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The role of the type of insulating liquid in the transformer temperature distribution

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The mineral oil is most frequently used liquid in insulation transformer system. However, increased interest in alternative insulating liquid for it, which includes synthetic ester and natural ester is observable for several years. However, for several years, the increased interest in insulating liquids as alternatives to mineral oil is observable, which include synthetic ester and natural ester. This is due to increasingly restrictive environmental legislation and fire safety. Mineral oil, in comparison with esters has a very good electric insulation properties and a lower viscosity. In turn the esters in comparison with oil, have a much greater biodegradability and have a much higher flash point, which suggests their favor. The influence of the type of insulating liquid on the efficiency of the cooling system of the transformer was presented in the paper. This efficiency was determined by designating the heat transfer coefficient α by liquids. This factor depends on the thermal properties of liquids, which includes the thermal conductivity λ, kinematic viscosity υ, specific heat c_p, density ρ, and thermal expansion β. For the study mineral oil, synthetic ester and natural ester were used. The measurements of thermal properties were carried out in the temperature range from 25°C to 80°C

KEYWORDS: mineral oil, synthetic ester, natural ester, power transformers

1. Introduction

The temperature in the transformer depends mainly on its load, windings and core losses, weather conditions and operational factors [1]. The type of liquid and temperature are among operational factors. These factors may influence the heat transfer by the liquid, which depends on thermal properties of the liquid. These properties include thermal conductivity, kinematic viscosity, specific heat, density and thermal expansion.

In the literature, there are given incomplete information regarding the impact of the above mentioned factors on thermal properties of the insulating liquids. This information shall relate primarily mineral oil [2]. Information on the thermal properties of alternatives for mineral oil liquids which include inter alia synthetic and natural esters are also unavailable [3, 4].

From the information above it can be concluded that many factors can be changed during operation of the transformer. These factors may impact on the thermal properties of insulating liquids and thereby its ability to heat dissipation. Therefore, this article analyzes the impact of the type of insulating liquid and temperature on the thermal properties of insulating liquids.

2. The purpose and scope of research

Analysis and comparison of thermal properties of insulating liquids used in the cooling system of the transformer and determine the extent to which they affect the heat transfer factor $\alpha_{pap-liquid}$ were the aim of the research. Factor $\alpha_{pap-liquid}$ determines the efficiency of heat pick up by the insulating liquid from the surface of transformer windings paper insulation. This factor is determined by the following equation:

$$\alpha_{pap-liquid} = c \cdot \delta^{3n-1} \cdot \Delta T^{n} \cdot g^{n} \cdot \beta^{n} \cdot c_{p}{}^{n} \cdot \rho^{n} \cdot \lambda^{1-n} \cdot \upsilon^{-n} \qquad (1)$$

where: c, n – constants dependent on the character of the flow, temperature, and geometry, δ – characteristic dimension connected with liquid flow [m], ΔT – temperature drop [°C], g – acceleration of gravity [$m \cdot s^{-2}$], β – thermal expansion [K^{-1}], c_p – specific heat [$J \cdot kg^{-1} \cdot K^{-1}$], ρ – density [$kg \cdot m^{-3}$], λ – thermal conductivity coefficient [$W \cdot m^{-1} \cdot K^{-1}$], υ – kinematic viscosity [$mm^2 \cdot s^{-1}$].

As we can see heat transfer factor $\alpha_{pap-liquid}$ depends on geometrical parameters of the transformer (c, n, δ), acceleration of gravity g and thermal properties of used insulating liquid (λ, υ, ρ, β, c_p).

Range of the experiments comprised the measurement of thermal conductivity coefficient λ, kinematic viscosity υ, specific heat c_p, density ρ and thermal expansion β. For the measurement of the coefficient λ authorship measuring system described in positions [5–7] was used. In turn, to the measurement of kinematic viscosity υ and density ρ the systems described in [8] were used. Specific heat c_p and thermal expansion β determined using the measurement systems described in the article [9].

