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The application of a molecular sieve for drying the insulation system of a power transformer in terms of improving its perational reliability

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Highlights

- Selectivity of water and hydrogen sorption through a 3A molecular sieve was shown.
- Use of 3A MS does not affect the diagnostics of transformers using the DGA method.
- Effectiveness of drying insulation using a 3A MS has been demonstrated.
- Drying efficiency was proved for cellulose impregnated with various liquid dielectrics.

Abstract

The first research objective was the assessment of the selectivity of water and hydrogen adsorption by the 3A molecular sieve (MS) in the terms of the safety of using the DGA (Dissolved Gas Analysis) method as a diagnostic technique. The second objective was to demonstrate the efficiency of drying the insulation system consisting of cellulose insulation impregnated with various insulating liquids in terms of improving safety and extending the service life of power transformers. In order to achieve the assumed objectives, measurement systems were prepared and material tests were carried out, based mainly on chromatographic analyzes and measurements of water content using the Karl Fischer titration method. On the basis of the obtained test results and the conducted physical analyzes, the selectivity of MS sorption was shown and it was explained that the facilitator of the adsorption of water molecules is their polar nature related to their large dipole moment. The high efficiency of drying cellulose insulation impregnated with various insulating liquids using MS was also demonstrated.

Keywords

power transformer, insulation system, drying, molecular sieve, mineral oil, natural ester, synthetic ester.

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1. Introduction

Power transformers are key elements of an electric power system. Their technical condition largely determines the reliability of electricity supply to the end user. During the long-term operation of a transformer, often exceeding 30 years, the condition of its insulation system is gradually deteriorating. One of the reasons is the increase in moisture of electrical insulating materials. For the construction of the transformer insulation system, mainly fibrous materials such as cellulose and aramid are used, which are impregnated with electrical insulating liquids, e.g. mineral oil, synthetic ester, natural ester, or silicone oil. Regardless of the materials used, the transformer insulation system gradually increases its level of moisture, especially the insulation system made of cellulose materials.

There are three main reasons for the presence of water in the transformer insulation system: (i) incomplete drying of the insulation system at the production stage – a well-dried transformer is characterized by moisture at the level of about 0.5% [19, 21], (ii) moisture penetration inside the transformer – in case of power and distribution transformers with a membrane-sealed conservator preservation system, the rate of water contamination is about 0.03% to 0.06% per year [5], (iii) oxidation of cellulosic materials and oil [17, 20].

Water is both a product and a catalyst in the degradation of electrical insulating materials. Its presence leads to the hydrolysis of cellulose, which reduces the degree of polymerization of this material. As a result, the mechanical strength of cellulose-based materials deteriorates. It may lead to a failure caused by winding movement resulting from high mechanical stresses during a short circuit [4]. The high level of moisture in the insulation system also contributes to the reduction of its electrical strength. With the increase in the relative saturation of the insulating liquid with water, a decrease in its breakdown voltage is observed [1]. The high level of water content in the insulation also reduces the inception voltage of partial discharges and their intensification [26]. Moreover, as the water content of cellulose insulation increases, there is a greater risk of a dangerous bubble effect [16, 24], which may cause pressure increase in the transformer tank and may be the cause of partial discharges.

Taking the above into account, it can be concluded that a high level of moisture in the transformer's insulation system may lead to its failure and requires a decision to reduce its load. To avoid serious

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consequences related to the high level of moisture in the transformer's insulation system, its moisture level should be monitored, and, if necessary, temporary drying should be carried out.

There are several methods available on the market for drying the transformer insulation system. These methods can be divided into two groups.

The first group of drying methods is based on the use of a vacuum. For these methods, it is necessary to drain the oil from the transformer tank, heat the insulation system, and apply a suitable underpressure. A very important part of the drying procedure is the heating of the insulation system. Heating of the insulation system can be carried out in several ways, the most effective of which include: heating the windings with a low frequency current (LFH—Low Frequency Heating) [3, 14] and heating the insulation elements using the vapor condensation heat of a liquid called solvent [2, 12]. Undoubtedly, the greatest advantage of vacuum drying methods is their high efficiency. Unfortunately, these methods also have several disadvantages. Cellulose deimpregnation due to pressure reduction may cause a reduction in its local electrical strength, leading to partial discharges. In the case of distribution transformers, there is often a problem with the application of a suitable underpressure, which results from the leakage of the transformer construction or the low compressive strength of the tank, which in many cases does not exceed 0.5 bar below atmospheric pressure. The use of such a reduced pressure does not allow proper drying of the insulation system. On the other hand, when the insulation system is heated with solvent vapors, there is a risk of explosion.

