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THERMAL PROPERTIES OF A MIXTURE OF SYNTHETIC AND NATURAL ESTERS IN TERMS OF THEIR APPLICATION IN HIGH VOLTAGE POWER TRANSFORMERS

WŁAŚCIWOŚCI CIEPLNE MIESZANINY ESTRÓW SYNTETYCZNYCH I ESTRÓW NATURALNYCH W ASPEKCIE ZASTOSOWANIA W TRANSFORMATORACH DUŻEJ MOCY*

The article presents research results of thermal properties of mixtures of synthetic and natural esters in terms of their application in the cooling system of a high-voltage power transformer during its operation. The investigated properties of an analysed mixture were: thermal conductivity coefficient λ, kinematic viscosity υ, density ρ, specific heat c_p, and thermal expansion β. On the basis of presented research results, the authors determined the heat transfer factor α of a mixture of synthetic and natural esters. This factor defines the ability of an insulating liquid to transport heat in the transformer, thus determining its reliability. For the research the authors used the following percentage proportions of the mixture of both the esters: 100/0, 95/5, 80/20, 50/50, 20/80, 5/95, 0/100. The measurements were taken for the temperatures: 25°C, 40°C, 60°C, and 80°C.

Keywords: *power transformers, natural esters, synthetic esters, heat transfer factor.*

W artykule przedstawiono wyniki badań właściwości cieplnych mieszaniny estrów syntetycznych i estrów naturalnych, w aspekcie ich zastosowania w układzie chłodzenia transformatora wysokiego napięcia w trakcie jego eksploatacji. Badanymi właściwościami analizowanej mieszaniny były przewodność cieplna właściwa λ, lepkość kinematyczna υ, gęstość ρ, ciepło właściwe c_p oraz rozszerzalność cieplna β. W oparciu o przedstawione wyniki badań określono współczynnik przejmowania ciepła α mieszaniny estrów syntetycznych i estrów naturalnych. Współczynnik ten określa zdolność cieczy elektroizolacyjnej do transportu ciepła w transformatorze, warunkując tym samym jego niezawodność. Do badań wykorzystano następujące procentowe proporcje mieszaniny obu estrów: 100/0, 95/5, 80/20, 50/50. 20/80, 5/95, 0/100. Pomiary przeprowadzono dla temperatury: 25°C, 40°C, 60°C i 80°C.

Słowa kluczowe: *transformatory energetyczne, estry naturalne, estry syntetyczne, współczynnik przejmowania ciepła.*

1. Introduction

The power transformer is one of the most important electric power devices. Its key element is the insulating system; transformer reliability and its long operation depends on it. A substantial majority of used transformers is filled with insulating liquids. Due to their good dielectric properties, these liquids function as electric insulation. Moreover, they also have advantageous thermal properties (thermal conductivity, viscosity, specific heat, density, and thermal expansion), so that they also play the role of a cooling agent [13, 26]. Taking into consideration the fact that heat transfer proceeds along the following way: heat source → paper impregnated with liquid → insulating liquid → tank → air, thermal properties of the liquid filling the inside of the transformer are of high importance in the process of this transfer [4, 14-16].

The most frequently used insulating liquid in the transformer, because of a low price and very well investigated properties, is mineral oil [10, 20, 26, 32]. However, more and more restrictive regulations and requirements concerning reliability of electric power devices filled with liquids influence reduction of its domination [2, 6, 7, 17, 18, 23]. Therefore, research centres all over the world conduct numerous investigations on liquids alternative to mineral oil. These include mainly synthetic esters and natural esters [3, 4, 12, 21]. These liquids are characteristic of many properties, which in reference to mineral oil, are considered as their advantages. They are, first of all, ecological values such as biodegradability and non-toxicity, and also operation safety connected with their high flash point and fire point [12, 21].

