Effect of Moisture on the Thermal Conductivity of Cellulose and Aramid Paper Impregnated with Various Dielectric Liquids

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Abstract: This paper presents the effect of the impact of moisture in paper insulation used as insulation of transformer windings on its thermal conductivity. Various types of paper (cellulose and aramid) and impregnated (mineral oil, synthetic ester, and natural ester) were tested. The impact of paper and impregnated types on the changes in thermal conductivity of paper insulation caused by an increase in moisture were analyzed. A linear equation, describing the changes in thermal conductivity due to moisture, for various types of paper and impregnated, was developed. The results of measuring the thermal conductivity of paper insulation depending on the temperature are presented. The aim of the study is to develop an experimental database to better understand the heat transport inside transformers to assess aging and optimize their performance.

1. Introduction

The power system is a collection of devices for the generation, transmission, distribution, storage, and use of electricity. Enabling the delivery of electricity for households, enterprises, and public utilities in a continuous and uninterrupted manner is based primarily on the functional connection and appropriate maintenance of this strategic infrastructure. From the point of view of the transmission and distribution of electricity, power transformers play an important role. Knowledge of the condition of the transformer is necessary to achieve maximum return on investment, as well as to minimize the costs associated with its operation [1,2].

At present, the age of most power transformers working in the power system exceeds 25 years, which may result in the need to revitalize or replace them in the coming years [3,4]. The efficiency of transformers depends mainly on the state of their insulation system [5–7]. The insulation system is a type of "transformer heart". Due to the fact that it consists of solid (cellulose and aramid paper) and

liquid (electrical insulating liquid), it may degrade mainly due to thermal stresses, but also electrical, mechanical, and chemical stresses occurring in the transformer operating state [8,9]. As a consequence, it may lead to transformer failure, i.e., affect its operational safety [10,11].

The degradation of the transformer insulation system is significantly dependent on the temperature inside the transformer, and strictly speaking on the temperature of the hottest spot HS in the transformer. The temperature of the hottest place in the transformer depends on the efficiency of its cooling, i.e., on the temperature increases in its individual elements–windings, oil-paper insulation of the windings, insulating liquid filling the transformer interior, and tank and air washing the tank [12]. The higher these temperatures increase, the higher the hot spot temperature [13]. It should also be noted that the HST temperature is also one of the main factors that limit the transformer load [14,15]. Therefore, it is important to effectively cool these devices by using materials with appropriate properties [16,17]. Due to the fact that the oil-paper insulation is the closest to the windings, i.e., the places with the highest temperature, it is particularly exposed to degradation.

The moisture content [18] is one of the main parameters allowing assessment of the condition of the oil-paper insulation of the transformer. The water content in oil-paper insulation increases with the transformer lifetime. Its presence may contribute to the degradation of the transformer insulation system by accelerating the aging processes occurring in it [19,20], which increases the probability of failure. Due to the role of power transformers and distribution transformers in the power system, this is a particularly significant problem [3,21].

Moisture in transformer windings insulation can cause some problems during operation, e.g., aging and electrical breakdown between its windings. Since transformer paper insulation carries a large portion of moisture, knowledge of water content in this part is essential [1,19,22]. Therefore, appropriate numerical multiphysical approaches [23–25] e.g., with ANSYS or COMSOL, constitutive thermal (e.g., thermal conductivity) and electrical (e.g., resistivity, breakdown voltage) material parameters and models are needed [26].

The main sources of moisture in the transformer are primary moisture, tank leaks, and chemical degradation of cellulose. Primary moisture is due to the highly hygroscopic nature of cellulose. Therefore, paper insulation can be characterized by the relative humidity of up to 8% at the final stage of transformer production [27]. Therefore, transformer manufacturers use a number of treatments that allow a reduction of the moisture content of the insulation to an acceptable level below 1% [28]. Tank leaks usually result from the degradation of gaskets on the bushing, radiator flanges, pumps, piping, etc., but may also be due to holes in the heat sinks or a metal tank [29]. In the event of a leak, there is a risk of moisture being sucked into the transformer through capillary action, which may lead to increased moisture in the transformer insulation system. The degradation of cellulose fibers, resulting from the elevated operating temperature of the transformer, is accompanied by water formation-free hydrogen atoms combined with oxygen to become a source of water and contribute to the increase in moisture in the transformer insulation. Due to the fact that the presence of water intensifies the process of further cellulose degradation along with the increasing transformer exploitation time, an increase in the dynamics of moistening of its insulation is also observed [30].

The impact of moisture on the properties of the transformer insulation system is the subject of research of many scientists around the world. The increase in moisture has a number of negative consequences that are important for the transformer insulation system, but also for its other elements. First of all, reducing the resistivity of insulation materials [31] and the breakdown voltage [32,33] belong to the most important of them. As a consequence, this may lead to a decrease in the initial voltage of partial discharges [30], thus contributing to an increase in the likelihood of an unexpected transformer failure [34,35]. An increase in the moisture level of the paper insulation also contributes to the increase of dielectric losses [36,37], thus contributing to the temperature rise inside the transformer. An increase in the moisture level of the transformer insulation system also leads to an increase in cellulose depolymerization rate [19], which contributes to the weakening of its mechanical properties and, consequently, to a shorter transformer life [38,39]. An increase in moisture can cause an increase

of probability of gas bubble formation in the insulating liquid, which is known as the bubble effect [3]. It can lead to an increase in pressure in the transformer tank, which may be a reason for insulating liquid leakage to soil. This can result in the loss of insulation inside the transformer and environmental contamination. The increase in moisture from 0.3%, which corresponds to the new insulation, to 4.5%, which corresponds to aged insulation, causes a 15-fold reduction in the lifetime of transformer insulation. By contrast, according to other sources, the increase in moisture insulation from 0.1% to 1.0% accelerates the aging process of paper insulation 10-fold. According to [40], the increase in moisture from 0.5% to 5.0% accelerates this process up to 100 times.

As it results from the above considerations, temperature and moisture play an important role in the transformer—both factors interact with each other in a kind of feedback, thus directly affecting the time of failure-free operation of the transformer. The higher the transformer operating temperature and humidity, the shorter the lifetime of the transformer insulation system. The analysis of cooling conditioning properties in various insulating liquids used in the transformer, together with the factors affecting them, has already been presented in the literature [41–43]. However, no information is available on the effects of various factors, including temperature and humidity, on the cooling efficiency of the paper insulation used in the transformer. Transformer paper insulation is a solid material; therefore, the cooling efficiency will depend on its thermal conductivity [16]. Therefore, in this paper, the impact of moisture on the thermal conductivity of paper insulation (cellulose and aramid) impregnated with various insulating liquids (mineral oil, synthetic esters, natural esters) used in transformers was examined and analyzed. These studies supplement the knowledge regarding heat transport in the transformer and can be used to calculate the temperature rise in the transformer, both at the design and operation stages. The influence of moisture on the thermal conductivity of materials is a very important issue, not only in terms of the operation of insulation systems of power devices but also in many other cases, such as the energy efficiency of buildings [44,45].

2. Materials and Methods

2.1. Used Materials

Kraft cellulose paper and Nomex® 926 aramid paper (DuPont, Wilmington, Delaware, DE, USA) [46] were used for the research.

Three commonly used types of insulating liquids were used to impregnate samples of both types of paper-mineral oil Nytro Draco (Nynas, Stockholm, Sweden) [47], synthetic ester Midel 7131 (M&I Materials, Manchester, UK) [48], and natural ester FR3 (Cargil, Minneapolis, MN, USA) [49].

