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Evaluation of Thermal Properties of Various Insulating Liquids Used in Power Transformers

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Abstract: This article is a summary of many years of work by the author, in which the thermal properties of various types of insulating liquids, used in power transformers, were evaluated. Recently, esters have been displacing mineral oil. There is a common view that mineral oil has better thermal properties than esters. This claim is supported by comparative results of tests of both materials as a liquid only filling the remaining volume of the transformer. The effect of the type of liquid on the thermal properties of the paper–oil insulation has not been analyzed so far. On this basis, the conclusions formulated may be incomplete. For this reason, the author has analyzed the influence of the type of liquid on both the thermal properties of the liquid filling the remaining volume of the transformer and the paper–oil insulation. It was proved that the more effective liquid filling the remaining volume of the transformer was indeed mineral oil. On the other hand, a more effective electrical insulating liquid, which is an element of paper–oil insulation, is a natural ester. A comprehensive assessment that takes into account both the paper–oil insulation and the remaining transformer volume showed that the natural ester proved to be a slightly more effective electrical insulating liquid than the other analyzed liquids.

Keywords: power transformers; insulating liquids; thermal properties

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1. Introduction

Insulating liquids play many important roles in power transformers. Such liquids are primarily an insulating medium, which is why they are required to have high electrical resistivity, high electrical strength and a low value of the dielectric loss coefficient. Insulating liquids are also designed to reduce an electric arc and the intensity of partial discharges [1–5]. An important role of insulating liquids is the transfer of heat to the environment [6,7]. Such heat is generated primarily in the windings and transformer core [8–12].

Recently, natural and synthetic esters have been replacing mineral oil. This is due to environmental factors and occupational safety. Environmental factors should be understood as the high biodegradability of esters compared to mineral oil. Occupational safety is mainly related to flash and burn points, and the calorific value of the liquid. Esters have a higher flash and burn points temperature compared to oil by more than 100 °C [13–18].

Intensive work is currently underway to identify the different properties of esters. The insulating properties have been quite widely recognized in comparison with the thermal properties [19–23]. The author has published many papers on the thermal properties of various insulating liquids [24–29].

Insulating liquid is basically present in two places in transformers. Such a liquid is an element of the paper–oil insulation of transformer windings (solid material). It is therefore an element that impregnates paper. The second place where liquid occurs in a transformer is the remaining volume of the transformer (liquid).

In the case of solid materials, the thermal conductivity coefficient λ determines their thermal properties according to the following formula [24]:

$$\Delta T = \frac{q \cdot p}{\lambda} \quad (1)$$

where ΔT—temperature increase in the layer with a thickness of p [°C], q—heat load of the heating surface [$W \cdot m^{-2}$], p—layer thickness [m], and λ—thermal conductivity coefficient [$W \cdot m^{-1} \cdot K^{-1}$]. The higher the value of the λ coefficient, the smaller the value of the temperature increase ΔT. This means that the higher the value of the thermal conductivity coefficient, the more effectively the material dissipates heat to the environment.

In the case of fluids (gases, liquids), the thermal properties are determined by the heat transfer coefficient α [25]:

$$\Delta T = \frac{q}{\alpha} \quad (2)$$

where ΔT—temperature increase in the liquid [°C], q—heat load of the heating surface [$W \cdot m^{-2}$], and α—heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]. As in Formula (1), the higher the value of the α value, the lower the ΔT value, which means more efficient heat dissipation to the environment.

Therefore, when analyzing the thermal properties of a liquid as a material constituting an element of paper–oil insulation (solid material), attention should be paid to the thermal conductivity coefficient λ. On the other hand, in the case of the liquid filling the remaining volume of the transformer, the heat transfer coefficient α should be analyzed.

There are many research results in the literature showing that mineral oil has better thermal properties than esters [30–36]. This claim is supported by comparative results of tests of both materials as a liquid filling the remaining volume of the transformer. The effect of the type of liquid on the thermal properties of the paper–oil insulation has not been analyzed so far. On this basis, the conclusions formulated may be incomplete. For this reason, the author has analyzed the influence of the type of liquid on both the thermal properties of the liquid filling the remaining volume of the transformer and the paper–oil insulation.

The articles [30,31] prove the influence of the type of liquid (esters, oil) on selected thermal properties such as viscosity, density, specific heat and thermal conductivity. The paper [32] shows that the addition of nanoparticles changes the density, viscosity and thermal conductivity of oil and esters. The article [33] analyzed how the addition of esters slows down the aging process of mineral oil. The article [34] analyzed the effect of the type of liquid on the aging rate of cellulose paper. The article [35] investigated the effect of the oil-ester mixture on the reduction of the oxidation phenomenon as well as the flash and autoignition temperatures. The article [36] describes how the replacement of oil with esters slows down the aging process of the paper–oil insulation, which was indicated by the degree of cellulose polarization. As can be seen, the research is incomplete. Firstly, it is not possible to determine the heat transfer coefficient α of liquid on their basis. Secondly, the effect of the type of liquid on the thermal conductivity coefficient λ of the paper–oil insulation was not analyzed.

