The impact of thermal ageing on the compression strength of radial spacers in power transformers

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***Abstract*— Radial spacers made of high-density pressboard play a critical role in power transformers, providing support and maintaining distance between winding disks for efficient dielectric oil flow through cooling ducts. However, prolonged exposure to high temperatures leads to chemical reactions and degradation of mechanical and dielectric properties, potentially compromising transformer integrity. In this study, high-density pressboard spacers immersed in paraffinic oil underwent thermal aging to simulate the transformer lifespan. Various chemical, dielectric, and mechanical parameters were measured, including AC breakdown voltage, dielectric dissipation factor (tan δ), permittivity, resistivity, moisture content, and oil acidity. Moreover, the degree of polymerisation and compressive stiffness of the pressboard were determined. By establishing mathematical relationships, it was possible to estimate the compressive stiffness indirectly and non-destructively, from the degree of polymerisation and oil acidity measurements. These findings offer valuable insights for evaluating the condition of radial spacers and ensuring the reliable operation of power transformers.**

Keywords*— *power transformers, radial spacers, thermal ageing, compressive mechanical properties, degree of polymerisation, acidity

I. Introduction

Power transformers are essential for the transmission and distribution of electrical energy. The insulation inside them is one of the components which are more vulnerable to different degradation processes. The most common dielectric liquid in which the solid insulation is immersed is mineral oil, which contributes to the cooling of the heat generated during operation. The solid insulation is mostly made of cellulosic materials, such as paper and board, due to their good behaviour as dielectrics and their relatively low cost. The components of the solid insulation which have both a dielectric and mechanical purpose, such as is the case of radial spacers, are commonly made of high-density pressboard.

During the lifespan of transformers, the combination of high temperatures and chemical reactions leads to the degradation of insulation properties. Furthermore, the mechanical stresses arising from specific electrical phenomena, including inrush currents and short-circuit faults in the windings [1][2], can cause substantial damage to cellulosic insulation. Inadequate insulation performance stands as one of the primary factors contributing to transformer failures. In the case of radial spacers, their compressive mechanical properties are of key importance. After studying the exiting literature [3], it can be concluded that the studies realistically resembling the conditions inside a power transformer are very unusual (some examples are [4]–[6]), and the compressive mechanical response of high-density pressboard has not been well documented. Moreover, the development of non-destructive techniques to measure parameters enabling an indirect estimation of the loss of mechanical integrity is required, as the removal of a relevant amount of paper/board from an operating transformer for its testing is not possible in most cases.

Some indicators that could be used to infer the mechanical state of the solid insulation could be the dissolved gases in the oil, measured through gas chromatography [7]. The presence of furanic compounds in the dielectric liquid, particularly 2-furaldehyde (2-FAL), is also an indicator of degradation [8]. The moisture content in both the oil and the cellulosic insulation is strongly related to the chemical reactions that produce the degradation of the solid insulation and the ageing of the oil. Besides, the frequency response analysis, which measures the overall resistance, inductance, and capacitance of the transformer, and compares them to the reference values of the transformer in good condition, see [2], is another indirect indicator.

In the present study, spacers made of high-density pressboard were thermally aged during different periods, while being immersed in paraffinic dielectric oil, and in presence of a copper coil as catalyser of ageing. Some dielectric and mechanical properties were measured and their evolution during the ageing process was studied. The remainder of this paper is organised as follows: the materials and methods are described in section II, the results are presented in section III and discussed in section IV. The conclusions of this research are exposed in section V.

II. Materials and Methods

A. Materials

The manufacturing properties of the radial spacers made of high-density pressboard are listed in Table I. The insulating liquid inside power transformers plays a relevant role in the chemical phenomena that lead to degradation of the solid insulation. As nowadays mineral oil is the most common of those liquids, the pressboard samples were immersed into uninhibited paraffinic oil during the ageing process, whose properties are presented in Table II.

B. Methods

- *Accelerated thermal ageing:*

Square samples of side 30 mm were extracted from the high-density pressboard spacers, introduced into an oven, and dried for 4 hours at 105 °C up to a moisture content of 1%, measured according to [9]. The paraffinic oil was also vacuum-dried for 3 hours at 105 °C, up to a moisture content of 32.1 ppm. The dried pressboard was immersed in oil for its impregnation during 24 h at 60 ºC.