Table 1 presents the combinations of papers impregnated with insulating liquids prepared for testing.

Table 1. Combinations of papers impregnated with insulating liquids.

Type of Tested Material	Abbreviation Used in the Text
Cellulose paper impregnated with mineral oil	CP-MO
Cellulose paper impregnated with synthetic ester	CP-SE
Cellulose paper impregnated with natural ester	CP-NE
Aramid paper impregnated with mineral oil	AP-MO
Aramid paper impregnated with synthetic ester	AP-SE
Aramid paper impregnated with natural ester	AP-NE
Unimpregnated cellulose paper	-
Unimpregnated aramid paper	-

In order to determine the impact of the structure of both tested types of paper on the thermal conductivity of the analyzed insulation systems, unimpregnated cellulose, and aramid paper samples were also prepared.

Due to the fact that the main goal was to analyze the impact of moisture on the thermal conductivity of the above-mentioned combinations of papers impregnated with different insulating liquids, samples with different water content in paper (WCP) were prepared. In accordance with [50–52], the water content in paper is defined as a ratio of water weight and dry weight of a paper sample expressed as a percentage.

Measurements of thermal conductivity of the analyzed materials were carried out for temperatures in the range of 25 to 100 °C. The lower temperature range resulted, first, from the capabilities of the measuring system. Secondly, for lower temperatures, thermal aspects do not play a significant role in the operation of transformers. First, the upper temperature range also resulted from the limitations of the measuring system. Secondly, situations where the working temperature of the paper insulation exceeds 100 °C are rare.

2.2. Preparation of Paper Samples with Various Moisture Content

To determine the effect of moisture of fibrous materials impregnated with various insulating liquids on their thermal conductivity, it was necessary to prepare samples of cellulosic and aramid materials with different water content. The sample preparation procedure included the following stages: (I) drying of the samples, (II) moistening the samples, (III) impregnation and conditioning the samples, and (IV) measuring the water content of the samples.

Samples of fibrous materials were dried in a vacuum chamber for eight hours, at a temperature of 90 ± 5 °C, at a pressure of 0.2 to 0.4 mbar. Such drying conditions enabled the water content of the samples to be reduced below 0.2%. Then, to obtain an appropriate level of water content, samples of materials were moistened in a controlled manner by placing them in a climate chamber forcing an appropriate level of relative humidity and temperature, in accordance with the water sorption isotherms in [53,54]. The moistening time of the samples in the chamber was 72 h. In this way, samples with water content in cellulose and aramid paper above 2.0% and 1.5%, respectively, were prepared. The difference in water content between cellulose and aramid samples is due to the different hygroscopicity of both materials.

Due to the inability to set the relative humidity of the air below 10% in the environmental chamber, the remaining samples with a lower moisture level were obtained by placing them in airtight vessels with the appropriate amount of water calculated on the basis of the sample weight, the volume of the vessels, and the assumed moisture level. Samples in sealed vessels were moistened for 168 h. Samples of fibrous materials prepared in this way were impregnated and conditioned in mineral oil, natural ester, or synthetic ester for a period of about 30 days. Before testing, the water content of fibrous material samples was determined using the Karl Fischer Test KFT method in accordance with the International Electrotechnical Commission standard IEC 60814 [53]. Methanol was used to extract water from fibrous samples.

After the thermal conductivity tests, the water content of fibrous materials was measured by control using the KFT method. These studies did not show a significant impact on the conditions of thermal conductivity tests on the change of water content in samples of fibrous materials. The differences in moisture were within the measurement error of the KFT method and did not exceed the 0.2 percentage point.

2.3. Thermal Conductivity Measurements

To measure the thermal conductivity coefficient λ of papers impregnated with insulating liquids, the self-developed measuring system presented in Figure 1 was used. This system has been described in more detail in publications [55,56].
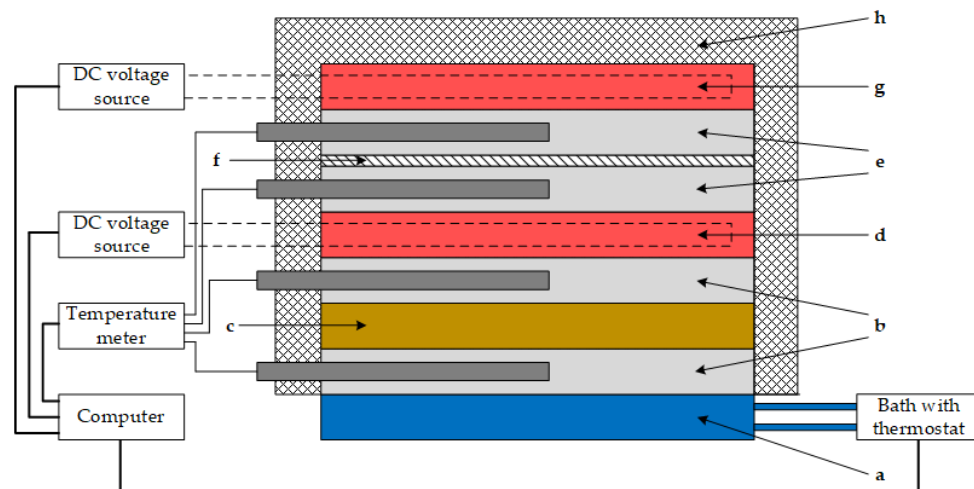
Figure 1. System for measuring the thermal conductivity coefficient λ of solid materials; **a**—cooler, **b,e**—auxiliary plates with measuring probes, **c**—test sample, **d**—main heater, **f**—auxiliary insulation, **g**—auxiliary heater, **h**—main insulation.

The used measuring system is based on the idea of measuring the thermal conductivity coefficient λ using fixed methods. The concept of measurement consists of causing in the test sample, of known thickness d and surface area S, a thermal disturbance ΔT. Based on these quantities, the coefficient of thermal conductivity λ can be determined from the relationship [56]:

$$\lambda = \frac{P}{S} \cdot \frac{d}{\Delta T} \tag{1}$$

where P is the heat of power source (W), S is the surface area of the tested sample (m^2), d is the thickness of the tested sample (m), and ΔT is the temperature drop in the tested sample (°C).

During the measurement, the tested sample (c) was placed between the main heater (d)—supplied with a constant voltage source and the cooler (a)—supplied with water from an external circuit. In the presented measuring system, the tested sample (c) was placed under the main heater (d) in order to eliminate the effect of convection on the temperature drop in the tested sample. The main heater (d) with the power P was designed to generate thermal energy which, penetrating through the sample, causes a decrease in temperature ΔT for a given thickness of sample d. The surface area of the main heater (and also the auxiliary heater) corresponds to the surface area of the tested sample S. The cooler (a) was designed to provide a constant temperature on the bottom surface of the sample. The temperature drop in the tested sample (c) was determined based on the temperature measurement in the auxiliary plates (b), which are made of aluminum and in which the measuring probes (Pt1000 measuring probes connected with the temperature recorder Apek APL 154 (Apek, Warsaw, Poland)) were placed. Auxiliary insulation (f) was placed over the main heater. In turn, an auxiliary heater (g) was placed over the auxiliary insulation to compensate for the heat flow from the main heater (d) in a vertically upward direction. The auxiliary heater (g), like the main heater, is powered by a DC voltage source. The task of the auxiliary heater (g) is to generate such an amount of heat that the indications of the measuring probes placed in the auxiliary plates (e) are the same, which means no heat flow in a perpendicular upward direction. In addition, to isolate heat loss in the measuring system, external insulation was also used (h). Adjusting the settings of both power supplies, as well as recording temperature was done using a special computer program written in the LabView environment (National Instruments, Austin, Texas, TX, USA).

