

Article

A New Concept of Applying Methanol to Dry Cellulose Insulation at the Stage of Manufacturing a Transformer

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Abstract: A decisive technical challenge for transformer manufacturers is correctly drying the cellulose insulation. During the production of a transformer, it is necessary to reduce its insulation's moisture content from about 8% to less than 1% in the shortest possible time period. The drying of insulation is a time-consuming process, and for high-power transformers, it can last up to three weeks. Several drying techniques are used during the production of a transformer, and all of them require heating up the insulation to a high temperature and applying a vacuum. Unfortunately, the use of a high drying temperature above 100 °C can cause a decrease in the degree of cellulose polymerization by over a dozen percentage points. This paper presents a new concept for drying cellulose insulation that does not require heating insulation and applying a vacuum. In this solution, methanol is used as the drying medium. The research results showed the possibility of drying cellulose insulation by means of methanol with different initial moisture contents. The possibility of completely drying pressboard of various thicknesses for a sufficient period of time was also proven. The paper also presents a new concept of both the device and the procedure for drying cellulose insulation by means of methanol.

Keywords: transformer; cellulose insulation; drying; methanol

1. Introduction

Power transformers play a significant role in the power system, both at the stage of electric energy generation (generator set-up transformers) and at the stage of its transmission and distribution (grid and distribution transformers). The reliability of transformers is a prerequisite for ensuring a continuity of electricity supply. Due to the high price of transformers, the maximum working time of these devices is extended, and in some cases, the lifetime of power transformers exceeds even 50 years [1,2].

The insulating system is a critical element of every transformer [3]. The most common solution is an insulating system made of cellulose materials (paper, pressboard) impregnated with mineral oil [4]. This is a proven solution that has been used on a large scale for nearly 100 years [5]. Unfortunately, during long-time exploitation, the insulation system undergoes aging caused by oxidation, thermolysis, and hydrolysis processes. The presence of moisture in solid and liquid transformer insulation plays a critical role in the transformer's life [6]. Moisture has been recognized as “enemy number one” of transformer insulation [7].

Water is both a catalyst in the process of cellulose depolymerization and the product of its oxidation. The water content in a transformer insulation system changes during its operation. The rate of the moistening process depends both on the design of the transformer and its load [8,9]. For transformers with a membrane-sealed conservator preservation system, the rate of water

contamination is about 0.03% to 0.06%, while for transformers with an open-breathing conservator, it is up to 0.2% per year [8].

The high level of water content in transformer insulation is dangerous not only due to the aging process of cellulose [10–12], but also due to a decrease in the insulation system's electrical strength [13–16], an increase in the probability of the appearance of partial discharges [17–19], and evolution of water vapor bubbles [20,21]. The presence of water in the cellulose insulation improves its thermal conductivity [22,23] but unfortunately significantly deteriorates the other above-mentioned parameters.

Thus, it is very important that a transformer, after the manufacturing process, has insulation with the lowest possible moisture content. The conditions prevailing in the transformer factory (air humidity and temperature) may cause the water content in the cellulose insulation to reach even eight percentage points by weight. Such insulation has poor dielectric properties; therefore, it must be dried before being impregnated with oil. Reducing the moisture level constitutes a challenge for power transformer manufacturers who want to offer high-quality products with acceptable residual moisture.

2. Drying Methods of Transformer Insulation

One of the requirements of a potential transformer's customer is a low level of the moisture insulation. The moisture of cellulosic materials after the production process should not exceed 1%, but the water content in very well dried insulation is even lower than 0.5% [8,24]. This is the average value of moisture of only a part of the cellulose insulation, which is determined most often by methods based on dielectric spectroscopy, such as FDS—frequency-domain spectroscopy, PDC—polarization and depolarization measurement, or RVM—recovery voltage measurement. It should be noted that the transformer's insulation system is very complex, and consists of cellulose materials of various thickness and density. This determines both the time and the parameters of the drying process [25,26]. After the drying process, both spaces with very well dried (<0.5%) and with poorly dried cellulose (>1%) can be found in the insulation system. Material that undergoes the drying process very well is thin, winding paper whose total thickness usually does not exceed 1 mm. In turn, the drying of thick elements such as angle rings, cylinders, or spacer blocks presents many problems.

