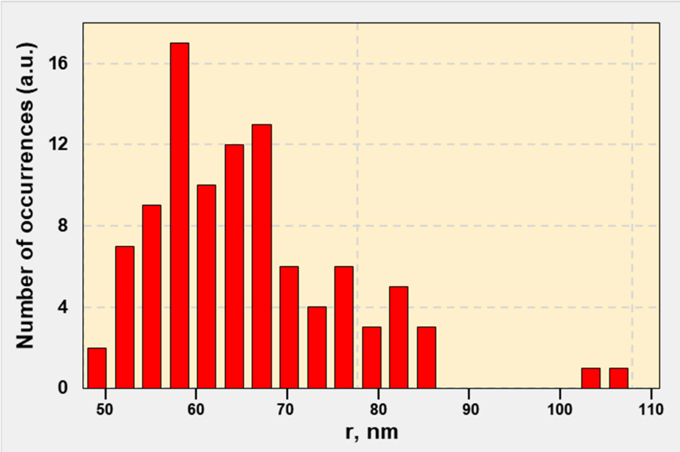


Figure 20. Number of occurrences of individual capillary radiuses. Data from [30].

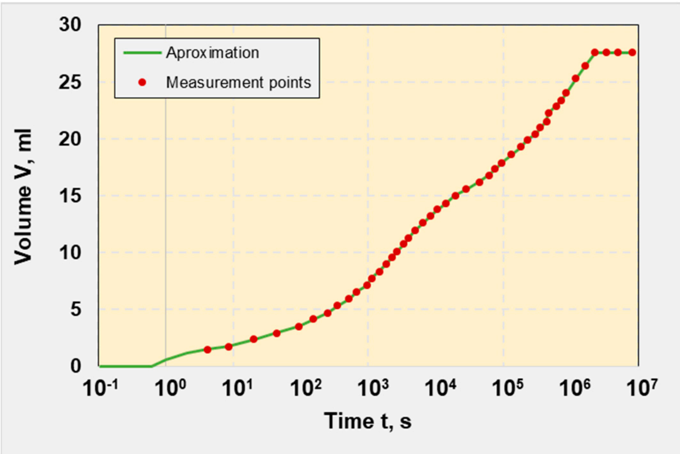


Figure 21. Time dependence of the volume of oil absorber by pressboard. Data from [31].

In 2018, a paper [32] was published in which the impregnation capacity of four dielectric fluids (mineral oil, synthetic ester, natural ester, and blended ester of low viscosity) on pressboard was analyzed. The impregnation tests were carried out at four different temperatures: 20 °C, 60 °C, 80 °C, and 100 °C. The results corroborated once more the worse impregnation capacities of the ester-type fluids concerning mineral oil and that the temperature activates the impregnation. Regarding the low-viscosity ester, as expected, it had better behavior than the other two esters (Figure 22).

Later, in 2019 [33], a paper was presented in which the influence between the duration of the vacuum created for the drying and impregnation processes and the appearance of partial discharges was studied. The authors tested 12 new and identical transformers, and the results showed that a vacuum contributes to reducing both moisture and air pockets within the solid insulation, so a longer vacuum duration and impregnation time result in low partial discharges (Figure 23), which corroborates the conclusions obtained in previous works by other authors [28].

That same year, 2019, a paper [34] was presented in which the impregnation at 70 °C with mineral oil and a synthetic ester of different rigid materials of cellulosic origin were analyzed. The authors offered the results of slopes of liquid height vs. square root of time (Table 7). Once again, the superiority of mineral oil impregnation was shown. The authors concluded that, in the analyzed materials, the phenolic wood block possesses the maximum impregnation rate in comparison with the rest of the materials.

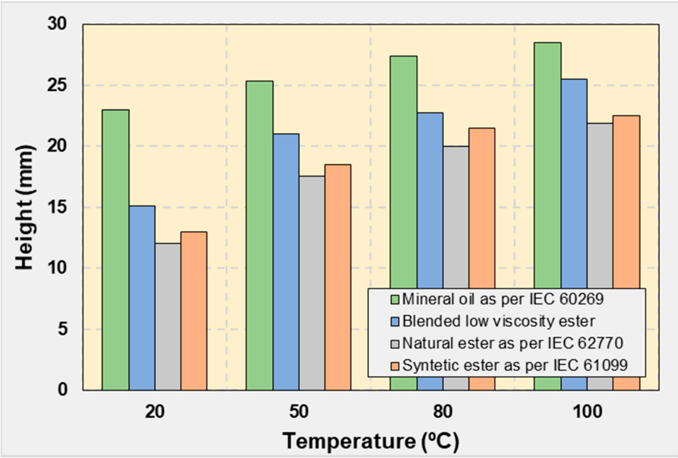


Figure 22. Dependence of the height of penetration of the liquid into pressboard on the temperature by the time of 200 min. Data from [32].