The second group of drying methods is based on the use of a liquid dielectric as the drying medium. This method uses the effect of the insulation system striving to the moisture balance. As a result of the moisture gradient, water migrates from cellulosic materials with higher relative humidity to the insulating liquid with lower relative water saturation. To keep the water content in the insulating liquid low, it is dried by means of an oil treatment plant connected to the transformer tank or using a container filled with hygroscopic material. The use of an oil treatment plant for drying transformer insulation is an ad hoc procedure, i.e. it is carried out when a high level of moisture is detected. After the drying process, the oil treatment plant is disconnected from the transformer. In turn, the adsorbers can be used for both ad hoc and continuous drying of insulation, which allows to keep the moisture of the solid insulation at a low level throughout the entire operation period. This approach allows extending the transformer insulation life and contributes to a significant improvement in the safety of its operation.

2. Application of a molecular sieve for drying the transformer – state of art, problems to be solved

The effectiveness of the drying process of the transformer solid insulation with the application of an insulating liquid, in which the water content is reduced with the use of an adsorbent, depends primarily on its specific surface area. Figure 1 compares the water content of various hygroscopic materials (aluminum oxide, silica gel, 3A molecular sieve) conditioned in air at 50°C and with different relative humidity forced by saturated salt solutions (2.11% - cesium fluoride, 11.10% - lithium chloride, 12.38% - lithium iodide, 30.54% - magnesium chloride, 45.44% - magnesium nitrate, 74.43% - sodium chloride) [11]. The results of the research presented in Figure 1 were obtained by the authors of the article at the stage of preliminary studies, the aim of which was to select a hygroscopic material characterized by a high steepness of the water sorption isotherm for low values of relative humidity.

Based on the data presented in Figure 1, it can be concluded that for low values of relative humidity, the 3A molecular sieve is characterized by a much higher water sorption capacity than silica gel and activated alumina. This is a key feature to keep the moisture content of the transformer insulation system low. Figure 2 shows the water sorption isotherms for new cellulose. For a relative humidity equal

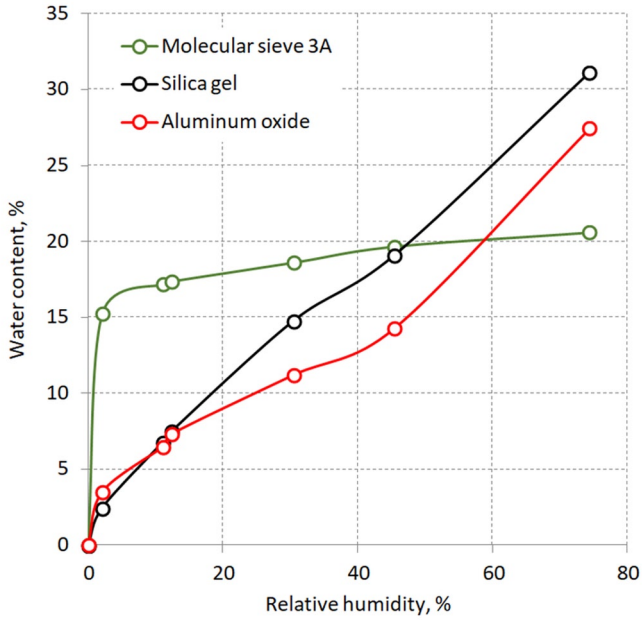

Fig. 1. Dependence of water content in adsorbents as a function of relative humidity of air at 50°C

to 5% and for cellulosic material temperature in the range of 30°C to 70°C (typical operating temperature range of a power transformer), the water content in this material ranges from 0.6 to 1.2%. It is a low level of moisture in cellulose insulation that allows to limit its aging processes and significantly improves the operational safety of the power transformer.

There are various types of molecular sieves available on the market, e.g. 3A, 4A, 5A, 13X, which differ significantly in structure. Their structure can be described by a general formula in the form [25]:

$$M_{n/m}^{m+} \cdot [Si_{1-n}Al_{n}O_{2}] \cdot zH_{2}O \tag{1}$$

where: M – metallic cation, m – cation charge, n – number of metal atoms, z – the number of moles of water.