Samples of mineral oil under the trade name Nytro Taurus manufactured by Nynas, a samples of synthetic ester having the trade name Midel 7131 manufactured by M&I Materials, and a samples of natural ester under the trade name Envirotemp FR3 produced by Cargil, were used for testing. Degree of the moisture and an acid number of samples of the liquids prepared for testing correspond to new liquids, used for filling new or renovated transformers. Mineral oil characterized by a degree of moisture about 2 ppm, and an acid number was less than 0.01 $mg_{KOH} \cdot g^{-1}$. The moisture degree of synthetic ester was equal 45 ppm, and its acid number was less than 0.03 $mg_{KOH} \cdot g^{-1}$. In turn, the degree of moisture of natural ester was equal 34 ppm, and the acid number was equal to 0.02 $mg_{KOH} \cdot g^{-1}$. Different degrees of the moisture result from different levels of water absorption of different types of insulating liquids and the permissible value of the degree of moisture according to the standard [10]. In the case of a different values of acid number was similar.

3. Measurement results

Table 1 and Figures 1 – 6 show the results of measurements of thermal properties of insulating liquids such as thermal conductivity coefficient λ, kinematic viscosity υ, specific heat c_p, density ρ, thermal expansion β, and the results of calculation of heat transfer α by the liquid, depending on the type of the liquid and temperature T.

Table 1. The results of measurements and calculations of thermal properties of insulating liquid, depending on its type, for different values of temperature T; new liquid

Kind of insulating liquid	Mineral oil	Synthetic ester	Natural ester
Properties	Temperature 25°C		
Thermal conductivity coefficient λ [$W\cdot m^{-1}\cdot K^{-1}$]	0.133	0.158	0.182
Kinematic viscosity υ [$mm^2\cdot s^{-1}$]	17.08	55.14	56.29
Specific heat c_p [$J\cdot kg^{-1}\cdot K^{-1}$]	1902	1905	2028
Density ρ [$kg\cdot m^{-3}$]	867	964	917
Thermal expansion β [K^{-1}]	0.00075	0.00076	0.00074
Heat transfer factor $\alpha_{pap-liquid}$ [$W\cdot m^{-2}\cdot K^{-1}$]	93.56	78.43	83.46
Properties	Temperature 40°C		
Thermal conductivity coefficient λ [$W\cdot m^{-1}\cdot K^{-1}$]	0.130	0.156	0.180
Kinematic viscosity υ [$mm^2\cdot s^{-1}$]	9.59	28.25	32.66
Specific heat c_p [$J\cdot kg^{-1}\cdot K^{-1}$]	1974	1964	2082
Density ρ [$kg\cdot m^{-3}$]	857	953	908
Thermal expansion β [K^{-1}]	0.00076	0.00077	0.00076
Heat transfer factor $\alpha_{pap-liquid}$ [$W\cdot m^{-2}\cdot K^{-1}$]	107.89	92.85	96.12
Properties	Temperature 60°C		
Thermal conductivity coefficient λ [$W\cdot m^{-1}\cdot K^{-1}$]	0.128	0.153	0.178
Kinematic viscosity υ [$mm^2\cdot s^{-1}$]	5.37	14.02	18.29
Specific heat c_p [$J\cdot kg^{-1}\cdot K^{-1}$]	2077	2052	2166
Density ρ [$kg\cdot m^{-3}$]	845	940	892
Thermal expansion β [K^{-1}]	0.00078	0.00078	0.00078
Heat transfer factor $\alpha_{pap-liquid}$ [$W\cdot m^{-2}\cdot K^{-1}$]	125.70	110.72	111.80
Properties	Temperature 80°C		
Thermal conductivity coefficient λ [$W\cdot m^{-1}\cdot K^{-1}$]	0.126	0.151	0.175
Kinematic viscosity υ [$mm^2\cdot s^{-1}$]	3.43	8.11	11.50
Specific heat c_p [$J\cdot kg^{-1}\cdot K^{-1}$]	2187	2149	2259
Density ρ [$kg\cdot m^{-3}$]	832	926	880
Thermal expansion β [K^{-1}]	0.00080	0.00079	0.00080
Heat transfer factor $\alpha_{pap-liquid}$ [$W\cdot m^{-2}\cdot K^{-1}$]	141.65	127.51	126.17

