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Analysis of heat transfer coefficient of synthetic and natural ester in the aspect of their application in power transformer

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Insulating liquids due to their properties are used in electrical power transformers, capacitors, connectors and high voltage power cables. One of the most important tasks for electrical insulating liquids is a heat transport out of the device. The heat transfer in the liquids depends on heat transfer coefficient. The heat transfer coefficient depends on a viscosity, thermal conductivity coefficient and thermal expansion coefficient. This paper shows results of calculations for heat transfer coefficient of insulating liquids used as insulation in electrical equipment, depending on the kind of liquid and temperature. Synthetic ester oil and natural ester oil were analyzed. The range of the temperature was changing from 25°C to 80°C.

KEYWORDS: heat transfer coefficient, high voltage power transformers, synthetic ester, natural ester

1. Introduction

One of the most important and expensive elements of electrical grid is high voltage power transformer. From its action depends proper functioning not only overhead power line but also many industrial equipment. The main task of power transformer is distribution and delivery of energy power at voltages, which are the best for the economy. Hence, the most fundamental matter is proper design and construct from the mechanical and thermal hand. At stage of design power transformer, the constructor must pay attention at many factors, which may have influence on his proper functioning. These factors include chiefly temperature of windings and insulation system in which the power transformer will be worked. The temperature is crucial for exploiting electrical equipment.

The insulation system of power transformers consists of solid insulation and insulating liquid. The solid insulation mainly consists of hard insulation, which is made of pressboard (sleeves, wedges, handlebars, etc.) and soft (paper on a transformer windings), whereas the mineral oil is used as the insulating liquid. However due to multiple breakdowns, which causing a threat for human life and health, contamination of soil and water, the producers of power transformers have been forced to carry out researches on alternative to mineral oil [1]. In the past synthetic oils PCB were also used (Polychlorinated biphenyl) but due to their carcinogenic properties. The European Union was decided to withdraw whole equipment with PCB. [2]. Synthetic and natural esters are become an alternative to mineral oil. They are characterized by very good thermal properties, biodegradability and moreover they are flame retardant [3, 4].

Both oil mineral and the alternatives insulating liquids such as synthetic and natural esters could be used in many applications. In the Table 1.1 the use of selected insulating fluids in the different types of electrical power equipment was presented. According to the table, the mineral oil is the most popular insulating liquid in electrical power equipment. Nowadays, the synthetic esters are being widely used only in case distribution transformer and traction transformer less often in power transformer. Presently, are not being used in the instrument transformers. Now, natural esters are being widely utilized only in distribution transformers, less often in power transformers. Currently, they are not being used in the case of traction transformers, and instrument transformers

Table 1.1. Application of different insulating liquid in electrical power equipment [4]

Kind of devices	Mineral oil	Synthetic esters	Natural esters
Power transformers	largely used	used but less common	used but less common
Traction transformers	largely used	largely used	currently not used
Distribution transformers	largely used	largely used	largely used
Instrument transformers	largely used	currently not used	currently not used

The insulating liquid together with the part made of cellulose creates a paper-liquid insulating system. Insulating liquids should be characterized by a high resistivity and breakdown voltage, low dielectric loss factor tgδ, high stability of electrical insulation properties and physicochemical and moreover indifference to construction materials and insulating [5].

This paper presents the results of calculations of heat transfer coefficient for a synthetic and natural ester. This factor determines the cooling efficiency of electrical power devices.

2. Heat transfer

In this chapter the way of heat transfer in power transformer and insulating liquids has been presented.

One of the most important tasks of insulating liquids is transfer of heat, which was produced during a operation. Energy losses are being caused by constantly remagnetizing of the core and the current flow through the windings of power transformer. The loss appears as a heat, which is causing heating up respective construction parts of the power transformer. On account of way the heat transfer in electrical equipment, component parts of power transformer could be divided on the two parts. In the first part, the heat is only produced for example in core and windings. In the second part the heat is transmitted for instance in paper, insulating liquids and tank. During the way of heat transfer from inside of power transformer to environment, heat is encountering various bodies: solid, gas and liquid. Heat transfer in solid bodies takes place via thermal conduction. In turn, heat transfer in liquids and gases depend on convection, kind of cooling system of the power transformer, natural or forced circulation of the insulating liquid, which is caused by the differences in density between heated oil and cooled oil. Moreover, outer constructions of the power transformer (tank) are emitting heat to environment due to radiation [6].

The Figure 2.1 presents the distribution of the temperature in the power transformer with the natural cooling system. The heat transfer is taking place on the way: source of the heat → impregnated paper by oil → insulating liquids → tank → air. Because insulating liquid fills the interior of the power transformer and saturates the solid insulation delving into its structure that in large extent corresponding to heat transfer in the power transformer. The heat transfer depends on mainly from two phenomenons. The first phenomenon is connected with the thermal conduction in the paper impregnated by liquid, the second one with taking over heat via liquid [8].