2. Theoretical Foundation

2.1. Scope of Tests of Thermal Conductivity Coefficient λ and Heat Transfer Coefficient α

In his research so far, the author has carried out measurements of the thermal conductivity coefficient λ in the case of paper–oil insulation impregnated with various liquids. Measurements of this coefficient were carried out depending on the type of liquid (mineral oil, natural ester, synthetic ester), type of paper (cellulose paper, aramid paper), paper moisture content (0 ÷ 7%) and temperature (25 ÷ 100 °C) [24].

The author studied the heat transfer coefficient α of insulating liquids also depending on various factors, such as the type of liquid (mineral oil, natural ester, synthetic ester), type of natural ester (standard, reduced viscosity), composition of the mixture (mineral oil—natural ester, mineral oil—synthetic ester, natural ester—synthetic ester), presence of nanoparticles (TiO_2), surface heat load q (1000, 2000, 3000 [$W \cdot m^{-2}$]), and the position of the heating element (vertical, horizontal) [25–28].

2.2. *Coefficient of Thermal Conductivity λ of Paper–Oil Insulation*

This section will describe the thermal conductivity coefficient λ of paper–oil insulation depending on the type of liquid, type of paper, moisture and temperature.

Figure 1 shows the values of the λ coefficient of paper–oil insulation depending on the type of impregnating liquid (mineral oil (a), synthetic ester (b), natural ester (c)). The highest value of thermal conductivity was measured for insulation impregnated with natural ester, followed by synthetic ester, and the lowest for mineral oil. The difference between the λ coefficient of the insulation impregnated with natural ester and the mineral oil ester was about 10%. This was true regardless of the temperature, the type of paper and the degree of moisture.

