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Bubble Effect Phenomenon in Modern Transformer Insulation Systems Using Aramid-Based Materials and Alternative Insulating Liquids

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Abstract: One of the possible causes of transformer failures is high moisture in the winding insulation system. In an extreme case, when the critical temperature is exceeded, a sudden release of water vapor from the transformer insulation, called the bubble effect, can occur. This article analyzes the initiation temperature of the bubble phenomenon in various solid insulation materials (Kraft cellulose paper and aramid-based high-temperature papers such as Nomex® 910 and Nomex® 926) immersed in two electro-insulating liquids (mineral oil and Midel 7131 synthetic ester). The initiation temperature of the bubble effect depends mainly on the moisture content of the solid insulation, but it was found to be slightly lower for high-temperature materials than for cellulose. However, after taking into account the differences related to uneven water absorption of the tested materials, the differences in the initiation temperature of individual solid materials are very small. Synthetic ester, compared to mineral oil, slightly increases the bubble initiation temperature, regardless of the solid material used.

Keywords: bubble effect; aramid insulation; high temperature insulation; power transformers; synthetic ester

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1. Introduction

Power transformers are one of the most important elements of the power system. Transformer failures often result in interruptions in the supply of electricity to consumers; furthermore, transformers are one of the most expensive elements of the electrical grid. The knowledge of the physical phenomenon that may lead to their failure, such as partial discharges [1], lightning impulse [2], or the bubble effect (b.e.) [3,4] is very important in the preventive diagnostic.

Effective and preventive diagnostics of power transformers allow for a significant reduction in the risk of failure [5]. Currently, a number of articles focusing mainly on checking the sensitivity of diagnostic methods [6–10] can be found in the literature.

One possible parameter that influences the failure rate of transformers is the amount of moisture in the transformer's solid insulation. After the production process there is always some amount of residual water in the insulation system. There are three major factors which cause an increase in the amount of water in the solid insulation of transformers: tank leakage, the chemical degradation of cellulose, and the effectiveness of drying the transformer before operation [11]. The presence of water in the solid insulation is a catalyst for aging processes, which shortens the lifetime of the active part. In addition, water has a negative effect on the dielectric parameters of the insulating system, e.g., by reducing the breakdown voltage of the insulating oil or decreasing the tensile strength of cellulose [12].

Insulation systems based on aramid insulation will generate less water as a degradation product. Aramid does not generate water. The water generation in aramid-based insulation systems comes from insulation components made of cellulose, which are often parts of hybrid insulation systems combining cellulose and aramid components. The more extensive use of aramid in the insulation system vs. cellulose components will reduce the rate of water introduction during equipment operation.

Because modern high-temperature insulating materials have been used in transformers for a relatively short time, the literature lacks research results of insulating systems composed of these materials in the context of the bubble effect phenomenon. This article fills this gap.

This paper presents the results of research on the bubble effect initiation temperature in insulation systems consisting of modern high-temperature insulation materials (Nomex® 926 (DuPont de Nemours, Inc., Wilmington, DE, USA), Nomex® 910 (Krempel GmbH, Vaihingen/Enz, Germany) and Midel 7131 (M&I Materials, Manchester, UK)) and, for comparative purposes, in the cellulose–mineral oil insulation system. The comparative analysis of these insulation systems are then presented.

2. Solid and Liquid Insulation Materials Used in Experiment

At the beginning of the 20th century, relatively few solid electrical insulating materials were known, of which cellulose was the most popular. In the 1930s of the 20th century, a revolution in electrical insulating materials was observed, mainly due to the increased involvement of material suppliers to the electrotechnical industry, which resulted in the development of new electrical insulating materials. The awareness of energy operators also increased, and the development of science made it possible to better understand the phenomenon occurring in the insulation systems. This allowed for the development of new high-temperature materials [13].

The use of high-temperature insulation in transformers brings a number of advantages [14,15]: it extends the lifetime of the insulation system, allows for greater short-term thermal overloads without significant loss of lifetime for the insulating material, and allows for better optimization of the construction.

The main disadvantage of high-temperature materials is their price, which is higher than the commonly used cellulose insulation. The use of aramid insulation with biodegradable ester can increase the total cost of the transformer by approximately 30% [16]; however, it should be mentioned that in some articles, the authors describe the use of high-temperature insulation materials for reducing the total price of the transformer or the complete electrical installation [17,18].

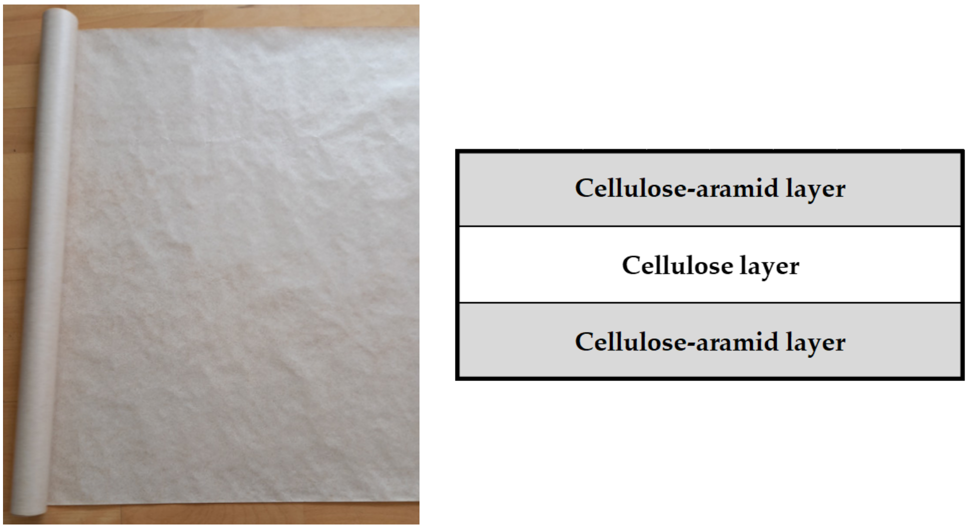
Among the high-temperature insulation materials, those made of aramid fibers are particularly popular. They belong to the group of polymers that have amide bonds –C(O)–NH–.