Thermal conductivity error $\Delta\lambda$ was calculated on the basis of the complete differential of Equation (1). The maximal value of the error was smaller than 2% (Appendix A).

3. Experiment Results and Analysis

3.1. Thermal Conductivity Coefficient of Unimpregnated Papers

Table 2 presents the results of measurements of the thermal conductivity of unimpregnated cellulose paper and unimpregnated aramid paper depending on the temperature. The WCP moisture level of both analyzed types of paper was similar and very low—it was 0.52% for cellulose paper and 0.44% for aramid paper, respectively.

Table 2. Thermal conductivity coefficient λ of cellulose and aramid unimpregnated papers at different temperatures *T*.

Temperature *T* (°C)	Thermal Conductivity Coefficient λ (W·m^{-1}·K^{-1})	
	Cellulose Paper	**Aramid Paper**
25	0.076	0.061
40	0.086	0.075
60	0.098	0.088
80	0.110	0.101
100	0.121	0.110

As can be seen from the presented results, the thermal conductivity of unimpregnated cellulose paper was about 9 to 25% higher (depending on the temperature) than the thermal conductivity of unimpregnated aramid paper. This difference decreases with increasing temperature. Both aramid and cellulose paper are polymers, the first of which is a synthetic polymer and the second a natural one. Polymers are characterized by a low value of thermal conductivity coefficient [57]. The thermal conductivity of this group of materials depends on many factors such as structure, molecular weight, density, and degree of crystallinity. As the polymer structure is ordered, its thermal conductivity increases. Both unimpregnated cellulose paper and unimpregnated aramid paper in their structure contain defective structures among other voids, amorphous areas, and entanglements, which impede the spread of heat [58]. They cause a large dispersion of phonons, which reduces heat transport. In addition, voids are filled with air, whose thermal conductivity is very small (0.025 W·m^{-1}·K^{-1}) [59], smaller than the thermal conductivity of papers. A higher value of the thermal conductivity coefficient of cellulose paper results from its density. Both analyzed types of paper were characterized by the same thickness—the thickness of a single layer of paper was 0.005 mm. The density of cellulose paper was 915 kg·m^{-3} and of aramid paper was 709 kg·m^{-3} [46]. This means that cellulose paper in its structure has less difficulty in transporting through heat voids, which are filled with air. Due to the fact that the thermal conductivity of paper is a resultant of the thermal conductivity of paper fibers and air trapped between the fibers, the thermal conductivity of unimpregnated cellulose paper is higher than the thermal conductivity of unimpregnated aramid paper.

3.2. Effect of the Moisture on the Thermal Conductivity of Impregnated Cellulose Paper

Table 3 and Figure 2 present the results of measurements of the thermal conductivity of cellulose paper impregnated with various electrical insulating liquids (mineral oil, synthetic ester, and natural ester) depending on the moisture content.

Comparing the results of the measurements given in Tables 2 and 3, it can be said that the treatment of cellulose paper impregnation with insulating liquids resulted in an increase in its thermal conductivity, which is associated with the replacement of air trapped in the pores of the paper with an insulating liquid which has about one order of magnitude greater thermal conductivity. This conductivity at 25 °C is equal to 0.133 W·m^{-1}·K^{-1} for pure mineral oil, 0.158 W·m^{-1}·K^{-1} for pure synthetic ester, 0.182 W·m^{-1}·K^{-1} for pure natural ester [60,61], and only 0.025 W·m^{-1}·K^{-1} for air.

Based on the measurement results shown in Table 3, it can be concluded that as the temperature increases, the coefficient of thermal conductivity of the impregnated cellulose paper increases, regardless

of the type of impregnating liquid. As is well known, the thermal conductivity of pure liquids decreases with temperature (except for water and glycerin). For tested pure insulating liquids in the examined temperature range of 25 to 80 °C, a decrease in their thermal conductivity by 0.007 W·m^{-1}·K^{-1} was observed regardless of their type [60]. However, the thermal conductivity of unimpregnated cellulose paper increased with increasing temperature, and this increase, in the studied temperature range of 25 to 80 °C, was 0.034 W·m^{-1}·K^{-1} (Table 2). This was due to the fact that both the thermal conductivity of gases and solids increase with temperature. Thus, it can be concluded that primarily the cellulose fibers were responsible for the heat transfer in impregnated cellulose paper, not the insulating liquid. In addition, the conductivity of cellulose paper impregnated with insulating liquids was higher than the conductivity of pure insulating liquids. The increase in the thermal conductivity of the oil-impregnated paper is similar for all tested liquids. In such complex systems, many factors influence heat conduction. However, a similar effect of the tested liquids on the interactions in the papers was observed [57,58]. Since the paper seems to be primarily responsible for heat conduction a similar effect is observed.

Table 3. Thermal conductivity coefficient λ of cellulose paper impregnated by various dielectric liquids depending on the water content of paper WCP, at different temperatures T.
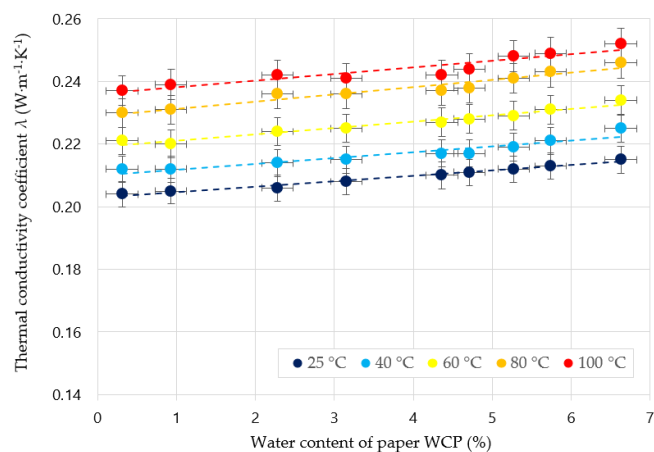
Type of Insulation System	Water Content of Paper WCP (%)	Temperature T (°C)				
		25	40	60	80	100
		Thermal Conductivity Coefficient λ (W·m^{-1}·K^{-1})				
Cellulose paper impregnated by mineral oil	0.50	0.152	0.164	0.176	0.191	0.204
	0.87	0.153	0.162	0.176	0.188	0.203
	1.03	0.150	0.162	0.176	0.189	0.206
	1.30	0.152	0.164	0.178	0.194	0.207
	1.68	0.155	0.167	0.184	0.200	0.213
	1.92	0.159	0.169	0.185	0.202	0.215
	2.24	0.158	0.168	0.182	0.198	0.213
	2.84	0.163	0.174	0.191	0.205	0.217
	4.00	0.163	0.173	0.190	0.203	0.217
	4.80	0.166	0.176	0.188	0.204	0.217
Cellulose paper impregnated by synthetic ester	0.18	0.174	0.185	0.198	0.211	0.220
	1.00	0.176	0.187	0.199	0.210	0.221
	2.38	0.178	0.190	0.202	0.212	0.223
	3.12	0.179	0.191	0.202	0.212	0.222
	4.11	0.180	0.194	0.206	0.217	0.225
	4.32	0.184	0.194	0.207	0.216	0.226
	4.85	0.185	0.199	0.208	0.219	0.227
	5.53	0.186	0.198	0.211	0.220	0.228
Cellulose paper impregnated by natural ester	0.31	0.204	0.212	0.221	0.230	0.237
	0.93	0.205	0.212	0.220	0.231	0.239
	2.28	0.206	0.214	0.224	0.236	0.242
	3.15	0.208	0.215	0.225	0.236	0.241
	4.36	0.210	0.217	0.227	0.237	0.242
	4.71	0.211	0.217	0.228	0.238	0.244
	5.27	0.212	0.219	0.229	0.241	0.248
	5.74	0.213	0.221	0.231	0.243	0.249
	6.63	0.215	0.225	0.234	0.246	0.252
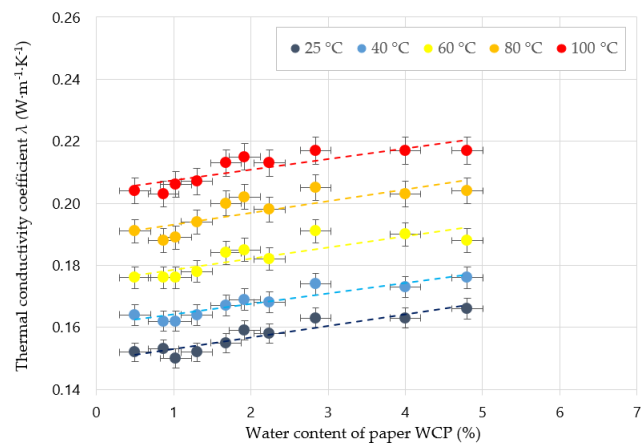
(**a**)
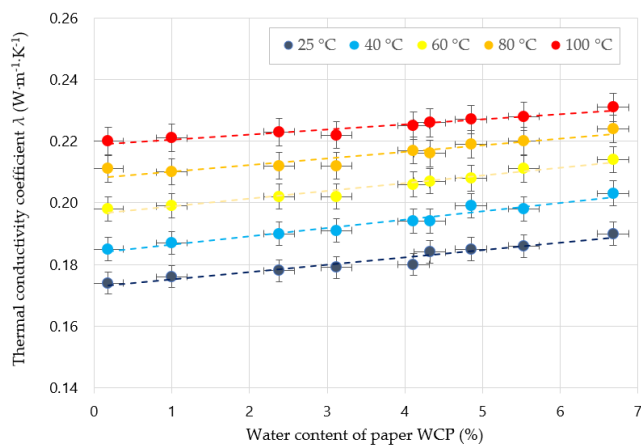
(**b**)

