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THERMAL PROPERTIES OF NATURAL ESTER AND LOW VISCOSITY NATURAL ESTER IN THE ASPECT OF THE RELIABLE OPERATION OF THE TRANSFORMER COOLING SYSTEM

WŁAŚCIWOŚCI CIEPLNE ESTRU NATURALNEGO I ESTRU NATURALNEGO O OBNIŻONEJ LEPKOŚCI W ASPEKcie NIEZAWODNOŚCI DZIAŁANIA UKŁADU CHŁODZENIA TRANSFORMATORA

The paper presents the results of comparative studies of thermal properties of various types of natural esters used as electro-insulating liquids in transformers. Adequate thermal properties of electro-insulating liquids ensure reliable work of transformers. Two natural esters were selected for the study – one commonly used in distribution transformers, the other characterized by low viscosity. Fourier Transform Infrared Spectroscopy and UV-Visible spectroscopy were used to examine the chemical structure of the examined esters. Properties such as thermal conductivity coefficient λ , kinematic viscosity ν , specific heat c_p , density ρ , and thermal expansion coefficient β were analyzed. Heat transfer factor α of the liquid was calculated on the basis of obtained properties. This factor defines the ability of an insulating liquid to heat transport in the transformer, thus determining its reliability. The authors put forward a thesis that a low viscosity natural ester will have a higher heat transfer factor α due to its low viscosity, which affects the factor α . The analysis of thermal properties was carried out for the following temperatures: 25, 40, 60, and 80°C. On the basis of the calculated factor α , the temperature drops in the transformer filled with the analyzed types of natural esters were determined. It has been shown that if a low viscosity natural ester is used in the cooling system of the transformer, the temperature of the hot-spot will be lower. This fact may contribute to more reliable work of transformers and extend its service life.

Keywords: natural ester, dielectrics, power transformer, thermal properties.

W pracy przedstawiono wyniki badań porównawczych właściwości cieplnych różnego rodzaju estrów naturalnych stosowanych jako cieczy elektroizolacyjne w transformatorach. Odpowiednie właściwości cieplne cieczy elektroizolacyjnych zapewniają niezawodną pracę transformatorów. Do badań wybrano dwa estry naturalne – jeden powszechnie stosowany w transformatorach rozdzielczych, drugi charakteryzujący się obniżoną lepkością. Do analizy struktury chemicznej badanych estrów wykorzystano spektroskopię w podczerwieni z transformacją Fouriera (FT-IR) oraz spektroskopię w ultrafiolecie i świetle widzialnym (UV-VIS). Analizowanymi właściwościami cieczy były przewodność cieplna λ , lepkość kinematyczna ν , ciepło właściwe c_p , gęstość ρ oraz rozszerzalność cieplna β . Na podstawie przedstawionych właściwości cieplnych obliczono współczynnik przejmowania ciepła α . Współczynnik ten określa zdolność cieczy elektroizolacyjnej do transportu ciepła w transformatorze, a tym samym określa jego niezawodność. Autorzy postawili tezę, że ester naturalny o obniżonej lepkości będzie miał wyższy współczynnik przejmowania ciepła α ze względu na jego obniżoną lepkość. Analizę właściwości cieplnych przeprowadzono dla czterech wartości temperatury: 25, 40, 60 i 80°C. Na podstawie obliczonego współczynnika α określono spadki temperatury w transformatorze wypełnionym analizowanymi estrami naturalnymi. Wykazano, że jeżeli w układzie chłodzenia transformatora stosowany jest ester naturalny o obniżonej lepkości, wówczas temperatura najgorętszego miejsca (ang. hot spot) będzie niższa. Fakt ten może przyczynić się do zwiększenia niezawodności pracy transformatorów i przedłużyć okres ich eksploatacji.

Słowa kluczowe: ester naturalny, dielektryki, transformator, właściwości cieplne.

1. Introduction

The beginning of the 21st century brought significant changes in transmission power grids. Performance requirements of electrical power equipment, including transformers, have also increased [5]. More and more stringent standards and regulations force transformer manufacturers to look for innovative solutions to fulfil them. At the same time, it should be noted that energy consumption in areas characterized by high population density (which increases from year to year) is constantly growing. Therefore, in addition to the use of dis-

tribution networks that are harmless to the environment and people, safe transformers are also required. As reported in numerous literature sources, even today large transformers, whose power exceeds several hundred MVA, should be integrated with large residential buildings. Therefore, issues such as fire safety and environmental protection are of particular importance [1, 35].