Their basic feature is the presence of a crystal structure with a homogeneous pore system. The extended internal surface of the sieve is available only for particles with a diameter smaller than the critical pore diameter. In the case of the 3A, 4A, 5A, and 13X sieve, only particles smaller than 3 Å, 4 Å, 5 Å, and 9 Å, respectively, can penetrate through the pores of the sieve. Therefore, when choosing a molecular sieve as the material used in the drying process, not only the specific surface of the sieve, which determines its adsorption capacity but most of all the pore size in this material, must be taken into account.

In the case of drying insulating liquids, it is important that the molecular sieve adsorbs only water molecules. Adsorption of other molecules may result in the occupation of active centers, which may result in a reduction of the adsorption capacity for water molecules.

Attention should also be paid to the diagnostic aspect of the presence of gases in electrical insulating liquids. Increased concentration of gases such as hydrogen, carbon monoxides, and hydrocarbons in the oil may indicate an imminent failure of the device. The presence of these gases is related to the chemical decomposition of the insulating liquid and cellulose insulation resulting from high temperature, as well as partial and high energy discharges.

Figure 3 shows the diameter of water and gas molecules present in insulating liquids in relation to the size of the pores in the 3A molecular sieve.

The data presented in Figure 3 show that the only molecules that can be adsorbed by the 3A molecular sieve are water and hydrogen, the particle diameter of which is respectively 2,64 Å i 2,89 Å. However, it should be taken into account that the increase in temperature causes

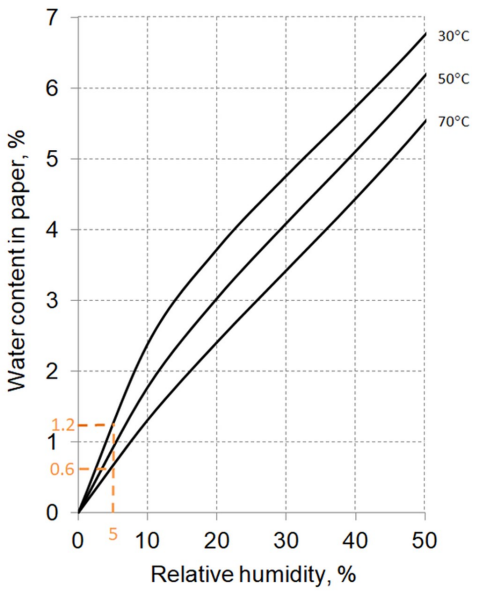

Fig. 2. Water sorption isotherms of new cellulose (degree of polymerization equal to 1360); based on [22]

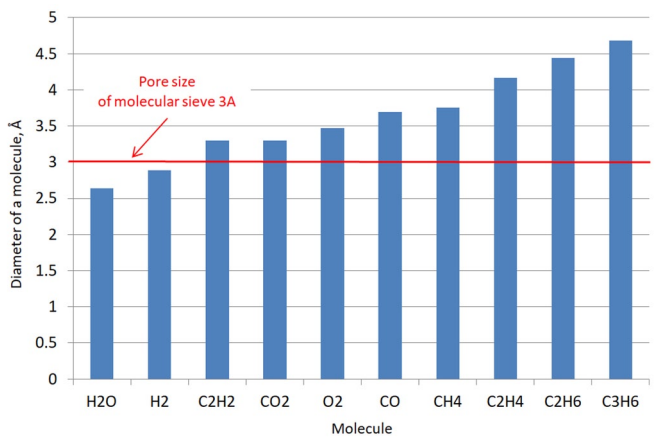

Fig. 3. Dimensions of water and gas molecules present in insulating liquids; based on data from [27]

greater flexibility of the crystal lattice of the sieve, thus enabling the adsorption of larger molecules [25]. According to the authors of [8], the gas molecule that can also be adsorbed by the 3A molecular sieve is acetylene. It is characterized by an uneven distribution of the space charge, which may cause it to be attracted to the molecular sieve. However, such adsorption can only take place at temperatures close to 130°C. This temperature can be achieved in a transformer, especially in the so-called hot-spot. It should be noted, however, that the molecular sieve reservoir is to operate outside the transformer tank, which will limit the temperature of the oil flowing through the molecular sieve to a value well below 100°C. This eliminates the problem of acetylene adsorption by the molecular sieve.

The possibility of adsorbing hydrogen molecules by the molecular sieve remains a problem. Hydrogen is a characteristic gas generated mainly as a result of the partial and high energy discharges in the insulating liquid [23]. In the case of hydrogen adsorption by the molecular sieve, problems may arise in the interpretation of the test results obtained by the DGA (Dissolved Gas Analysis) method. It should be noted that this is the basic diagnostic method for power transformers.