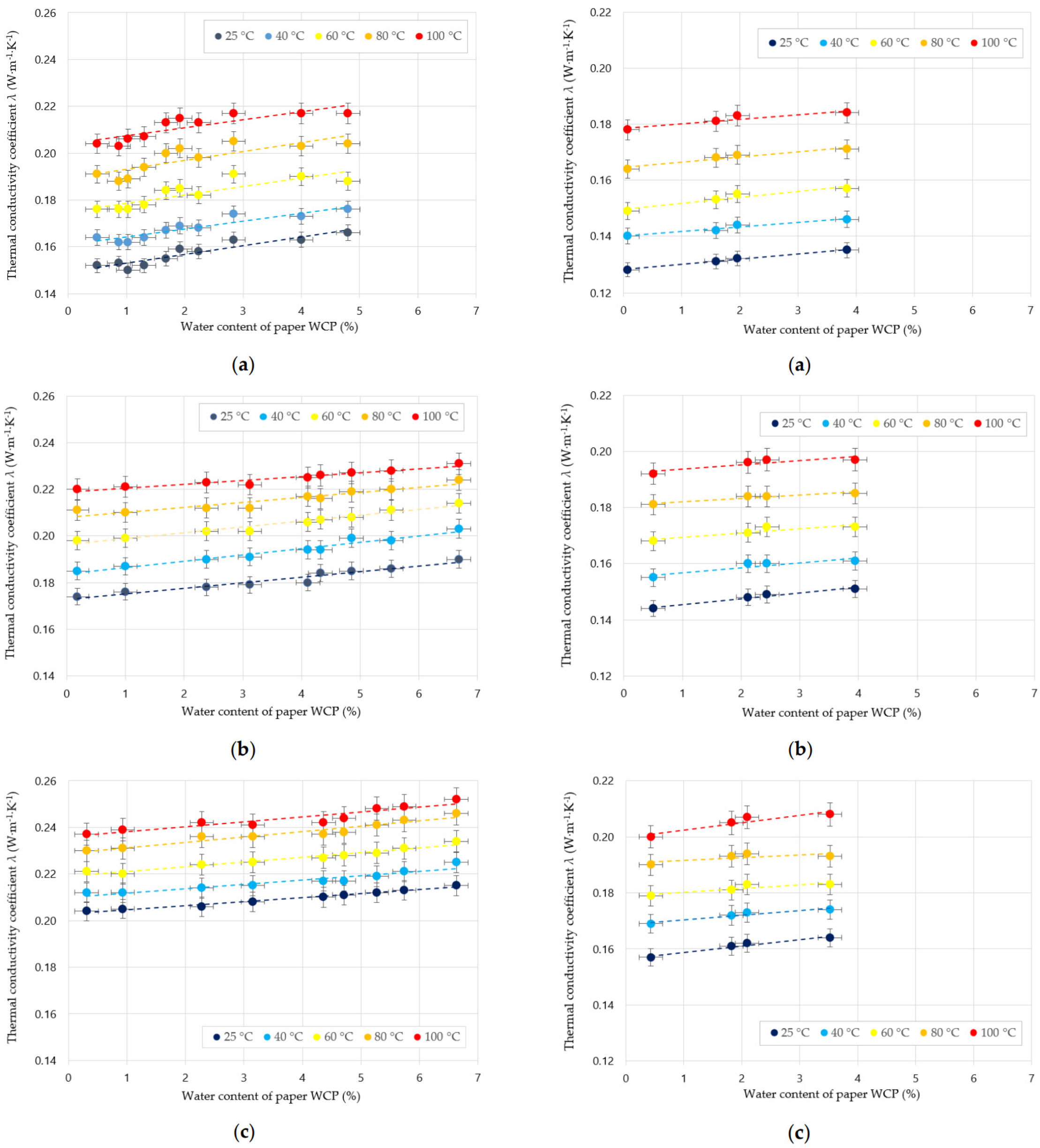

Figure 1. Thermal conductivity coefficient λ of cellulose paper (**left side**) and aramid paper (**right side**) insulation impregnated by different dielectric liquids as a function of water content of paper

WCP and temperature T; (**a**) insulation impregnated by mineral oil; (**b**) insulation impregnated by synthetic ester; (**c**) insulation impregnated by natural ester [24].

Figure 1 shows the thermal conductivity λ values of paper–oil insulation depending on the type of paper. Cellulose paper (left part of the figure) and aramid paper (right part of the drawing) were analyzed. Cellulose paper had a higher λ value compared to aramid paper. The difference in λ for both types of paper was about 20%. This phenomenon was observed regardless of the type of impregnating liquid, temperature and degree of moisture in the insulation.

As can be seen in Figure 1, as the temperature increases, the thermal conductivity coefficient of paper–oil insulation increases. An increase in temperature in the range of 25 °C to 100 °C resulted in an increase in the λ coefficient by about 20%. This is true regardless of the type of impregnating liquid, the type of paper and the moisture content of the paper–oil insulation. The increase in thermal conductivity, caused by the increase in temperature, is a very positive and desirable phenomenon. Higher thermal conductivity is desirable when high temperature is present.

On the basis of Figure 1, the influence of moisture in paper–oil insulation on its thermal conductivity was analyzed. The moisture content varied from 0% to less than 7% (for cellulose paper) and to about 3.5% (for aramid paper). The increase in moisture caused a significant increase in the λ coefficient by about 10%. This trend was observed regardless of the type of liquid, type of paper and temperature. The increase in the thermal conductivity of paper–oil insulation, caused by the increase in moisture, can be explained by the thermal conductivity of water. Unmoistened paper has a thermal conductivity of about 0.2 $W \cdot m^{-1} \cdot K^{-1}$, while water has a conductivity of about 0.6 $W \cdot m^{-1} \cdot K^{-1}$. Thus, an increase in the content of a substance with a higher conductivity (water) must have caused an increase in the thermal conductivity of paper, which has a thermal conductivity several times lower. The increase in thermal conductivity, caused by the increase in moisture, is a very positive phenomenon. An increase in moisture has many negative effects, including an increase in the dielectric loss coefficient, which causes the temperature to rise. Thus, the increase in thermal conductivity makes it easier to dissipate heat to the environment.

2.3. Heat Transfer Coefficient α of Insulating Liquids

This section presents the heat transfer coefficient α, an insulating liquid depending on the type of liquid, the type of natural ester, the composition of the mixture, the presence of TiO_2 nanoparticles, the surface heat load, and the position of the heating element.

Figure 2 shows the values of the heat transfer coefficient α depending on the type of insulating liquid, for different values of the surface heat load q. The analyzed liquids were mineral oil, natural ester with reduced viscosity, natural ester and synthetic ester. The highest value of the α coefficient was measured for mineral oil and the lowest for synthetic ester. The difference in the heat transfer coefficient α between mineral oil and synthetic ester was about 15%.

In Figure 2, the effect of the type of natural ester on the heat transfer coefficient α can be observed. As can be seen, the natural ester with reduced viscosity had a higher value of α compared to standard natural ester by about 10%. This phenomenon was observed regardless of the value of the surface heat load q.

Figure 2 shows the influence of the surface heat load q on the value of the heat transfer coefficient α of insulating liquids. As the heat load increases in the range of 1000 to 3000 $W \cdot m^{-2}$, the α coefficient increases by about 50%. This phenomenon can be observed regardless of the type of liquid. This is a very positive situation, because an increase in heat load is to be understood as an increase in temperature. The increase in the heat transfer coefficient α, caused by the increase in heat load, facilitates the release of heat to the environment.