Fire safety is directly related to the exploitation of the transformer. It is estimated that the risk of transformer fires is low but not negligible. However, in the event of a fire, the consequences are very serious. This applies first of all to transformers filled with insulating

liquids, which are located in urban areas characterized by a large concentration of population, as well as located near water reservoirs and landscape parks. Therefore, in addition to the appropriate electrical parameters to be met by the transformer, the environmental and fire properties of the used insulating liquid should also be taken into account [9, 11].

Limitation of soil and water contamination in the event of a transformer failure can be reduced by using environmentally friendly electro-insulating liquids. Currently, most of the working transformers are filled with mineral oil. Recently, however, an increase in interest in liquids alternative to mineral oil, including natural esters, can be observed [30, 38]. These liquids are already used not only in distribution transformers but also in transmission transformers [23, 33]. It is worth noting that the first transformers designed at the end of the 19th century were filled with natural esters (vegetable oils). The increased interest in vegetable oils, in the context of their application in electrical power equipment, results directly from their properties. In contrast to mineral oil, these liquids exhibit a number of features that in the context of environmental protection are considered their main advantages. These are primarily high biodegradability [8, 15], low toxicity [8, 41] and properties that directly translate into fire safety – high fire point and flash point [11, 28, 29, 36].

In addition to the above-mentioned properties of insulating liquids, one of their key tasks, in addition to providing adequate electrical insulation, is the cooling of the transformer. Due to the fact that the electro-insulating liquid constitutes the largest volume element of the transformer cooling system, it mainly determines the effectiveness of its cooling [25]. In the case of electro-insulating liquids, the cooling effect is related to the heat transfer effect of the liquid and is determined on the basis of the heat transfer factor α . In turn, this factor depends to a large extent on the thermal properties of liquids, which include thermal conductivity λ , kinematic viscosity ν , specific heat c_p , density ρ , and thermal expansion coefficient β [13, 32]. Therefore, the temperature in the transformer to a large extent will depend on the properties of the used electro-insulating liquid.

A high temperature is the main factor that contributes to the acceleration of aging processes in the transformer insulation system. Each temperature which rises above the limit value, apart from the acceleration of aging processes, also entails a number of other negative effects such as increased gas emission [7, 22, 40] or deterioration of thermal and dielectric properties [10, 24, 31]. It can also contribute to the danger both for the device itself, as well as for operating personnel and the environment. In the past, failure of transformers has often been the cause of their fire and destruction. As a result, in addition to significant material losses associated with the loss of property and possibility of using energy, there was also contamination of soil and water [6, 9, 26].

This paper presents the results of research on thermal properties of vegetable oils used as an electro-insulating medium in transformers. Two popular natural esters, one of which is widely used in distribution transformers, and the other with low viscosity, have been compared in terms of transformer cooling capacity. The results of the research and their discussion are presented in the following chapters.

2. Purpose, range, methodology, and investigated objects

2.1. Purpose and range of the work

Comparison of the heat transport capacity of popular vegetable oils used as an electro-insulating medium in transformers was the purpose of this work. The scope of work included measurements of thermal properties of the analyzed insulating liquids depending on the temperature. Thermal properties such as thermal conductivity λ , kinematic viscosity ν , specific heat c_p , density ρ , and thermal expansion

coefficient β were studied. Measurements of thermal properties of the tested vegetable oils for temperature 25, 40, 60, and 80°C were carried out. On the basis of the measured thermal properties, according to the formula (1), the heat transfer factor α by the analyzed electro-insulating liquids was calculated [12, 13]:

$$\alpha = \sqrt[n+1]{c \cdot \lambda^{1-n} \cdot g^n \cdot \delta^{3n-1} \cdot \beta^n \cdot \rho^n \cdot c_p^n \cdot \nu^{-n} \cdot q^n} \quad (1)$$

where: α – heat transfer factor [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$], n , c – constants dependent on the flow character, temperature and geometry, λ – thermal conductivity coefficient [$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$], g – gravity [$\text{m} \cdot \text{s}^{-2}$], δ – characteristic dimension [m], β – thermal expansion [K^{-1}], ρ – density [$\text{g} \cdot \text{l}^{-1}$], c_p – specific heat [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$], ν – kinematic viscosity [$\text{mm}^2 \cdot \text{s}^{-1}$], q – surface thermal load [$\text{W} \cdot \text{m}^{-2}$].