In this paper, the authors present the results related to the study of the selectivity of hydrogen and water adsorption by a 3A molecular sieve. These studies are important in terms of the effectiveness of the use of a molecular sieve for drying the insulation system and the possibility of using the DGA diagnostic method in the case of transformers dried with this sorbent.

In the previously published studies on the use of a molecular sieve for drying the transformer insulation system, the authors presented, inter alia, the results of research on the influence of temperature on the drying efficiency of insulating liquids. These studies show that the dynamics of liquid drying increases with the temperature increase. The papers [7,10] showed that the molecular sieve can also be used in the drying of liquids alternative to mineral oil, such as synthetic and natural esters. When considering the insulating system of a power transformer, it must be borne in mind that it consists of insulating liquid and cellulose materials. Due to its high hygroscopicity, cellulose insulation contains over 95% of the water present in the entire transformer insulation system. Therefore, drying only the liquid insulation does not solve the problem of high moisture of the entire insulation system. Drying of the insulating liquid causes a moisture gradient. The oil-paper insulation system strives to moisture equilibrium. In such a situation, the water migrates from the moist cellulose insulation to the mineral oil dried by a molecular sieve. In this way, the water content in the solid insulation is gradually reduced. The authors of the work [15] demonstrated the effectiveness of this method of drying in the case of two 49-year-old transformers, in which cellulose insulation was impregnated with mineral oil.

Currently, more and more emphasis is placed on the use of natural and synthetic esters mainly due to their good fire properties (high flash and fire points) and high biodegradability [6,9]. One of the features of these liquids is the much higher water solubility than in mineral oil. The authors put forward a thesis that by using a molecular sieve as a drying agent, it is possible to significantly reduce the water content in cellulose materials, regardless of the electro-insulating liquid used in the transformer's insulation system. This effect can be achieved at the normal operating temperature of the transformer. Research confirming the effectiveness of this method of drying cellulose insulation impregnated with natural and synthetic esters is important due to the aging, and thus the dampening process, of an increasing population of this type of transformers.

3. Selectivity of the 3A molecular sieve in terms of water and hydrogen adsorption

3.1. Materials preparation and measurement procedure

In order to check the sorption selectivity of the 3A molecular sieve, it was necessary to prepare mineral oil with increased water and hydrogen content. To obtain the appropriate humidity of the oil, it was moistened in a climatic chamber forcing an air temperature of 30°C and relative humidity of 40%. The moisture content of the mineral oil prepared in this way was 26 ppm. In turn, to obtain a high hydrogen content in the analyzed mineral oil sample, the HG 2200 hydrogen generator was used. Generated hydrogen was injected into an oil-filled bottle. The oil prepared in this way was left in a closed bottle for two weeks to allow the hydrogen to dissolve in it.

Thereafter, 16 vials were prepared each with a volume of 57 ml. The vials were divided into four sets of four samples. All four sets of vials were filled with mineral oil, while the 3A molecular sieve was added to the vials of Sets II and IV. The amount of sieve added was about 1% of the weight of the oil. The 3A molecular sieve (Sigma Aldrich Cat no. 105704) of the following formula was used in the research:

$$K_9Na_3\left(AlO_2\right)_{12}\left(SiO_2\right)_{12}\cdot 27H_2O \tag{2}$$

Before adding to the vials, the sieve was activated at 260°C for 6 hours and then further degassed for 2 hours in a vacuum chamber at 0.2 mbar and 90°C.

Then all vials were closed with aluminum crimp caps with ptfe/silicone septum. The vials were placed in a heat chamber to ensure a constant temperature of 35°C. In order to assess the selectivity of water and hydrogen sorption through a molecular sieve, their concentrations were measured after 2 and 7 days from the moment of closing them in vials. After 2 days, the concentration of water and hydrogen was tested in the samples from the first set (I - MO), which contained only oil, and from the second set (II - MO + MS), which contained oil with molecular sieve. The same was done for the third (III - MO) and fourth (IV - MO + MS) sets after 7 days. Table 1 presents the list of samples prepared for the tests.

The water content in the oil was measured using the Karl Fischer coulometric method (KFT) in accordance with IEC 60814 [13]. The 831 KF Coulometer by Metrohm was used for the measurements. The Hydranal - Coulomat CG reagent was used as the catholyte, while the Hydranal - Coulomat Oil reagent was used as the anolyte.