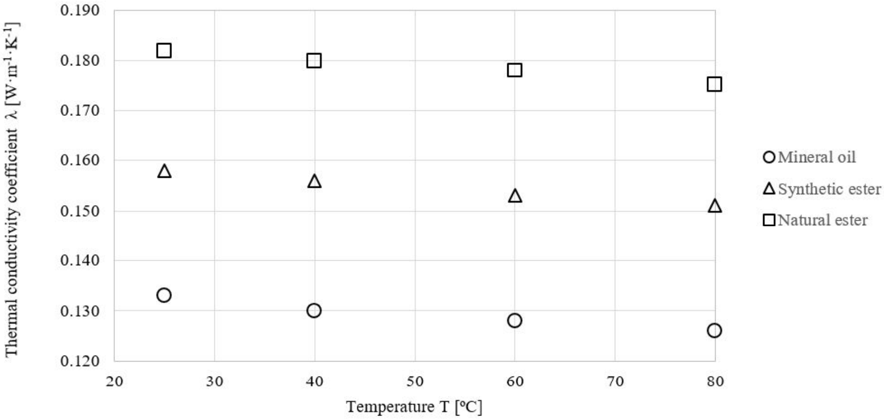

Fig. 1. Dependence of thermal conductivity coefficient λ of the type of liquid and the temperature *T*

Comparing the results of measurements of thermal conductivity λ of analyzed liquids it can be concluded that the esters, regardless of the temperature, have a much higher coefficient λ in relation to the mineral oil. At a temperature 25°C thermal conductivity of synthetic ester was higher by 18.8%, and natural ester was higher by 36.8% of the thermal conductivity of the mineral oil. In turn, at a temperature of 80°C thermal conductivity of synthetic ester was higher by 19.8%, and natural ester was higher by 38.9% of thermal conductivity of the mineral oil.

Thermal conductivity is caused by the random motion of particles and atoms and connected with it return of energy during the collision. In the synthetic and natural ester, due to the stronger interaction with another molecules, distances between the molecules are smaller than in case of mineral oil, so that transfer of kinetic energy is facilitated.

With increasing temperature from 25°C to 80°C the decrease in thermal conductivity of all the analyzed insulating liquids was noticeable. In case of mineral oil thermal conductivity decreased by 5.3%, in case of synthetic ester by 4.4%, and in case of natural ester by 3.8%.

Thermal conductivity of analyzed insulating liquids decreases with the increase of temperature due to increased distance between the molecules of the liquid. Increase in the distance makes it difficult transfer of kinetic energy with the result that the thermal conductivity of the liquid decreases.

On the basis of measurement (Tab. 1 and Fig. 2) results it can be seen that the mineral oil was characterized by lowest kinematic viscosity, regardless of temperature. At a temperature of 25°C kinematic viscosity of the synthetic ester was 223% and natural ester was 230% greater than kinematic viscosity of mineral oil. In turn, at 80ºC, kinematic viscosity of synthetic ester was 136% and natural ester was 235% greater than kinematic viscosity of the mineral oil.

Kinematic viscosity of the liquid results from their chemical structure. Higher viscosity of synthetic and natural ester was probably associated with stronger intermolecular interactions. Stronger interactions result that forces internal friction in the esters are much greater than the friction forces in mineral oil.

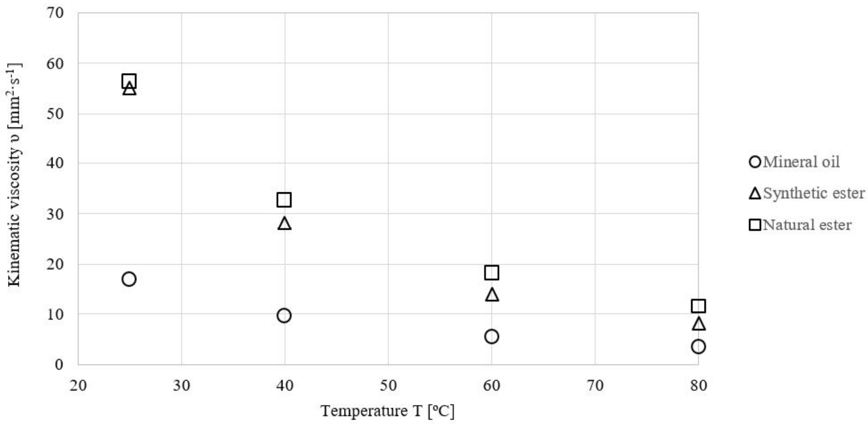

Fig. 2. Dependence of the kinematic viscosity υ of the type of liquid and the temperature T