The above formula shows that the increase in thermal conductivity, density, specific heat, and thermal expansion coefficient will result in an increase in the heat transfer factor α . In turn, the increase in kinematic viscosity will cause a decrease in the factor α .

2.2. Methodology

The thermal conductivity of the tested vegetable oils was measured using a measuring system designed and built by the authors, described in the article [14]. In turn, the kinematic viscosity of the tested liquids was determined using Ubbelohde viscometers in accordance with the standard [20]. The density of both esters was determined based on the standard [21]. In turn, the thermal expansion coefficient was measured in accordance with the standard [2].

Due to the fact that the authors did not have the measurement system described in the standard [3], the specific heat of the tested vegetable oils was determined using the Mettler Toledo DSC1 differential scanning calorimeter (Figure 1). The measurement of specific heat consisted in determining the heat flux transmitted during heating to the sample of the test liquid, which was placed in an aluminium crucible, and the heat flux transmitted to the reference sample (empty crucible). Prior to the measurements, a temperature program defining the course of the measurement procedure was defined. It is important that in the temperature range in which the measurement is performed, the test sample is thermally stable; i.e. there are no changes in it. This action causes that the sample temperature of the tested liquid changes in the same way as the temperature of the reference sample – according to the adopted temperature program. In order to properly determine the specific heat of the tested vegetable oils at the initial temperature (25°C) and final temperature (80°C) it was found that the measurement of the stream of heat transmit to them should start at 5°C and end at 105°C. In the first stage of the temperature program implementation, the tested vegetable oils were cooled to 5°C and maintained at this temperature for 5 minutes. Then they were heated at a speed of 5°C per minute to 105°C. In the last step of measurement of the sample was maintained at 105°C for 5 minutes.

Specific heat was measured under an inert gas atmosphere (argon 50 ml·min⁻¹) at a heating rate of 10°C·min⁻¹. The mass of an oil sample was about 35 mg. All specific heat measurements were blank curve corrected. The measurements of blank curves were performed before the sample measurements. Then, in accordance with the previously established procedure, measurements of samples of the tested liquid were performed.

In the last step, on the basis of the dependence of the thermal flux transmitted to the liquid sample on the temperature, using the Mettler STARe Evaluation program, the specific heat of the tested vegetable oils was determined. The specific heat was determined based on the dependence:



Fig. 1. Differential scanning calorimeter Mettler Toledo DSC 1

$$c_p = \frac{dH}{dt} \cdot \frac{dt}{\beta_s} \cdot \frac{1}{m_s} \quad (2)$$

where: dH/dt – heat flux [$W \cdot s^{-1}$], β_s – sample heating speed (dT_s/dt) [$K \cdot s^{-1}$], m_s – sample weight [kg].

Fourier Transform Infrared Spectroscopy was used to examine the chemical structure of the examined esters. The IR spectra were recorded on a Nexus Nicolet model 5700 FTIR (Thermo Electron Scientific Instruments Corporation, USA) spectrometer in the $400\text{--}4000\text{ cm}^{-1}$ range (at room temperature) with a spectral resolution 4 cm^{-1} . The samples of oils were taken from hermetically sealed containers right after their opening and were scanned in the form of thin films between KBr plates.

The UV-VIS spectra were recorded on a Jasco V-530 apparatus in the $200\text{--}1000\text{ cm}^{-1}$ range (at room temperature). For investigations, the solutions of natural esters in heptane were prepared by dissolving 2 mg of sample in 5.5 ml of solvent. Measurements were carried out in disposable cuvettes.