Lately, the process of replacing the insulating liquid filling the transformer with another (*retrofilling*) has been more and more popular. This happens when the transformer up to now has been filled with one liquid (usually mineral oil) and now it is filled during a repair with another liquid (most often with synthetic or natural esters) [8, 18]. Retrofilling does not guarantee full removing of the original liquid because its small amount remains in the saturated paper insulation, windings, core, and other hardly-accessible crevices of the transformer. Then, unintentionally, a mixture is created which consists of remains of the original liquid (its amount does not exceed 8%) and the new liquid that the modernized unit is filled with, as described by Fofana et al in [8]. There are also investigations concerning intentional use of two or more insulating liquids in order to obtain a mixture characteristic of better properties in reference to the base liquids. This research concerns most often mixtures of mineral oil with synthetic or natural esters [6, 7, 10, 11, 17, 22, 23, 27, 30].

The research on the mixtures which are currently conducted in many research centres all over the world, concern mainly their electric properties, not thermal ones, which is not a proper approach. We

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** should take into consideration that the application of insulating liquid mixtures, which in reference to the base liquids are characteristic of better electric properties and worse thermal properties, will result in accelerating the ageing process of the transformer's insulating liquid as a consequence of higher work temperature. As a result, this will reduce the time of its operation. Therefore, the research on the mixtures should tend to combine their electric, physicochemical, and thermal properties as described Nadolny et al in [19]. Dua et al undertook such an attempt in [5], in which they analysed a possibility to apply mixtures of insulating liquids while paying attention to their most important properties. However, with a lack of full information concerning thermal properties of the mixtures, such an approach can be difficult or impossible to do.

As it was mentioned before, a considerable number of articles referring to mixtures of insulating liquids present research results of their electric properties. In [6, 27, 29, 30] the authors present research results concerning the influence of proportions of oil and esters and the level of ageing on such electric properties as the dielectric loss factor tg(δ), electric permeability, and breakdown voltage. In turn, Suwarno in [28] presented the influence of thermal ageing of a mixture of mineral oil and natural ester on such electric properties as breakdown voltage, resistivity, the dielectric loss factor, and electric permittivity. Moreover, Trnka et al in [31] show research results concerning biodegradability of mixtures of mineral oil and natural ester. McShane et al in [18] also present information concerning the influence of proportions of mineral oil and natural ester on the flash point and fire point as well as pour point.

The literature does not provide complete information concerning thermal properties of insulating liquid mixtures. The only available data are those concerning selected thermal properties of mixtures of mineral oil with synthetic esters and mixtures of mineral oil with natural esters. In [23, 30] we can find information concerning viscosity of a mixture of mineral oil and synthetic esters depending on their proportions. The authors also provide information concerning the influence of temperature on mixture viscosity whose mineral oil content is 20% and 80%. In turn, McShane et al in [18] present information concerning viscosity of a mixture of mineral oil and natural esters depending on their proportions. However, these data were presented only for the mixtures whose temperatures were 40ºC and 100ºC. In [27, 29] we can find data concerning the influence of temperature and the proportions on the density of mixtures based on mineral oil and natural esters.

There is no investigations according thermal properties of insulating liquids mixtures. As it can be seen on the basis of references, only partial information about viscosity and density of mineral oil and the esters are available. There is no information according the influence of temperature and mixture proportion on rest thermal properties, such as thermal conductivity, specific heat and thermal expansion. There is no information about mixtures of natural esters and synthetic esters, either.

Independently of the way the mixture is created, the purpose of its application is the improvement of insulating liquid properties. Thus the research on properties of mixtures of different insulating liquids are primary in terms of their influence on the period of the transformer's life and adapting it to existing standards and regulations. Moreover, another important issue is compatibility of the newly created mixture with the remaining materials which make the insulating system of the transformer, because only such a mixture will enable prolonging its operation period and reliable work. Therefore, complete information about thermal properties of insulating liquid mixtures are desirable and they will also allow completing missing knowledge in the field of properties of new insulating liquids, which is the focus of this article.