An increase in temperature from 25ºC to 80ºC resulted in a significant decrease of kinematic viscosity υ analyzed insulating liquids. In case of mineral oil kinematic viscosity decreased by 80%, in case of synthetic ester by 85%, and in case of natural ester by 80%. The decrease in viscosity of the liquid, caused by the higher temperature, is connected with reducing the forces of attraction between molecules of the liquid due to increase of their kinetic energy. The energy of particles increases due to the temperature rise. At higher temperatures, particles move at higher speeds, which weakens the intermolecular forces. As a results, internal friction forces are diminished and viscosity is reduced.

As shown in Table 1 and in Figure 3 natural ester has the highest specific heat c_p. At a temperature of 25ºC specific heat of synthetic ester was 0.2%, and natural ester was 6.6% greater than specific heat of mineral oil. In turn, at a temperature of 80°C specific heat of synthetic ester was 1.7% lower, and natural ester was 3.3% greater than the specific heat of mineral oil.

Specific heat is directly connected to heat capacity of the substance. Heat capacity determines the amount of energy that particles of the substance may adopt. The heat capacity is a function of the degrees of freedom of the molecule. It means that the larger the particle, the greater number of degrees of freedom are their characteristics. Natural ester and mineral oil particles are larger than synthetic ester particles, which means that they can store more energy. If the molecule can take more energy (because it has more degrees of freedom), it is characterized by enhanced heat capacity. In turn, if heat capacity of the substance is higher, the specific heat is greater.

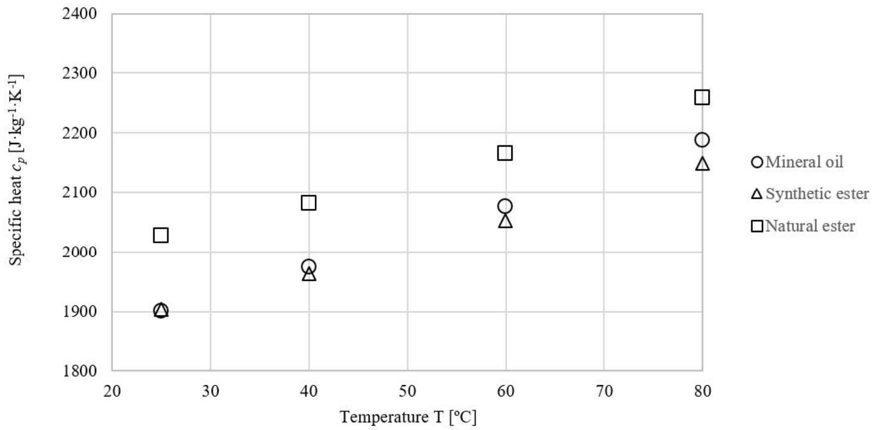

Fig. 3. Dependence of the specific heat c_p of the type of liquid and the temperature T

The increase in temperature from 25°C to 80°C caused the increase of specific heat c_p of analyzed insulating liquids. In case of mineral oil, the specific heat increased by 15%, in case of synthetic ester by 13%, and in case of natural ester by 11%.

Specific heat of insulating liquids increases with temperature because kinetic energy and potential oscillations of atoms of molecules of insulating liquid also increases (it is possible more degrees of freedom). The kinetic energy is higher, that the rate of moving particles is greater.

Analyzing the density (Tab. 1 and Fig. 4) of test insulating liquids it can be concluded that mineral oil, independently of the temperature, has the smallest density. At a temperature of 25°C density of synthetic ester was 11.2%, and natural ester was 5.8% greater than the density of mineral oil. In turn, at a temperature of 80°C density of synthetic ester was 11.3%, and natural ester was 5.8% greater than the density of mineral oil.

