Heat transfer coefficient as parameter describing ability of insulating liquid to heat transfer

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Abstract. The paper presents the results of the measurements of heat transfer coefficient of insulating liquids used in transformers. The coefficient describes an ability of the liquid to heat transport. On the basis of the coefficient, effectiveness of cooling system of electric power devices can be estimated. Following liquids were used for the measurements: mineral oil, synthetic ester and natural ester. It was assumed that surface heat load is about 2500 $W \cdot m^{-2}$, which is equal the load of transformer windings. A height of heat element was 1.6 m, because it makes possible steady distribution of temperature on its surface. The measurements of heat transfer coefficient was made as a function of various position of heat element (vertical, horizontal). In frame of horizontal position of heat element, three suppositions were analysed: top, bottom, and side.

1 Introduction

Proper work of high voltage transformers depends on many factors. One of them is relatively low operating temperature, which is provided by effective cooling system [1-3]. The system consists of insulating liquid, which fills all free space and gaps in transformer. Heat transfer coefficient α determines the ability to heat transfer of the liquid. The bigger value of the coefficient, the more effective heat transfer between source of the heat and environment.

Knowledge of coefficient α of insulating liquid is essential at the design stage of the transformer (computer optimization) [4,5]. It can be also useful for transformers diagnostics [6,7]. It is assumed, that coefficient α is basically constant, and depends only on temperature. Meanwhile, reconnaissance research of the paper authors has shown that the coefficient α depends on many other factors, such as type of insulating liquids (mineral oil, synthetic ester, natural ester), the position of the heating element (vertical, horizontal), the length of the heating element and surficial heat load value. Disregard of the factors may lead to incorrect design of the transformer, which can result in increased temperature of work. Increased temperature is a reason of intensive ageing process of insulating system of transformers. The increase of temperature of several degrees results in a double reduction in the lifetime of the transformer.

According of Montsinger law (law of 8 degrees), reliability of paper insulation, impregnated with mineral oil, as a function of temperature, is described by following formula [8,9]:

$$t = 7.154 \cdot 10^4 \cdot e^{-0,0865 \cdot T} \qquad (1)$$

where:

t – absolute lifetime of transformer insulation [years],
T – insulation work temperature [°C].

The law is based on the initial assumption that at a temperature of 95 °C lifetime of insulation transformer is 20 years. Such a lifetime is adopted by many transformer designers. This law specifies the lifetime of transformer insulation working in any temperature. The name of “the law of 8 degrees” means that the increase or decrease in temperature of 8 °C will result in, respectively, double shortening or lengthening the lifetime of transformer insulation (Fig. 1). At temperature of 95 °C the lifetime of transformer insulation is 20 years. At a temperature of 8 degrees lower (87 °C) the lifetime is twice as long and is 40 years, and a temperature of 8 degrees higher (103 °C) the lifetime is twice less and is only 10 years. Some drawback of Montsinger law is that the law does not consider other factors such as moisture and oxygen influence [10,11].

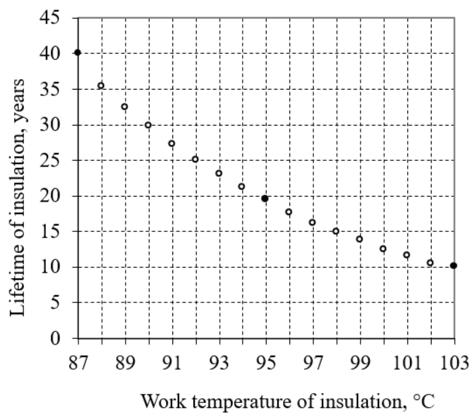

Fig. 1. Lifetime of transformer insulation t as a function of work temperature T according to the Montsinger law of 8 degrees, based on formula (1).

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DOI: 10.1051/e3sconf/20171901026

Bussing and Arrhenius-Dankin formulas, used in US to evaluate the influence of temperature on ageing process of insulation system made from organic materials, are similar in physical sense to Montsinger law [12,13].

2 Aim and range of investigation

The purpose of the research is the determination of heat transfer coefficient α of insulating liquid as a function of the liquid type and position of heating element. Following liquids were investigated: mineral oil (Nynas Draco), synthetic ester (Midel 7131) and natural ester (Envirotemp FR3). All material parameters of mentioned liquids are described in authors papers [1-3,14-17]. Vertical and horizontal positions of the heating element were analyzed. In frame of horizontal position of the element, three positions of cooling surface relative to the heating element (top, bottom, side – Fig. 2) were investigated. Each measurement was repeated three times.

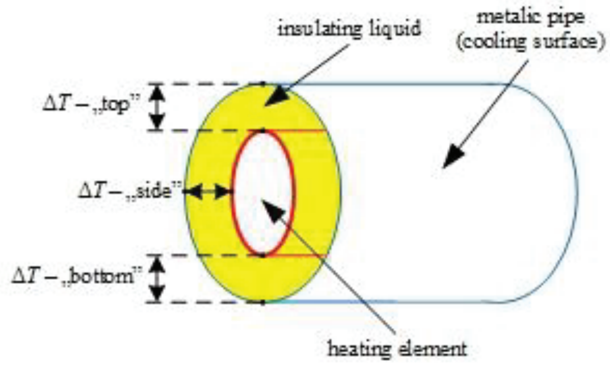

Fig. 2. Three positions of cooling surface relative to the heating element: top, bottom, and side.

