MEASUREMENT OF THERMAL CONDUCTIVITY COEFFICIENT OF INSULATING LIQUIDS USING AUTHORING MEASUREMENT SYSTEM

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Abstract. The paper presents the results of measurements of the thermal conductivity coefficient of the selected insulating liquids according to the temperature. The value of the thermal coefficient of tested insulating liquids at temperatures from 20°C to 100°C was determined. Measurement of thermal conductivity was conducted by the use of presented authoring measurement system. The obtained results are essential to the design of power devices structures.

Keywords: thermal conductivity coefficient, insulating liquids, measurement techniques

POMIAR WSPÓŁCZYNNIKA PRZEWODNOŚCI CIEPLNEJ WŁAŚCIWEJ CIECZY ELEKTROIZOLACYJNYCH Z WYKORZYSTANIEM AUTORSKIEGO UKŁADU POMIAROWEGO

Streszczenie. W artykule przedstawione zostały wyniki pomiarów współczynnika przewodności cieplnej właściwej wybranych cieczy elektroizolacyjnych w zależności od temperatury. Określona została wartość współczynnika przewodności cieplnej badanych cieczy elektroizolacyjnych w przedziale temperatury od 20°C do 100°C. Pomiar przewodności cieplnej przeprowadzono przy wykorzystaniu przedstawionego autorskiego układu pomiarowego. Uzyskane wyniki są istotne z punktu widzenia projektowania konstrukcji urządzeń elektroenergetycznych.

Słowa kluczowe: przewodność cieplna właściwa, ciecze elektroizolacyjne, technika pomiarowa

Introduction

Power transformer is one of the most expensive and the most important power devices used for the transmission and distribution of electricity. For over a hundred years, for providing appropriate conditions of isolation and cooling, the power transformers are filled with mineral oils. Unfortunately, mineral oils are characterized by poor thermal properties, including a low thermal conductivity coefficient whereby, their cooling properties are not sufficient in many cases.

Several years ago there was the concept of using natural and synthetic esters in high voltage power transformers in place of heretofore applied mineral oils. The trend in the use of esters as insulating liquids results mainly from the increasingly restrictive regulations concerning environmental protection and the conditions of safe use of the power devices.

Natural and synthetic esters, unlike mineral oil, have a high coefficient of biodegradability and high flash point and burning, which makes them non-flammable liquids. Unfortunately, poor diagnosis of thermal properties of natural and synthetic esters is one of the main contraindications in their use. Currently, the use of natural and synthetic esters, due to their high price and poor identified properties, confined almost only to the distribution transformers installed in densely populated areas or particular fire hazard [3].
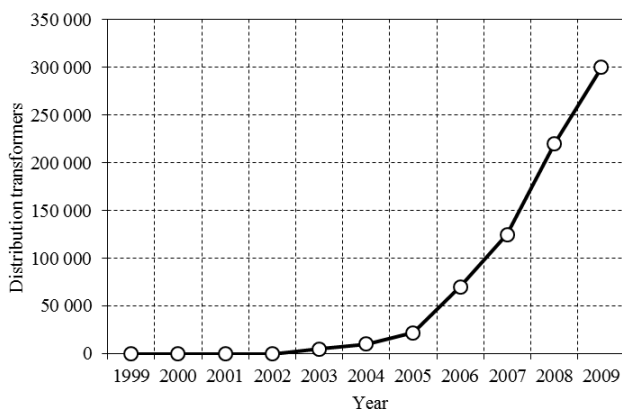

Fig. 1. Amound of distribution transformers in service filled with natural esters – worldwide [3]

Figure 1 shows the increase in the use of natural esters in distribution transformers installed worldwide. Since 2003, the diametrical growth in the number of distribution transformers

filled with natural ester is recorded. Recently, a tendency to use of natural and synthetic esters in power transformers is also observed. However, their use has been limited mostly to situations that require a high level of fire protection and environment protection.

One of the key properties of thermal insulating liquids, which affect their ability to transport of heat, is the thermal conductivity coefficient. The thermal conductivity coefficient determines the amount of heat flowing through the cube with the edges of 1 m, within 1 s, and the temperature drop between the opposite faces of a cube equal to 1 K [6, 10].

Measurement of thermal conductivity of natural and synthetic esters is significant in terms of comparison of thermal conductivities of esters and previously used mineral transformer oils. For this purpose, system for measuring the thermal conductivity of the liquids was designed, constructed and tested. This article is dedicated to the measurements of the thermal conductivity coefficient λ using authoring measurement system.

1. Authoring measurement system

The chapter presents the authoring system for measuring thermal conductivity coefficient λ of insulating liquids. The concept of measuring the thermal conductivity coefficient using designed measurement system was also presented.

The measuring concept of thermal conductivity coefficient is to call in the sample of tested liquids thermal disturbances and to observe changes of the temperature distribution. In other words, the thermal conductivity coefficient λ is determined by passing through the sample of tested liquids specific heat flux and observing the changes of the temperature distribution on both sides at a fixed heat flow [7].