Both the time and final effect of drying depend strongly on the method that is used. The insulation drying methods that are used at the stage of transformer manufacturing require the heating of cellulose and the use of a suitable underpressure. The heating up of the insulation system is achieved by:

- Placing the insulation system in a vacuum dryer—conventional method
- Heat of solvent evaporation—vapor phase drying method
- Direct or low frequency current flow through the windings—LFH method (low-frequency heating)

The conventional drying method consists of heating the insulation system in the dryer by using hot air and reducing the pressure. The insulation system is heated to a temperature of 85–130 °C. After heating, the pressure in the dryer is lowered to below 1 mbar, which results in an increase in the rate of water evaporation [27]. Unfortunately, the evaporation of water is accompanied by a decrease in the temperature of the insulation. The reheat of insulation by heaters placed in the walls of the dryer is ineffective due to the small temperature difference between the walls of the dryer and the insulation system [28]. For this reason, several cycles of insulation heating and pressure reduction are needed in order to dry the insulation sufficiently. This significantly extends the drying time of the insulation.

The vapor-phase drying method consists of heating the insulation system with the heat of solvent vapor condensation and reducing the pressure [28–30]. Solvent vapor at a high temperature of about 130 °C is introduced into the dryer, in which the pressure is reduced to 7 hPa. This way, the effect of immediate condensation of the solvent on the surface of the insulation system is obtained, which allows for fast heating of the insulation [28]. Solvent vapors reach hard-to-reach areas of the insulation system, which enables its uniform heating. Another advantage of this method is the washing out of

post-production impurities from the insulation system. Solvent losses are estimated at about 1–1.5% of the mass of dried insulation [28]. The remaining residual solvent in the cellulose insulation is dissolved by the oil. One of the significant disadvantages of this method is the risk of explosion. Solvent vapor with air is an explosive mixture; therefore, extreme caution is required during the drying process.

Another method used to dry the transformer consists of heating the insulation as a result of a direct current or low-frequency current flowing through the windings and applying a vacuum. A more technically advanced and more efficient drying technique is the use of the low-frequency heating (LFH) method. In this method, the insulation is heated from the inside with a low frequency current supplied to the high-voltage (HV) windings. The low-voltage (LV) windings remain short circuited. Usually, a current frequency in the range of 0.4 Hz to 2 Hz is used [31]. The reduced frequency enables obtaining a suitable value of the heating current at a relatively low supply voltage. The LV windings are heated by the current flowing as a result of the transformation of the voltage from the HV windings. HV and LV windings can heat up to typical drying temperatures of 110–120 °C [31]. During electrical heating, the vacuum level is kept at approximately 30 mbar for safety reasons (Paschen's law). After heating is stopped, the pressure is lowered to below 1 mbar [32]. Drying by means of the LFH method can be assisted by spraying the windings with hot oil, which is done to improve the drying dynamics and heating uniformity of the whole of the insulation. It should be noted that in this method, the insulation of the windings (paper wrapped around a copper wire, radial spacers) is mainly heated, and the elements that are distanced from the windings (cylinders or angle rings) are heated to a much worse degree. For this reason, these elements are much more difficult to dry.

Heating the insulation to a high enough temperature is of key importance for effective transformer insulation drying in all of the above-mentioned methods. On one hand, the high temperature improves the drying process, but on the other hand, it contributes to the degradation of cellulose. The main component of cellulose insulation is cellulose fibers. These fibers are made of macrofibers, which in turn are made of microfibrils. Microfibrils consist of elementary fibers, which are made of cellulose chains [33]. The cellulose chains consist of β -D-glucopyranosyl units. The number of such units per chain is called the degree of polymerization (DP). New cellulose paper will have a DP of about 1200–1300 [34,35]. The literature data [11,34] state that the paper in a transformer will have a DP of about 1000 after the factory drying process.

Table 1 presents the research results of Przybyłek [36], which confirm the decrease in the degree of cellulose polymerization during the factory drying of transformer insulation. The research tests were carried out for five different cellulose materials that were used as a paper wrap around a copper wire in power transformers. It was found that, as a result of the drying process, the average decrease in the degree of cellulose polymerization was about 13.7%.