(**c**)

Figure 2. Thermal conductivity coefficient λ of cellulose paper impregnated by various dielectric liquids depending on the water content of paper WCP and temperature T: (**a**) cellulose paper impregnated by mineral oil; (**b**) cellulose paper impregnated by synthetic ester; (**c**) cellulose paper impregnated by natural ester.

Analyzing the measurement results presented in Table 3, it can be seen that the thermal conductivity of cellulose paper impregnated with various insulating liquids increased with increasing

moisture content. Water probably penetrated into the pores of the paper. The increase in thermal conductivity of impregnated paper, caused by an increase in moisture, was associated with about four times greater thermal conductivity of water (about 0.60 W·m^{-1}·K^{-1}) [60] compared to the thermal conductivity of the analyzed pure insulating liquids (average 0.15 W·m^{-1}·K^{-1}) [61]. The increase in the thermal conductivity of the impregnated cellulose paper, accompanied by the increase in moisture, was practically independent of the type of insulating liquid. The average value of the increase in thermal conductivity fluctuated in the range of 5 to 7% for all types of analyzed liquids. However, the increase in paper thermal conductivity, caused by an increase in moisture, depended on the measurement temperature. As the temperature increased, the increases in thermal conductivity of the impregnated cellulose paper were becoming smaller.

In summary, moisture in cellulose insulation increased the thermal conductivity of this insulation. Thus, moisture, in addition to many of the disadvantages described at the beginning of this article, also has positive features. Greater thermal conductivity of cellulose insulation will result in more efficient heat dissipation from the transformer windings to the cooling liquid. This in turn can lower the hot spot temperature.

### 3.3. Effect of the Moisture on the Thermal Conductivity of Impregnated Aramid Paper

Table 4 and Figure 3 present the results of measurements of the thermal conductivity of aramid paper impregnated with various insulating liquids (mineral oil, synthetic ester, and natural ester) depending on the moisture content.

Based on the results of the measurements, it can be seen that the thermal conductivity of aramid paper, impregnated with insulating liquids, similar to cellulose paper, was higher than the thermal conductivity of unimpregnated aramid paper (containing only air in pores) [60,61]. However, this increase was smaller than for cellulose paper and at a temperature below 60 °C, it did not exceed the thermal conductivity of insulating liquids. It is possible, therefore, that in this case conduction at the liquid-aramid paper interface is less effective.
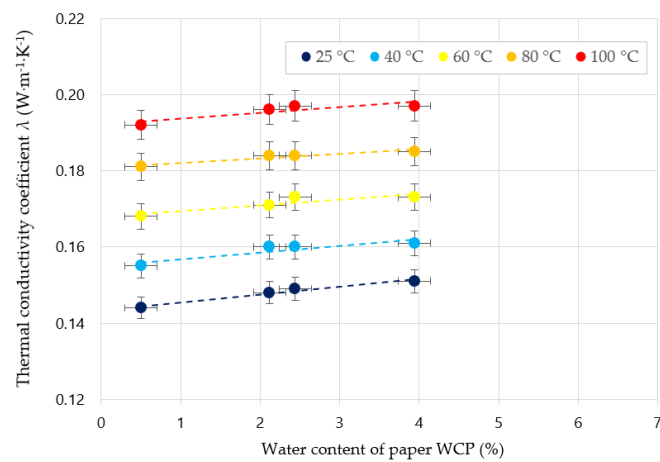
As in the case of cellulose paper, it can also be seen that the thermal conductivity of all analyzed samples of aramid paper increased with increasing temperature. This means that the heat transfer in impregnated aramid paper, as in the case of cellulose paper, is carried out primarily through the paper fibers, not the insulating liquid.