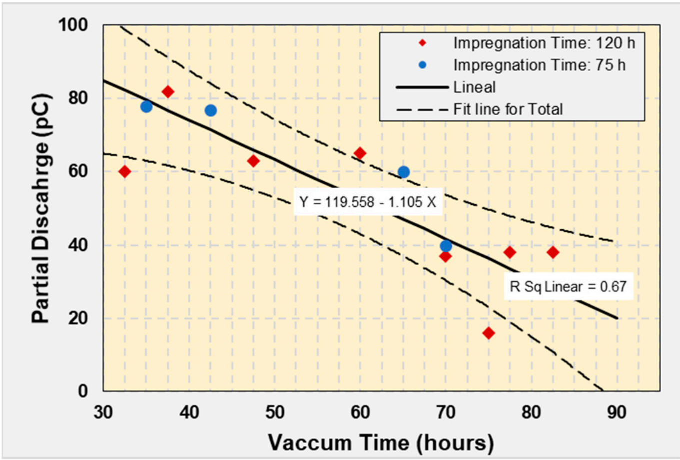


Figure 23. Relationship between vacuum duration and partial discharge value. Data from [33].

Table 7. Slopes (cm/$\sqrt{}$s) of oil height vs. square root of time, from [34].

Type of Insulating Rigid Component		Mineral Oil	R	Synthetic Ester	R
Laminated pressboard T-IV block	Frontal	1.7292	0.9289	1.5326	0.9418
	Sideway	0.7634	0.9931	0.7582	0.9968
Laminated pressboard T-IV bushing insulation		1.8348	0.9546	0.5452	0.9982
Laminated pressboard T-IV sheet (thickness 1 mm)		2.0761	0.9955	1.6001	0.9959
Laminated pressboard T-IV sheet (thickness 2 mm)		1.2403	0.9988	0.8140	0.9933
Laminated pressboard T-IV spacer		1.0440	0.9975	0.4456	0.9972
Laminated pressboard T-IV strip	Frontal	1.3120	0.9978	0.7281	0.9959
	Sideway	0.6350	0.9939	0.0532	0.9968
Phenolic wood block	Frontal	2.9192	0.9949	1.8334	0.9908
	Sideway	5.1290	0.8982	3.4661	0.9172

In 2021, the same research group published a paper [14] in which the impregnation with mineral oil, natural ester, and synthetic ester of eight solid dielectrics—four papers (Crepe, DDP, Kraft, and PSP) and four rigid components (Laminated pressboard T-IV blocks, Laminated pressboard T-IV bushing insulation, Laminated pressboard T-IV sticks and Phenolic wood blocks)—were evaluated at different temperatures. The results of the papers showed that the Crepe and the PSP impregnate easier than the Kraft and the DDP. Likewise, it was verified that of the rigid components analyzed, the Phenolic wood blocks are the ones that best impregnate. In the same way, they verified that by increasing the impregnation temperature of the synthetic ester up to 60 °C and of the natural ester up to 74 °C, impregnations similar to those obtained with mineral oil are achieved (Table 8). The results for the synthetic ester are similar to those offered by some previous works by other authors [18,19,27]; however, the results for the impregnation with natural ester are at a higher temperature.

Table 8. Impregnation ratios of the dielectric materials at the equivalent temperatures pointed by the constraining materials, from [14].

λ	25 °C–Mineral Oil	61 °C–Synthetic Ester	74 °C–Natural Ester
Crepe	3.6848	3.2885	3.3015
DDP	3.1300	1.8372	1.9675
Kraft	2.6531	2.2817	2.3713
PSP	3.7321	2.2817	3.1292
T-IV Block	1.0055	1.0055	1.0837
T-IV Bussing insulation	2.0762	1.8082	1.8185
T-IV Stick	1.4442	1.2838	1.0055
Phenolic Wood	2.4769	2.0287	2.3050

In 2022, this same group, continuing with their previous work, presented a paper [35] in which they offered the experimental data of the impregnation ratio of mineral oil and natural ester on Crepe paper, Diamond Dotted Paper (DDP), Kraft, and Presspaper (PSP) (Figure 24); the tests were carried out between 31 and 80 °C. The results, in addition to corroborating that the impregnation with the natural ester is worse than that carried out with mineral oil, showed that Crepe and PSP papers impregnate more easily than Kraft and DDP (Figure 25).