Table 1. Degree of polymerization (DP) of cellulose before and after factory drying [36].

Material	Paper No. 1	Paper No. 2	Paper No. 3	Paper No. 4	Paper No. 5
DP before drying process	1185	1180	1238	1422	1325
DP after drying process	1080	1080	1059	1267	984
Decrease of DP during drying	105	100	179	155	341
Percentage decrease of DP, in %	9	8	14	11	26

During the power transformer's operation, the degree of cellulose polymerization gradually decreases [10,24]. The dynamic of this process depends mainly on the temperature and water content in cellulose insulation [11,37]. IEC 60076-7 [38] suggests, in accordance with Montsinger's law, that the aging of transformer insulation is double (or halved) for every 6 °C in the range of 80–140 °C [11]. A cellulose material with a degree of polymerization below 350 is considered to be aged [39], which is associated with poor mechanical strength. The exploitation of devices insulated by aged cellulose

materials is risky, particularly in the case of high mechanical stresses, which often lead to winding movement and damage to fragile insulation [11].

It can be estimated that the decrease in the degree of cellulose polymerization caused by the process of drying insulation at the stage of transformer manufacturing can result in a shortening of its technical life by up to five years. This increases the risk of serious failures and also forces faster transformer repair or replacement.

The temperature of the drying process should be lowered in order to prevent excessive aging of the insulation at the stage of transformer manufacturing. Unfortunately, the consequence of this is prolonged drying time and problems with achieving the assumed moisture level, particularly in thick materials. During transformer operation, this water successively migrates to the oil, and then to cellulose with a lower relative humidity.

A method that uses methanol as a medium for removing water from cellulose is free of the disadvantages associated with the drying of the insulation using the techniques described above. The author put forward the hypothesis that the methanol can be used for drying all of the insulation at the stage of transformer manufacturing, before impregnating the cellulose with an insulating liquid. The possibility of using this method for the effective drying of cellulosic materials is demonstrated in the next chapter.

3. Drying of Cellulose Materials by Means of Methanol

3.1. *The Application of Methanol for the Extraction of Water from Fibrous Material—Previous Experience*

Very high solubility of water in methanol and its ability to extract water from cellulose was used in two methods of moisture measurement. The first of these is the standardized Karl Fischer method [40], while the second is a technique based on the use of near-infrared spectrophotometry [41]. Both methods have a common feature; namely, they measure the water content in cellulose material and they require its earlier, total extraction from the tested sample. Such extraction is possible using methanol, as evidenced by the results of research presented in the CIGRE brochure [42] and publication [41].

The CIGRE brochure [42] presents the results of interlaboratory tests on the water content in pressboard samples obtained by means of the Karl Fischer titration method. As mentioned above, for the Karl Fischer reaction, it is necessary to extract water from the sample. For this purpose, seven laboratories used the evaporative technique for water extraction, while five laboratories used water extraction with methanol. Similar results were obtained for both techniques of measuring the water content, which indicate the possibility of using methanol for total water extraction.

In [41] Przybyłek described the method of water content measurement in electroinsulating fibrous materials using near-infrared spectrophotometry (NIR method). This method is based on the extraction of water from cellulosic material to methanol. In [41], very good agreement was found in the results obtained by means of the NIR method, the Karl Fischer titration method, and the weight method for both cellulose and aramid samples that were both non-impregnated and impregnated with mineral oil. The obtained results revealed the possibility of using methanol for the effective extraction of water from fibrous materials.

The research results described above constituted a starting point for the tests conducted here to answer the following question: is it possible to apply methanol for effective drying of a large-sized transformer's insulation system at the stage of its manufacturing before oil impregnation? In order to answer this question, it was necessary to conduct research related to assessing both the influence of water concentration in methanol and the thickness of cellulosic materials on the effectiveness and dynamics of the drying process.