Table 4. Thermal conductivity coefficient λ of aramid paper impregnated by various dielectric liquids depending on the water content of paper WCP, at different temperatures T.
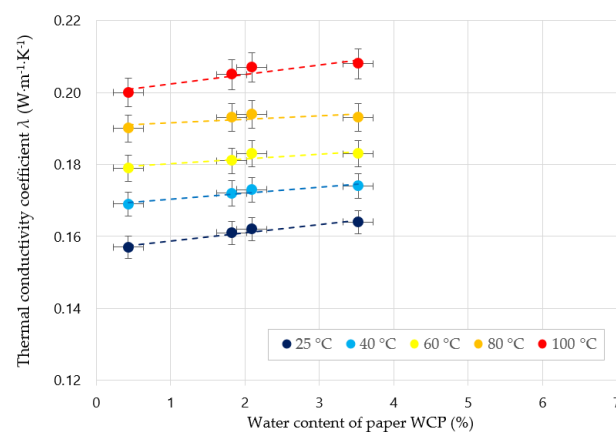
Type of Insulation System	Water Content of Paper WCP (%)	Temperature T (°C)				
		25	40	60	80	100
		Thermal Conductivity Coefficient λ (W·m^{-1}·K^{-1})				
Aramid paper impregnated by mineral oil	0.07	0.128	0.140	0.149	0.164	0.178
	1.59	0.131	0.142	0.153	0.168	0.181
	1.96	0.132	0.144	0.155	0.169	0.183
	3.84	0.135	0.146	0.157	0.171	0.184
Aramid paper impregnated by synthetic ester	0.50	0.144	0.155	0.168	0.181	0.192
	2.12	0.148	0.160	0.171	0.184	0.196
	2.44	0.149	0.160	0.173	0.184	0.197
	3.94	0.151	0.161	0.173	0.185	0.197
Aramid paper impregnated by natural ester	0.43	0.157	0.169	0.179	0.190	0.200
	1.82	0.161	0.172	0.181	0.193	0.205
	2.09	0.162	0.173	0.183	0.194	0.207
	3.52	0.164	0.174	0.183	0.193	0.208
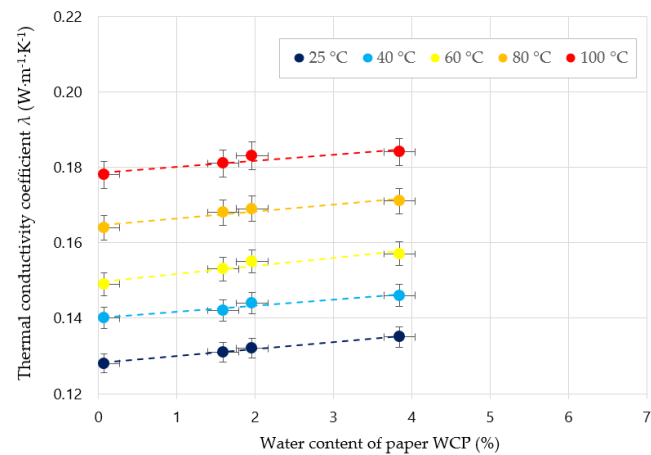
(a)

(b)

(c)

Figure 3. Thermal conductivity coefficient λ of aramid paper impregnated by various dielectric liquids depending on the water content of paper WCP and temperature *T*: (**a**) aramid paper impregnated by mineral oil; (**b**) aramid paper impregnated by synthetic ester; (**c**) aramid paper impregnated by natural ester.

Analyzing the results of the measurements in Table 4, it can be seen that the thermal conductivity of aramid paper impregnated with various insulating liquids, like in the case of cellulose paper,

increased with increasing moisture. Water, which has four times greater thermal conductivity than the thermal conductivity of pure insulating liquids, is responsible for this result [61]. It interacts with the paper, probably binds to it, and penetrates into its pores.

The increase in thermal conductivity of impregnated aramid paper, accompanying the increase in moisture, was practically independent of the type of insulating liquid, and its average value was in the range of 3 to 5% for all types of analyzed liquids. It can be associated with the similar influence of all investigated oils (EN, ES, OM) on aramid paper. However, the increase in thermal conductivity of aramid paper, caused by an increase in moisture, similar to cellulose paper, depended on temperature. For higher temperature values, the increases in thermal conductivity of aramid paper were getting smaller.

In summary, the moisture content of aramid insulation slightly increases its thermal conductivity. Thus, as in the case of cellulose paper, a slightly higher thermal conductivity of aramid insulation will result in more efficient heat dissipation from the transformer windings, which will contribute to a lower value of the hot spot.

3.4. Comparison of Thermal Conductivity of Impregnated Cellulose and Aramid Paper in the Context of Their Moisture

Based on the results of the measurements presented in Tables 3 and 4, it can be stated that the increase in the moisture content of the paper insulation caused an increase in its thermal conductivity, both for cellulose and aramid paper.

The increase in thermal conductivity, caused by moisture, in the case of cellulose paper was 5 to 7%, and in the case of aramid paper, this increase was slightly smaller, equal to 3 to 5%. The reason for this was certainly the upper limit to which the samples could be moistened, which was 5 to 7% WCP for cellulose paper, and only 4% WCP for aramid paper. On this basis, it can be said that moisture in the paper causes a similar increase in thermal conductivity, regardless of the type of paper.

The increase in thermal conductivity caused by moisture was getting smaller as the temperature increased. This regularity was observed for practically all types of impregnating liquid and for both types of analyzed paper (cellulose and aramid).

Figure 4 presents the coefficient of thermal conductivity of paper, depending on moisture, for various types of paper, and impregnating liquid. The values of thermal conductivity are presented for 80 °C, as the most typical temperature for paper insulation of transformer windings.
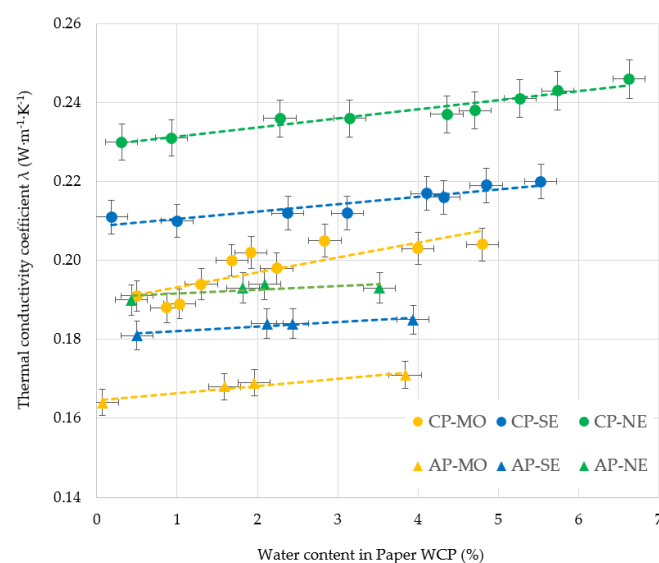

Figure 4. Thermal conductivity of paper insulation depending on moisture WCP measured at 80 °C, for various types of paper and insulating liquid.

As can be seen in Figure 4 the thermal conductivity of paper insulation increases linearly with increasing moisture content. On this basis, a linear equation has been proposed, describing the thermal conductivity of paper insulation depending on moisture:

$$\lambda = a + b \cdot (WCP) \tag{2}$$

where a is the thermal conductivity of paper insulation for zero moisture ($W \cdot m^{-1} \cdot K^{-1}$), b is the coefficient determining the impact of moisture on the thermal conductivity of a given material ($W \cdot m^{-1} \cdot K^{-1} \cdot \%^{-1}$), and WCP is a percentage of water content in paper insulation (%). The parameters *a* and *b* of the linear equations were obtained for the six combinations of analyzed materials (Table 5).

Table 5. The parameters *a* and *b* of the linear equations for the six combinations of analyzed materials; Δa and Δb mean absolute standard error of parameters *a* and *b*, respectively.

Material	a	Δa	b	Δb
	($W \cdot m^{-1} \cdot K^{-1}$)		($W \cdot m^{-1} \cdot K^{-1} \cdot \%^{-1}$)	
CP-MO	0.189	0.002	0.0038	0.0009
CP-SE	0.209	0.001	0.0019	0.0003
CP-NE	0.229	0.001	0.0023	0.0002
AP-MO	0.135	0.001	0.0018	0.0004
AP-SE	0.181	0.001	0.0012	0.0003
AP-NE	0.191	0.002	0.0010	0.0007

The *b* factor, determining the effect of moisture on the thermal conductivity of a given material, has very different values depending on the type of paper. For cellulose paper, these values ($0.0021 \div 0.0038$ ($W \cdot m^{-1} \cdot K^{-1} \cdot \%^{-1}$)) are much higher than for aramid paper ($0.0010 \div 0.0018$ ($W \cdot m^{-1} \cdot K^{-1} \cdot \%^{-1}$)). This means that the same moisture content of paper insulation causes a greater (about two times) increase in the thermal conductivity of cellulose paper than aramid paper. On this basis, it can be concluded that cellulose paper is more sensitive to moisture than aramid paper from the point of view of its thermal conductivity.