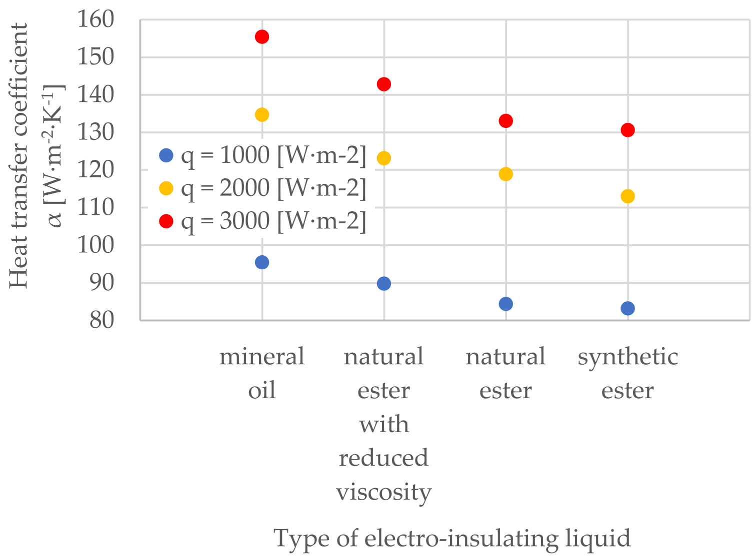

Figure 2. The heat transfer coefficient α as a function of the type of insulating liquid for various values of heat load of cooled surface q [25].

Figures 3–5 show the influence of the composition of the mixture of mineral oil—natural ester, mineral oil—synthetic ester and natural ester—synthetic ester on the heat transfer coefficient α.

Figure 3 shows the ratio α, the mineral oil-natural ester mixture. As can be seen, as the content of natural ester in the mixture increases, the heat transfer coefficient α practically decreases. It is true that for the content of natural ester equal to 5% there is a certain maximum of the α factor, but from a practical point of view it can be omitted. This is true regardless of the temperature value. The decrease in the α coefficient, which accompanies the increase in the content of natural ester, can be explained by the lower thermal conductivity coefficient of natural ester compared to mineral oil, as mentioned earlier.

Figure 4 shows the influence of the composition of the mineral oil-synthetic ester mixture on its heat transfer coefficient. As in Figure 3, an increase in synthetic ester results in a decrease in the α ratio of the mixture. The reason for this is the lower heat transfer coefficient α synthetic ester compared to mineral oil. This situation occurred regardless of the temperature value.

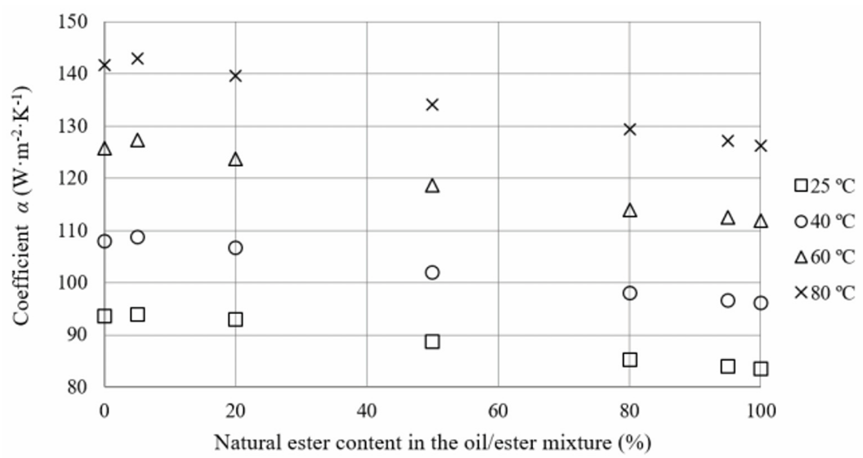

Figure 3. Heat transfer coefficient α of the mineral oil and natural ester mixture of [26].

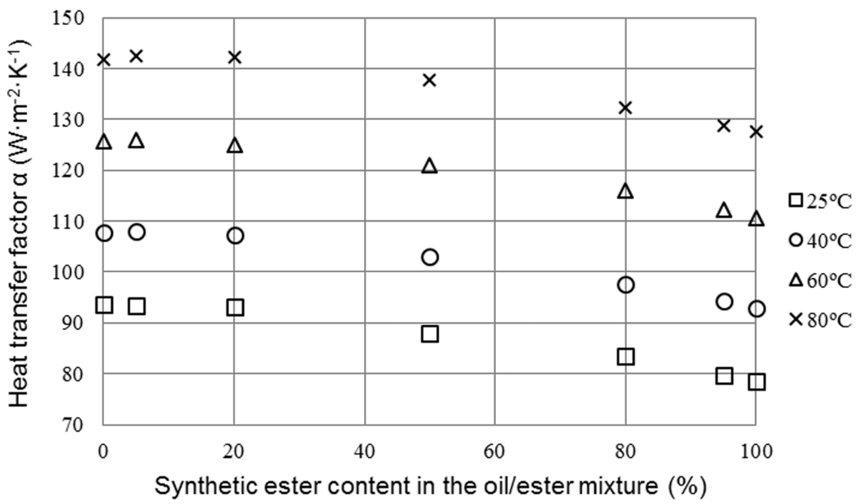

Figure 4. Heat transfer coefficient α of the mineral oil and synthetic ester mixture of [27].