One of the most popular producers of aramid materials is DuPont, with a series of Nomex® products. Among their developments, the following can be distinguished: aramid papers (like Nomex® 926), aramid pressboards, and thermally upgraded cellulose paper enhanced with aramid (Nomex® 910).

Nomex® 926 is a high-temperature insulation material designed for operation in transformers with liquid insulation, while its operation in dry transformers is not allowed [19]. It is only available in one 0.05 mm thickness (Figure 1). It can be purchased in the form of a roll or already wound on a conductive wire. Nomex® 926 is made entirely of aramid.

Nomex® 910 is a new generation high-temperature (thermally upgraded) insulation used in power transformers [20]. It is a combination of the insulation consisting of aramid fiber and the classically used cellulose. It consists of layers combining high-temperature aramid fibers and high-quality, thermally upgraded cellulose (Figure 2). Due to the fact that Nomex® 910 consists of cellulose and the same aramid as the one used in the Nomex® 926 product, the parameters of this combined product fall between both ingredients [16,21].

Figure 1. A photograph of the Nomex® 926 used in the experiment.



(**a**) (**b**)

Figure 2. A photograph (**a**) and cross-section diagram (**b**) of the Nomex® 910.

Mineral oil is an electro-insulating liquid product based on petroleum, which, like any other insulating liquid, fulfills a number of functions in transformers: cooling of the active part, providing electrical insulation, and impregnation of the transformer solid insulation, which increases its lifetime and provides good insulating properties.

Recently, a growing interest in alternative insulating liquids (i.e., other than mineral oil) can be observed, mainly due to a desire to protect the environment. Today, the policy of the European Union places great emphasis on environmental protection. Synthetic esters, such as the Midel 7131, fit perfectly into this policy, because unlike traditionally used mineral oil, they are more degradable than mineral oil [14].

Table 1 shows a comparison of the parameters of the synthetic ester Midel 7131 and the mineral oil Orlen Oil Trafo En.

The biggest advantages of synthetic esters include [22–24]: better biodegradability than mineral oil (in case of spills, however, it must be treated immediately as if it were mineral oil), greater fire safety due to a high flash point, good electrical parameters (similar to mineral oils), and higher water absorption than mineral oils.

Higher water absorption (depending on the temperature, it can be several dozen times higher than mineral oil) causes the extraction of water from the wet solid insulation of transformers [25,26], which extends the lifetime of this insulation and thus the entire transformer [27].

The biggest disadvantage of synthetic esters application, as in the case of aramid materials, is their price (they are much higher in price than mineral oil). Nevertheless, both materials (synthetic esters and aramid insulation) are used in many demanding applications where the highest technical performance is appreciated by users, and the higher cost of individual materials can be compensated by optimized design of the transformers and benefits are proven for the complete transformer installations.

On the performance side, the viscosity of synthetic esters is almost three times higher than the viscosity of mineral oils, which makes cooling of the active part more difficult (it requires a more efficient cooling system).

Table 1. Comparison of the parameters of the synthetic ester Midel 7131 and the mineral oil Orlen Oil Trafo En [22–24].

Parameter	Unit	Midel 7131	Orlen Oil Trafo En
Density at 20 °C	kg/m^3	970	870
Kinematic viscosity at 40 °C	mm^2/s	29.5	9.6
Pour point	°C	−60	−51
Flash point	°C	260	146
Fire classification in accordance with IEC 61100/IEC 61039 [28,29]	–	K3	0
Biodegradability	%	89	10
Breakdown voltage	kV	>75	69
Dielectric loss factor at 90 °C	–	<0.0080	0.0015

Table 2 shows the values of the relative permittivity of various insulating materials. Adsorption and physical desorption of water are the result of electrostatic phenomena between the cellulose fibers and water. Greater polarization of the cellulose fibers results in the adsorption of more water. The permittivity of a material can be taken as a measure of the polarity of a material. For this reason, the electrical permittivity of materials is extremely important in terms of the occurrence of the bubble phenomenon.

Table 2. Relative permittivity of various insulating materials [14,19].

Insulating Material	Relative Permittivity at 25 °C ε_r [–]
Mineral oil	2.2
Synthetic ester	3.2
Cellulose paper in mineral oil	3.3–4.1
Aramid paper in mineral oil	2.94

3. Bubble Effect

The bubble effect (b.e.) phenomenon can be defined as a rapid release of water vapor from the solid insulation of the transformer after exceeding a certain temperature (known as the b.e. initiation temperature).

The value of the b.e. initial temperature is most dependent on the moisture in the insulation [11]. The other parameters (for example, the type of paper and oil used) have only a minor effect. This temperature decreases with an increase in the moisture content of the insulating material [11], decreases in the degree of cellulose polymerization [30], and increases in the content of gases dissolved in the oil [31].