2.3. Investigated objects

Two different commercial electro-insulating liquids were tested during the experiment. Both tested esters have the same plant origin,

Table 1. Some physicochemical and dielectric properties of used natural esters [8, 39, 43]

Property	Natural ester 1 (NE 1)	Natural ester 2 (NE 2)
Density at 20°C [$\text{kg} \cdot \text{m}^{-3}$]	920	890
Kinematic viscosity at 0°C [$\text{mm}^2 \cdot \text{s}^{-1}$]	207	84
Kinematic viscosity at 40°C [$\text{mm}^2 \cdot \text{s}^{-1}$]	36	17
Kinematic viscosity at 100°C [$\text{mm}^2 \cdot \text{s}^{-1}$]	8	4.6
Pour point [$^\circ\text{C}$]	-21	-28
Flash point [$^\circ\text{C}$]	330	200
Fire point [$^\circ\text{C}$]	360	270
Permittivity at 20°C	3.2	2.8
Dissipation factor at 90°C and 50 Hz	0.02	0.04
Breakdown strength IEC 60156 2.5 mm [kV]	73	70
Biodegradability	Readily biodegradable	Readily biodegradable

however, they differ in basic parameters. The first of the analyzed natural esters (natural ester NE 1) is widely used in distribution transformers. Its structure is based on a glycerol backbone, to which three naturally occurring groups of fatty acids are attached. It was developed from vegetable oils and additives that increase its efficiency [8]. The second of the tested natural esters (natural ester NE 2) is characterized by low viscosity. Like other vegetable oils, its structure is based on triglycerides, but as a result of the chemical modification, their content is lower. In this ester, the ratio of triglycerides to monoesters is about 50%/50% [39]. Data concerning the fundamental physicochemical and dielectric properties of the tested electro-insulating liquids are presented in Table 1.

3. Results

3.1. Fourier transform infrared spectroscopy FT-IR

Investigated vegetable oils are natural esters, i.e. triglycerides – fatty acid esters, containing a mixture of saturated and unsaturated fatty acids with different carbon length chains containing one to three double bonds. Therefore, their infrared absorption spectra should differ. On Figure 2 IR spectra of investigated vegetable oils are presented. Comparison of these two spectra revealed that there are no substantial differences between them if we took under consideration the main absorption bands. We can observe slight differences in the intensity of some bands as well as some shifts in their position. The main difference is observed in the so-called fingerprint

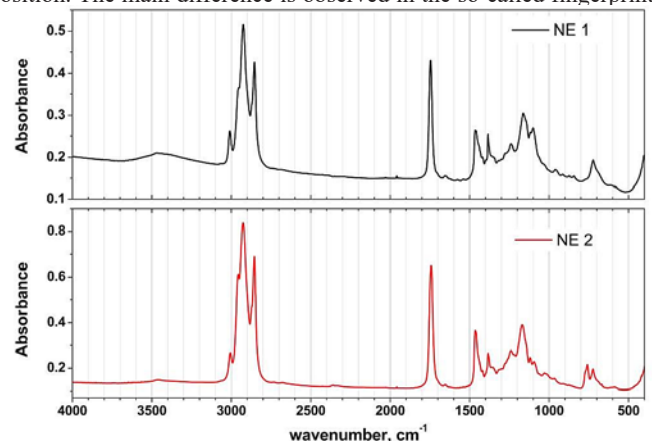


Fig. 2. FT-IR spectra of investigated esters NE 1 and NE 2 at room temperature

region, below 1500 cm^{-1} ; where each different compound produces its own unique pattern of peaks. Spectral bands in the regions $3000\text{--}2800\text{ cm}^{-1}$ and $1500\text{--}1350\text{ cm}^{-1}$ correspond to aliphatic hydrocarbons, while the bands in the regions $3040\text{--}3000\text{ cm}^{-1}$, $1680\text{--}1600\text{ cm}^{-1}$, and $680\text{--}730\text{ cm}^{-1}$ correspond to olefin vibrations, whereas peaks in the regions $1770\text{--}1715\text{ cm}^{-1}$, $1300\text{--}1100\text{ cm}^{-1}$ are attributed to vibrations of esters. The exact positions of the individual bands in the spectra of investigated oils are given in Table 2.