The phenomenon of the thermal conductivity is related to thermal conductivity of impregnated paper via oil and insulating liquid. The thermal conductivity is characterized by thermal conductivity coefficient λ of the paper. In turn, the phenomena of taking over heat in liquids depend on many thermal properties such as: thermal conductivity of liquid λ, viscosity υ, density ρ, specific heat capacity c_p and thermal expansion β. However, coefficient, which characterized thermal properties of the insulating liquids, is heat transfer coefficient α.

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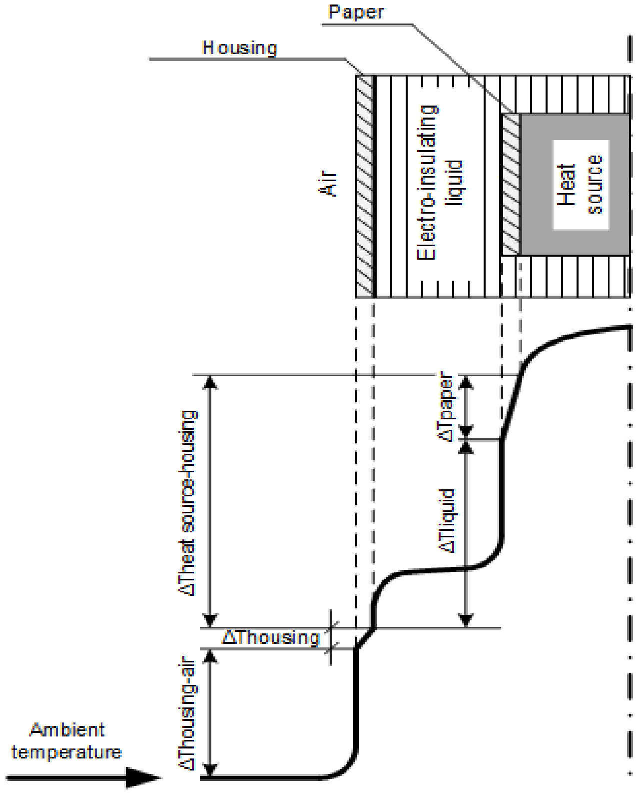

Fig. 2.1. The distribution of the temperature in the power transformer with natural cooling system [7]

Based on the similarity theory for phenomenon related to heat transfer via natural and forced convection could get the following characteristic numbers [9]:

– Nusselt number, determining the movement of heat in the stream of fluid with the penetration of heat through a boundary surface:

$$Nu = \frac{\alpha \cdot \delta}{\lambda} \tag{1}$$

where: α – heat transfer coefficient, δ – the characteristic dimension associated with the fluid flow, λ – thermal conductivity,

– Grashof number, determining the ratio of buoyancy forces to the forces of internal friction of the fluid:

$$Gr = \frac{\beta \cdot g \cdot \delta^3 \cdot \Delta T}{\upsilon^2} \tag{2}$$

where: β – thermal expansion, *g* – gravitational acceleration, ΔT – the temperature difference between the heat source and the temperature of the cooling liquid, υ – viscosity,

– Prandtl number, determining the similarity of fluid:

$$Pr = \frac{\upsilon \cdot \rho \cdot c_p}{\lambda} \tag{3}$$

where: ρ – density.

The equation for natural convection in steady state for heat transfer and liquid flows takes the form:

$$Nu \approx f(Gr,Pr) \tag{4}$$

Taking into account dimensions and the experimental studies on the above functions, it could be written in approximately that:

$$Nu = c \cdot (Gr \cdot Pr)^n \tag{5}$$

where: *n* – constant depending on the nature of convection:, *c* – geometric constant.

Hence heat transfer coefficient *α* is equal:

$$\alpha = c \cdot \lambda^{1-n} \cdot g^n \cdot \delta^{3n-1} \cdot \beta^n \cdot \Delta T^n \cdot \rho^n \cdot c_p{}^n \cdot \upsilon^{-n} \tag{6}$$

In order to ensure the best possible exchange of heat on the way: heat source → environment. This is important that the insulating liquid should be characterized by as high as it is possible coefficient of thermal conductivity and specific heat. In addition, it is also desirable to viscosity, density and thermal expansion should be small.

The temperature rise in the insulating liquid is counted according to equation (7):

$$\Delta T = \frac{q}{\alpha} \tag{7}$$

where: *p* – surface heat load.