The density of a substance is associated with the intermolecular interactions and results from their construction. Higher density of esters resulted from the fact that the forces of intermolecular interactions in the esters are probably greater than the forces of intermolecular interactions in mineral oil. Larger intermolecular forces in esters cause that molecules of esters are not distanced from each other as particles of mineral oil. Because the particles in mineral oil are spaced further apart, the volume is greater, and density is smaller.

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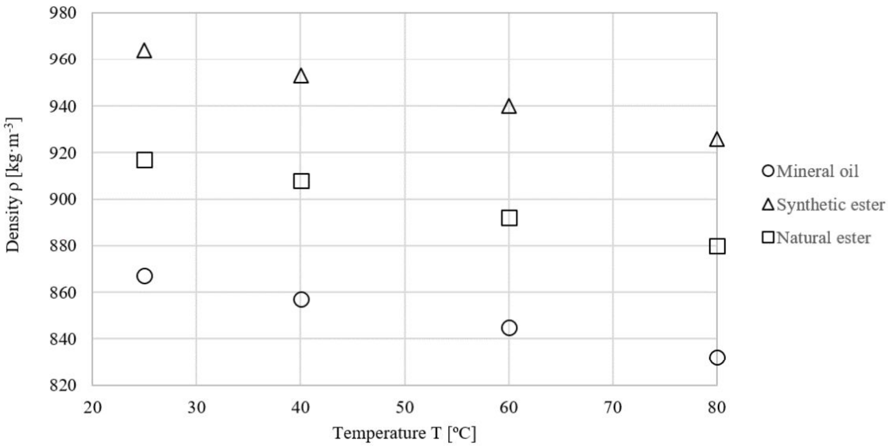

Fig. 4. Dependence of the density ρ of the type of liquid and the temperature *T*

The increase in temperature from 25ºC to 80ºC resulted in a decrease of density ρ of all analyzed insulating liquids. In case of mineral oil, the density decreased by 4.0% in case of synthetic ester by 3.9%, and in case of natural ester by 4.0%.

The density of the insulating liquids decreases as temperature rises because the liquids particles move at higher speeds. Higher particle velocity of liquids caused reduces intermolecular forces. Consequently, particles move away from each other thereby causing an increase the volume of liquid. The increase in volume of the liquid causes a decrease in its density.

On the basis of information in Table 1 and in Figure 5 it is possible concluded that thermal expansion of analyzed insulating liquids is comparable. At a temperature of 25ºC thermal expansion of synthetic ester was 1.3% higher and natural ester was 1.3% lower than thermal expansion of mineral oil. In turn, at a temperature of 80ºC thermal expansion of the synthetic ester was 1.3% lower than the extensibility of mineral oil. Thermal expansion of natural ester was equal to thermal expansion of the mineral oil. The differences in thermal expansion of each liquid, as in case of density, resulted from the difference in strength of intermolecular interactions.

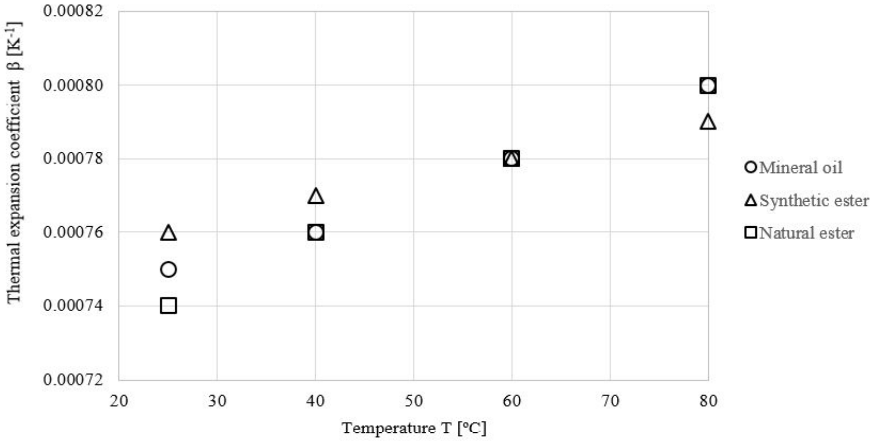

Fig. 5. Dependence of the thermal expansion β of the type of liquid and the temperature T

The temperature increase from 25°C to 80°C resulted in an increase in thermal expansion coefficient β of all analyzed insulating liquids. In case of mineral oil thermal expansion increased by 6.7%, in case of synthetic ester by 4.0%, and in case of natural ester by 8.1%.