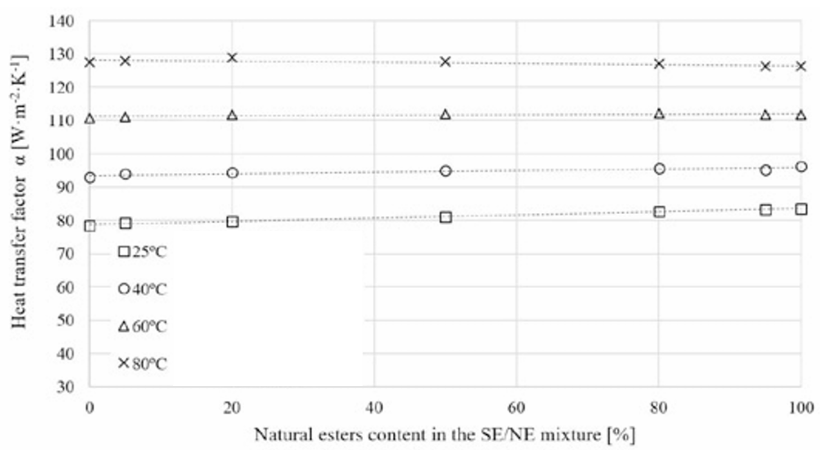

Figure 5. Heat transfer coefficient α of the mixture of natural ester and synthetic ester [28].

Figure 5, as well as Figures 3 and 4, shows the influence of the composition of the natural ester—synthetic ester mixture on the value of its α coefficient. With the increase in natural ester content, the heat transfer coefficient practically does not change. This is due to the approximate value of the α ratio of both types of esters. This phenomenon was independent of temperature values.

Table 1 presents the measurements results of the heat transfer coefficient α of synthetic ester doped with TiO_2 nanoparticles, depending on temperature. As can be seen, the addition of TiO_2 increases the α rate by only 1 ÷ 2%. Thus, the addition of nanoparticles to insulating liquids to improve other properties does not significantly change their thermal properties.

Table 1. Heat transfer coefficient α of pure synthetic ester (SE), synthetic ester admixed by a surface-active substance SPAN 20 (SE + SPAN 20), and synthetic ester admixed by SPAN 20 and TiO_2 (SE + SPAN 20 + TiO_2) as a function of temperature [29].

Temperature	SE	SE + SPAN 20	SE + SPAN 20 + TiO_2
25 °C	83.41	83.54	85.61
40 °C	98.44	98.78	100.24
60 °C	116.84	115.98	118.33
80 °C	134.13	134.39	135.95

Figure 6 shows the heat transfer coefficient α of different insulating liquids depending on the position of the heat source, for a surface heat load of 3000 $W \cdot m^{-2} \cdot K^{-1}$. As can be seen, regardless of the type of liquid, a horizontal position was characterized by a higher α ratio of about 30% compared to a vertical position. To explain the differences of coefficient α for vertical and horizontal positions of the heat source, it is necessary to study the path along which the heat source heats the liquid. In a horizontal position, the liquid heats up relatively quickly over a short path that is equal to half the circumference of the heat source. For a vertical position, the length of the path along which the liquid heats up is longer, equal to the length of the heat source. This is a reason why heat transfer is less efficient in a vertical position than in a horizontal position.

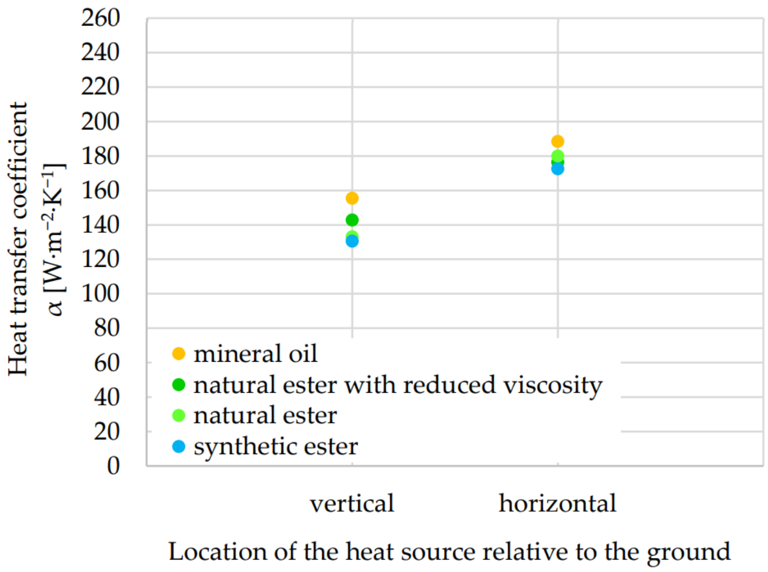

Figure 6. The heat transfer coefficient α, as a function of the position of the heat source, with various types of insulating liquids, surface heat load q = 3000 $W \cdot m^{-2}$ [25].