2. Research goal and range

The goal of the undertaken investigations was to determine the influence of proportions of synthetic esters with natural esters on thermal properties of the created mixture. The research range covered measurements of thermal properties of the created mixture such as: thermal conductivity coefficient λ, kinematic viscosity υ, specific heat c_p, density ρ, and thermal expansion coefficient β. These properties determine the ability of the liquid to heat transfer: the heat transfer factor α. The heat transfer factor α was determined on the basis of the equation presented by Dombek and Nadolny in [4]:

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

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

For the measurements of the mentioned above properties the authors used synthetic esters named Midel 7131 manufactured by the company M&I Materials and natural esters named Envirotemp FR3 manufactured by the company Cargil. The measurements of the properties were done according to standards [1, 9, 24, 25] using measurement systems which had been tested before on insulating liquids of thermal properties known from the literature. In order to do the investigations, the authors prepared mixtures of synthetic and natural esters of the following percentage concentrations of both the esters: 100/0, 95/5, 80/20, 50/50, 20/80, 5/95, and 0/100. The measurements were taken for the temperatures of 25ºC, 40ºC, 60ºC, and 80ºC. The research results are presented in the subsequent section.

3. Measurement results

3.1. Thermal conductivity λ of a mixture of synthetic and natural esters

Table 1 and Figure 1 present measurement results of thermal conductivity λ of a mixture of synthetic and natural esters for different temperature values. With an increase of the natural ester content thermal conductivity of the mixture increases. Thermal conductivity λ increased by 15.2% (for 25°C), by 15.4% (for 40°C), by 16.3% (for 60°C), and by 15.9% (for 80°C). This increase was independent of temperature. The reason of thermal conductivity increase is higher λ of natural esters in comparison to synthetic esters [4]. In natural esters, because of stronger interaction of molecules, distances among them

Table 1. Measurement results of thermal conductivity λ of a mixture of synthetic and natural esters

Thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$]							
Temperature	Proportion of synthetic esters (SE) and natural esters (NE)						
	100% SE 0% NE	95% SE 5% NE	80% SE 20% NE	50% SE 50% NE	20% SE 80% NE	5% SE 95% NE	0% SE 100% NE
25°C	0.158	0.161	0.163	0.170	0.178	0.181	0.182
40°C	0.156	0.159	0.162	0.168	0.176	0.178	0.180
60°C	0.153	0.155	0.159	0.166	0.174	0.177	0.178
80°C	0.151	0.153	0.157	0.163	0.171	0.174	0.175

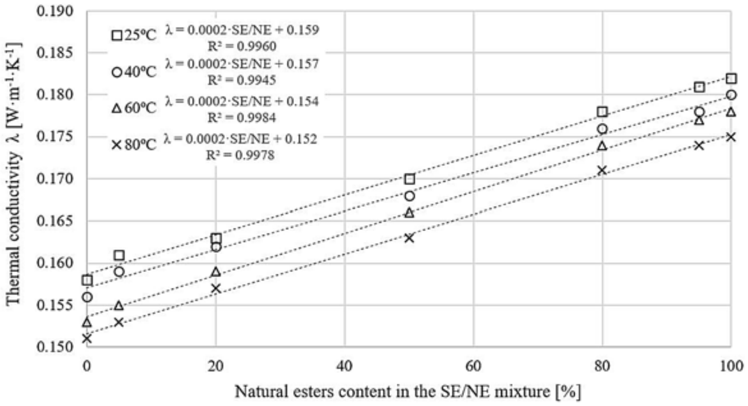

Fig. 1. Thermal conductivity λ of a mixture of synthetic and natural esters

are shorter than for the case of synthetic ester, thus kinetic energy transfer is easier. This means that the higher content of natural esters the better will be thermal conductivity of the mixture, which can advantageously affect the ability of the mixture to transfer heat in the transformer.

With temperature increase we can also notice a decrease of thermal conductivity of the analysed mixtures. This drop is caused by distance increase among the molecules of the liquid which, as a result, makes kinetic energy transfer more difficult. Eventually, this causes lowering thermal conductivity of the analysed liquids.