TABLE I. PROPERTIES OF THE TESTED RADIAL SPACERS

High-density pressboard		
Property	***Unit***	***Value***
Thermal class	°C	105
Apparent density	g/cm^3	1.2
Nominal Thickness	mm	2
Tensile Strength in MD	MPa	124
Tensile Strength in CD	MPa	92
Elongation at breakage in MD	%	3.9
Elongation at breakage in CD	%	4.6
Compressibility	%	4.8
Shrinkage, in ZD	%	4.4
Shrinkage, in MD	%	0.4
Shrinkage, in CD	%	0.5

TABLE II. PROPERTIES OF THE DIELECTRIC OIL

Uninhibited paraffinic oil		
Property	***Unit***	***Value***
Density at 20°C	g/cm^3	0.839
Viscosity at 40°C	mm^2/s	9.98
Viscosity at -30°C	mm^2/s	925.85
Flash point	ºC	176
Pour point	°C	-48
Interfacial tension	mN/m	43
Dielectric dissipation factor, 90ºC	-	0.00198
Acidity	mg KOH/g	<0.01
Water content	mg/kg	15
Furfural content	mg/kg	<0.05

After that, 45 pressboard samples (total mass of around 95 g) were introduced into a stainless-steel vessel filled with 700 ml of paraffinic oil, and with pieces of a copper coil (with a total mass of around 1340 g). Those quantities were selected in order to have approximately the same pressboard/copper proportion that is present in the windings of power transformers. Then, the vessels were vacuum-sealed, and an inert atmosphere was created by filling them with nitrogen. The vessels were aged in an oven at 150 °C for: 3 days, 1 week, 2 weeks, 6 weeks, 12 weeks and 20 weeks.

- *Experiments for obtaining chemical and dielectric properties:*

Different dielectric properties of the paraffinic oil were obtained to characterise its degradation. Its AC breakdown voltage (BDV) was measured at room temperature following [10]. The dielectric dissipation factor (tan δ), the permittivity and the resistivity of the oil were measured following [11]. The moisture content, which has a critical impact on the dielectric properties of the oil and on the response of the solid cellulosic insulation, was measured following [9]. Acidity of the oil was measured through potentiometric titration according to [12]. The DP of the high-density pressboard was measured according to [13]. The results of the mentioned experiments are presented in section III.

- *Experiments for obtaining mechanical properties:*

The purpose here is to study how the mechanical response to compressive loading of the radial spacers varies as the material degrades due to ageing. Although studies obtaining the tensile properties of paper and board following [14] are very usual, there are no accepted standards to test pressboard for electrical purposes under compressive loading. The compressive stiffness is a mechanical property that measures how a material withstands deformations in the thickness direction under compression. A high stiffness of the radial spacers implies lower deformations, and a better mechanical integrity for the whole power transformer.

To measure the stiffness, 5 square pressboard samples, with a 30 mm side, were stacked to make a prism. Three cycles of loading and unloading were applied by means of a servo-hydraulic universal testing machine, equipped with a ±5 kN load cell and an actuator with a ±50 mm stroke. The load was transferred through a steel loading plate equipped with a ball joint, see Fig. 1 (a). As pre-compression of the pressboard affects its stress-strain behaviour [5], two first cycles were used to stabilise the sample, and the stiffness was obtained from the third cycle.

The testing machine increased the load up to 4 kN at a speed of 0.1 kN/s and records the compressive load (N) and the deformation of the board sample (mm). The compressive stress would be obtained as in equation (1), where F is the compressive load (in N). The deformation suffered by the compressed prism is the sum of the deformations suffered by each of the 5 square pressboard samples, which can be assumed to be approximately the same, see equation (2). The compressive stiffness of the prism was obtained as the slope of the load curve, following equation (3), in which F_1 and F_2 are two load levels (in N), and d_1 and d_2 are the compressive displacements (in mm) produced by those loads, see Fig. 2.

$$\sigma = F/(\pi 12^2)\ (MPa) \tag{1}$$

$$K_{pressboard} = 5 \cdot K_{prism}\ (N/mm) \tag{2}$$

$$K_{prism} = (F_2 - F_1)/(d_2(F_2) - d_1(F_1))\ (N/mm) \tag{3}$$

The radial spacers were subjected to two different kinds of tests. In tests A, the compression was performed in open-air at room temperature, see Fig. 1 (a). In tests B, the spacers were compressed while being immersed in dielectric oil at 80 ºC, which is a feasible temperature inside operating power transformers, see Fig. 1 (b).

Fig. 1. Radial spacers under compressive loading in (a) type A tests and (b) type B tests, immersed in paraffinic oil.

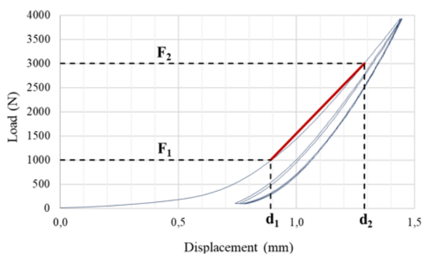

Fig. 2. Process for obtaining the compressive stiffness of the radial spacers from the force-displacement curves.