3.2. *The Influence of Water Concentration in Methanol on the Effectiveness of Cellulose Insulation Drying*

The moisture level of cellulose insulation after the transformer manufacturing process results from the climatic conditions that prevail in the production hall. For an air temperature of 20 °C and a relative

humidity of about 50–60%, the water content in cellulose is about 7–8% [43]. Drying can be considered effective if the water content decreases to about 0.7 percentage points by weight. This is the level of moisture that can be obtained by transformer manufacturers using traditional drying techniques, and is acceptable to their purchasers. The mass ratio of mineral oil to the cellulose materials in the transformer lies in the wide range of 6:1 to 30:1. The drying procedure assumes filling the transformer tank with methanol. Taking into account the oil density (0.88 kg/L) and methanol density (0.792 kg/L), the mass ratio of methanol to cellulose was calculated to be in the range of from 5.4:1 to 27:1. Assuming a reduction of the water content in cellulose during the drying process by seven percentage points, the water concentration in methanol, for the mass ratio as calculated above, will be in the range of about 0.26% to 1.3%.

The effectiveness of water extraction from cellulose by means of methanol has been confirmed in papers [41,42] and regarding the moisture measurement methods (Section 3.1). However, it should be noted that a low water concentration in methanol is recommended in both methods of measuring the water content. According to the standard [40], the water content in methanol intended for water extraction from cellulose should not exceed 0.02%, while the water content in methanol after this process should be lower than 0.126%. The question then arises of whether it is possible to effectively dry the transformer's cellulose insulation with methanol in which the water concentration is very high and reaches a level of about 1%. To answer this question, an experiment was designed to evaluate the effectiveness of cellulose paper drying by means of methanol at varying water concentrations.

3.2.1. Measurement Procedure

Methanol that was “pure for analysis” was used for the research. According to the manufacturer, its initial water concentration was about 0.02%. This methanol was poured into four vials that were each 45 mL in volume. Subsequently, various volumes of water were added to the three vials so as to obtain methanol samples with a moisture content of about 0.2%, 0.6%, and 1%. This moisture corresponded to the different drying conditions of the transformer insulation system. The initial concentration of water (C_{pi}) in the methanol samples was measured using the Karl Fischer titration method, according to the standard [40]. The results of these measurements are given in Table 2. Methanol prepared in this manner was used to dry the cellulose paper samples, which had previously been conditioned in air at a temperature of 22 °C and a humidity of 55%. The thickness of the paper was 0.055 mm, and its grammage was 47.6 g/m².

An evaluation of the dynamics and efficiency of drying cellulose paper by means of methanol with different concentrations of water was possible due to the use of near-infrared spectrophotometry.

The near-infrared spectrophotometry method was used to measure the water content in fibrous materials and is described in detail by Przybyłek in [41]. In this method, the absorbance of a wave that was 1939 nm in length passing through methanol is measured. In methanol, water is extracted beforehand from the cellulose. From Formula (1) taken from [41], the water concentration in methanol resulting from its extraction from cellulose material is calculated. On the basis of this concentration and the mass of methanol (M_m) in the spectrophotometer cuvette, the mass of water in methanol (M_w) is determined. Knowing both the mass of water and mass of paper (M_p), it is possible to calculate the percentage of water content in cellulose (WCP_{NIR}).

A Jasco V-570 spectrophotometer and a cuvette with an optical path of 10 mm made of Infrasil quartz glass were used to measure the absorbance. The transmittance of Infrasil quartz glass is about 95% for the chosen wavelength. The cuvette selected for the experiments was additionally equipped with a screw cap with a silicon membrane covered with polytetrafluoroethylene, which allowed eliminating the problem of methanol evaporation during the measurements.

The procedure that was used for assessment of the effectiveness and dynamics of the cellulose drying process by means of using methanol at varying water concentrations included the following steps:

1. Filling the spectrophotometer cuvette with methanol of mass (M_m) and water concentration (C_{pi}) measured by means of the Karl Fischer Titration (KFT) method
2. Measurement of absorbance (Abs_i) for methanol at water concentration (C_{pi})
3. Inserting a paper sample of mass (M_p) into a cuvette filled with methanol
4. Measurement of absorbance (Abs_t) after time t
5. Mixing methanol in the cuvette for 30 s
6. Repeating steps (4) and (5) every four minutes until the absorbance value (Abs_f) is steady

On the basis of the results obtained during realization of the above-described procedure, the following parameters were calculated: the concentration of water in methanol (C_p), the mass of water (M_w), the water content in paper samples (WCP_{NIR}), and the concentration of water in methanol (C_{pf}).