3 Measurement system

Measurement system consists of heat model of transformer (Fig. 3), temperature sensors and a system to register a temperature. Heat model of transformer consists of the heating element and metallic pipe (cooling surface). Space between metallic pipe and the heating element was filled by insulating liquid.

Height of metallic pipe was 2 m, its diameter was 88.9 mm, the thickness of the pipe wall was 3.2 mm. The heating element was electric heater, its length was 1.6 m, and its diameter was 22 mm. Lateral surface of the heating element was 0.11 m^2. All mentioned data were necessary to calculate surficial heat load p (formula (2)). Space between the heating element and metallic pipe was filled by the liquid with volume 8 liters.

Two sensors to measure temperature were placed on external surface of the heating element and external surface of metallic pipe. The temperature difference ΔT, measured using the sensors, was temperature decrease necessary to calculate heat transfer coefficient α of the liquid, using following formula:

$$\alpha = p \cdot (\Delta T)^{-1} \qquad (2)$$

where:
α – heat transfer coefficient of insulating liquid [$W \cdot m^{-2} \cdot K^{-1}$],
p – surface heat load [$W \cdot m^{-2}$],
ΔT – temperature decrease in insulating liquid [K].

Authors decided to place one of the sensors on external surface of metallic pipe, because it was more convenient, comparing to internal surface of the pipe. In this case, measured temperature difference ΔT consists of two temperature differences: in liquid and in the pipe. However, temperature difference in metallic pipe is much smaller comparing to the difference in liquid, what is caused by relatively big thermal conductivity λ of the metal. Finally, temperature difference in the pipe can be omitted.

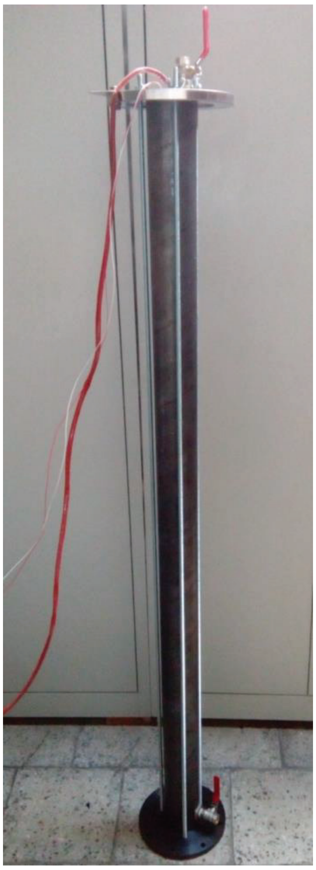

Fig. 3. Picture of measurement system: metallic pipe filled by insulating liquid, the heating element placed inside metallic pipe.

Applied voltage to the heating element was 101 V, applied current was 2.75 A. Surface heat load on lateral surface of the heating element was 2525 $W \cdot m^{-2}$.

Temperature on the heating element surface, and on metallic pipe surface, was stable after about 5 hours.
In order to increase an accuracy of measurement, registration of temperature using the sensors was made after 6 hours since the voltage was applied on the heating element.

DOI: 10.1051/e3sconf/20171901026

4 Results

Table 1 presents measurement results of heat transfer coefficient α of insulating liquid as a function of liquid type and position of the heating element.

Independently from position of the heating element, mineral oil has the biggest heat transfer coefficient *α*. The coefficient *α* of mineral oil was a dozen percent bigger than the coefficient *α* of natural and synthetic esters. For example, for vertical position of the heating element, coefficient *α* for mineral oil was 115.9 $W \cdot m^{-2} \cdot K^{-1}$, and for natural ester was 93.5 $W \cdot m^{-2} \cdot K^{-1}$ – about 19% smaller. So big difference results in different temperature decrease ΔT in the liquid. The decrease ΔT for mineral oil was 21.8 °C, and for natural ester was 27.0 °C (Table 1). It means that in case of transformer filled with natural ester, temperature will be bigger by more than 5 °C, compared to transformer filled with mineral oil. So big difference of temperature will make the ageing process of transformer insulation system faster, it means it will make the ageing process of whole transformer faster. Low viscosity of mineral oil, comparing to viscosity of both types of esters, is a reason of the biggest heat transfer coefficient *α* of the oil.

Table 1. Heat transfer coefficient *α* of insulating liquid as a function of liquid type and position of the heating element, estimated using temperature decrease measurements; T_1 – temperature on cooling surface [ºC], T_2 – temperature on the heating element [ºC], ΔT – temperature decrease in liquid [ºC], α – heat transfer coefficient of the liquid [$W \cdot m^{-2} \cdot K^{-1}$].