The hydrogen content of the oil was measured using a 8610C Toga gas chromatograph by SRI Instruments. Extraction of hydrogen from the oil was performed by headspace technique (70°C, 2 h). To measure the hydrogen concentration, a chromatograph equipped with a column with a 5A molecular sieve and a thermal conductivity detector was used.

3.2. Research results and their discussion

Table 1 shows the results of measurements of hydrogen and water content in mineral oil. To check the selectivity of the molecular sieve for the adsorption of water and hydrogen, it was decided to perform measurements after 2 and 7 days from the preparation of the samples. Previous studies by the authors show that this time is sufficient for drying the oil by means of molecular sieve.

Figures 4a and 4b compare the average values of hydrogen and water concentration in mineral oil without and with the molecular sieve, respectively, after 2 and 7 days from the preparation of the samples.

The main aim of the research was to compare the effect of the presence of a molecular sieve on the concentration of hydrogen and water in mineral oil. Analyzing the average results of hydrogen and water concentration, measured two days after the preparation of the samples, presented in Figure 4a, it can be clearly stated that the presence of a molecular sieve did not affect the reduction of hydrogen in the mineral oil, but caused its considerable drying. The concentration of hydrogen in the mineral oil remained at around 7700 ppm in both cases, while the water content decreased by 16 ppm, i.e. around 62%. The lack of influence of the molecular sieve on the hydrogen concentration is also confirmed by the results presented in Figure 4b, presenting the results obtained after 7 days from the preparation of the samples. In this case, the hydrogen content in the oil with and without molecular sieve remained at the level of about 5700 ppm, while the water content decreased to the level of 7 ppm. The differences in hydrogen concentrations for the samples of non-dried oil and those dried with molecular sieve for two days are small and are within the range of measurement uncertainty using the DGA method used for the tests. The same conclusions can be drawn when comparing the hydrogen concentrations for the samples of non-dried oil and those dried with molecular sieve for seven days.

The difference in the hydrogen content in the samples tested after two (7700 ppm) and seven days (5700 ppm) is mainly due to the hydrogen infiltration at the glass-ptfe interface. Vials dedicated to gas chromatography, closed with an aluminum cap with a silicone septum covered on one side with polytetrafluoroethylene, were used for the tests. This material is a barrier to hydrogen. However, due to the small diameter of the hydrogen molecules, they can easily penetrate any leaks. All vials were closed using a crimper with the same pressing force. The loss of hydrogen in the oil from vials 8 to 16 was at the same level, thus not due to the adsorption of hydrogen through the molecular sieve that was placed in vials 13 to 16.

Due to the size of the molecule, both hydrogen and water can penetrate the intercrystalline space of the 3A molecular sieve. However, as it turns out, this is not sufficient for the sieve to be able to adsorb hydrogen. The difference in the ability of the 3A molecular sieve to adsorb water and hydrogen should be seen in the polarity of both mol-

Table 1. Water and hydrogen content in oil - a summary of the measurement results

Time	Set	Sample No	Weight of oil, g	Weight of molecular sieve, g	Hydrogen content in oil, ppm	Water content in oil, ppm
After two days	I – MO	1	25.339	0	7759	26
		2	25.723	0	7745	27
		3	24.748	0	7915	28
		4	25.333	0	7632	26
		Average:			7763	27
	II – MO+MS	5	25.594	0.305	7996	10
		6	26.373	0.315	7761	10
		7	25.421	0.309	7547	10
		8	25.750	0.301	7503	10
		Average:			7702	10
After seven days	III MO	9	25.625	0	5820	26
		10	25.193	0	5976	25
		11	25.348	0	5698	24
		12	26.095	0	5593	27
		Average:			5772	26
	IV – MO+MS	13	24.778	0.312	5677	7
		14	25.781	0.300	5463	7
		15	24.874	0.307	5991	8
		16	25.942	0.307	5776	8
		Average:			5727	7