Figure 2 shows the authoring measurement system used to determine the thermal conductivity coefficient of liquids. Designed and built measurement system allows to call the thermal disorder ΔT, and to measure it in the sample of tested liquids with the thickness d and the surface area S. Suitable thermal disturbance in the sample is obtained by using a heat source with power P and the use of the cooling system. On the basis of above mentioned values thermal conductivity coefficient of liquids is determined from the formula:

$$\lambda = \frac{P}{S} \cdot \frac{d}{\Delta T} \qquad (1)$$

For measurement, a sample of the liquid should be placed between the main heater and cooler. It was assumed that the thickness d of the surface area S of all tested samples of liquid will be the same. The main heater with power P and surface area S is

designed to produce heat flux flowing through a sample of the liquid to the cooler. Heat flow generates temperature drop ΔT in the sample liquid. The task of the cooler is to provide a constant temperature on the lower surface of the tested liquid. The measurement of temperature fall ΔT and power readout of main heater occurs with a fixed heat flux. Knowing all of the physical quantities, using the formula (1) the thermal conductivity of the tested insulating liquids is defined. The correctness of the measurement is determined by the elimination of lateral heat loss and heat loss vertically upwards. Main heater should ensure the flow of heat perpendicularly down through the liquid sample. For this purpose, secondary heater which eliminates heat flow vertically upwards, or produces a heat flux, which causes the temperature values recorded directly above the main heater and the auxiliary heater are equal.
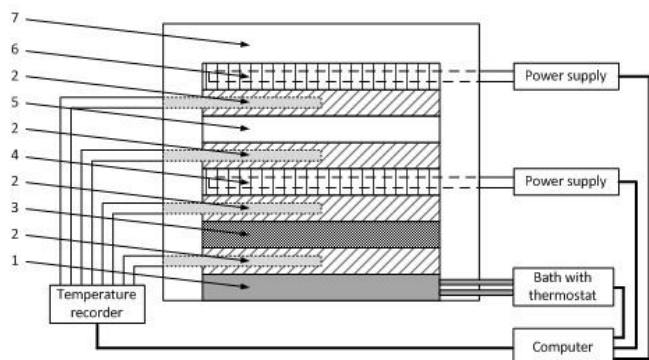

Fig. 2. Scheme of system to measure the thermal conductivity coefficient λ of liquids with associated measuring instruments and power supply, 1–cooler, 2–secondary electrode with probes (thermal), 3–sample of the liquids, 4–main heater, 5–secondary insulation, 6–secondary heater, 7–isolation [4]

The implementation of the measurement procedure also required the selection of a suitable temperature drop ΔT on a sample of the liquid. The choice of temperature decrease was conditioned meeting two criteria. First, the drop in temperature should be as small as possible in order to accurately determine the effect of temperature on the measurement of the thermal conductivity coefficient λ. Secondly, this value should be large enough to reduce uncertainty of thermal conductivity measurement. On the basis of these criteria, it was decided that the temperature drop ΔT in a sample of the liquid will be 5K.

2. Measurement system tests

This chapter describes the tests of authoring system for measuring thermal conductivity coefficient λ of the insulating liquids. Testing of the system was to check the tightness of the measuring system during the measurement, removing bubbling formed during filling of the system with liquid and measurement of the thermal conductivity of liquids with known from the literature thermal conductivity coefficient.

The first of the problems with which it was necessary to face during testing of the authorial measuring system were leaks that caused oil leakage from the system. Loss of liquid from the measuring system caused false results of measurements of thermal conductivity coefficient of tested liquid. As a result, the thermal conductivity obtained by the measurement of the thermal conductivity corresponded to the system air-insulating liquid. Leaks in the measurement system are eliminated through the use of additional sealing. Therefore, in the secondary electrodes located above and below the surface of the liquid sample used sealing in the form of rings. The use of additional sealing allowed to eliminate the problems of measuring leaks.

Another problem, which is of high importance for the accuracy of thermal conductivity coefficient λ of liquids, was air bubbles that were formed during the filling the system with tested liquid. In order to overcome this problem it was decided to enter into part of the system, that contains the examined liquid, (so called oil pan) two-channel tube with a diameter of 2 mm. One of

the channels is used for supplying liquid to the oil pan. Liquid is recessed into the system at a slight pressure. The second conduit is used to vent air and removal of air bubbles generated in the final stage of filling pan with insulating liquid. In addition, excess liquid associated with the increase in liquid volume during the measurements at high temperatures, is removed through this channel. This follows directly from the expansion of the tested insulating liquid coefficient.