The bubble effect causes a local deterioration of the insulation system parameters and, consequently, may lead to the failure of the transformer. For this reason, it is extremely dangerous. Some of the most important negative effects of the bubble phenomenon are an increase in pressure inside the tank (what can cause insulation liquid leakage and fire) [32] and deterioration of electrical insulating parameters. The value of the breakdown voltage of the insulation system after the occurrence of the bubble phenomenon may decrease even by 60% [33].

Moisture in the solid insulation has the greatest impact on the level of the bubble initiation temperature. Therefore, it is extremely important to control the degree of moisture in this insulation during transformer operation. The bubble effect initiation temperature can vary strongly depending on the moisture content of the insulation [34].

An increase in the transformer insulation temperature to the point where the bubble effect occurs can be caused by a number of factors, including: failure of the cooling system, short-term or long-term overload, or partial blockage of the oil channel cooling the windings.

The research presented in [32] shows that for the cellulose–mineral oil insulation system, the increase in cellulose moisture from 1% to 5% causes a very large drop in the bubble initiation temperature (from 180 °C to 100 °C). It should be noted that the mentioned values of the bubble initiation temperature are within the permissible temperatures achieved by the insulation of transformers in operation [14,35].

It must be also pointed out that a key reason for moisture increase in an insulation system is the degradation of cellulose during a long-term transformer operation. Water is a cellulose degradation product. The same increase of moisture in an insulation system will not happen in an insulation system based on aramid. Aramid does not generate water in temperatures near the normal operation temperatures. Only overheating it to temperatures beyond 250 °C may result is minimal water generation. Hence, aramid-based insulation systems may be assumed to operate at lower moisture levels than cellulose-based systems.

The research proved that the initiation temperature of the bubble phenomenon in cellulose insulation immersed in alternative insulating liquid (such as synthetic ester or natural ester) is higher than in the traditionally used mineral oil [36,37]. This relates to the higher hygroscopicity of esters. Perkasa showed in his research [36] that the bubble effect occurs in cellulose paper between 3–6% water content in the same conditions on approximately the same time for both mineral and vegetable oil.

In research conducted by Oommen and Lindgren, an empirical formula can be found (1) which allows for a calculation of the bubble effect initiation temperature in a cellulose paper–mineral oil insulation system [31]. The formula also takes into account the effects of pressure and the amount of dissolved gases in the oil.

$$T = \left[\frac{6996.7}{22.454 + (1.4495 \cdot \ln(WCP)) - \ln(P)}\right] - \left[e^{(0.473 \cdot WCP)} \cdot \left(\frac{g}{30}\right)^{1.585}\right] \quad (1)$$

where:

T—bubble effect initiation temperature [K],
WCP—water content of cellulose paper [%],
P—total pressure affecting on the bubble [Torr],
g—dissolved gas content in the oil [%].

It is also worth noting that the potential risks resulting from the formation of bubbles in the insulation of power transformers are still a popular topic, and were published in the recently issued CIGRE publications [38,39].

4. Experiment

The aim of this research was to compare the bubble initiation temperature in the following measurement systems: cellulose paper–mineral oil, cellulose paper–synthetic ester, Nomex® 910 aramid/cellulose paper–mineral oil, Nomex® 910 aramid/cellulose paper–synthetic ester, Nomex® 926 aramid paper–mineral oil, Nomex® 926 aramid paper–synthetic ester.

The main assumption put forward in the research is as follows: the initiation temperature of the bubble phenomenon in complex insulation systems significantly depends on the polarity of the components making up the insulation system; dielectric permittivity is a simple measure of the polarity of a material.

Two electro-insulating transformer liquids were used in the experiment: Orlen Trafo EN mineral oil and Midel 7131 synthetic ester, in which three different insulating solid materials were immersed: Nomex® 926, Nomex® 910 and Kraft cellulose paper. Materials were not aged. Each solid insulation had a different electrical permittivity and hygroscopicity.

The tested specimens were prepared in such a way that the paper volume was the same in each (the thickness of the insulation material was 1.15 mm from each side). For this purpose, each material sample was cut to a width of 10 cm, and its length was chosen to compensate the difference in the thickness of the individual materials (cellulose thickness—0.075 mm, Nomex® 910 thickness—0.080 mm, Nomex® 926 thickness—0.050 mm). Before moisturizing, each sample was wound on a cylindrical aluminum patron with dimensions 120 mm long and 16 mm in diameter (Figure 3).

Figure 3. Tested insulation materials wound on patrons.

The preparation of insulating materials for the experiment consisted of a number of time-consuming activities. First, solid materials were subjected to a vacuum drying process for 8 h in temperature 105 °C and pressure 4×10^{-1} mbar. Then, tested materials were conditioned in the Binder MKF240 E3 climate chamber (BINDER GmbH, Tuttlingen, Germany), which was set to specific parameters of air humidity and temperature until the desired moisture content of the samples was achieved. Figure 4 presents the results of paper moisturizing at different levels of relative humidity at 40 °C. Due to the limitations of the climatic chamber some specimens were also moisturized at other temperatures. Data related to samples conditioned in other temperatures are not presented in Figure 4, but all are collected in Table 3. During conditioning, the water content of the samples was controlled by the mass method or by the Karl Fischer titration method. In the mass method, the mass of dry and moisturized samples were designated. Knowing the weight of the dry sample, it is possible to determine the weight of the water in the insulating system, which allowed for the determination of the percentage of moisture content of the tested samples obtained by the following equation:

$$W = \frac{m_{as} - m_d}{m_{as}} \cdot 100\%, \quad (2)$$

where:

W—moisture content in solid insulation [%],
m_{as}—mass of the test sample [g],
m_d—mass of the material after drying [g].