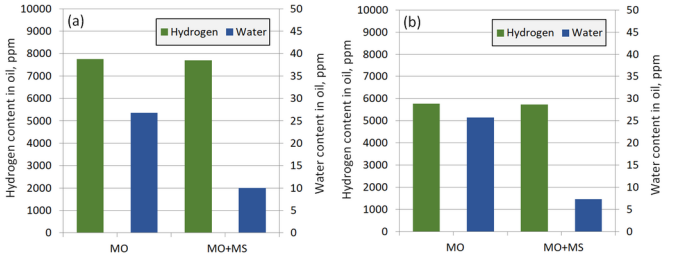

Fig. 4. Comparison of the average values of hydrogen and water concentration in mineral oil samples without (MO) and with molecular sieve (MO + MS) after two (a) and seven (b) days from the preparation of the samples

ecules. The water molecule is polar and its dipole moment is 1.85 D [18]. Hydrogen is a symmetrical diatomic molecule that does not have a dipole moment. It is the polar nature of water that allows it to be attracted and adsorption by a molecular sieve. Among the diagnostic gases found in insulating liquids, carbon monoxide, propylene, and propane also have a dipole moment greater than zero, respectively (0.112 D), (0.366 D), and (0.084 D), but due to the size of the molecules, none of these gases can be adsorbed by the 3A molecular sieve.

4. Drying efficiency of cellulose insulation impregnated with various insulating liquids

4.1. Materials preparation and measurement procedure

The aim of the research was to check the possibility of using a molecular sieve for effective drying of cellulose insulation impregnated with mineral oil, natural ester, and synthetic ester. The drying conditions of the materials were to correspond to the conditions occurring during the operation of a typical power transformer. Therefore, drying was carried out at 50°C. The ratio of the weight of cellulose to the volume of the insulating liquid was 0.12. The dried cellulose materials were two types of pressboard, one 0.5 mm thick and the other 6 mm thick, with the initial moisture content given in Table 2. The weight ratio of thin to thick pressboards was 0.2. Three twin sets of pressboards were prepared to be impregnated successively with mineral oil, natural ester, and synthetic ester.

Preparation of pressboards for drying comprised the following stages:

- preparation of three sets of pressboards consisting of 7 pieces of thick pressboard strips with dimensions 280:19:6 mm and 18 sheets of thin pressboards with dimensions 235:26:0.5 mm,
- drying of the pressboard in a vacuum chamber (90°C±5°C, 0.2 mbar, 48 h),
- conditioning of pressboards in a climatic chamber (40°C, 16%rH, 264 h),
- impregnation of three sets of pressboards successively with mineral oil, natural ester, and synthetic ester in a vacuum chamber (10 mbar, 0.5 h),
- conditioning of pressboards impregnated with various insulating liquids in the climatic chamber (40°C, 16%rH, 240 h),
- measurement of water content in pressboards impregnated with various insulating liquids using the Karl Fischer titration method (KFT) in accordance with the standard [13].

Each of the three sets of pressboard materials was placed in a separate 2-liter bottle. The bottles were filled with mineral oil (Orlen Trafo EN), natural ester (FR3), and synthetic ester (Midel 7131). The initial water content of these liquids was measured by the KFT method. Table 2 presents information on the sets of cellulose materials impregnated with various insulating liquids prepared for drying with the use of a molecular sieve.

Figure 5 shows a diagram of the measurement system used in the process of drying insulation materials with the use of a molecular sieve.

This system consisted of four basic elements connected by silicone hoses:

(1) bottle (B) with cellulose materials (CM) impregnated with electro-insulating liquid (EL),
(2) peristaltic pump (PP) forcing the liquid to flow in the system,
(3) three-way valve (TWV), which enables a liquid sample to be taken with a syringe (S) for testing the water content by the KFT method,
(4) cartridge with molecular sieve (MS).

Table 2. Summary of data on cellulose materials and insulating liquids prepared for drying with the use of a molecular sieve

Set	Water content in pressboard 0.5 mm, %	Water content in pressboard 6 mm, %	Water content in the liquid, ppm	Weight of 3A molecular sieve, g
Set I Pressboard impregnated with mineral oil	3.36	3.04	27	58
Set II Pressboard impregnated with natural ester	3.29	2.85	50	58
Set III Pressboard impregnated with synthetic ester	3.59	2.89	200	58