2.4. Summary

The thermal properties of insulating liquids depend on many factors. In the case of liquids constituting the paper–oil insulation, a significant influence of the type of liquid, type of paper, moisture and temperature on the thermal conductivity of coefficient λ was observed. In the case of the liquid filling the remaining volume of the transformer, there is also a large influence from the type of liquid, the type of natural ester, the composition of the mixture, the surface heat load and the position of the heating element on heat transfer coefficient α.

By analyzing various insulating liquids that are part of paper–oil insulation, it turned out that the natural ester is the most effective at releasing heat to the environment. However, in the case of the liquid that fills the remaining volume of the transformer, it was the mineral oil, not the natural ester, that turned out to be the liquid that most favorably affected the transformer's cooling system. Thus, from the point of view of thermal properties, the selection of the optimal liquid turns out to be quite a complicated task.

3. Introduction to Results and Discussion

The next section presents the results of the calculation of temperature rise simultaneously in the paper–oil insulation and in the remaining volume of the transformer for all three analyzed liquids. These calculations were based on the values of thermal properties of the liquid, which were measured by the author. In this way, it was possible to select one liquid that has the most favorable thermal properties, both as a liquid impregnating the paper–oil insulation and as a liquid that fills the remaining volume of the transformer.

The results of the calculation of the temperature rise ΔT are presented at the places of the transformer where the insulating liquid is located. Such increments occur:

- In paper–oil insulation ΔT_{paper};
- In an insulating liquid, in the remaining volume of transformer, near paper–oil insulation $\Delta T_{paper\text{-}liquid}$;
- In the insulating liquid, in the remaining volume of transformer, near the transformer tank $\Delta T_{liquid\text{-}tank}$.

The total temperature rise ΔT_{total} in the elements, where the insulating liquid is present, will therefore be the sum of all the increments mentioned earlier, according to the following formula:

$$\Delta T_{total} = \Delta T_{paper} + \Delta T_{paper\text{-}liquid} + \Delta T_{liquid\text{-}tank} \quad (3)$$

Given that the temperature increases of $\Delta T_{paper\text{-}liquid}$ and $\Delta T_{liquid\text{-}tank}$ occur in the liquid, Formula (3) can be simplified to:

$$\Delta T_{total} = \Delta T_{paper} + \Delta T_{liquid} \quad (4)$$

The temperature increase ΔT_{paper} occurs in the solid material, so it will be determined by Formula (1). On the other hand, the $\Delta T_{paper\text{-}liquid}$ and $\Delta T_{liquid\text{-}tank}$ increments are present in the liquid. Thus, their values will be determined on the basis of Formula (2). For calculation purposes, it is assumed that:

- The thickness of the paper–oil insulation p is equal to 1.5 mm;
- The moisture content of the paper–oil insulation is equal to about 1%;
- The temperature, on the basis of which the thermal conductivity coefficient λ of the paper–oil insulation in Figure 1 was selected, is equal to 100 °C;
- The surface heat load, which was used to determine the ΔT_{paper} value, is equal to 3000 $W \cdot m^{-2}$;
- The surface heat load q, on the basis of which the heat transfer coefficient α of the liquid near the paper–oil insulation from Figure 2 was selected, and which was adopted for the determination of the $\Delta T_{paper\text{-}liquid}$ value, is equal to 3000 $W \cdot m^{-2}$;
- Surface heat load q, on the basis of which the heat transfer coefficient α of the liquid near the transformer tank from Figure 2 was selected, and which was used to determine the value of $\Delta T_{liquid\text{-}tank}$, is equal to 1000 $W \cdot m^{-2}$.

4. Results

Table 2 shows the results of the calculations of the temperature rise ΔT at the transformer sites referred to in Section 3: ΔT_{paper}, $\Delta T_{paper\text{-}liquid}$, $\Delta T_{liquid\text{-}tank}$ and ΔT_{total}.

Table 2. Temperature rises ΔT_{paper} (cellulose paper, aramid paper), $\Delta T_{paper\text{-}liquid}$, and $\Delta T_{liquid\text{-}tank}$ for different types of insulating liquids.