Liquid type	Position of the heating element	Position of cooling surface	T_1	T_2	ΔT	α
Mineral oil Nynas Draco	vertical	-	75.5	97.3	21.8	115.9
	horizontal	top	69.1	82.3	13.2	190.8
		side	64.3	80.1	15.8	160.2
		bottom	57.4	73.9	16.5	152.7
Natural ester Envirotemp FR3	vertical	-	77.4	104.4	27.0	93.5
	horizontal	top	68.4	84.2	15.8	159.5
		side	63.8	81.7	17.9	140.8
		bottom	57.3	76.1	18.8	134.3
Synthetic ester Midel 7131	vertical	-	75.3	101.5	26.2	96.6
	horizontal	top	66.3	84.1	17.8	142.1
		side	64.0	81.7	17.7	142.7
		bottom	57.5	75.7	18.2	138.5

Comparing natural and synthetic esters it is possible to say that coefficient *α* of synthetic ester was a few percent bigger than coefficient *α* of natural ester. Horizontal position (top position of cooling surface relative to the heating element) was an exception. In this case, coefficient *α* of natural ester was bigger than coefficient *α* of synthetic ester.

On the basis of measurement results it can be concluded that type of used insulating liquid has some influence on heat transfer coefficient *α* of the liquid. From the point of view of the effectiveness of transformer cooling system, the use of mineral oil is more efficient, compared with synthetic or natural esters. In turn, comparing natural and synthetic esters, it can be said that there is no difference between the esters from coefficient α point of view.

Obtained results are consistent with other results of authors described in their papers [14-17]. In the papers, heat transfer coefficient α was calculated on the basis of measurements of five thermal properties of the liquid: thermal conductivity λ, specific heat c_p, viscosity υ, density ρ, and thermal expansion coefficient β.

Independently from type of the liquid, bigger heat transfer coefficient *α* was for horizontal position of the heating element, comparing with vertical position. For example for mineral oil, for vertical position coefficient *α* was 115.9 $W \cdot m^{-2} \cdot K^{-1}$, and for horizontal position (top position of cooling surface relative to the heating element) coefficient *α* was 190.8 $W \cdot m^{-2} \cdot K^{-1}$ – about 65% bigger. In first case, temperature decrease in mineral oil ΔT was 21.8 °C, and in second case ΔT was 13.2 °C (Table 1). Difference of temperature decreases ΔT was 8.6 °C in favor of the horizontal position of the heating element. These differences probably result of path length, which must be done by hot liquid from the heating element to cooling surface.

In case of vertical position of the heating element, the path is relatively long, because it is equal to the length of the heating element and a length of metallic pipe. In turn, for horizontal position of the heating element, the path of hot liquid from the heating element to cooling surface is relatively very short, almost equal to the thickness of the liquid.

Analyzing three variants of horizontal position of the heating element, it must be concluded that heat transfer coefficient *α* is the biggest in case of variant of top position of cooling surface relative to the heating element. In turn, coefficient *α* is the smallest in case of variant of bottom position of cooling surface relative to the heating element. In first case, transfer of heat is based on natural convection phenomenon – the move of hot liquid from the heating element up to cooling surface. In second case, transfer of heat is not based on natural convection, because hot liquid is on top (close to the heating element), and cool liquid is bottom (close to cooling surface). That is why transfer of heat in based mainly on thermal conductivity phenomenon. For example, for mineral oil, coefficient *α* was 190.8 $W \cdot m^{-2} \cdot K^{-1}$ for variant of top position of cooling surface relative to the heating element, and only 152.7 $W \cdot m^{-2} \cdot K^{-1}$ (about 20% smaller) for variant of bottom position of cooling surface relative to the heating element. Temperature decrease ΔT was 13.2 °C in first case, and 16.5 °C in second case. Difference of temperature

 DOI: 10.1051/e3sconf/20171901026

decreases ΔT was 3.3 °C in favor of the variant of top position of cooling surface relative to the heating element.

On the basis of mentioned results, it can be said that position of the heating element has significant influence on heat transfer coefficient α of the liquid. Horizontal position makes that coefficient α is tens of percent bigger than coefficient α for vertical position. In turn, in frame of horizontal position, heat transfer coefficient α is the biggest for variant of top position of cooling surface relative to the heating element.

5 Conclusions

Type of used insulating liquid has some influence on heat transfer coefficient α of the liquid. Mineral oil has much bigger heat transfer coefficient α compared to natural and synthetic esters. Comparing natural and synthetic esters, it must be concluded that there is no difference between the esters from coefficient α point of view.

Position of the heating element has influence on heat transfer coefficient α of the liquid. Horizontal position makes that coefficient α is tens of percent bigger than coefficient α for vertical position. In case of horizontal position, heat transfer coefficient α is the biggest for variant of top position of cooling surface relative to the heating element, comparing to other variants.

The research was financed from resources of the Ministry of Science and Higher Education for statutory activities No. 04/41/DS-PB/4293, name of the task: The Influence of Various Parameters on Thermal Properties of Dielectric Liquids Used in High Voltage Transformer

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