Samples with a very low value of moisture content were prepared with a different method: by gradual moisturizing of bone-dry samples in the air with simultaneous continuous control of the sample mass.

Aramid-based materials conditioned in the same conditions (temperature and air humidity) were less moisturized than cellulose due to their lower ability to absorb water, which may be associated with the lower polarity of aramid (Figure 4). Different materials prepared under the same conditions in a climate chamber had different absolute moisture value, which directly affects their bubble effect initiation temperature. This phenomenon is very important during interpretation of the results obtained in the experiments.

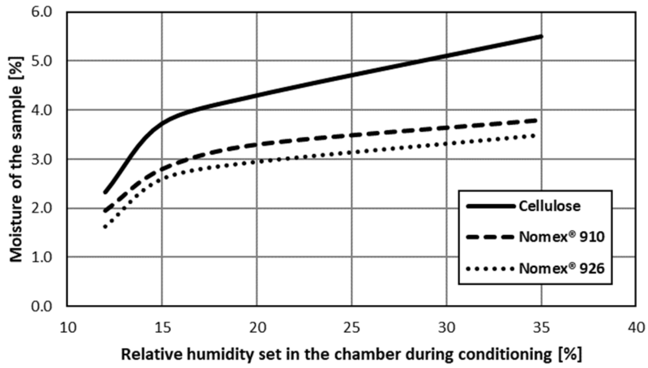


Figure 4. Moisture characteristics of the tested materials depending on the relative air humidity in the climatic chamber during conditioning at 40 °C.

The mineral oil and synthetic ester used in the research were degassed by placing them in a vacuum until the gassing stopped. The process took place at room temperature. Before testing, the paper samples were impregnated in the liquid for about 48 h at room temperature and then degassed in vacuum. Impregnation was performed in ambient temperature, therefore the migration of water between samples and insulation liquid was very slow and could be neglected. Bubble effect measurements started after about 10 min, counting from placing the samples in the test stand filled with insulation liquid in ambient temperature in order to stabilize the measurement conditions.

The moisture content of samples used in the experiment is presented in Table 3 below.

Table 3. Moisture content of samples used in experiment.

Moisture of Cellulose Paper (in Oil) [%]	Moisture of Cellulose Paper (in Midel 7131) [%]	Moisture of Nomex® 910 (in Oil) [%]	Moisture of Nomex® 910 (in Midel 7131) [%]	Moisture of Nomex® 926 (in Oil) [%]	Moisture of Nomex® 926 (in Midel 7131) [%]
0.66	0.65	0.56	0.56	0.50	0.50
1.85	1.85	1.21	1.25	0.95	0.95
1.85	1.85	1.95	2.04	1.03	1.17
2.37	2.38	2.05	2.70	1.56	1.66
2.80	2.70	2.71	2.88	1.58	1.66
3.66	3.73	2.90	3.30	1.97	1.95
3.78	3.74	3.30	3.80	2.50	2.56
4.30	4.30	3.30	4.90	2.58	2.60
4.30	5.50	3.80	-	2.95	2.95
5.50	5.50	3.80	-	2.95	3.50
5.50	6.14	4.87	-	3.50	3.50
6.17	-	-	-	3.50	3.84
-	-	-	-	4.04	-

For bubble effect observation, a heater was inserted into each patron with an insulation wound on it and immersed in the tested electro-insulating liquid (Figure 5). The temperature of the patron was measured by a thermocouple inserted into a hole especially made for this purpose. During the tests, the temperature of the solid insulation was slowly increased, initially at a rate of approximately 1 ^{0}C/s. Close to the expected initiation temperature of the bubble effect, the rate was decreased to a value of approximately 0.1 ^{0}C/s. The heating of the sample from room temperature to the occurrence of bubbling took about 6–8 min.

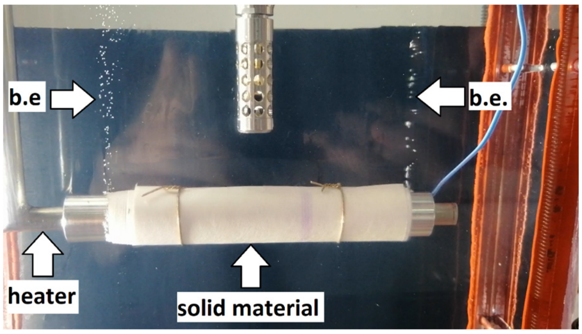


Figure 5. The sample of Nomex® 926 during the bubble effect test immersed in an insulating liquid.

5. Results and Discussion

5.1. Presentation of Research Results

The tests were carried out in accordance with the procedure described in point 4. The number of measurement points is specified in Table 3. Figures 6–8 show the measurement results obtained during the experiment. Each measurement point is marked with a blank dot.

The color of the background is related to the insulating liquid used during the experiment (yellow: mineral oil Orlen Trafo EN, green: synthetic ester Midel 7131).

The type of the curve corresponds to the solid insulation material (solid line: cellulose Kraft paper, dashed line: Nomex® 910, dotted line: Nomex® 926).

The comparison of the research results for individual materials used in the experiment is presented in the following chapters. Due to the legibility of the drawings, the marking of measurement points was abandoned in the later part of the analysis.