Equation (1) taken from Przybyłek [41] was used to calculate the concentration of water in methanol (C_p) extracted from the cellulose sample:

$$C_p = \frac{Abs_f - Abs_i - 0.0016}{0.5237}, \quad (1)$$

The mass of water (M_w) extracted from the paper sample was calculated from the formula:

$$M_w = \frac{C_p \cdot M_m}{100 - C_p}, \quad (2)$$

To calculate the water content in paper samples (WCP_{NIR}), the following formula was used:

$$WCP_{NIR} = \frac{M_w}{M_p - M_w} \times 100, \quad (3)$$

The concentration of water in methanol (C_{pf}) after drying the paper samples was calculated from the formula:

$$C_{pf} = C_{pi} + C_p. \quad (4)$$

3.2.2. Research Results and Discussion

The research results obtained in the course of the above-described procedure are presented in Table 2.

Table 2. Results of measurements used to calculate the water content in paper (WCP_{NIR}) after the drying process—evaluation of the efficiency of water extraction from cellulose paper by means of methanol at various water concentrations.

Sample	C_{pi} %	M_m g	Abs_i -	M_p g	Abs_f -	C_p %	M_w mg	WCP_{NIR} %	C_{pf} %
0.02%	0.0236	3.7713	0.9773	0.0771	1.0568	0.1487	5.61	7.81	0.1723
0.2%	0.2102	3.7550	1.0801	0.0739	1.1541	0.1384	5.19	7.54	0.3485
0.6%	0.5961	3.8197	1.2881	0.0745	1.3596	0.1335	5.10	7.33	0.7296
1%	1.0121	3.8156	1.5127	0.0737	1.5864	0.1376	5.25	7.62	1.1497

The water concentration in methanol C_{pt} and the water content in paper WCP_{NIRt} were calculated based on data from Table 2, absorbance Abs_t measured after time t from the start of water extraction, and the transformed Formulas (1)–(4). The results of these calculations are shown in Figure 1.

An analysis of the results that is presented in Table 2 and Figure 1 showed that the paper drying efficiency was similar for methanol, with an initial moisture content in the range of 0.02% to 1%. The drying dynamics were the same in all of the cases. The highest rate of drying was observed during the first 20 min of the experiment. During this time, the water content in the paper samples decreased from about 7.6% to about 0.7%. In all of the cases, the paper-drying process ended after 39 min from the beginning of water extraction. After this time, a fluctuation of the water concentration in methanol was observed, which was related to absorbance resolution.

The research results show the possibility of using methanol, even with a significant concentration of water exceeding 1%, for the efficient drying of a transformer's cellulose insulation.

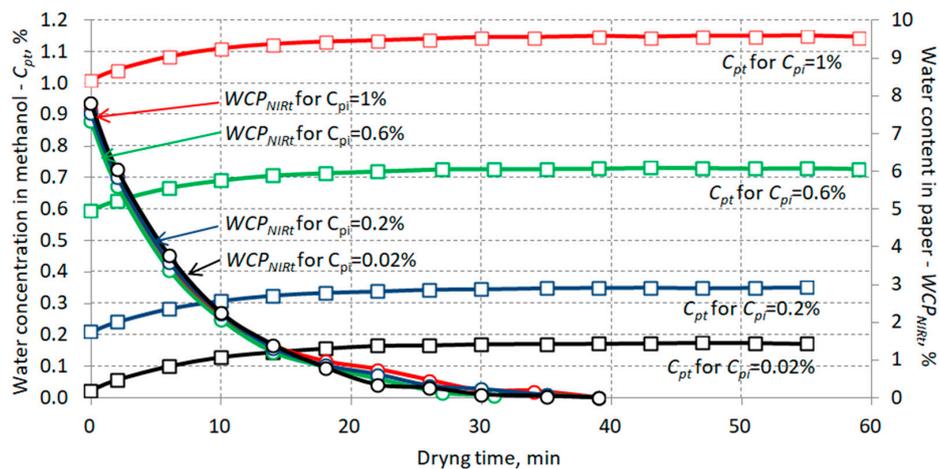


Figure 1. Comparison of water concentration in methanol C_{pt} and water content in paper WCP_{NIRt} depending on drying time for initial water concentration in methanol 0.02%, 0.2%, 0.6%, and 1%.