The situation is similar when analyzing the *b* factor depending on the type of insulating liquid. For mineral oil, the *b* factor is about twice as high as for both types of analyzed esters. This means that the same moisture content causes a double increase in thermal conductivity of paper impregnated with mineral oil compared to the thermal conductivity of paper impregnated with synthetic or natural ester. On this basis, it can be said that mineral oil is more sensitive to moisture than the analyzed esters from the point of view of thermal conductivity of paper impregnated with these liquids.

In conclusion, it can be said that the most susceptible paper insulation to changes in its thermal conductivity, caused by moisture, was cellulose paper impregnated with mineral oil, for which the coefficient *b* was 0.0038 ($W \cdot m^{-1} \cdot K^{-1} \cdot \%^{-1}$). In turn, the least susceptible paper insulation to changes in its thermal conductivity was aramid paper impregnated with synthetic or mineral ester, for which the coefficient *b* is four times smaller, equal to $0.0010 \div 0.0012$ ($W \cdot m^{-1} \cdot K^{-1} \cdot \%^{-1}$).

The obtained equations are useful for determining the temperature field of the transformer at the design stage, and especially during its operation when the moisture content of paper insulation increases over the years. In recent years, advanced diagnostic techniques have been developed very dynamically that enable the determination of moisture content in paper insulation. These methods are based on the phenomenon of dielectric spectroscopy (Recovery Voltage Measurement RVM, Frequency Domain Spectroscopy FDS) [62,63].

4. Conclusions

Moisture in the paper insulation increased its thermal conductivity, regardless of the type of paper and insulating liquid that the paper has been impregnated with. In the case of cellulose paper,

this increase is 5 to 7%, and for aramid paper, the increase in thermal conductivity fluctuates within 3 to 5%. The increase in thermal conductivity of paper insulation, caused by moisture, is associated with a much higher water conductivity (about 0.60 (W·m^{-1}·K^{-1})) compared to the conductivity of both unimpregnated paper (0.06 ÷ 0.12 (W·m^{-1}·K^{-1})), as well as used pure insulating liquids (about 0.15 (W·m^{-1}·K^{-1})).

The increase in thermal conductivity caused by moisture became smaller as the temperature increased. This relationship was observed for practically all types of impregnating liquids and for both types of analyzed papers.

Based on the obtained results, it was found that the same moisture content of paper insulation caused a greater (about two times) increase in the thermal conductivity of cellulose paper than aramid paper. Thus, cellulose paper was more sensitive to moisture than aramid paper in terms of its thermal conductivity. The same moisture content caused a two-fold increase in the thermal conductivity of paper impregnated with mineral oil compared to the thermal conductivity of paper impregnated with synthetic or natural ester. This means that mineral oil is more sensitive to moisture than the analyzed esters from the point of view of thermal conductivity of paper impregnated with these liquids.

Obtained equations, describing the effect of moisture on the thermal conductivity of paper insulation, can be useful for determining the temperature field of the transformer both at the design stage and during its operation.

Appendix A. Thermal Conductivity Error Estimation

Thermal conductivity error was calculated on the basis of the complete differential of equation, which helps to calculate the conductivity:

$$\lambda = f(p, q, \Delta T) = \frac{p \cdot d}{\Delta T} \tag{A1}$$

where λ is the thermal conductivity coefficient (W·m^{-1}·K^{-1}), p is the surficial thermal load (W·m^{-2}), d is the thickness of sample (m), and ΔT is the temperature difference on the sample surfaces (K).

By expanding the λ function into Taylor series around the measurement values and neglecting words higher than the first row and replacing infinitely small increments of variables with independent finite increments, we will get:

$$\Delta \lambda = \left| \frac{\partial \lambda}{\partial p} \right| \cdot \Delta p + \left| \frac{\partial \lambda}{\partial d} \right| \cdot \Delta d + \left| \frac{\partial \lambda}{\partial \Delta T} \right| \cdot \Delta(\Delta T) \tag{A2}$$

and

$$\Delta \lambda = \left| \frac{d}{\Delta T} \right| \cdot \Delta p + \left| \frac{p}{\Delta T} \right| \cdot \Delta d + \left| -\frac{p \cdot d}{(\Delta T)^2} \right| \cdot \Delta(\Delta T) \tag{A3}$$

It should be noted, that:

$$p = \frac{U \cdot I}{S} \tag{A4}$$

where U is the voltage of heater (V), I is the current of heater (A), and S is the surface of the sample (m^2).

It means, that:

$$\Delta p = \left|\frac{\partial p}{\partial U}\right| \cdot \Delta U + \left|\frac{\partial p}{\partial I}\right| \cdot \Delta I + \left|\frac{\partial p}{\partial S}\right| \cdot \Delta S \tag{A5}$$

and

$$\Delta p = \left|\frac{I}{S}\right| \cdot \Delta U + \left|\frac{U}{S}\right| \cdot \Delta I + \left|-\frac{I \cdot U}{S^2}\right| \cdot \Delta S \tag{A6}$$

It should be noted, that:

$$S = x \cdot y \tag{A7}$$

where x is the length of the sample (m) and y is the width of the sample (m).

It means, that:

$$\Delta S = \left|\frac{\partial S}{\partial x}\right| \cdot \Delta x + \left|\frac{\partial S}{\partial y}\right| \cdot \Delta y \tag{A8}$$

and

$$\Delta S = \left|y\right| \cdot \Delta x + |x| \cdot \Delta y \tag{A9}$$

Summarizing:

$$\Delta \lambda = \left|\frac{d}{\Delta T}\right| \cdot \left(\left|\frac{I}{S}\right| \cdot \Delta U + \left|\frac{U}{S}\right| \cdot \Delta I + \left|-\frac{I \cdot U}{S^2}\right| \cdot \left(\left|y\right| \cdot \Delta x + |x| \cdot \Delta y\right)\right) + \left|\frac{p}{\Delta T}\right| \cdot \Delta d + \\ + \left|-\frac{p \cdot d}{(\Delta T)^2}\right| \cdot \Delta(\Delta T) \tag{A10}$$

Parameters d, ΔT, I, U, S, p, x, and y are measurement results or equipment setting values. All Δd, $\Delta(\Delta T)$, ΔU, ΔI, Δx, and Δy mean accuracy of used equipment and measurers, which are known. It is possible to calculate thermal conductivity error $\Delta \lambda$ on the basis of equations (A10). The value of maximal relative error was smaller than 2%.