Figure 1 presents measurement results with the trend line, equation of the approximation model, and determination factor. The results were approximated with the linear equation:

$$\lambda = a \cdot SE / NE + b \tag{2}$$

where: a, b – constants which are material parameters of the SE/NE mixture. Constant a is equal to tangent of inclination angle of the straight line to the axis of ordinates. This constant determines changes of thermal conductivity λ of an SE/NE mixture caused by the natural ester content. Constant b is equal to thermal conductivity λ for the natural ester content in the SE/NE mixture equal to 0%.

Results of the calculations of the remaining thermal properties (subsections 3.2-3.6) like for the case of thermal conductivity λ were also approximated with the linear function.

3.2. Kinematic viscosity υ of a mixture of synthetic and natural esters

Table 2 and Figure 2 present measurement results of kinematic viscosity υ of a mixture of synthetic and natural esters. As it is shown, viscosity of the mixture increases by respectively 2.1% (for 25°C), by 15.6% (for 40°C), by 30.5% (for 60°C), and by 41.8% (for 80°C) with an increase of the natural ester content. With temperature increase, the viscosity increase resulting from increasing the natural ester content is clearer and clearer. This is caused by higher viscosity of natural esters, as presented by Dombek and Nadolny in [4]. Kinematic viscosity of liquids results directly from their chemical structure. Higher viscosity of natural esters is connected with stronger intermolecular interactions. These interactions in natural esters make forces of internal friction greater than for synthetic esters. Thus, mixture viscosity increases with increase of natural ester content, which can negatively affect the ability of the mixture to transfer heat in the transformer.

We can notice that when the temperature rises the viscosity of the mixture decreases. This drop should be linked with decreasing of attraction forces acting among liquid molecules as a result of a decrease of their kinetic energy. Kinetic energy increase results from temperature increase. In turn, when the temperature is higher the molecules move at higher velocities, which weakens intermolecular forces and as a result causes decrease of internal friction forces and viscosity decrease.

3.3. Specific heat c_p of a mixture of synthetic esters and natural esters

Table 3 and Figure 3 present measurement results of specific heat c_p of a mixture of synthetic esters and natural esters.

Table 2. Results of kinematic viscosity υ measurements of a mixture of synthetic and natural esters

Kinematic viscosity υ [mm²·s⁻¹]							
Temperature	Proportion of synthetic esters (SE) and natural esters (NE)						
	100% SE 0% NE	95% SE 5% NE	80% SE 20% NE	50% SE 50% NE	20% SE 80% NE	5% SE 95% NE	0% SE 100% NE
25°C	55.14	55.18	55.32	55.62	56.02	56.25	56.29
40°C	28.25	28.34	28.69	29.91	31.84	32.58	32.66
60°C	14.02	14.16	14.59	15.78	17.32	18.16	18.29
80°C	8.11	8.23	8.59	9.57	10.71	11.32	11.50

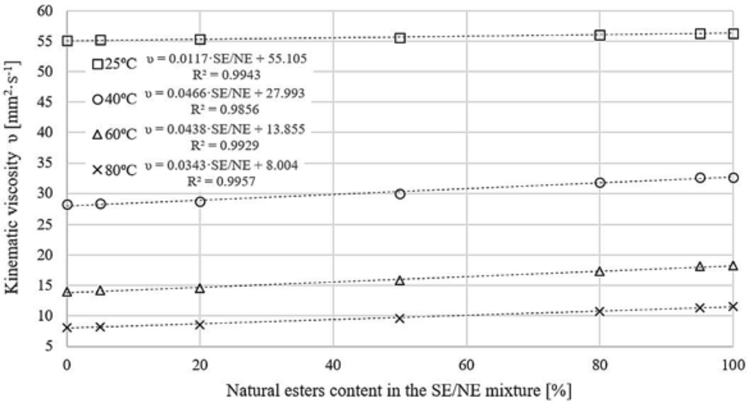

Fig. 2. Kinematic viscosity υ of a mixture of synthetic and natural esters

Table 3. Measurements results of specific heat c_p of a mixture of synthetic esters and natural esters