Insulating Liquid	ΔT_{paper}	$\Delta T_{paper\text{-}liquid}$	$\Delta T_{liquid\text{-}tank}$	$\Delta T_{liquid} = \Delta T_{paper\text{-}liquid} + \Delta T_{liquid\text{-}tank}$	ΔT_{total}
Cellulose paper					
mineral oil	21.7	15.9	7.7	23.6	45.3
synthetic ester	20.4	17.4	8.9	26.3	46.7
natural ester	18.8	16.7	7.8	24.5	43.3
Aramid paper					
mineral oil	24.9	15.9	7.7	23.6	48.4
synthetic ester	23.4	17.4	8.9	26.3	49.8
natural ester	22.5	16.7	7.8	24.5	47.0

The smallest temperature rise ΔT_{paper} in insulation was observed for natural ester. This means that the natural ester is the most effective impregnating liquid, taking into account the thermal properties. This fact was observed for both cellulose paper (18.8 °C) and aramid paper (22.5 °C). For the other impregnating liquids, the temperature increases in the paper insulation were higher by about 1.5 °C for synthetic ester and by about 2.5 °C for mineral oil.

The smallest temperature increase in the ΔT_{liquid} filling the remaining volume of the transformer was observed for mineral oil (23.6 °C). Higher increments were observed for natural ester (about 1.0 °C more) and for synthetic ester (about 3.0 °C more). It follows that mineral oil is the most advantageous insulating liquid, filling the remaining volume of the transformer, from the point of view of thermal properties.

Taking into account both the paper insulation and the remaining volume of the transformer, the smallest temperature rise ΔT_{total} was observed for natural ester (43.3 °C for cellulose paper, 47.0 °C for aramid paper), followed by mineral oil (about 1.5 ÷ 2.0 °C more) and synthetic ester (about 3.0 °C more). It follows that the most effective insulating liquid, constituting the element of paper insulation and filling the remaining volume of the transformer, is the natural ester, followed by mineral oil, and the least effective is the synthetic ester. This fact was observed for both cellulose and aramid paper.

5. Discussion

The results of the research described in Section 3 are quite puzzling. A question may be asked why, in the case of paper insulation, the most effective liquid turned out to be the natural ester, and in the case of the remaining volume of the transformer—mineral oil. In order to answer this question, it is necessary to analyze what factors affect the temperature increase in paper insulation, which is a solid material, and what factors affect the temperature increase in the remaining volume of the transformer, which is filled with liquid.

In Section 1, it is stated that the temperature increase in a solid material, which is paper–oil insulation, is determined by the thermal conductivity coefficient λ. This property is a material feature. It describes the ability of a material to dissipate heat through thermal conductivity, which is the predominant mode of heat dissipation in solid materials.

On the other hand, the temperature increase in liquids depends on the heat transfer coefficient α. This property describes the ability of a given liquid to dissipate heat through both thermal conductivity and convection. This type of heat dissipation is characteristic of fluids (liquids, gases). This property is the resultant of many properties of a given liquid, which include:

- Thermal conductivity coefficient λ;
- Specific heat c_p;
- Kinematic viscosity υ;
- Thermal expansion coefficient β;
- Density ρ.

The relationship between the heat transfer coefficient α and the properties on which this coefficient depends is described by the following formula [25]:

$$\alpha = c \cdot \lambda^{1-n} \cdot g^{n} \cdot \delta^{3n-1} \cdot \beta^{n} \cdot \Delta T^{n} \cdot \rho^{n} \cdot c_p^{n} \cdot \upsilon^{-n} \tag{5}$$

where c, n—geometrical constants, g—gravity [$m \cdot s^{-2}$], δ—characteristic dimension usually denoting the length of the heating element [m], β—coefficient of thermal expansion [K^{-1}], ρ—density [$kg \cdot m^{-3}$], c_p—specific heat [$J \cdot kg^{-1} \cdot K^{-1}$], and υ—kinematic viscosity [$mm^2 \cdot s^{-1}$].

The numbers n and c depend on the product of Grashof (Gr) and Prandtl (Pr), i.e., the type of flow, as shown in Table 3. The values of n are in the range of 0 to 0.333, so they are positive and below the value of 1.

Table 3. Values of geometric constants c and n [37].

Nature of the Flow	Gr·Pr	c	n
no flow	$<10^{-3}$	0.45	0
laminar flow	$10^{-3} \div 5 \times 10^{2}$	1.18	0.125
transitional flow	$5 \times 10^{-3} \div 2 \times 10^{7}$	0.54	0.250
turbulent flow	$>2 \times 10^{7}$	0.14	0.333

On the basis of knowing the value of the constant n from Table 3, it can be concluded that the exponents of all expressions of the right-hand side of Formula (5) will always be positive, except for the kinematic viscosity υ. This means that an increase in material properties such as specific heat c_p, thermal conductivity coefficient λ, coefficient of thermal expansion β and density ρ will result in an increase in the heat transfer coefficient α. On the other hand, an increase in the viscosity υ will result in a decrease in the value of the α coefficient.