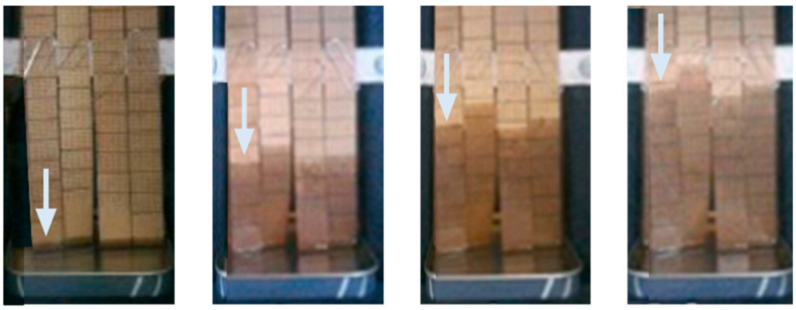


Figure 24. The advance of impregnation length over time for cellulosic papers: PSP, Kraft, DDP, and Crepe, from left to right (the arrow marks the level of impregnation of the liquid on the paper on the left).

In 2022, an experimental work was published [36] in which impregnation with a natural ester and a vegetable ester of three different sizes of cellulose laminated blocks (40 ×40 × 25.4 mm, 90 × 90 × 25.4 mm and 180 × 180 × 25.4 mm) was evaluated, comparing it with the results using a mineral oil. The results once again showed that ester impregnation lasts a longer time than mineral oil impregnation (Figure 26). However, impregnation can be activated by increasing the temperature (Figure 27), and in this case, at 70 °C the authors managed to impregnate the esters in a similar manner to using mineral oil at room temperature. This agrees with the results that were previously published in [14] for vegetal esters. They also observed that drying cellulosic materials in a vacuum before their impregnation accelerated the impregnation process.

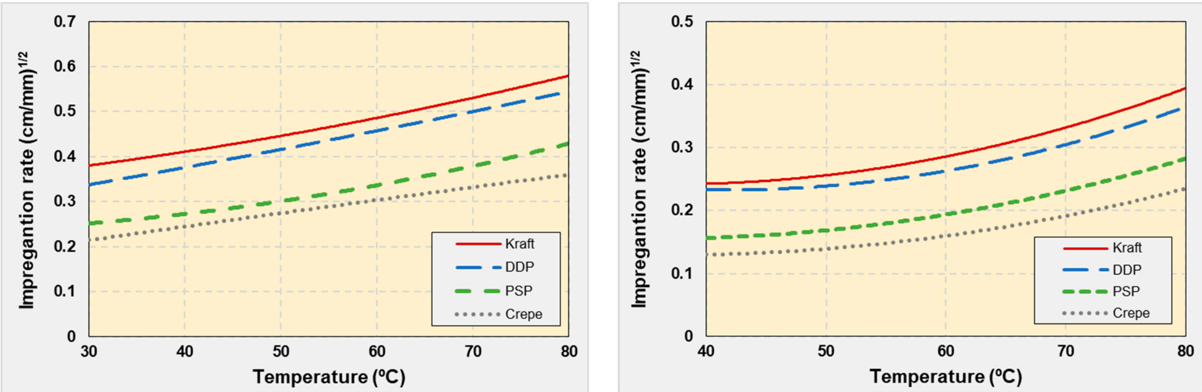


Figure 25. Variation of impregnation ratio with temperature for mineral oil and natural ester. Data from [35].

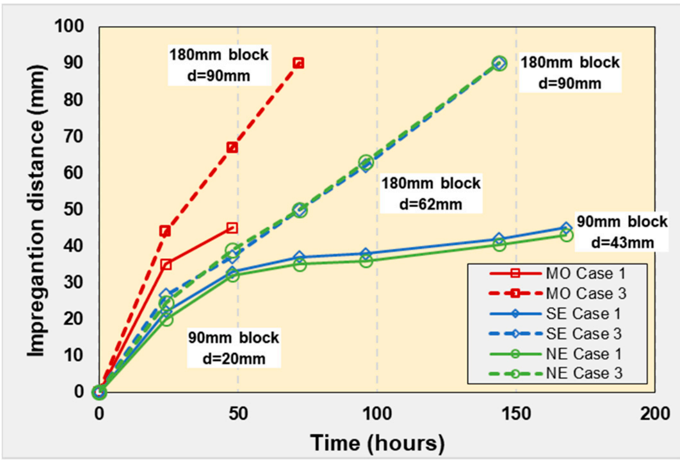


Figure 26. Impregnation behavior and visual evaluation of cross-impregnated samples of cellulose laminated blocks at different conditions. Data from [36].