III. Results

During the ageing process, the BDV decreased up to 58.6%, due to the formation of ageing subproducts, see Fig. 3 (a). The smallest value of the BDV measured after 336 hours is produced by the moisture content in the oil, which reached the highest value at 336 hours of ageing. The tan δ, which depends on the conductivity and polarity of the oil, increased 450% with the ageing, see Fig. 3 (b). The effect of thermal degradation was remarkable at the beginning of the ageing process. The resistivity, depicted together with the tan δ, decreased especially at the beginning and suffers some slight increases coinciding with the reduction of the tan δ. The variations in both magnitudes are produced by the reduction of conductivity due to a low moisture content.

The acidity of the oil increased during the ageing due to the degradation of both the pressboard and the oil, reaching a value of 0.63 mg KOH/g at the end of the ageing process, see Fig. 4. The high acidity, together with the drastic reduction of the BDV and the high increase of the tan δ, indicate a significant degradation of the mineral oil during the studied ageing period.

The DP of the high-density pressboard is also represented in Fig. 4, being its initial value around 1000. The most drastic variation happens during the first day of thermal ageing, when a value of 180 is reached and, after that, the degradation rate slows down, reaching a final value of 10.2. However, although those values would mean a total fragile state for thin Kraft insulation, the apparent consistency of the pressboard was more or less similar during the whole ageing duration. That suggests that other parameters, different than the DP, should be used to infer the mechanical compressive integrity of the pressboard spacers.

The evolution of the previous properties is interlinked, as the oxidation of the cellulose causes the decrease of the DP, and the generated acids are catalysers for the hydrolysis of the cellulose[15], which subsequently leads to DP reduction [16]. Oxidation also generates water that can react later on through hydrolysis. Water and acids not only degrade the cellulosic insulation, but also produce changes in the dielectric properties of the oil [17].

Three compressive tests were performed over the pressboard prism for each of the studied ageing durations, in order to get an average value for the compressive stiffness. The response of pressboard to compressive loading is strongly non-linear, see Fig. 5, due to its porous structure, which collapses while being compressed, introducing a plastic deformation. Thus, the first two compressive cycles cause the densification of the material, and the compressive stiffness was obtained from the third cycle, as previously indicated in Fig. 2. The values of $F_1 = 1000$ N and $F_2 = 3500$ N and their correspondent displacements were introduced in equation (3).

The variation of the compressive stiffness of the high-density pressboard as a function of the ageing duration is shown in Fig. 6 for both performed tests, those in open air at room temperature (A) and immersed in oil at 80 ºC (B). In both cases, the degradation due to ageing reduces the compressive stiffness. As expected, the high-density pressboard is more deformable in tests B. It was considerably more time-consuming to perform tests B than tests A, but a strong linear correlation ($R^2 = 0.992$) was found between the stiffness measured in both tests, see equation (4). That is a very relevant finding, because it allows the estimation of the material response under compressive loading immersed in dielectric liquid from tests performed in open-air.

$$K_{Tests\ B} = 1.135 \cdot K_{Tests\ A} - 4.7336 \text{ (kN/mm)} \quad (4)$$

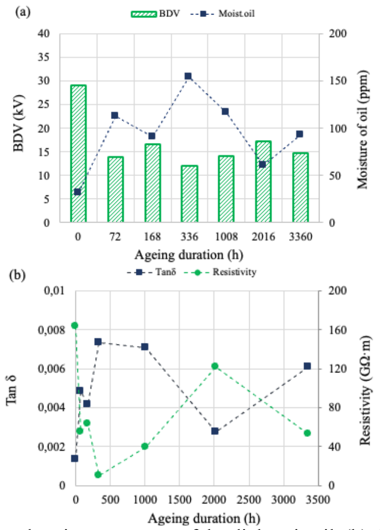

Fig. 3. (a) BDV and moisture content of the dielectric oil, (b) dissipation factor (tan δ) and resistivity, as a function of thermal ageing duration.

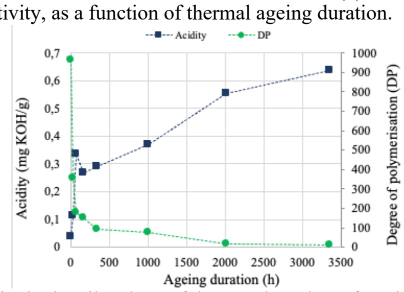

Fig. 4. Acidity in the oil and DP of the pressboard as a function of thermal ageing duration.