3.2. UV-visible spectroscopy

The UV-VIS spectra of investigated natural esters were performed in heptane because this saturated hydrocarbon is essentially transparent in UV-VIS range. Therefore, absorption bands in the investigated range should be gen-

Table 2. Evaluation of FT-IR spectra of investigated esters NE 1 and NE 2 [17, 34, 44]

Wavenumber [cm ⁻¹]		Assignment
NE 1	NE 2	
3467	3460	Overtone of C=O of ester group
3009	3006	=C-H stretching symmetric vibration of the <i>cis</i> double bonds
2954	2956	asymmetric stretching vibration of C-H of aliphatic -CH ₃ groups due to the alkyl rest of triglycerides present in large quantities in vegetable oils
2925	2926	C-H asymmetric stretching vibration of aliphatic CH ₂ group
2854	2855	C-H symmetric stretching vibration of aliphatic CH ₂ group
1746	1742	C=O stretching vibration of the ester carbonyl functional groups of the triglycerides
1655	1653	C=C stretching vibration of <i>cis</i> -disubstituted olefins, RHC=CHR
1465	1464	C-H bending vibration of CH ₂ and CH ₃ aliphatic groups
1384	1383	C-H bending symmetric vibration of CH ₂ groups
1239	1240	C-O stretching vibration of ester groups
1163	1169	C-O stretching vibration of ester groups
1100	1095	C-O stretching vibration of ester groups
961	967	out-of-plane bending vibration of trans -HC=CH- group of disubstituted olefins
914	910	out-of-plane bending vibration of <i>cis</i> -HC=CH- group
722	723	overlapping of C-H rocking vibration of CH ₂ and the out-of-plane vibration of <i>cis</i> -HC=CH- group of disubstituted olefins

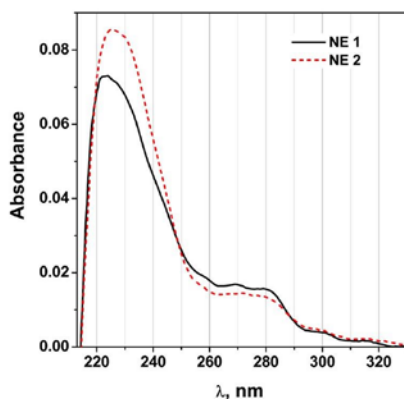


Fig. 3. UV-VIS spectra of the natural esters' samples NE 1 and NE 2 in heptane

Table 3. UV-VIS absorption bands of investigated natural esters NE 1 and NE 2 in heptane

NE 1		NE 2	
Wave length λ [nm]	Absorbance	Wave length λ [nm]	Absorbance
224	0.0730	225	0.0856
269	0.0169	271	0.0145
279	0.0157	277	0.0137
314	0.0017	314	0.0022

erated mainly by investigated oils samples. The tested esters NE 1 and NE 2 contain chromophore groups in their structures, i.e. unsaturated bonds and carbonyl groups, the groups of atoms that contain electrons which are responsible for the absorption in UV-VIS range. In unsaturated compounds, $\pi \rightarrow \pi^*$ passes become possible, and alkenes absorb ~ 170 nm. It should be noted here that the position of this band is significantly influenced by the presence of substituents. While carbonyl compounds in addition to the $\pi \rightarrow \pi^*$ transition can also undergo the transformation of $n \rightarrow \pi^*$, which absorb at a relatively longer wavelength of 280-300 nm. Due to the structure of the tested

compounds, absorption bands in the range of 200-400 nm were expected. Figure 3 shows the UV-VIS spectra of investigated natural esters (NE 1 and NE 2), where four main absorption bands are visible. The maxima positions of these bands are very similar for tested samples but slightly shifted (Table 3) and they are in agreement with $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ electron transitions due to the presence of C=C and C=O functional groups in unsaturated triglycerides, as was mentioned above.

3.3. Thermal properties

Table 4 presents the results of the thermal properties of the investigated natural esters (NE and NE 2). As it results from the presented measurements, the thermal conductivity of the low viscosity natural ester (NE 2), regardless of temperature, is higher than the thermal conductivity of the natural ester (NE 1)

by about 6%. Differences in the thermal conductivity of both esters result from the lower molecular weight of the monoesters present in the low viscosity natural ester. Lower molecular weight means that a molecule is characterized by fewer degrees of freedom, and therefore a greater thermal conductivity.