3.3. The Influence of Water Concentration in Methanol on the Effectiveness of Cellulose Insulation Drying

The thickness of cellulose materials has a very large impact on the rate and efficiency of drying the insulation by using all of the methods, including the one based on methanol as a drying medium. A drying time of the transformer cellulose insulation that is too long significantly increases the cost of manufacture of the device. In turn, drying efficiency that is too low does not allow for the elimination of water from thick elements of the insulation system. During the transformer's operation, water from thick structures migrates slowly to other parts of the system, and is a catalyst in the aging process of both solid and liquid insulation.

The aim of the research conducted here was to check the effectiveness and dynamics of drying cellulose materials of various thicknesses by means of methanol. Table 3 presents the properties of the materials selected for the research. Before drying, these materials were conditioned in air at 23 °C and a humidity of 30%.

Table 3. The properties of the investigated cellulose materials.

Sample	Thickness mm	Basic Weight g/m ²	Density kg/m ³
Pressboard 0.5 mm	0.548	515	939
Pressboard 1 mm	1.110	1167	1051
Pressboard 2 mm	2.104	2354	1119
Pressboard 3 mm	3.384	3908	1155

3.3.1. Measurement Procedure

The procedure described in Section 3.2 was applied in order to evaluate the drying efficiency of pressboard of different thicknesses, with the exception that subsequent absorbance measurements

were taken every 3 min. The mass ratio of methanol to cellulose material was 8:1, which corresponds to the mass ratio of oil to cellulose that can occur in a power transformer.

3.3.2. Research Results and Discussion

Table 4 shows the research results obtained in accordance with the procedure described above. The table contains the results of water content measurement in paper (WCP_{NIR}) obtained by means of the spectrophotometric method.

Table 4. Results of measurements used to calculate the water content in paper (WCP_{NIR}) after the drying process—evaluation of the efficiency of water extraction from pressboard of various thickness by means of methanol.

Sample	C_{pi} %	M_m g	Abs_i -	M_p g	Abs_f -	C_p %	M_w mg	WCP_{NIR} %	C_{pf} %
Pressboard 0.5 mm	0.0236	3.7397	0.9799	0.467	1.3148	0.6363	23.95	5.41	0.6599
Pressboard 1 mm	0.0236	3.6968	0.9799	0.460	1.3242	0.6543	24.35	5.59	0.6779
Pressboard 2 mm	0.0236	3.7864	0.9776	0.469	1.3204	0.6516	24.83	5.59	0.6752
Pressboard 3 mm	0.0236	3.6926	0.9776	0.466	1.3181	0.6470	24.05	5.44	0.6706

The results of water concentration in methanol (C_p), the mass of water extracted from the sample (M_w), the water content in pressboard (WCP_{NIR}), and the concentration of water in methanol after the drying process (C_{pf}) were calculated by means of Equations (1)–(4), respectively.

The water concentration in methanol C_{pt} and water content in paper WCP_{NIRt} were calculated based on: data from Table 4, absorbance Abs_t measured after time t from the start of the drying process, and transformed Formulas (1)–(4). The results of these calculations are shown in Figure 2.