Taking into account the parameters from equation (7), the heat transfer coefficient has form:

$$\Delta T = \left(\frac{q}{c \cdot \delta^{3n-1} \cdot \lambda^{1-n} \cdot g^n \cdot \beta^n \cdot v^{-n} \cdot \rho^n \cdot c_p^n} \right)^{\frac{1}{n+1}} \tag{8}$$

On the base on equation above it is possible to say, that the temperature increase in oil depends on surface heat load q, geometric parameters (c, n, δ), gravitational acceleration *g* and thermal properties of liquid (λ, υ, ρ, β, c_p).

3. The heat transfer coefficient – results of the calculations

3.1. Introduction

In this chapter the results of the calculation for the heat transfer coefficient via insulating liquids in electrical power equipment were presented.

For the calculations have been used the following insulating liquids:

– synthetic ester MIDEL 7131 made by M&I Materials,
– natural ester Midel eN made by M&I Materials.

For determine the heat transfer coefficient for insulating liquids the equation (6) was used. The constants of geometric c and n depend on kind of flow, which is described by product of Grashof and Prandtl Numbers and are assumed form like in the Table 3.1.

Table 3.1. Values for the geometric parameters *c* and *n* depend on the type of flow [9-11]

The nature of the flow	**Gr·Pr**	**c**	**n**
No flow	$<10^{-3}$	0,45	0
Laminar flow	$10^{-3} \div 5\cdot 10^{2}$	1,18	0,125
The flow of transition	$5\cdot 10^{-3} \div 2\cdot 10^{7}$	0,54	0,25
Turbulent flow	$>2\cdot 10^{7}$	0,135	0,333

3.2. The heat transfer coefficient in the depending on kind of insulating liquid

In this section of a chapter the results of the calculation of the heat transfer coefficient depending on type of the insulating liquid were described.

The heat transfer coefficient for above insulating liquids was calculated on the basis of literature data and thermal properties of the insulating liquids from the Table 3.2.

It was assumed that the characteristic dimension δ is 1 m, and surface heat load is 1500 [W/m^2], because these values are typical of high-voltage power transformers.

The product of the Grashof and Prandtl number for the insulating liquids is fulfilled for turbulent flow. Hence, geometric constant *c* is set to 0.135, and the constant *n* depends on the nature of the convection and assumes a value of 0.333. On the basis of the measurement, values and from the equations (6) and (8) the heat transfer coefficient for the liquid and the temperature rise in the analyzed insulating liquid filled transformers was calculated.

The thermal properties of the insulating liquids in temperature 60°C in the Table 3.2 were presented. Analyzing the obtained results it could be concluded that the synthetic ester had the highest heat transfer coefficient in the temperature 60°C.

Table 3.2. The thermal properties of the insulating liquids in the temperature 60°C [4]

Thermal properties	**Unit**	**Synthetic Ester**	**Natural Ester**
		MIDEL 7131	**MIDEL eN**
Thermal conductivity *λ*	**W/(m·K)**	0,141	0,172
Viscosity *υ*	**mm^2/s**	14.0	19.4
Specific heat capacity c_p	**J/(kg·K)**	1994	1911
Density *ρ*	**g/l^{-1}**	941	892
Thermal expansion *β*	**1/K**	0,00078	0,00074
Heat transfer coefficient *α*	**$W/(m^2·K)$**	92,94	91,17
Temperature raise ΔT	**°C**	16,14	16,45

In the analyzed temperature, the natural ester was had the heat transfer coefficient about 2% smaller than in comparing to synthetic ester. Taking into account the temperature rise in the analyzed insulating liquids it could be noticed that the temperature of the hot spot in power transformer will be smaller than in case of using the synthetic ester. Thus, in relation to the natural esters, the use of synthetic esters gives better heat transfer from the interior of power transformer.

3.3. Heat transfer coefficient depending on the temperature

In this subsection the results of calculation of the heat transfer coefficient via insulating liquids depending on temperature were presented.

In the Table 3.3 the thermal properties of the synthetic ester and the results of calculation of the heat transfer coefficient via insulating liquids depending on temperature were shown. Based on the results of calculation it could be concluded, that together with temperature rise also rising heat transfer coefficient synthetic ester, and hence its ability to heat transfer. This is connected all above with the significant increase in viscosity and a certain increase of the specific heat capacity and thermal expansion, which is accompanied temperature rise. The growth of the heat transfer coefficient is desired, because in the case of rising load of electrical power equipments also the temperature is rising in their interior. Increasing the heat transfer coefficient insulating liquid allowing for more effective cooling.

The thermal properties of the natural ester and the results of heat transfer coefficient calculation depending on temperature were presented in Table 3.4. Based on the results of calculation it could be concluded, that together with the temperature rise, same like for synthetic ester, the heat transfer coefficient for natural esters is growing. This is mainly due to a significant decrease in viscosity and an increase in specific heat capacity and thermal expansion of natural esters.