On the basis of Table 4, it can also be seen that as the temperature rises, the thermal conductivity of both esters decreases. This is related to the increase in the mobility of ions and free electrons. The temperature rise causes the ions to vibrate more intensively, and the electrons move faster in all directions. This action hinders the orderly movement and consequently the transfer of energy, which results in reduced thermal conductivity.

On the basis of the presented research results, it can be stated that depending on the temperature, the kinematic viscosity of the natural ester NE 2 is lower than the viscosity of the natural ester NE 1 by about 50-58%. Differences in viscosities of both esters result from their molecular weight and structure – the effect of intermolecular interactions (the stronger the molecular interactions, the stronger are the internal friction forces). Analyzing the structure of both liquids, it can be seen that the natural ester NE 1 is a mixture of triglycerides [8]. In turn, the natural ester NE 2 is a mixture of triglycerides and monoesters [13]. The reduced viscosity of the natural ester NE 2 is mainly due to the addition of monoesters to triglycerides.

Similarly to the previous case, it can be seen that as the temperature increases, the kinematic viscosity of both esters decreases. This is due to the fact that as the temperature rises, the kinetic energy of molecules increases. Particles with increased energy more easily overcome the attraction forces of molecules with which they are adjacent. In addition, at a higher temperature, the molecules move faster, which also results in a reduction of the attraction forces between the molecules. As a consequence, as the temperature rises, the viscosity of the tested insulating liquids decreases.

As can be seen from the Table 4, the specific heat of the low viscosity natural ester (NE 2), regardless of analyzing temperature, is less than the specific heat of the natural ester (NE 1) by about 8%. The differences in specific heat of both tested natural esters arise from

Table 4. Thermal properties of investigated natural esters as a function of temperature

Property	Kind of liquid	Temperature			
		25 °C	40 °C	60 °C	80 °C
Thermal conductivity λ [W·m ⁻¹ ·K ⁻¹]	NE 1	0.182	0.180	0.178	0.175
	NE 2	0.193	0.190	0.188	0.186
Kinematic viscosity ν [mm ² ·s ⁻¹]	NE 1	56.3	32.7	18.3	11.5
	NE 2	28.3	17.1	10.0	6.7
Specific heat c_p [J·kg ⁻¹ ·K ⁻¹]	NE 1	2028	2082	2166	2259
	NE 2	1860	1910	1990	2080
Density ρ [kg·m ⁻³]	NE 1	917	908	892	880
	NE 2	885	876	863	851
Thermal expansion β coefficient [K ⁻¹]	NE 1	0.00074	0.00076	0.00078	0.00080
	NE 2	0.00075	0.00077	0.00078	0.00081

their construction – because the specific heat is a function of substance construction and is associated with oscillatory, rotational and translational movements of the molecule. As previously mentioned, the low viscosity natural ester (NE 2) is a mixture of triglycerides and monoesters. Monoesters are characterized by lower molecular weight, and therefore their molecules will also be smaller. In turn, the smaller the molecule is, the less energy it can store (it has a lower thermal capacity).

Analyzing Table 4, it can also be seen that the specific heat of both esters increases with increasing temperature. The increase in specific heat is related to the decrease in the density of the substance (caused by the increase in the thermal expansion coefficient) and the increase in the kinetic energy of the atom's oscillation of the molecules of the both investigated natural esters. Therefore, the increase in temperature increases the degrees of freedom available to the molecules, which results in an increase in specific heat.

As results from the presented results, the density of the low viscosity natural ester (NE 2) is lower than the density of the natural ester (NE 1) by about 3.5%. Similarly, as in the case of viscosity, this is related to intermolecular interaction forces. The intermolecular forces in the natural ester (NE 1) are higher than in the case of the low viscosity natural ester (NE 2). As a consequence, its molecules are not separated from each other as in the case of a low viscosity natural ester.

As the temperature rises, the density of the analyzed insulating liquids is noticeably reduced. Similarly, as in the case of specific heat, this is related to the increase of kinetic energy. Molecules oscillate with increasing frequency, which results in the weakening of intermolecular forces and increasing the distance of molecules from each other.

As can be seen from Table 4, the analyzed natural esters are characterized by a similar thermal expansion coefficient. Minimal differences, as in the case of density, results from the intermolecular forces of the examined natural esters.