References

1. Garcia, B.; Villarroel, E.D.; Garcia, D.F. A multiphysics model to study moisture dynamics in transformer. *IEEE Trans. Power Deliv.* **2019**, *34*, 1365–1373. [CrossRef]
2. Sikorski, W.; Szymczak, C.; Siodla, K.; Polak, F. Hilbert curve fractal antenna for detection and on-line monitoring of partial discharges in power transformers. *Eksploatacja i Niezawodność Maint. Reliab.* **2018**, *20*, 343–351. [CrossRef]
3. Gielniak, J.; Graczkowski, A.; Moranda, H.; Przybylek, P.; Walczak, K.; Nadolny, Z.; Moscicka-Grzesiak, H.; Gubanski, S.M.; Feser, K. Moisture in cellulose insulation of power transformers: Statistics. *IEEE Trans. Dielectr. Electr. Insul.* **2013**, *20*, 982–987. [CrossRef]
4. Toudja, T.; Chetibi, F.; Beldjilali, A.; Moulai, H.; Beroual, A. Electrical and physicochemical properties of mineral and vegetable oils mixtures. In Proceedings of the IEEE 18th International Conference on Dielectrics Liquids (ICDL), Bled, Slovenia, 29 June–3 July 2014; pp. 1–4.
5. Jeong, J.-I.; An, J.-S.; Huh, C.-S. Accelerated aging effects of mineral and vegetable transformer oils on medium voltage power transformers. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 156–161. [CrossRef]
6. Emsley, M.; Stevens, G.C. Kinetic and mechanisms of the low temperature degradation of cellulose. *Cellulose* **1994**, *1*, 26–56. [CrossRef]
7. Liao, R.; Liang, S.; Sun, C.; Yang, L.; Sun, H. A comparative study of thermal aging of the transformer insulation paper impregnated in natural ester and in mineral oil. *Eur. Trans. Electr. Power* **2010**, *20*, 518–533. [CrossRef]
8. Bandara, K.; Ekanayake, C.; Saha, T.K.; Annamalai, P.K. Understanding the aging aspects of natural ester based insulation liquid in power transformer. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 246–257. [CrossRef]
9. Hao, J.; Liao, R.; Chen, G.; Ma, Z.; Yang, L. Quantitative analysis ageing status of natural ester-paper insulation and mineral oil-paper insulation by polarization/depolarization current. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 188–199. [CrossRef]

10. Dombek, G.; Nadolny, Z. Thermal properties of mixtures of mineral oil and natural ester in terms of their application in the transformer. In Proceedings of the International Conference Energy, Environment and Material Systems (EEMS), Polanica-Zdroj, Poland, 13–15 September 2017; pp. 01040-1–01040-6.

11. Seytashmehr, A.; Fofana, I.; Eichler, C.; Akbari, A.; Borsi, H.; Gockenbach, E. Dielectric spectroscopic measurements on transformer oil-paper insulation under controlled laboratory conditions. *IEEE Trans. Dielctr. Electr. Insul.* **2008**, *10*, 903–917. [CrossRef]

12. Dombek, G.; Nadolny, Z.; Marcinkowska, A. Effects of nanoparticles materials on heat transfer in electro-insulating liquids. *Appl. Sci.* **2018**, *8*, 2538. [CrossRef]

13. IEC 60076-2:2011. *Power Transformers—Part 2: Temperature Rise for Liquid-Immersed Transformers*; International Electrotechnical Commission (IEC): New York, NY, USA, 2011.

14. Godina, R.; Rodrigues, E.M.G.; Matias, J.C.O.; Catalao, J.P.S. Effect of loads and other key factors on oil-transformer ageing: Sustainability benefits and challenges. *Energies* **2015**, *8*, 12147–12186. [CrossRef]

15. Wang, C.; Wu, J.; Wang, J.; Zhao, W. Reliability analysis and overload capability assessment of oil-immersed power transformers. *Energies* **2016**, *9*, 43. [CrossRef]

16. Lopatkiewicz, R.; Nadolny, Z.; Przybylek, P.; Sikorski, W. The influence of chosen parameters on thermal conductivity of windings insulation describing temperature distribution in transformer. *Przeglad Elektrotechniczny* **2012**, *88*, 126–129. (In Polish)

17. Dombek, G.; Nadolny, Z. Electro-insulating nanofluids based on synthetic ester and TiO_2 or C_{60} nanoparticles in power transformer. *Energies* **2018**, *11*, 1953. [CrossRef]

18. Xia, G.; Wu, G.; Gao, B.; Yin, H.; Yang, F. A new method for evaluating moisture content and aging degree of transformer oil-paper insulation based on frequency domain spectroscopy. *Energies* **2017**, *10*, 1195. [CrossRef]

19. Betie, A.; Meghnefi, F.; Fofana, I.; Yeo, Z. Modelling the insulation paper drying process from thermogravimetric analyses. *Energies* **2018**, *11*, 517. [CrossRef]

20. N'chos, J.S.; Fofana, I.; Hadjadj, Y.; Beroual, A. Review of physicochemical-based diagnostic techniques for assessing insulation condition in aged transformers. *Energies* **2016**, *9*, 367. [CrossRef]

21. Bhalla, D.; Bansal, R.K.; Gupta, H.O.; Hari, O.M. Preventing power transformer failures through electrical incipient fault analysis. *Int. J. Perform. Eng.* **2013**, *9*, 23–31. [CrossRef]

22. Sparling, B.; Aubin, J. Assessing water content in insulating paper of power transformers. *Electr. Energy T&D Mag.* **2007**, *11*, 30–34.

23. Cui, Y.; Ma, H.; Saha, T.; Ekanayake, C.; Wu, G. Multi-physics modelling approach for investigation of moisture dynamics in power transformers. *IET Gener. Transm. Dis.* **2016**, *10*, 1993–2001. [CrossRef]

24. Smolka, J.; Nowak, A.J. Experimental validation of the coupled fluid flow, heat transfer and electromagnetic numerical model of the medium-power dry-type electrical transformer. *Int. J. Therm. Sci.* **2008**, *47*, 1393–1410. [CrossRef]

25. Yatsevsky, V.A. Hydrodynamics and heat transfer in cooling channels of oil-filled power transformers with multicoil windings. *Appl. Therm. Eng.* **2014**, *63*, 347–353. [CrossRef]

26. Mithun, M.; Thankachan, B. A novel, cost effective capacitive sensor for estimating dissolved moisture in transformer oil. In Proceedings of the 10th International Conference on Sensing Technology (ICTS), Nanjing, China, 11–13 November 2016; pp. 1–6.

27. Oommen, T.V.; Prevost, T.A. Cellulose insulation in oil-filled power transformers: Part II maintaining insulation integrity and life. *IEEE Electr. Insul. Mag.* **2006**, *22*, 5–14. [CrossRef]

28. Su, Q.; James, R.E. *Condition Assessment of High Voltage Insulation in Power System Equipment*, 1st ed.; The Institution of Engineering and Technology: London, UK, 2008; pp. 121–158.

29. Wickman, S.H. Transformer bushings and oil leaks. *Transform. Mag. Spec. Ed. Bushing* **2017**, *4*, 148–154.

30. Sokolov, V.; Aubin, J.; Davydov, V.; Gasser, H.P.; Griffin, P.; Koch, M.; Lundgaard, L.; Roizman, O.; Scala, M.; Tenbohlen, S.; et al. *Moisture Equilibrium and Moisture Migration within Transformer Insulation Systems*; Cigré Technical Brochure 349; International Council on Large Electric Systems (CIGRE): Paris, France, 2008.

31. Li, Y.; Zhou, K.; Zhu, G.; Li, M.; Li, S.; Zhang, J. Study on the influence of temperature, moisture and electric field on the electrical conductivity of oil-impregnated pressboard. *Energies* **2019**, *12*, 3136. [CrossRef]

32. Saha, T.K.; Purkait, P. Understanding the impacts of moisture and thermal aging on transformer's insulation by dielectric response and molecular weight measurements. *IEEE Trans. Dielectr. Electr. Insul.* **2008**, *15*, 568–582. [CrossRef]

33.　Huang, L.; Wang, Y.; Li, X.; Wei, C.; Lu, Y. Effect of moisture on breakdown strength of oil-paper insulation under different voltage types. In Proceedings of the IEEE International Conference on High Voltage Engineering and Application (ICHVE), Athens, Greece, 10–13 September 2018; pp. 1–4.