Specific heat c_p [J·kg⁻¹·K⁻¹]							
Temperature	Proportion of synthetic esters (SE) and natural esters (NE)						
	100% SE 0% NE	95% SE 5% NE	80% SE 20% NE	50% SE 50% NE	20% SE 80% NE	5% SE 95% NE	0% SE 100% NE
25°C	1905	1910	1923	1957	1977	2021	2028
40°C	1964	1969	1984	2014	2022	2069	2082
60°C	2052	2057	2078	2108	2117	2158	2166
80°C	2149	2154	2189	2218	2219	2246	2259

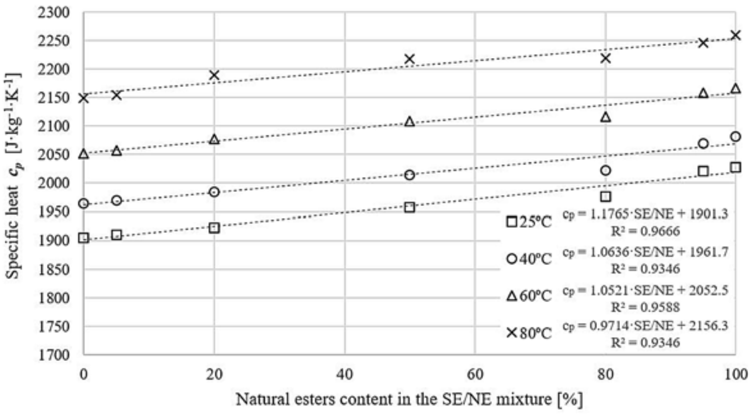

Fig. 3. Specific heat c_p of a mixture of synthetic esters and natural esters

With an increase of the natural ester content the specific heat of the mixture increased slightly. Specific heat increased by 6.5% (for 25°C), by 6.0% (for 40°C), by 5.6% (for 60°C), and by 5.1% (for 80°C). With temperature rise, the increase of specific heat of the mixture caused by increasing the natural ester content, slightly decreased. The increase of c_p of the mixture is caused by a higher value of specific heat of natural esters in comparison to the heat of synthetic esters. Specific heat is related to heat capacity, which determines the amount of energy that the molecules are able to absorb. Moreover, heat capacity is a function of molecule freedom degrees. It results from the above that the greater the particles the greater the number of freedom degrees they are characteristic of. Molecules of natural esters are larger than molecules of synthetic esters, therefore they can store more energy. The more energy a molecule can absorb the greater its heat capacity. In turn, the greater is heat capacity of a liquid, the greater its specific heat. As a result, an increase of the natural ester content caused an increase of specific heat of the mixture, which can result in improvement of the mixture's ability to heat transfer in the transformer.

With temperature increase, specific heat increase is noticeable. This is connected with kinetic energy increase and potential oscillation of ester molecule atoms, thus a larger number of freedom degrees is possible. Kinetic energy is the greater, the greater the velocity of the moving molecules.

3.4. Density ρ of a mixture of synthetic esters and natural esters

Table 4 and Figure 4 present measurement results of density ρ of a mixture of synthetic and natural esters. With an increase of the natural ester content, the density of the mixture decreased a little. Density ρ decreased by 4.9% (for 25°C), by 4.7% (for 40°C), by 5.1% (for 60°C), and by 5.0% (for 80°C). The density drop was practically independent of temperature. The drop of density ρ results from the fact that density of natural esters is a little lower than density of synthetic esters. Minor density differences of the analysed liquids result from differences of intermolecular interactions. Thus we can conclude that with an increase of the natural ester content in the mixture, the density of such a mixture will decrease, affecting negatively its ability to transfer heat in the transformer.

Mixture density decreases with temperature increase because the molecules of the liquid move at greater velocity. Higher molecule velocity affects decreasing intermolecular forces, which eventually results in increasing distances among them. The increase of the distance among the molecules causes increase of the liquid volume, which means decrease of its density.