Furthermore, it can be seen that the thermal expansion coefficient of the tested natural esters increases with increasing temperature. Similarly, as in the previous case, this is related to the weakening of the intermolecular forces. Consequently, the molecules move away from each other, increasing the volume of liquid.

3.4. Heat transfer factor

Table 5 presents the results of calculations of the heat transfer factor α of investigated vegetable oils depending on the temperature.

Heat transfer factor α was determined on the basis of Equation (1). As is apparent from the calculations, low viscosity natural ester (NE 2), depending on the analyzed temperature, is characterized by a heat transfer factor of 15-19% higher than the heat transfer factor of natural ester (NE 1). The higher heat transfer factor of low viscosity natural ester results from its individual thermal properties. As can be seen from Table 4, this ester is characterized by a higher thermal conductivity coefficient, lower kinematic viscosity, as well as lower specific heat. Other properties (density and thermal expansion coefficient) are similar. The viscosity of the liquid has a decisive influence on the value of the heat transfer factor α , and this one is much lower in the case of the natural ester NE 2.

Table 5. Calculations results of heat transfer factor α of natural esters as a function of temperature

Kind of Liquids	Heat transfer factor α , [W·m ⁻² ·K ⁻¹]			
	Temperature			
	25°C	40°C	60°C	80°C
Natural Ester (NE 1)	83.46	96.12	111.80	126.17
Low Viscosity Natural Ester (NE 2)	99.32	112.95	129.73	145.05

4. Discussion

The electro-insulating liquid constitutes the largest volume element of the transformer insulation system. Thus, it plays an important role in the process of its cooling. Therefore, based on the measured thermal properties and the heat transfer factor calculated on their basis, the temperature drop in the insulating liquid was determined – the temperature drop ΔT between the windings and the tank. This temperature drop was calculated using the relationship:

$$\Delta T = \frac{q}{\alpha} \quad (3)$$

It has been assumed that the surface thermal load of windings is 2500 W·m⁻², as this is a typical value for the surface of the transformer's windings [45]. The results of calculations of the temperature drop in the natural ester (NE 1) and in the low viscosity natural ester (NE 2) are shown in Table 6.

As it can be seen from Table 6, the temperature drop that occurs in the natural ester having reduced viscosity is lower. This decrease is from 2.6 to 4.8 °C and it is lower than in the case of the natural ester NE 1. This means that the use of low viscosity natural ester will have a positive effect on the transformer cooling system – the lower temperature drop in the liquid is, the hot spot temperature will be lower, what will have a significant impact on transformer reliability.

The impact of temperature on transformer lifetime, calculated from Montsinger's law, can be expressed by:

$$t = 7.154 \cdot 10^4 \cdot e^{-0.0865 \cdot T} \quad (4)$$

Table 6. Calculations results of temperature distribution in natural ester and low viscosity natural ester; $q=2500 \text{ W}\cdot\text{m}^{-2}$

Liquid temperature	Kind of liquid	Heat transfer factor α [$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$]	Temperature decrease in liquid ΔT [$^{\circ}\text{C}$]	Difference of ΔT between natural ester (NE 1) and low viscosity natural ester (NE 2) [$^{\circ}\text{C}$]
25 $^{\circ}\text{C}$	Natural Ester (NE 1)	83.46	30.0	4.8
	Low Viscosity Natural Ester (NE 2)	99.32	25.2	
40 $^{\circ}\text{C}$	Natural Ester (NE 1)	96.12	26.0	3.9
	Low Viscosity Natural Ester (NE 2)	112.95	22.1	
60 $^{\circ}\text{C}$	Natural Ester (NE 1)	111.80	22.4	3.1
	Low Viscosity Natural Ester (NE 2)	129.73	19.3	
80 $^{\circ}\text{C}$	Natural Ester (NE 1)	126.17	19.8	2.6
	Low Viscosity Natural Ester (NE 2)	145.05	17.2	

Table 7. Transformer lifetime calculated from Montsinger's law for investigated esters; *on the assumption that lifetime of transformer filled by low viscosity natural ester NE 2 is 20 years

Lifetime of transformer filled by natural ester (NE 1)* [year]	Difference between lifetime of transformer filled by natural ester (NE 1) and low viscosity natural ester (NE 2) [year]
13.2	6.8
14.3	5.7
15.3	4.7
15.9	4.1

where: t – transformer lifetime [year], working in T temperature [$^{\circ}\text{C}$]. The lifetime t is 20 years if transformer temperature T is 95°C . The results of calculations are presented in Table 7.