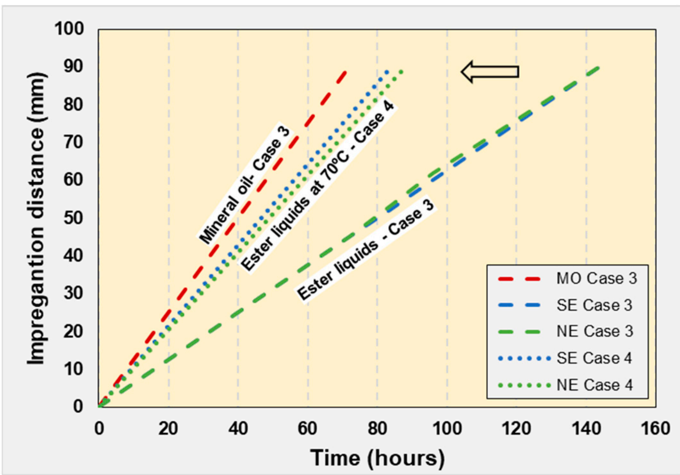


Figure 27. Influence of temperature in the impregnation of cellulose laminated blocks with natural and synthetic ester liquids. Data from [36].

The work also evaluated the breakdown voltage of impregnated pressboard samples (60 × 60 × 1.6 mm) after 6 and 24 h of impregnation. They also evaluated the relative permittivity (dielectric constant) at different temperatures of a natural ester, comparing it with that of a mineral oil in different types of solid insulation. Regarding this value, the results showed the superiority of the natural ester over the mineral oil (Figure 28).

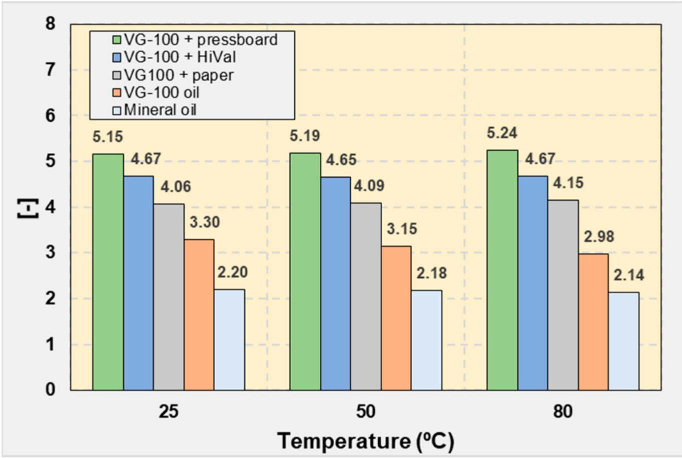


Figure 28. The relative permittivity of different insulating systems at different temperatures. Data from [36].

Case 1: laminated block samples were placed in glass containers with oil at 60 °C, and the impregnation process was at room temperature.

Case 3: cellulose block samples (180 mm) were placed in an impregnation chamber with an additional drying process at 0.07 mbar (50 μm) for 8 h.

Finally, in 2022, a study [37] was published regarding the design of transformers that use biodegradable fluids instead of traditional mineral oils. They studied the designs required for three different transformers (Table 9) and offered data on the final designs in terms of physical and electrical dimensions (Table 10). The authors concluded that the repercussion of the liquid change is not significant in terms of transformer dimensions (<2%). Regarding the weight, in small powers, the design for the ester type can increase it by more than 7%, with this increase being less as the power increases (<2.5% for high powers). Regarding the losses, small power transformers suffer small variations (<2%), while medium and large ones reach higher values (<7%).

Table 9. Data from the three studies' transformers, from [37].