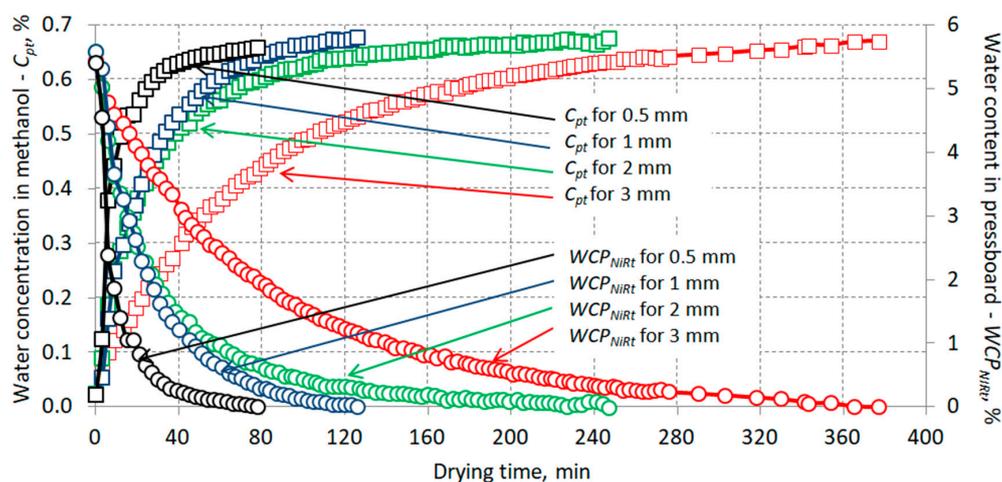


Figure 2. Comparison of water concentration in methanol C_{pt} and water content in paper WCP_{NIRt} depending on the drying time for pressboard with thicknesses of 0.5 mm, 1 mm, 2 mm, and 3 mm.

The research results show that the water content in the pressboard samples before drying was similar and equal to about 5.5%. The drying effect was similar regardless of the material's thickness. It has been shown that the drying time of cellulose materials by means of methanol strongly depends on their thickness. The highest dynamics of drying was observed for pressboard samples of the smallest thickness. Figure 3 shows a comparison of the time necessary for the reduction of water content in pressboard of different thicknesses during the drying process from the initial moisture content of 5.5% to a level of 1%, 0.5%, and 0.1%

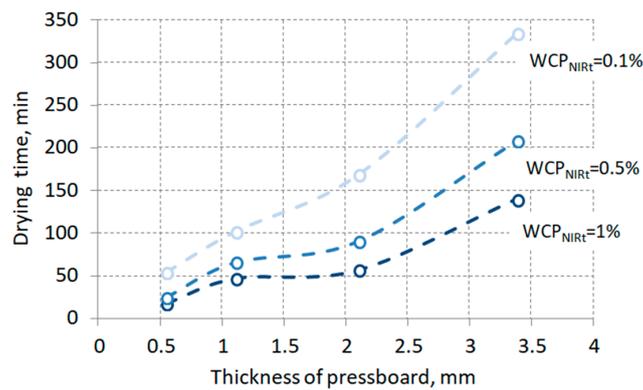


Figure 3. Time necessary for reduction of water content in pressboard of different thicknesses during the drying process from the initial moisture content of 5.5% to a level of 1%, 0.5%, and 0.1%.

For a sample with a thickness of 0.548 mm, the time needed to dry it from 5.5% to 1%, 0.5%, and 0.1% was equal to 18 min, 25 min, and 54 min, respectively, while the time needed to dry the sample with a thickness of 3.384 mm to the same levels of moisture was equal to 140 min, 209 min, and 335 min. The obtained results showed the possibility of using methanol for the fast and effective drying of cellulosic materials, even those of considerable thickness.

4. The Concept of a System for Drying Transformer Cellulose Insulation by Means of Methanol

Based on the results of the research presented in Section 3, the concept of a device enabling the drying of solid transformer insulation by means of methanol was prepared. The proposed solution concerns the drying of a transformer at the stage of its manufacture, before impregnating the cellulose with an insulating liquid. The device scheme is shown in Figure 4.