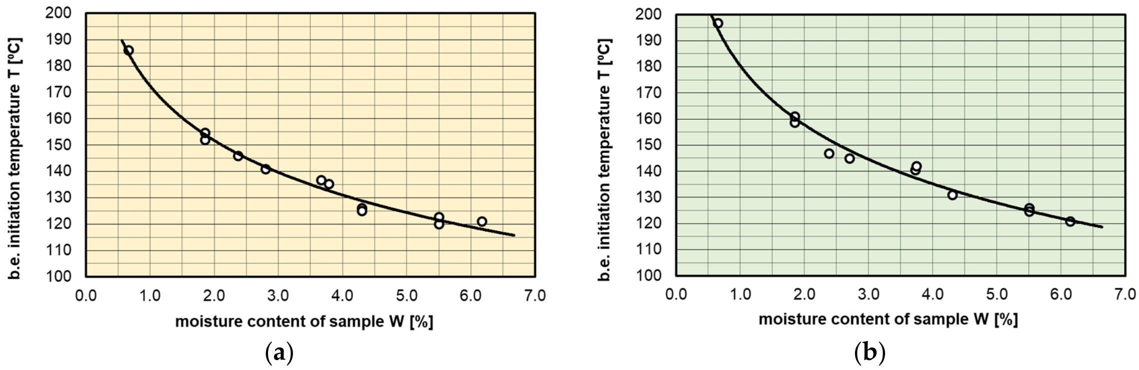


Figure 6. Measurement results of the bubble effect initiation temperature for cellulose paper immersed in mineral oil Orlen Trafo EN (**a**) and synthetic ester Midel 7131 (**b**).

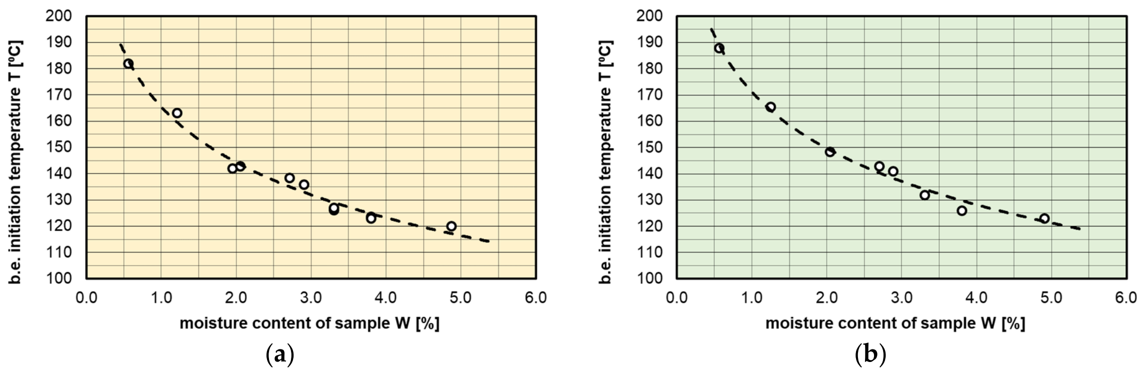


Figure 7. Measurement results of the bubble effect initiation temperature for Nomex® 910 paper immersed in mineral oil Orlen Trafo EN (**a**) and synthetic ester Midel 7131 (**b**).

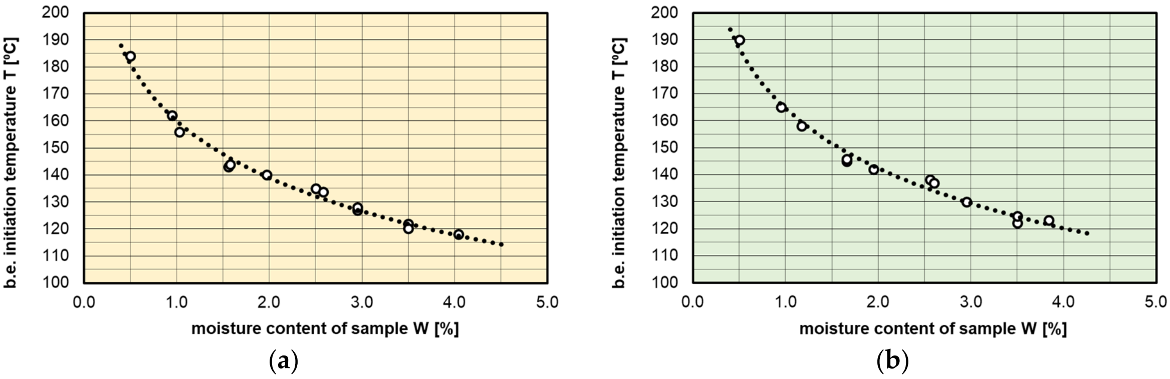


Figure 8. Measurement results of the bubble effect initiation temperature for Nomex® 926 paper immersed in mineral oil Orlen Trafo EN (**a**) and synthetic ester Midel 7131 (**b**).

5.2. Bubble Effect Initiation Temperature Comparison of Electro-Insulating Liquids

Two insulating liquids were used in the experiment: mineral oil Orlen Trafo EN and synthetic ester Midel 7131. All tested solid materials immersed in the synthetic ester were characterized by a slightly higher bubble initiation temperature than in the case of immersion of these materials in mineral oil (Figure 9).