Table 4 shows the values of the thermal properties of mineral oil, synthetic ester and mineral ester at different temperatures. These properties are the coefficient of thermal conductivity λ, the specific heat c_p, the viscosity υ, the density ρ and the coefficient of thermal expansion β. The data presented in Table 4 are the results of the author's measurements.

Table 4. Thermal properties of different pure insulation liquids for various temperatures [29].

	25 °C	**40 °C**	**60 °C**	**80 °C**
Thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$]				
mineral oil	0.133	0.130	0.128	0.126
synthetic ester	0.158	0.156	0.153	0.151
natural ester	0.182	0.180	0.178	0.175
specific heat c_p [$J \cdot kg^{-1} \cdot K^{-1}$]				
mineral oil	1902	1974	2077	2187
synthetic ester	1905	1964	2052	2149
natural ester	2028	2082	2166	2259
kinematic viscosity υ [$mm^2 \cdot s^{-1}$]				
mineral oil	17.1	9.6	5.4	3.4
synthetic ester	55.1	28.3	14.0	8.1
natural ester	56.3	32.7	18.3	11.5
density ρ [$kg \cdot m^{-3}$]				
mineral oil	867	857	845	832
synthetic ester	964	953	940	926
natural ester	917	908	892	880
thermal expansion coefficient β [K^{-1}]				
mineral oil	0.00075	0.00076	0.00078	0.00080
synthetic ester	0.00076	0.00077	0.00078	0.00079
natural ester	0.00074	0.00076	0.00078	0.00080

The natural ester has about 40% higher thermal conductivity λ compared to the conductivity of mineral oil, regardless of temperature. This is probably the reason why paper insulation impregnated with natural ester has a higher thermal conductivity (by about 10%) than paper impregnated with mineral oil, as mentioned in Section 2.2.

When analyzing the heat transfer coefficient α of insulating liquids, it is necessary to study all the material properties listed in Table 4. As mentioned earlier, the thermal conductivity λ of natural ester is about 40% higher than that of mineral oil. This has a positive effect on the α ratio of natural ester. The specific heat c_p of natural ester is about 5% higher than the specific heat of mineral oil, regardless of temperature. This fact also has a positive effect on the heat transfer coefficient α of natural ester. The density ρ of natural ester is also about 5% higher than that of mineral oil, regardless of temperature, which has a positive effect on the α ratio of natural ester. Thermal expansion coefficient β of natural ester and mineral oil have practically comparable values. Thus, this coefficient does not affect the differences in the heat transfer coefficient α of the compared liquids. The kinematic viscosity of natural ester υ is more than 200% higher than that of mineral oil, regardless of temperature. This fact significantly affects the advantage of the heat transfer coefficient α of mineral oil.

Comparing the natural ester and mineral oil, it turned out that the values of the three thermal properties (thermal conductivity coefficient λ, specific heat c_p, and density ρ) had a more favorable effect on the heat transfer coefficient α of the natural ester. However, the viscosity υ of the natural ester was more than 200% higher than the density of mineral oil, resulting in a higher α factor of mineral oil compared to the natural ester by about 15%, as mentioned in Section 2.3. The kinematic viscosity υ turned out to be a thermal property that had a key impact on the heat transfer coefficient α of the analyzed liquids.

6. Conclusions

Comparing the thermal properties of insulating liquids, it turned out that the natural ester was the most beneficial liquid impregnating paper insulation. This is due to the high thermal conductivity coefficient λ of the natural ester compared to the conductivity of other liquids.

Analyzing the thermal properties of insulating liquids, it turned out that mineral oil was the most beneficial liquid filling the remaining volume of the transformer. This is mainly due to the several-fold lower viscosity υ of the oil compared to the viscosity of other liquids.

Taking into account the temperature increases both in the paper–oil insulation and in the remaining volume of the transformer, it should be stated that the natural ester turned out to be the most advantageous insulating liquid, followed by mineral oil, and the least favorable liquid was the synthetic ester.

An electrical insulating liquid can have different thermal properties. This depends on whether the liquid being assessed is as a paper–oil insulation impregnating liquid or as a liquid filling the remaining transformer volume.

Therefore, when designing or modifying a transformer cooling system filled with esters, not mineral oil, it is necessary to take into account not only the heat flow in the insulating liquid filling the remaining volume of the transformer, but also in the paper–oil insulation. This will allow for a more accurate estimation of the temperature in the hottest areas of the transformer.

From a theoretical point of view, the best solution would be to use a natural ester in the case of paper–oil insulation, and have mineral oil filling the remaining volume of the transformer. Such a solution would be characterized by the most effective cooling systeheat transfer to the environment. For now, the implementation of such a solution is practically impossible.

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