34.　Wang, Y.; Xiao, K.; Chen, B.; Li, Y. Study of the impact of initial moisture content in oil impregnated insulation paper on thermal aging rate of condenser bushings. *Energies* **2015**, *8*, 14298–14310. [CrossRef]

35.　Sikorski, W.; Walczak, K.; Przybylek, P. Moisture migration in an oil-paper insulation system in relations to online partial discharge monitoring of power transformers. *Energies* **2016**, *9*, 1082. [CrossRef]

36.　*Experiences in Service with New Insulating Liquids*; Cigré Technical Brochure 436; International Council on Large Electric Systems (CIGRE): Paris, France, 2010.

37.　Christina, A.J.; Salam, M.A.; Rahman, Q.M.; Wen, F.; Ang, S.P.; Voon, W. Causes of transformer failures and diagnostic methods—A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1442–1456. [CrossRef]

38.　Shroff, D.H.; Stannett, A.W. A review of paper aging in power transformers. *IEEE Proc. C Gener. Transm. Distrib.* **1985**, *132*, 312–319. [CrossRef]

39.　Lundgaard, L.E.; Hansen, W.; Linhjell, D.; Painter, T.J. Aging of oil-impregnated paper in power transformers. *IEEE Trans. Power Deliv.* **2004**, *19*, 230–239. [CrossRef]

40.　Mosinski, F. The influence of water and oxygene on load and lifetime of power transformers. In Proceedings of the Transformer During Operation Conference, Kolobrzeg, Poland, 20–22 April 2005; pp. 117–119. (In Polish)

41.　Daghrah, M.; Wang, Z.; Liu, Q.; Hiker, A.; Gyore, A. Experimental study of the influence of different liquids on the transformer cooling performance. *IEEE Trans. Power Deliv.* **2019**, *34*, 588–595. [CrossRef]

42.　Velandy, J.; Garg, A.; Narasimhan, C.S. Thermal performance of ester oil transformers with different placement of cooling fan. In Proceedings of the 9th Power India International Conference (PIICON), Sonepat, India, 29 February–1 March 2020; pp. 1–7.

43.　Velandy, J.; Garg, A.; Narasimhan, C.S. Continuos thermal overloading capabilities of ester oil transformer in oil directed cooling conditions. In Proceedings of the 9th Power India International Conference (PIICON), Sonepat, India, 29 February–1 March 2020; pp. 1–7.

44.　Cabeza-Prieto, A.; Camino-Olea, M.S.; Rodriguez-Esteban, M.A.; Llorente-Alvarez, A.; Saez-Perez, M. Moisture influence on the thermal operation of the late 19th century brick façade, in a historic building in the city of Zamora. *Energies* **2020**, *13*, 1307. [CrossRef]

45.　Nikitsin, V.I.; Alsabry, A.; Kofanov, V.A.; Backiel-Brzozowska, B.; Truszkiewicz, P. A model of moist polymer foam and a scheme for the calculation of its thermal conductivity. *Energies* **2020**, *13*, 520. [CrossRef]

46.　DuPontTM Nomex® 926. Technical Data Sheet. Available online: https://www.dupont.com/fabrics-fibers-and-nonwovens/nomex-electrical-insulation.html (accessed on 3 May 2020).

47.　Nynas Nytro Draco Technical Data Sheet. Available online: http://www.smaryoleje.pl/nynas.html (accessed on 4 May 2020).

48.　Midel 7131 Synthetic Ester Transformer Fluid. FIRE Safe and Biodegradable. Available online: https://www.midel.com/app/uploads/2018/05/MIDEL-7131-Product-Brochure.pdf (accessed on 4 May 2020).

49.　Cargill Dielectric Fluids. EnvirotempTM FR3TM Fluid. Available online: https://www.cargill.com/doc/1432160189547/fr3-dielectric-fluid-data-sheet.pdf (accessed on 4 May 2020).

50.　Martin, D.; Perkasa, C.; Lelekakis, N. Measuring paper water content of transformers: A new approach using cellulose isotherms in nonequilibrium conditions. *IEEE Trans. Power Deliv.* **2013**, *28*, 1433–1439. [CrossRef]

51.　Atanasova-Höhlein, I.; Agren, P.; Beauchemin, C.; Cucek, B.; Darian, L.; Davidov, V.; Dreier, L.; Gradnik, T.; Grisaru, M.; Koncan-Gradnik, M.; et al. *Moisture Measurement and Assessment in Transformer Insulation—Evaluation of Chemical Methods and Moisture Capacitive Sensors*; International Council on Large Electric Systems (CIGRE): Paris, France, 2018.

52.　*IEC 60814. Insulating Liquids—Oil-Impregnated Paper and Pressboard—Determination of Water by Automatic Coulometric Karl Fischer Titration*; International Electrotechnical Commission (IEC): New York, NY, USA, 1997.

53.　Przybylek, P. Water saturation limit of insulating liquids and hygroscopicity of cellulose in aspect of moisture determination in oil-paper insulation. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 1886–1893. [CrossRef]

54.　Przybylek, P. A Comparison of bubble evolution temperature in aramid and cellulose paper. In Proceedings of the IEEE International Conference on Solid Dielectrics (ICSD), Bologna, Italy, 30 June–4 July 2013; pp. 983–986.

55.　Lopatkiewicz, R.; Nadolny, Z.; Przybylek, P. The influence of water content on thermal conductivity of paper used as a transformer windings insulation. In Proceedings of the IEEE International Conference on the Properties and Applirations of Dielectric Materials (ICPADM), Bangalore, India, 24–28 July 2012; pp. 1–4.

56. Lopatkiewicz, R.; Nadolny, Z.; Przybylek, P. Influecne of water content in paper on its thermal conductivity. *Przeglad Elektrotechniczny.* **2010**, *86*, 55–58. (In Polish)

57. Chen, H.; Ginzburg, V.V.; Yang, J.; Yang, Y.; Liu, W.; Huang, Y.; Du, L.; Chen, B. Thermal conductivity of polymer-based composites: Fundamentals and applications. *Prog. Polym. Sci.* **2016**, *59*, 41–85. [CrossRef]

58. Chae, H.G.; Kumar, S. Minaking strong fibres. *Science* **2008**, *319*, 908–909. [CrossRef]

59. Vargaftik, N.B.; Filippov, L.P.; Tarzimanov, A.A.; Totski, E.E. *Handbook of Thermal Conductivity of Liquids an Gases*, 1st ed.; CRC Press: Cleveland, OH, USA, 1994; pp. 48–75.

60. Dombek, G.; Nadolny, Z. Liquid kind, temperature, moisture, and ageing as an operating parameters conditioning reliability of transformer cooling system. *Eksploatacja i Niezawodność—Maintenance and Reliability* **2016**, *18*, 413–417. [CrossRef]

61. Dombek, G.; Nadolny, Z. Influence of paper type and liquid insulation on heat transfer in transformers. *IEEE Trans. Dielectr. Electr. Insul.* **2018**, *25*, 1863–1870. [CrossRef]

62. Kuang, Y.C.; Chen, G.; Jarman, P. Recovery voltage measurement on oil-paper insulation with simple geometry and controlled environment. In Proceedings of the IEEE International Conference on Solid Dielectrics (ICSD), Toulouse, France, 5–9 July 2004; pp. 1–4.

63. Wang, S.; Wei, J.; Yang, S.; Dong, M.; Zhang, G. Temperature and thermal aging effects on the frequency domain spectroscopy measurement of oil-paper insulation. In Proceedings of the IEEE 9th International Conference on the Properties and Applications of Dielectric Materials (ICPADM), Harbin, China, 19–23 July 2009; pp. 329–332.