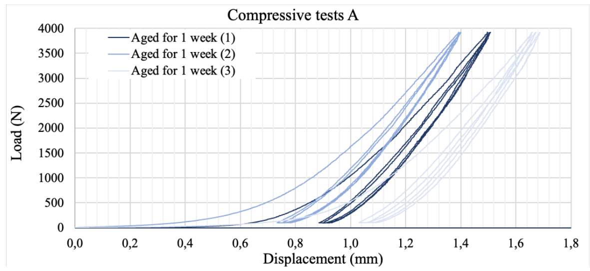

Fig. 5. Compressive Test A over the pressboard prism for an ageing duration of 1 week.

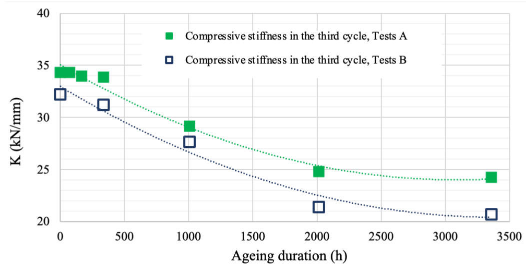

Fig. 6. Evolution of the compressive stiffness of the spacers as a function of ageing duration.

The compressive stiffness of the pressboard obtained from tests A is plotted in Fig. 7 as a function of the acidity and the DP, both measured after the considered ageing durations. A logarithmic function relating the stiffness and the DP is the one which best fits the experimental data ($R^2 = 0.794$), see equation (5). For the case of the acidity and the stiffness, a quadratic fitting shows a good correlation ($R^2 = 0.882$), see equation (6).

$$K_{Tests\ A} = 2.6171 \cdot ln(DP) + 19.117\ (\mathrm{kN/mm}) \quad (5)$$

$$K_{Tests\ A} = -37.665\,A^2 + 6.0073A + 34.55(\mathrm{kN/mm}) \quad (6)$$

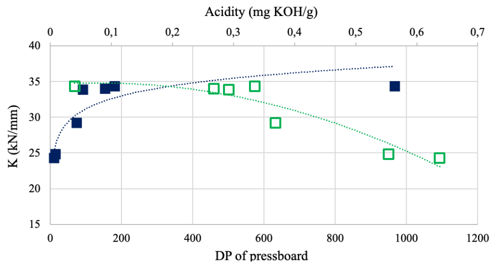

Fig. 7. Compressive stiffness of the high-density pressboard as a function of the DP and the acidity.

IV. Discussion

The aim of this research was to resemble as best as possible the most extreme conditions that could happen near the end-of-life of an operating power transformer. Thus, a very high ageing temperature of 150 ºC was applied, and a high mass of copper pieces was introduced in the vessels. Several chemical, dielectric and mechanical properties of the oil and the pressboard spacers were measured, see section II.

Regarding the results of compressive tests over the spacers, the stiffness when the pressboard is immersed in oil at 80 ºC can be estimated from the value obtained in open-air, which is a really useful finding, because it facilitates the experiments. Equation (4) can be calibrated for other materials, ageing conditions and testing conditions.

Although the DP is the parameter most commonly used in the literature devoted to cellulosic insulation in transformers, and it is intrinsically related with the tensile mechanical response of the thin paper insulation, the same does not happen when studying the compressive response of high-density components. The spacers still withstand high compressive loads with a very low DP value. Then, it will be inappropriate to use the DP as end-of-life criterion for high-density pressboard components, as it is typically done with the thin paper insulation.

There is a moderately strong logarithmic relationship between the DP of the pressboard and the compressive stiffness during the whole ageing duration, see equation (5). A second-degree polynomial function relates the acidity of the oil (in mg KOH/g) and the compressive stiffness of the spacers, see equation (6). Again, similar expressions could be obtained for other materials and ageing conditions. The use of the acidity as chemical parameter related with the mechanical properties is very convenient when the purpose is to monitor the state of power transformers during operation, because its measurement does not require extraction of samples of the solid insulation.

V. Conclusions

Radial spacers of power transformers have both a dielectric and mechanical purpose, as the mechanical integrity of the electric machine depends on their performance. The compressive stiffness is the mechanical parameter that can be used to characterise the material response to compressive loading. The compressive stiffness reduces due to thermal degradation, but much slower than the DP of the high-density pressboard. It would be possible to indirectly infer the value of the compressive stiffness from the acidity of the oil, in mg KOH/g, according to equation (6). This is very convenient, as the acidity of the oil can be measured in operating transformers.

Furthermore, the pressboard still shows a good mechanical integrity after 20 weeks of ageing in a very aggressive environment, confirming the suitability of this material for being used in the structural components of power transformers. In the future, it would be of interest to compare the results shown in this work with those obtained when testing different materials (such as other dielectric liquids), or applying different ageing conditions (such as temperature and moisture content).

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