There is evidence [27, 37] that paper insulation in transformers ages more slowly in vegetable oil. It may be that an increase in oil temperature may shorten significantly the expected service life of the paper insulation. According to Montsinger's law, lowering the transformer's working temperature by 8°C may result in a two-fold increase in the lifetime of its insulation system. Therefore, taking into account the calculation presented in Table 6, it can be concluded that such a difference in temperature can affect the life of the transformer. However, it should be remembered that a certain drawback of Montsinger's law is the fact that it concerns paper insulation impregnated with mineral oil, and also does not take into account other factors accelerating the aging process of transformer insulation, such as moisture and the influence of oxygen.

On the basis of Table 7, it is possible to say, that lifetime of the transformer, filled by a regular natural ester, can be from 4 to almost 7 years shorter, than a lifetime of transformer filled by low viscosity natural ester. This means that the service life can be reduced by about $1/3$, assuming that the transformer is designed for 20 years of work.

Besides the positive impact on transformer lifetime, the reduced temperature has also a positive impact on the work conditions of the transformer, too. It means that lower temperature is able to decrease some accidents, such as breakdown or partial damages. This fact should be also treated as a positive influence on the reliable work of transformers.

On the other hand, IEC 60076-7 [18] states that the lifetime of the transformer insulation system is halved for every increase in its working temperature by 6°C . As it can be seen from the presented calculations of temperature drops, the type of used liquid is important

from the point of view of the lifetime of electrical power equipment. However, it should be noted, as McShane and others in [27] state, that the paper insulation of the transformer, impregnated by a natural ester, undergoes 5 to 8-fold slower decomposition than the paper impregnated by mineral oil. Therefore, in vegetable oils, the increased degradation resulting from the elevated temperature will in some way be balanced by the rate of degradation in this oil.

As it results from the above calculations, the thermal properties of the liquid filling the transformer influence the cooling efficiency of the transformer. There are many publications that emphasize the effect of viscosity on the temperature field of transformers [4, 16, 42]. It affects the efficiency of heat transfer in both natural and forced circulation of liquids. Consequently, this translates to the operating temperature of the transformer. In addition, it should be noted that it may also affect the operation of some transformer internal components, such as internal on-load tap-changers [19].

5. Conclusions

The heat transfer factor α of the low viscosity natural ester (NE 2) turned out to be higher than factor α of the commonly used natural ester (NE 1). The reason for this, as could be expected, was primarily the lower viscosity ν (by about 50-60%) of the natural ester NE 2, but also the higher thermal conductivity coefficient λ . On the basis of the obtained results, it was calculated that the transformer filled with low viscosity natural ester will be 3-5 $^{\circ}\text{C}$ cooler. Taking into account the law of Montsinger's, it can be concluded that this will translate into a longer working life of the transformer and its more reliable work.

The temperature decrease by a few degrees is not without significance for the transformer. Too high temperature inside the transformer contributes to the acceleration of the aging processes of its insulation system – insulation materials are subject to faster disintegration. If a transformer becomes too hot internally, then the insulation materials will degrade faster, and the operating lifetime of the transformer will be shortened. Thermal modelling of the transformer allows, therefore, to ensure that the elements of its insulation system do not fail prematurely. The right transformer design using thermal modelling allows ensuring that the cellulosic insulation is adequately cooled, and that the temperature increase at hot spots is not excessive, what has a positive impact on transformer reliability.

It is well recognized, that mineral oil is the best cooling liquid, used in power transformer, comparing to other esters (natural, synthetic, and low viscosity esters). On the other hand, mineral oil has not satisfied environmental properties, such as flash point, fire point, and biodegradability. Future investigations should be focused on investigations of mineral oil and low viscosity natural ester mixture. The

mixture should have better cooling properties (heat transfer factor) than pure low viscosity natural ester and still satisfied environmental properties.

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