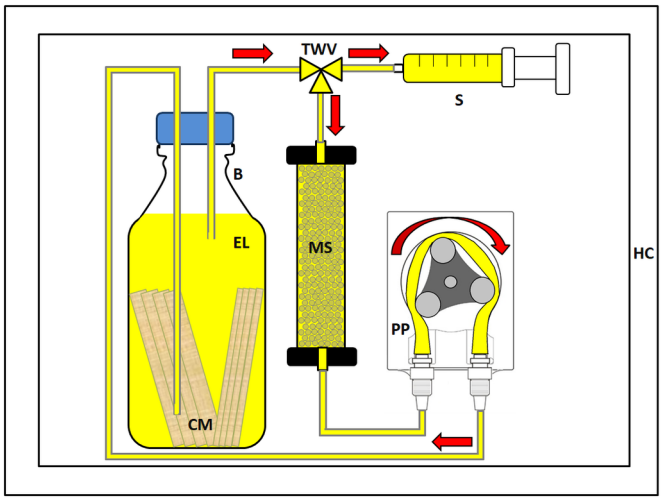

Fig. 5. Scheme of the measuring system used for drying cellulose materials with the use of a molecular sieve; B – bottle, CM – cellulosic materials, EL – electro-insulating liquid, PP – peristaltic pump, TWV – three-way valve, S – syringe, MS – molecular sieve, HC – heat chamber

The system was placed in a heat chamber (HC), the task of which was to maintain a constant temperature at 50°C. After the pump was turned on, the liquid circulated between the molecular sieve reservoir and the bottle containing the cellulosic materials. To assess the dynamics of the drying process, samples of the pressboard and insulating liquid were taken at certain time intervals. The water content in

both cellulose materials and insulating liquids was determined using the KFT method. The total drying time was two months. At the same time, cellulose materials impregnated with mineral oil, natural ester, and synthetic ester were dried using three twin measuring systems shown in Figure 6.

Fig. 6. Three measuring systems placed in a heat chamber used for drying cellulose materials impregnated with mineral oil, natural ester, and synthetic ester

4.2. Research results and their discussion

Figures 7 and 8 show the results of the research on the water content in thin and thick pressboards at various stages of their drying.

Table 3 presents the results of measurements of water content in electrical insulating liquids (*WCL*) at various stages of the drying process. Relative saturation (*RS*) of the liquids was calculated by the formula (3). For the calculations, the water saturation limit (*S*) was assumed for mineral oil, natural ester, and synthetic ester, respectively, equal to 155 ppm, 1437 ppm, and 2739 ppm [22]. The results of these calculations are shown in Figure 9:

$$RS = \frac{WCL}{S} \cdot 100 \tag{3}$$

The use of a molecular sieve allowed to maintain a low level of moisture in insulating liquids throughout the drying process (Fig. 9). After 7 days from the beginning of the drying process, the relative humidity of all insulating liquids was kept below 5%. According to

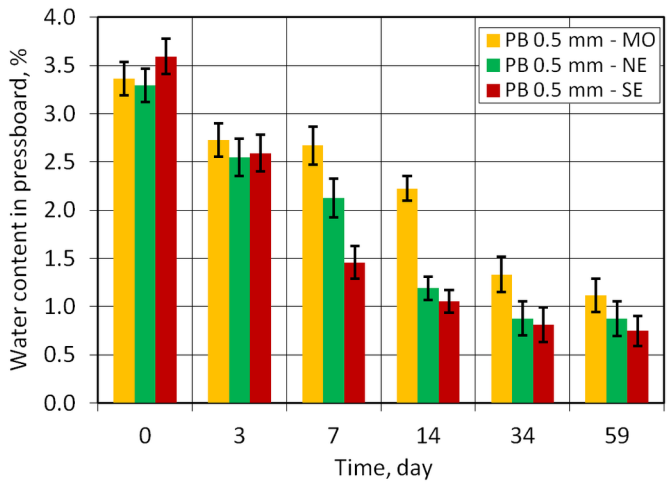

Fig. 7. Water content in a 0.5 mm thick pressboard at different stages of its drying with marked expanded measurement uncertainty for the confidence level equal to 95%

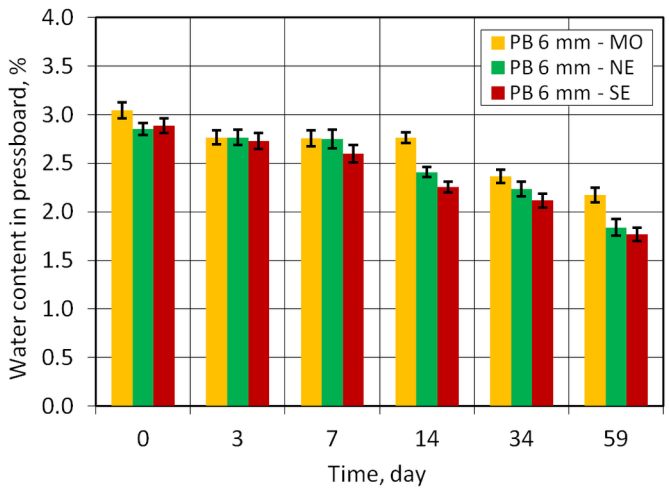

Fig. 8. Water content in a 6 mm thick pressboard at different stages of its drying with marked expanded measurement uncertainty for the confidence level equal to 95%

the data from Figure 2, such a low level of relative humidity should allow drying of the cellulose insulation to the level of about 1%. In the case of the 0.5 mm thick pressboards, the water content of 1% was achieved for both esters after about two weeks. In the case of mineral oil, this time was much longer and amounted to approximately 59 days.