The growth in thermal expansion coefficient of the liquid with the temperature resulted from the fact that molecules of the liquid vibrate with increasing frequency, thereby enhancing their average speed. Particles move away from each other as a result of higher speeds. Therefore, with increasing distance between the liquid molecules spatial dimensions of liquid are increased.

On the basis of the above described thermal properties, using the formula (1), the heat transfer coefficient by the liquid at the surface of paper insulation of windings was determined. As is apparent from Table 1 and Figure 6, at temperature 25°C factor $\alpha_{pap\text{–}liquid}$ of synthetic ester was 16.2%, natural ester was 11.8% less than the factor $\alpha_{pap\text{–}liquid}$ of mineral oil. In turn, at a temperature of 80°C factor $\alpha_{pap\text{–}liquid}$ of synthetic esters was 10.0%, and natural esters was 10.9% lower than the factor $\alpha_{pap\text{–}liquid}$ of mineral oil. As we can see, at the surface of paper windings insulation, independently of the temperature, the mineral oil was characterized by the highest heat transfer factor.

The increase in temperature from 25°C to 80°C resulted in an increase in heat transfer factor $\alpha_{pap\text{–}liquid}$ of all analyzed insulating liquids. In case of mineral oil, heat transfer factor increased by approximately 51%, in case of synthetic ester by about 63%, and in case of natural ester by about 51%. As we can see, at the surface of paper windings insulation, independently of the temperature, the mineral oil was characterized by the highest heat transfer factor.

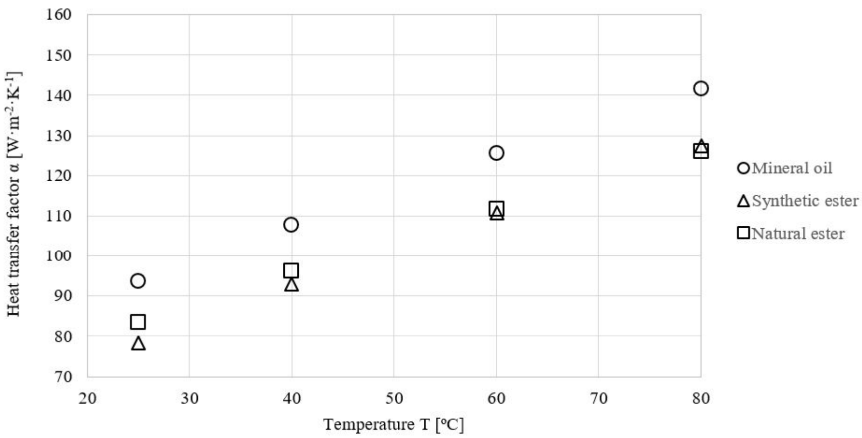

Fig. 6. Dependence of the heat transfer factor α of the type of liquid and the temperature T

4. Summary

On the basis of the measurements and calculations it can be concluded that mineral oil is characterized by highest heat transfer factor $\alpha_{pap\text{–}liquid}$. Heat transfer factor of other analyzed insulating liquids was smaller. In case of synthetic ester, depending on the temperature, heat transfer factor was a few percent (10–16%) less than heat transfer factor of mineral oil. In turn, in case of natural ester heat transfer factor was slightly more than 10% lower than heat transfer factor of mineral oil, independently of the temperature.

The higher value of heat transfer factor by mineral oil resulted from its thermal properties. Specific heat, density and thermal expansion of all analyzed insulating liquids were similar. They have had no significant effect on the differences of heat transfer factor. Thermal conductivity of both types of esters was by several dozen percent greater than the conductivity of mineral oil. Thus, its effect on the heat transfer factor of esters was preferred. In turn, kinematic viscosity of the ester was hundreds of percent greater than the viscosity of the oil. This fact caused that heat transfer factor had the highest value in case of mineral oil.

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