Table 3.3. The thermal properties for synthetic ester depending on temperature [4, 12]

Thermal properties	Unit	Temperature			
		20°C	40°C	60°C	80°C
Thermal conductivity *λ*	**W/(m·K)**	0,144	0,143	0,141	0,139
Viscosity *υ*	**mm²/s**	70	28	14	8
Specific heat capacity c_p	**J/(kg·K)**	1880	1933	1994	2023
Density *ρ*	**g/l^{-1}**	0,97	0,956	0,941	0,926
Thermal expansion *β*	**1/K**	0,00075	0,00077	0,00078	0,00079
Temperature raise ΔT	**°C**	24,28	19,19	16,14	14,09
Heat transfer coefficient *α*	**$W/(m^2·K)$**	61,78	78.17	92,94	106,41

Table 3.4. The thermal properties for natural ester depending on temperature [4, 12]

Thermal properties	Unit	Temperature			
		20°C	40°C	60°C	80°C
Thermal conductivity *λ*	**W/(m·K)**	0.177	0.175	0.172	0.167
Viscosity *υ*	**mm²/s**	84.08	37.0	19.4	12.3
Specific heat capacity c_p	**J/(kg·K)**	1849	1879	1911	1947
Density *ρ*	**g/l^{-1}**	918	905	892	879
Thermal expansion *β*	**1/K**	0.00071	0.00073	0.00074	0.00076
Temperature raise ΔT	**°C**	23.66	19.24	16.45	14.79
Heat transfer coefficient *α*	**$W/(m^2·K)$**	63.39	77.96	91.17	101.46

Analyzing the temperature rise of the hot spot in power transformer in respect to insulating liquid, presented in the Tables 3.3 and 3.4, it could be said that the temperature of hot spots will be the highest in case of using natural ester, which temperature is equal 80°C. Then the hot spot reaches a temperature equal to 94,79°C. The use of synthetic ester would allow the reduction of this temperature to 94.09°C, that is about 0.7°C.

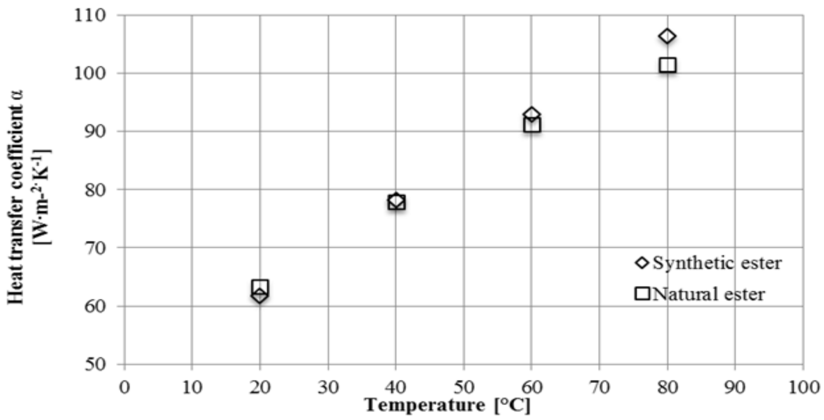

Fig. 3.1. The heat transfer coefficient α for synthetic esters and natural ester, depending on the temperature

The heat transfer coefficient for synthetic and natural esters in the Figure 3.1 was presented. As apparent from the figure, in the temperature 20°C, natural esters were characterized by the highest heat transfer coefficient. In turn, in the temperature range from 40°C to 80°C, the synthetic ester has a higher heat transfer coefficient α.

4. Summary

The efficiency of electrical power equipment cooling system depends on the heat transfer coefficient of insulating liquid. In turn, the heat transfer coefficient depends on thermal conductivity, viscosity, density, specific heat coefficient and thermal expansion. The higher thermal conductivity, specific heat capacity, density and thermal expansion are, the more effective the transport of heat to environment through the insulating liquid is. In turn, the higher viscosity is, the worse heat transfer is.

On the base of calculation it could be said, that the natural ester was characterized the highest heat transfer coefficient in the 20°C temperature. In turn, in range of temperature from 40°C to 80°C the synthetic ester has the highest heat transfer coefficient. It means that, in this range of temperature, synthetic esters in relation to natural esters are enabling more effective heat transfer outside the electrical power equipment.

Together with the temperature rise of synthetic ester to 80°C, its the heat transfer coefficient also rising to about 70%, in relation to 20°C. In turn, the heat transfer coefficient for natural ester in the temperature 80°C, is about 60% bigger than heat transfer coefficient in temperature 20°C. The growth of coefficient alpha is associated with decline of viscosity, the increase in specific heat transfer coefficient and thermal expansion for the above mentioned insulating liquids.

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