Table 4. Measurement results of density ρ of a mixture of synthetic esters and natural esters

Density ρ [kg·m⁻³]							
Temperature	Proportion of synthetic esters (SE) and natural esters (NE)						
	100% SE 0% NE	95% SE 5% NE	80% SE 20% NE	50% SE 50% NE	20% SE 80% NE	5% SE 95% NE	0% SE 100% NE
25°C	964	962	955	941	926	919	917
40°C	953	951	944	931	917	910	908
60°C	940	938	930	916	902	894	892
80°C	926	924	917	903	889	882	880

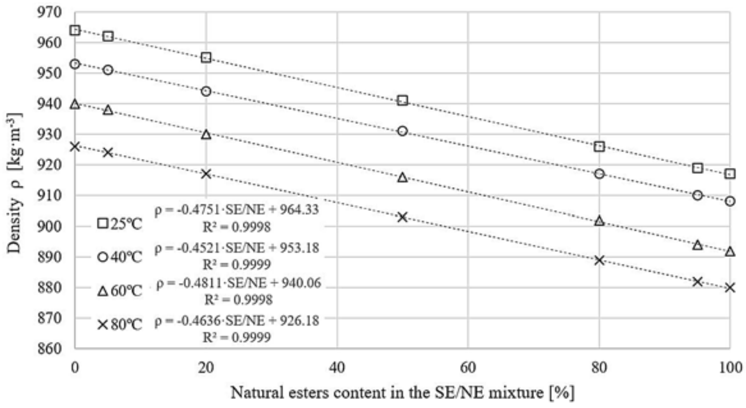

Fig. 4. Density ρ of a mixture of synthetic esters and natural esters

3.5. Thermal expansion β of a mixture of synthetic esters and natural esters

Table 5 and Figure 5 present measurement results of thermal expansion β of a mixture of synthetic and natural esters. As it is shown, an increase of natural ester content caused slight changes of thermal expansion of the mixture. Thermal expansion β decreased by 2.6% (for 25°C) and by 1.3% (for 40°C), it did not change its value for 60°C and increased by 1.3% (for 80°C). Minor changes of thermal expansion of the analysed liquids, like in the case of density, result from differences of intermolecular interactions. This means that with an increase of the natural ester content in the mixture, the thermal expansion of such a mixture changes slightly. This change should not significantly affect the ability of the mixture to heat transfer in the transformer.

With temperature increase, there is a noticeable increase of thermal expansion of the mixture. This increase results from the fact that liquid molecules vibrate at higher and higher frequency so their velocity increases. As a result of the velocity increase, the liquid molecules start moving apart, thus its spatial dimensions increase.

3.6. Heat transfer factor α of a mixture of synthetic esters and natural esters

Table 6 and Figure 6 present calculation results of the heat transfer factor α of a mixture of synthetic and natural esters. The calculations were done on the basis of measurement results of the thermal properties described in subsections 3.1-3.5.

The increase of the natural ester content in the SE/NE mixture basically caused increase of factor α. Its reason was an increase of thermal conductivity and specific heat resulting

Table 5. Measurement results of thermal expansion β of a mixture of synthetic esters and natural esters

Thermal expansion β [K^{-1}]							
Temperature	Proportion of synthetic esters (SE) and natural esters (NE)						
	100% SE 0% NE	95% SE 5% NE	80% SE 20% NE	50% SE 50% NE	20% SE 80% NE	5% SE 95% NE	0% SE 100% NE
25°C	0.00076	0.00076	0.00076	0.00075	0.00075	0.00074	0.00074
40°C	0.00077	0.00078	0.00077	0.00077	0.00077	0.00075	0.00076
60°C	0.00078	0.00078	0.00078	0.00078	0.00079	0.00078	0.00078
80°C	0.00079	0.00079	0.00080	0.00080	0.00081	0.00080	0.00080

Table 6. Calculation results of the heat transfer factor α of a mixture of synthetic esters and natural esters