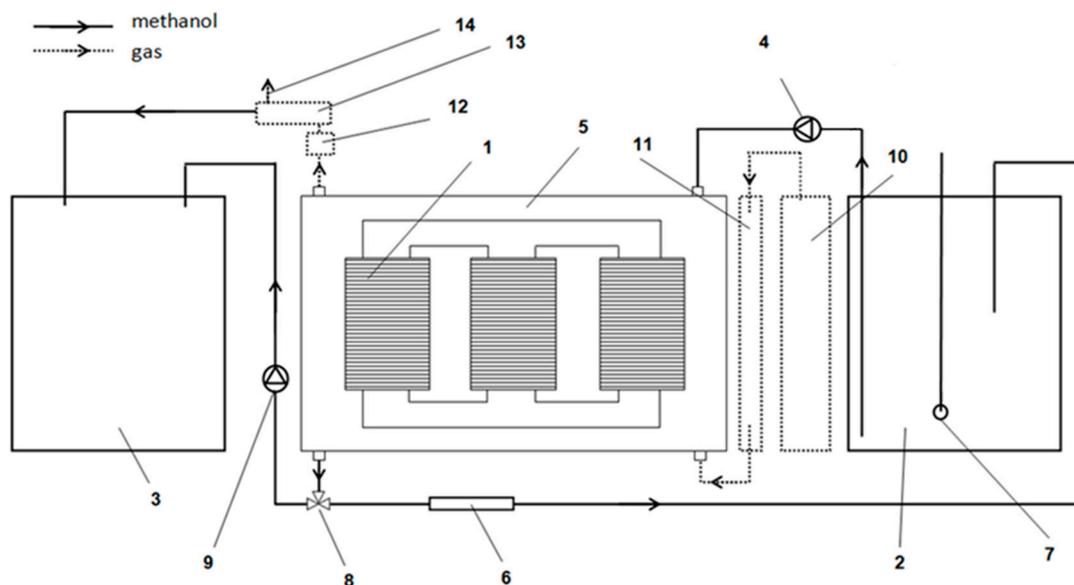


Figure 4. System for drying cellulose insulation by means of methanol; (1) insulation system, (2) tank for methanol with a low water concentration, (3) tank for methanol with an increased level of water, (4) pump, (5) transformer tank, (6) particulate filter, (7) NIR sensor, (8) three-way valve, (9) pump, (10) air compressor or nitrogen accumulator, (11) molecular sieve filter, (12) sensor for control of the concentration of methanol vapor, (13) methanol vapor condenser, (14) gas outlet [36].

The device for drying the insulation system (1) via extracting water by means of methanol consists of the following elements: two tanks, one used for methanol with a low water concentration (2), and the other for methanol with an increased level of water (3) as a result of the drying process. By means of a pump (4), a continuous flow of methanol is forced into the closed-cycle drying transformer (5) and tank (2). A particulate filter (6) is installed in the circulation, which eliminates the impurities remaining in the insulation system after the transformer manufacturing process. During the methanol cycle, the water concentration is monitored by means of an NIR sensor (7) measuring the absorbance of a wave with a length of 1939 nm passing through the methanol containing the extracted water. The moisture level of the insulation is estimated on the basis of the dependence of absorbance on the water concentration in methanol and by taking the mass of the dried insulation into account [41]. After reaching the assumed level of moisture, the three-way valve (8) is set to pumping the methanol, using the pump (9) to the tank (3). Thus, the prepared insulation system is blown with dry gas (10—air compressor or nitrogen accumulator) and additionally dried by means of a molecular sieve filter (11). The concentration of methanol vapor in the gas leaving the transformer tank is controlled by means of the sensor (12). The methanol vapor is condensed using a condenser (13) and the methanol runs down into the tank (3), while the gas escapes into the atmosphere via the outlet (14). Once the methanol is completely evaporated from the insulation, the drying process is terminated. It is possible to use an additional filter with molecular sieves 3A in a closed cycle to improve the efficiency of insulation drying. This material enables the effective removal of water from methanol.

5. Conclusions

The article presents a new concept of using methanol for drying the cellulose insulation of a transformer at the stage of its manufacture. The research results showed the possibility of using methanol, even with a significant concentration of water exceeding 1%, for the efficient drying of a transformer's cellulose insulation. It was also proved that it is possible to completely dry pressboard of various thicknesses in a satisfactory period of time. Even in the case of thick pressboard (3.384 mm), drying time did not exceed 6 h.

Based on the obtained research results, the concept of a device and procedure for drying the cellulose insulation of a transformer by means of methanol is presented. The advantages of the proposed method include:

- Maintaining the initial level of degree of cellulose polymerization after the drying process
- The possibility of complete and uniform drying of the whole of cellulose insulation
- Washing out post-production impurities from the insulation system
- No need to apply a vacuum
- Simplicity of the drying process
- Short drying time

It should be noted that even methanol with a moisture of 1% can still be successfully used for the effective drying of cellulose. Nevertheless, the repeated use of methanol in the drying process will cause an increase in the water concentration to a level at which it will be necessary to dry it. Inexpensive methanol treatment is a prerequisite for the cost-effectiveness of the cellulose insulation drying method. This issue is currently the subject of further research.

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