In the case of drying the pressboard with a thickness of 6 mm, a significant effect of the type of insulating liquid on the drying rate was also observed. In the case of mineral oil, the drying efficiency was the lowest. In the case of mineral oil, two-month drying allowed to reduce the water content in the 6 mm thick pressboards to the value of 2.2%, and in the case of both esters to the level of approx. 1.8%. When analyzing the graphs in Figure 9, it can be concluded that the drying

Table 3. Results of measurements of water content in insulating liquids during the drying process

Time, day		0	3	7	14	34	59
Mineral oil	S, ppm	27	10	8	8	5	5
	RS, %	17.3	6.3	4.9	4.9	3.5	3.0
Natural ester	S, ppm	50	24	25	29	30	31
	RS, %	3.5	1.7	1.7	2.0	2.1	2.2
Synthetic ester	S, ppm	200	27	30	32	28	29
	RS, %	7.3	1.0	1.1	1.2	1.0	1.1

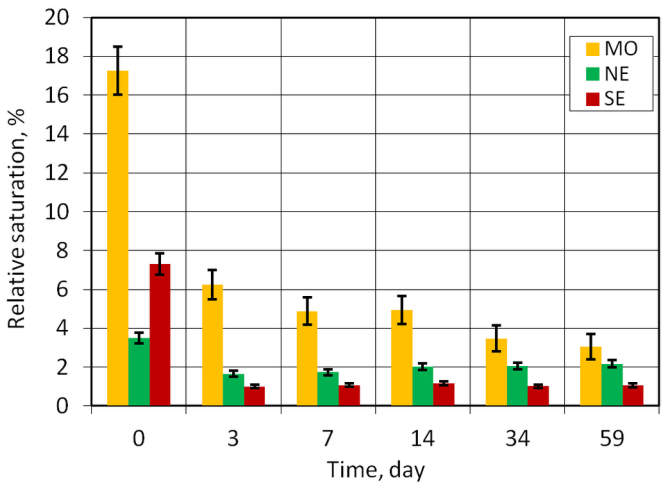

Fig. 9. Relative saturation (RS) of insulating liquids as a function of drying time with marked expanded measurement uncertainty for the confidence level equal to 95%

process of thick pressboard is not finished. The drying efficiency in both the first and the second month was similar.

The lower drying efficiency in the case of thick cellulosic materials is explained by the long time necessary for water to migrate from the inside to the outer structures. In this case, the type of insulating liquid does not substantially affect the drying rate. The situation is different in the case of thin materials, where the solubility of water in the insulating liquid is of great importance.

5. Conclusions

The aim of the research was to demonstrate the safety and effectiveness of the use of 3A molecular sieve for drying the transformer insulation system.

It has been shown that water is adsorbed from the mineral oil flowing through the molecular sieve, while the presence of the sieve does not affect the concentration of hydrogen. Although the water and hydrogen molecules' size allows them to penetrate through the pores of the sieve into its intercrystalline space, due to their polarity, it is the water molecules are attracted and adsorbed by the sieve. This is a very important conclusion that allows to state that the use of a molecular sieve will not affect the interpretation of the DGA results used for transformer diagnostics.

The conducted research also allowed to demonstrate the efficiency of drying using a molecular sieve the insulation system consisting of cellulose insulation impregnated with various electro-insulating liquids. Moreover, it was found that it is possible to effectively dry the insulation system, the temperature of which is 50°C, which corresponds to the transformer operating temperature. In the case of a higher temperature of the insulating system, greater drying efficiency should be expected because with increasing temperature the solubility of water in insulating liquids increases, while the hygroscopicity of cellulose decreases.

The obtained test results allow to demonstrate the safety and efficiency of drying the transformer insulation system during its operation with the use of a 3A molecular sieve. This method does not require the transformer to be switched off during the drying process. Moreover, it is free from the disadvantages of methods requiring the application of vacuum and high insulation temperature.

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