Heat transfer factor α [W·m^{-2}·K^{-1}]							
Temperature	Proportion of synthetic esters (SE) and natural esters (NE)						
	100% SE 0% NE	95% SE 5% NE	80% SE 20% NE	50% SE 50% NE	20% SE 80% NE	5% SE 95% NE	0% SE 100% NE
25°C	78.43	79.17	79.60	80.98	82.58	83.21	83.46
40°C	92.85	93.97	94.27	95.04	95.50	95.22	96.12
60°C	110.72	111.18	111.81	112.00	112.09	111.64	111.80
80°C	127.51	127.88	128.83	127.70	127.10	126.19	126.17

whereas changes of the remaining thermal properties remained at a constant level. The obtained results were predictable because the heat transfer factor of natural esters was greater than factor α of synthetic esters in the temperature range 25÷60ºC. At 80ºC factor α of natural esters was a little lower than of synthetic esters.

The analysis of Figure 6 does not show a clear maximum of factor α. This means that it is difficult to provide optimal proportions of both the esters. The only conclusions that come is the statement that in the case of the temperatures up to 60ºC, the application of natural esters is a more advantageous solution in terms of transformer cooling. At the temperature of 80ºC, factors α of both the esters are comparable.

4. Conclusions

An increase of the natural ester content in the SE/NE mixture caused changes of many thermal properties. Thermal conductivity increased by over 10 percent. Specific heat and density increased by a few percent. Viscosity, depending on temperature, increased by from a few to tens of percent. Thermal expansion practically did not change its value. The result of such changes was an increase of the heat transfer factor α, depending on temperature, by from a few to over 10 percent.

The SE/NE mixture did not have an optimal composition, in terms of the value of the heat transfer factor α. In fact, for 60ºC and 80ºC there are certain maxima but their values are only hardly by 1% higher for the value of factor α for 100% of synthetic ester (mixture 100/0) or 100% of natural ester (mixture 0/100). In such a situation we can state that from the practical point of view, the application of the SE/NE mixture is not justified.

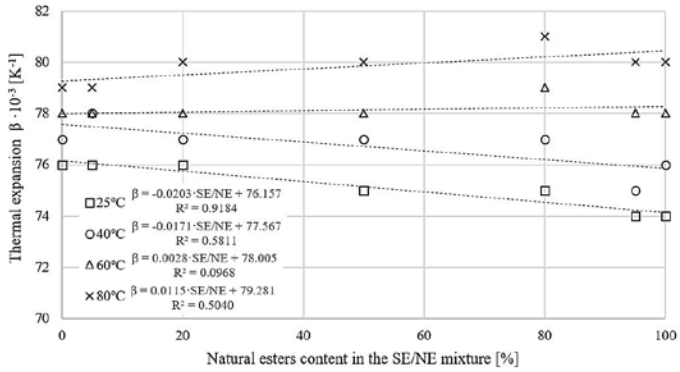

Fig. 5. Thermal expansion β of a mixture of synthetic esters and natural esters

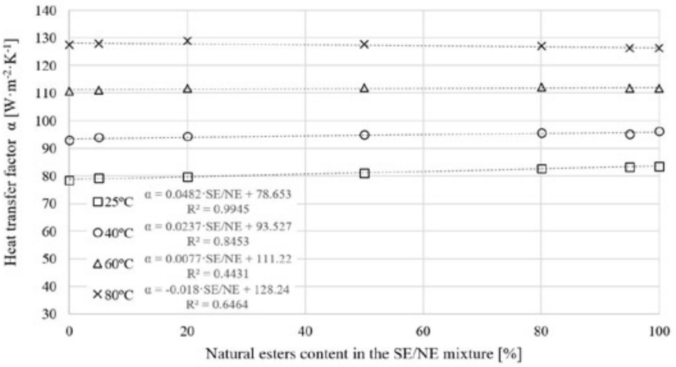

Fig. 6. Heat transfer factor α of a mixture of synthetic esters and natural esters

from adding natural esters, despite viscosity increase and decrease of density and thermal expansion. The authors also found that increases of factor α were getting smaller with temperature increase. The reason of this effect was a significant viscosity increase which resulted from adding natural esters for a higher and higher temperature values

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