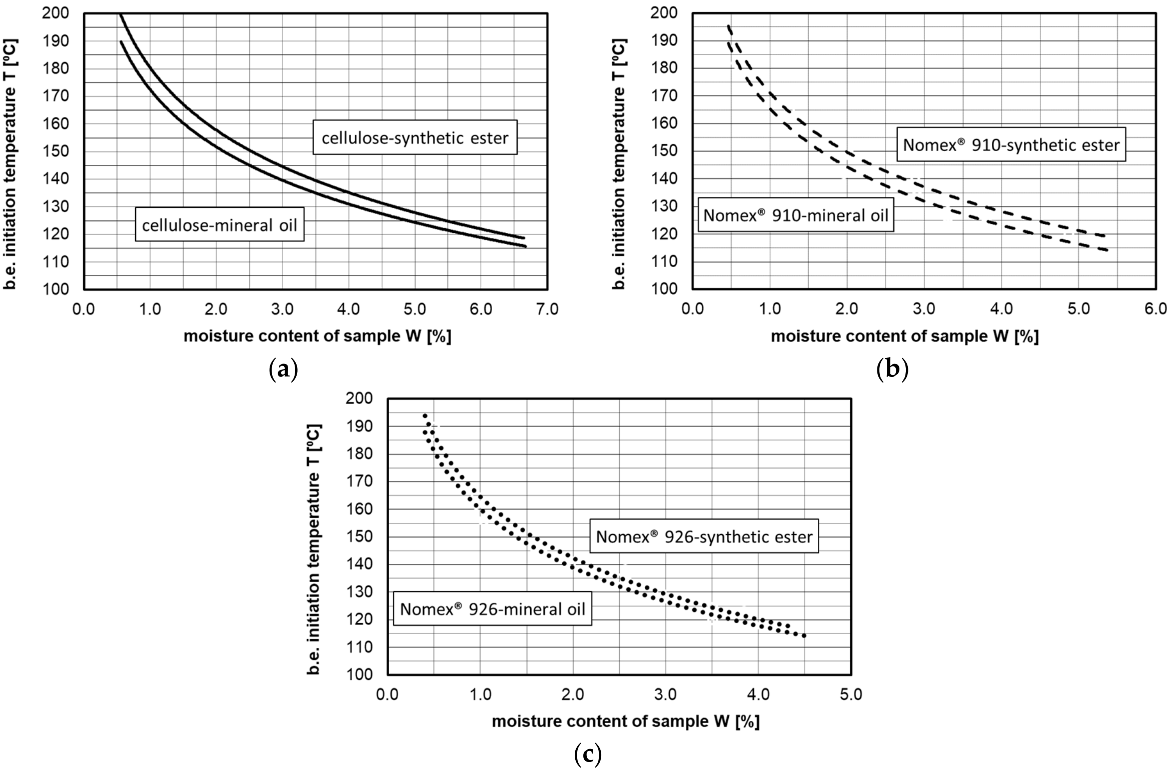


Figure 9. The influence of the insulating liquid (mineral oil Orlen Trafo EN, synthetic ester Midel 7131) on the bubble effect initiation temperature for different materials: Cellulose (**a**), Nomex® 910 (**b**) and Nomex® 926 (**c**).

The b.e. initiation temperature difference between tested electro-insulating liquids obtained from measurement curves is presented in Tables 4–6. The largest percentage difference between the two tested liquids can be found for cellulose (4.1%), while Nomex® 910 and Nomex® 926 have 2.0% and 2.4%, respectively. This highest difference observed for cellulose paper may be related to the fact that the cellulose had the highest moisture adsorption of all tested materials, and it is most sensitive to moisture migration effects observed in liquid-immersed insulation systems.

Table 4. Comparison of b.e. initiation temperature of cellulose immersed in tested electro-insulating liquids obtained from measurement curves.

Sample Moisture [%]	B.e. Initiation Temperature for Cellulose in Oil [°C]	B.e. Initiation Temperature for Cellulose in Ester [°C]	Difference Between b.e. Initiation Temperature in Ester and Oil [°C]	Percentage Difference Between b.e. Initiation Temperature in Ester and Oil [%]
1	172.5	180.7	8.2	4.8
1.5	160.3	167.7	7.4	4.6
2.0	151.7	158.5	6.7	4.4
2.5	145.1	151.3	6.3	4.3
3.0	139.6	145.5	5.9	4.2
3.5	135.0	140.6	5.6	4.1
4.0	131.0	136.3	5.3	4.0
4.5	127.5	132.5	5.0	3.9
5.0	124.3	129.1	4.8	3.9
5.5	121.5	126.1	4.6	3.8
6.0	118.9	123.3	4.4	3.7
6.5	116.5	120.7	4.2	3.6
		Average:	5.7	4.1

Table 5. Comparison of b.e. initiation temperature of Nomex® 910 immersed in tested electro-insulating liquids obtained from measurement curves.