Transformer's Features	Case 1	Case 2	Case 3
Power (MVA)	20	50	125/40
Connection configuration	YNd11	YNd11	YNYN0 + d11
HV nominal value (kV)	63	132	232
LV nominal value (kV)	30	30	66
Regulation HV winding	±10 × 1.5%	±9 × 0.889%	(+6; −10) × 1207%
Cooling method	ONAN	ONAF/ONAN	ONAF/ONAN
BIL (kVp)	325/170	550/170	850/325
Voltage application (kVp)	140/70	230/70	360/140

Case 3: cellulose block samples (180 mm) were placed in an impregnation chamber with an additional drying process at 0.07 mbar (50 μm) for 8 h.

Case 4: similar to Case 3 but maintaining the fluid at a temperature of 70 °C.

Table 10. Final design of the transformers, from [37].

	Case 1			Case 2			Case 3		
Feature	**MO**	**Ester**	**Impact (%)**	**MO**	**Ester**	**Impact (%)**	**MO**	**Ester**	**Impact (%)**
Length (mm)	4608	4664	+1.21	5309	5386	+1.45	7600	7698	+1.29
Width (mm)	3443	3445	+0.058	3496	3519	+0.65	4613	4553	−1.30
Height (mm)	4168	4222	+1.29	4639	4711	+1.55	5895	5909	+0.23
Short-circuit impedance (%)	8.31	8.46	+0.15	9.99	10.68	+0.69	14.96	15.31	+0.35
Installation mass (kg)	52,774	65,056	+6.22	92,239	96,334	+4.43	230,919	235,698	+2.06
Transport mass (kg)	38,108	41,005	+7.6	64,288	68,382	+6.36	150,421	154,077	+2.43
Off-load losses (W)	10,590	10,403	−1.76	20,306	20,140	−0.81	40,897	42,651	+4.29
Load-losses (W)	93,131	94,119	+1.06	204,029	218,195	+6.94	320,176	334,134	+4.36

As a summary of the publications analyzed in this work, Table 11 is included, which indicates the topics that the published articles deal with.

Table 11. Topics of published works.

Topics	**Reference Number**																						
Impregnation theory			17	18	19			22															
Dielectric properties								22		24				28	29				33			36	
Temperature	14			18	19	20		22		24			27	28				32			35	36	
Pressure						20													33				
Esters fluids	14			18	19								27	28				32		34	35	36	37
Paper	14									24					29						35		
Pressboard				18	19			22	23				27	28	29	30	31	32				36	
Rigid dielectrics	14			18	19	20							27							34		36	
Manufacturing		16					21				25	26											37

3. Conclusions

Solid cellulosic materials are impregnated with dielectric liquids mainly to eliminate any air pockets that they may contain. This helps to make the dielectric properties of solids more homogeneous, which reinforces their dielectric strength and therefore hinders the appearance of partial discharges. As is known, this is one of the main phenomena that contributes to the deterioration of solid dielectric materials and therefore reduces the useful life of the machines in which they are used.

If the impregnation procedure is not correct, potentially disastrous failures can result. Consequently, transformer manufacturers must be cautious, promoting techniques and methods that ensure adequate impregnation and adapting this process to the type of fluid used.

It has been known for some time, both in the scientific literature and by transformer manufacturing companies, that the time required to carry out a correct impregnation is reduced if the temperature is raised and if a vacuum is created inside the solids. Although it is difficult to make the initial pressure zero, it is possible to achieve a relative vacuum that helps speed up the impregnation process. Regarding the increase in temperature, it should be noted that in addition to improving the impregnation process, it tends to accelerate the degradation of cellulosic materials, so it is not advisable to exceed temperatures of the order of 60 °C. The use of these two techniques contributes to reducing manufacturing times and improving productivity (and with it the economic aspects of manufacturing), therefore increasing the competitiveness of the company.

Today, esters are a real alternative in distribution transformers. Regarding power transformers, there are a few companies that are carrying out field tests and trying to obtain real data on the operation and maintenance of power transformers with esters, but since these tests have started recently and the lifetime of these machines can exceed 30 years, it is unlikely that in the short term these large machines will begin to use esters on a massive scale.

Currently, there are very few studies on the impregnation process of different solid dielectrics with ester-type fluids; and in addition, these studies are carried out under different conditions (for example, using different initial moisture contents of both solids and liquids), so it is very difficult to draw conclusions. Much more research is needed in this regard, and we need to establish standard conditions for conducting the experiments.

In summary, it can be said that both the appearance and evolution of solid dielectrics of cellulosic origin, as well as the appearance of safer and more ecological alternative liquid dielectrics, such as esters, make it necessary to adapt impregnation processes to these new materials. In this sense, although some studies have been carried out, there are gaps in both knowledge and experience regarding the behavior of the new fluids.

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