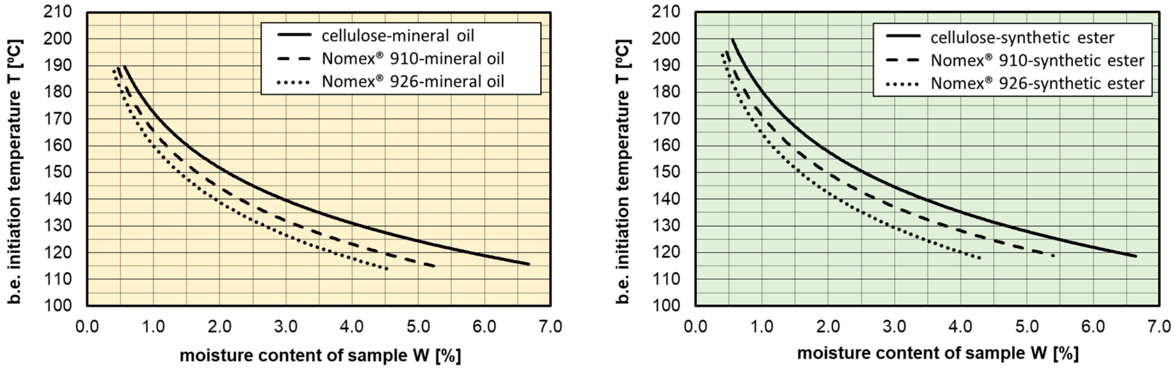
Sample Moisture [%]	B.e. Initiation Temperature for Cellulose in Oil [°C]	B.e. Initiation Temperature for Cellulose in Ester [°C]	Difference Between b.e. Initiation Temperature in Ester and Oil [°C]	Percentage Difference Between b.e. Initiation Temperature in Ester and Oil [%]
0.5	186.9	192.3	5.4	2.9
1.0	166.1	170.3	4.3	2.6
1.5	153.9	157.5	3.6	2.3
2.0	145.2	148.4	3.1	2.1
2.5	138.5	141.3	2.8	2.0
3.0	133.1	135.5	2.5	1.8
3.5	128.4	130.6	2.2	1.7
4.0	124.4	126.4	2.0	1.6
4.5	120.9	122.7	1.8	1.5
5.0	117.7	119.4	1.6	1.4
		Average:	2.9	2.0

Table 6. Comparison of b.e. initiation temperature of Nomex® 926 immersed in tested electro-insulating liquids obtained from measurement curves.

Sample Moisture [%]	B.e. Initiation Temperature for Cellulose in Oil [°C]	B.e. Initiation Temperature for Cellulose in Ester [°C]	Difference Between b.e. Initiation Temperature in Ester and Oil [°C]	Percentage Difference Between b.e. Initiation Temperature in Ester and Oil [%]
0.5	181.1	186.7	5.7	3.1
1.0	160.0	164.6	4.6	2.9
1.5	147.7	151.6	3.9	2.7
2.0	138.9	142.4	3.5	2.5
2.5	132.1	135.2	3.1	2.3
3.0	126.6	129.4	2.8	2.2
3.5	121.9	124.5	2.6	2.1
4.0	117.8	120.2	2.4	2.0
4.5	114.2	116.4	2.2	1.9
		Average:	3.4	2.4

5.3. Bubble Effect Initiation Temperature Comparison of Solid Materials

Figure 10 shows the results of the research on the bubble effect initiation temperature depending on the moisture content of the tested materials (cellulose paper, Nomex® 910 and Nomex® 926). Cellulose paper has the highest b.e. initiation temperature values, while high-temperature materials have lower values. Nomex® 910, since it consists of both ingredients, cellulose and aramid, shows an intermediate performance.



(**a**) (**b**)

Figure 10. Comparison of the bubble effect initiation temperature for cellulose (solid line), Nomex® 910 (dashed line) and Nomex® 926 (dotted line) immersed in mineral oil Orlen Trafo EN (**a**) and synthetic ester Midel 7131 (**b**).

In the range of the moisture content of the solid material between 0.5% to 4.5%, the difference between the average b.e. initiation temperature of cellulose compared to Nomex® 910 and Nomex® 926 is, respectively, 6.5 °C and 12.8 °C in mineral oil and 10.1 °C and 16.1 °C in ester.

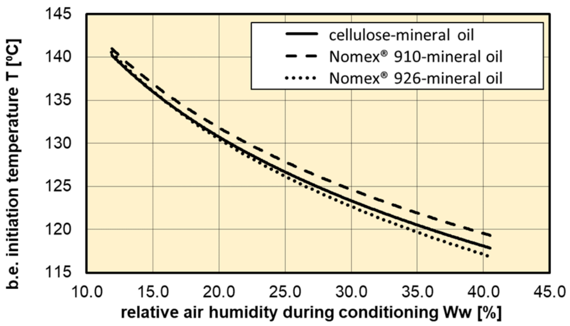
In addition, the assumption about the influence of the electric permittivity of the tested materials on their bubble initiation temperature was confirmed. The higher the electric permittivity value of material corresponds to a higher b.e. initiation temperature. Cellulose at a temperature of 25 °C has a relative electric permittivity of 3.3–4.1 in mineral oil, while aramid paper has 2.9 (Table 2).

The analysis of various solid materials in terms of their resistance to the occurrence of the dangerous phenomenon of bubbling is more complicated than it may seem. Particular attention should be paid to the fact that different insulation materials absorb water differently under the same conditions, as shown in Figure 4. Hence, a simple analysis of the b.e. initiation temperature values of various materials depending on their initial moisture content is useful, but may lead to wrong conclusions.

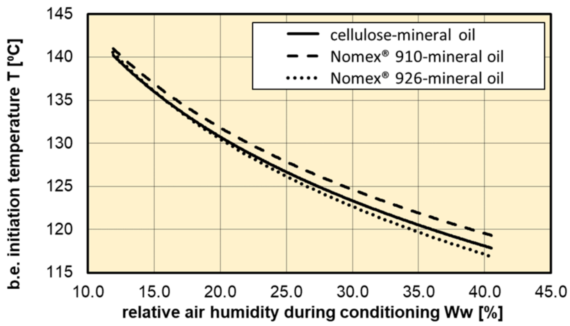
Figure 11 shows a comparison of the bubble effect initiation temperature depending on the relative air humidity in the climate chamber during the conditioning of materials at a temperature of 40 °C for selected solid materials.

The charts do not show the range of the lowest tested moisture contents and the highest bubble initiation temperatures, but indicate the effect of different moisture absorption in different insulating papers. The test results in Figure 11 are presented only for those measuring points that were conditioned at the same temperature, but with different values of relative air humidity. It should be noted that all the tested materials were characterized with similar values of the bubble initiation temperature. However, the Nomex® 910 material had a slightly higher b.e. initiation temperature, while Nomex® 926 had slightly lower values. Although, the observed differences in the range of 2–3 °C can be considered negligible from the perspective of application in an operating transformer.

The main conclusion from the presented results is the fact that despite much higher permissible operating temperatures of insulation systems composed of high-temperature aramid materials, the bubble initiation temperature is almost identical as for cellulose. It should be also noted that because aramid materials conditioned under the same relative humidity absorb less water than cellulosic materials, the bubble effect in these materials is less intense, which was also visually confirmed during the experiments. Figure 12 shows the comparison of b.e. intensity in the tested materials. Based on the figure, it can be concluded that the bubble effect is characterized by a similar intensity (the number and size of water vapor bubbles) for Kraft cellulose paper and Nomex® 910 materials. This can be explained by the fact that both materials contain cellulose. The Nomex® 926 aramid paper is characterized by a lower intensity of the bubble phenomenon, which is related to the lower amount of water absorbed by aramid materials (Figure 4).



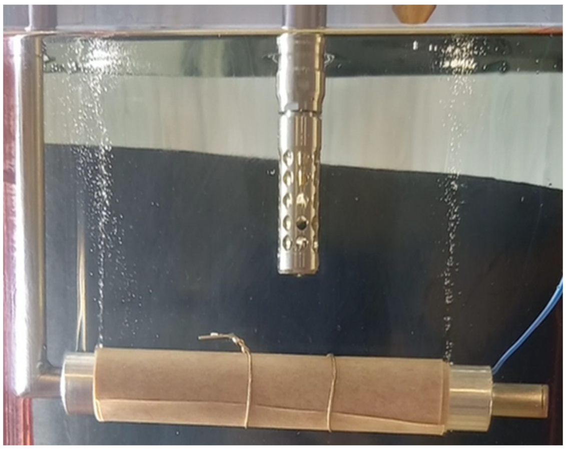
(**a**)



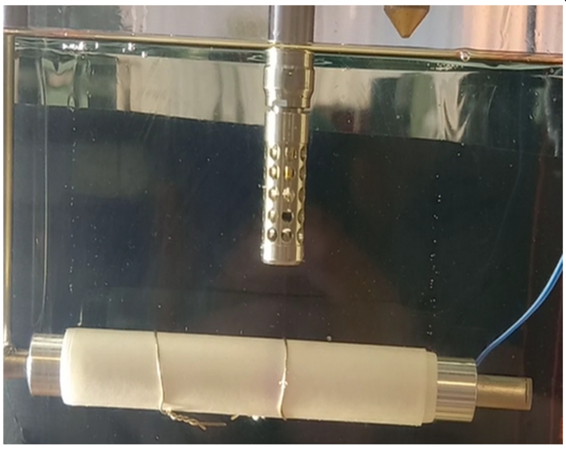
(**b**)

Figure 11. Comparison of the bubble effect initiation temperature depending on the relative air humidity in climate chamber during the conditioning of materials at a temperature of 40 °C for cellulose (solid line), Nomex® 910 (dashed line) and Nomex® 926 (dotted line) immersed in mineral oil Orlen Trafo EN (**a**) and synthetic ester Midel 7131 (**b**).

(**a**)



(**b**)



(**c**)

Figure 12. Intensity comparison of b.e. recorded for samples conditioned in air of the same relative humidity and at the same temperature. (**a**) Kraft cellulose paper, (**b**) Nomex® 910 and (**c**) Nomex® 926.

The reason why the bubble initiation temperature in Nomex® 910 material is higher can be explained by the fact that Nomex® 910 consists of both ingredients (cellulose and aramid). The water desorbed from the aramid fiber may be initially adsorbed by cellulose, which could have a significant impact on limiting the development of the bubbling phenomenon.

6. Conclusions

In recent years, modern insulation systems using alternative insulating liquids (e.g., synthetic esters) or alternative solid insulation (e.g., based on aramid) gained great popularity. Therefore, further research connected with the use of alternative dielectrics is extremely important.

The bubble effect is a dangerous phenomenon for the transformer's insulation system. Water desorbed from conductor insulation during the bubble effect can cause a breakdown in the insulation system and, as a consequence, failure of the transformer.

The bubble effect initiation temperature depends mainly on the moisture content of the solid insulation that makes up the insulation system but is slightly affected by the type of insulating liquid.

The main conclusions from this research can be found below.

(1) All the tested materials were characterized with similar values of the bubble initiation temperature. However, the Nomex® 910 material had a slightly higher b.e. initiation temperature, while Nomex® 926 had slightly lower values. Although, the observed differences in the range of 2–3 °C can be considered negligible from the perspective of application in an operating transformer.
(2) All tested materials have a slightly lower initiation temperature of the bubble phenomenon when they are immersed in mineral oil, and higher when immersed in synthetic ester.
(3) The difference in the temperature of the bubble effect initiation of the tested materials decreases with their relative humidity. Aramid-based materials obtain less moisture than cellulose-based materials, which partially eliminates the differences in the bubble effect initiation temperature.

In the future, the authors plan to investigate the impact of other parameters of solid and liquid insulation on the initiation temperature of the b.e. phenomenon (for example, polarity). The authors also plan to present the results of the analysis of the b.e. initiation temperature in high-temperature insulation systems in the context of their operating temperatures allowed by the standard [35].

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