Table. 1. Results of the authoring measurement system paired with the values given by literature

| Kind of liquid | Thermal conductivity coefficient λ [W/m·K] | | | | | |
| | Mineral oil Nynas Nytro Taurus | | Synthetic ester Midel 7131 | | Natural Ester Envirotemp FR3 | |
Temperature	From Literature[13]	From mesurement	From Literature[12]	From mesurement	From Literature[11]	From mesurement
20°C	0.126	0.135	0.144	0.158	0.167	0.182
40°C	-	-	0.143	0.156	-	-
60°C	-	-	0.141	0.152	-	-
80°C	-	-	0.139	0.150	-	-
100°C	-	-	0.136	0.147	-	-

The authoring measurement system tests were carried out on the basis of thermal conductivity measurement of liquid with known from the literature values of the thermal conductivity coefficient λ. To the tests of the measurement system three insulating liquids were selected. For the tests mineral oil Nynas Nytro Taurus, synthetic ester Midel 7131 and natural ester Envirotemp FR3 have been used. In the case of mineral oil and natural esters literature gives only the values of thermal conductivity at 20°C [2, 3, 9]. The correlation of the thermal conductivity coefficient and temperature is known only in the case of synthetic ester Midel 7131 [12]. Therefore, the measuring system tests were conducted using the listed insulating liquids at the temperature range in which the thermal conductivity of tested insulating liquids is known. It was assumed that the measurements of thermal conductivity coefficient is considered a successful, if the results do not differ by more than 10% of the data reported in the literature. The test results of authorial measuring system were summarized with the results given by the literature and they were presented in table 1.

Carried out tests of designed and constructed measurement system allow to state that obtained thermal conductivity values are within the accepted 10% margin of error. The same, the proper operation of the measuring system can be indicated.

3. Measurements' results

The chapter presents the results of measurements of the thermal conductivity coefficient λ of commonly used insulating liquids.

Effective heat dissipation from the transformer by the insulating liquid depends largely on convection and thermal conductivity [3]. Convection is associated with the thermal properties syndrome, such as viscosity, specific heat and thermal expansion coefficient. These properties lead to heat exchange with the environment by moving the liquid. Whereas, thermal conductivity is carried out in the liquid. All of these characteristics have a significant influence on the heat transfer coefficient α, meaningful from the point of heat loss to the environment.

As mentioned in chapter 2, the literature data concerning the thermal conductivity coefficient of insulating liquids in most cases provide information regarding the temperature of 20°C. In contrast, the normal operating temperature of the transformer is in the range of 50-70°C. Therefore, it is necessary to determine the

value of the thermal conductivity coefficient of insulating liquids at a temperature, that is greater than 20°C. Literature data indicate that the thermal conductivity of mineral oils is about 0.11-0.16 W/m·K [2, 8], synthetic esters 0.15-0.16 W/m·K [1, 2, 8], and the natural esters 0.16-0.17 W/m·K [1, 2, 8, 9]. However, these thermal conductivity values refer to a temperature of 20°C.
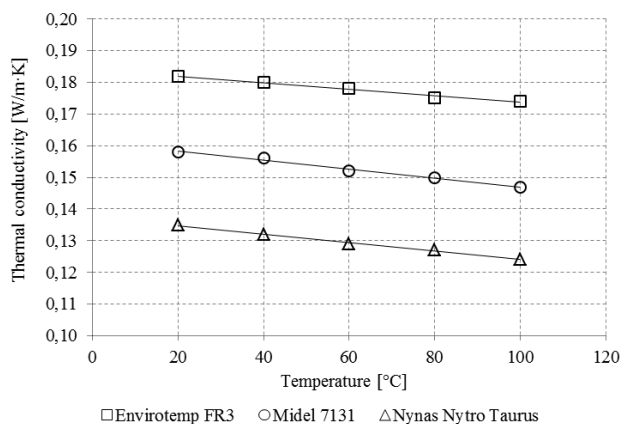

Fig. 3. Correlation graph *of* thermal conductivity coefficient and temperature for different types of insulating liquids

The graph 3 shows the correlation of the thermal conductivity coefficient of examined insulating liquids and the temperature determined by the use of the authoring measurement system. On the basis of the graph it can be concluded that the natural esters with respect to mineral oil and synthetic esters, have a much higher thermal conductivity coefficient in the entire temperature range. The thermal conductivity of the tested natural esters at temperature range from 20°C to 100°C is from 0.182 W/m·K to 0.174 W/m·K. In the case of other examined insulating liquids, the thermal conductivity is much lower, and in the analyzed temperature range is suitably from 0.158 W/m·K (for synthetic esters) to 0.147 W/m·K, and from 0.135 W/m·K to 0124 W/m·K (for mineral oil). Thus, the high thermal conductivity coefficient is in favor of natural and synthetic esters. Thereupon, both natural and synthetic esters, compared to mineral oil, show a much higher viscosity, higher thermal conductivity coefficient λ can to some extent compensate higher viscosity of esters.

Thermal properties of insulating liquids are important for the design of power devices. Currently, no data are available concerning the impact of moisture and solid insulation aging products and insulating liquids on the thermal conductivity of the liquids. These results would avoid errors in calculations and mathematical simulations during the design phase of construction of power devices. In addition, weak identification of thermal properties, especially the thermal conductivity of new insulating liquids, like natural esters and synthetic esters is one of the concerns of their use as insulating liquids in high-voltage power transformers. Thus, there is a need to conduct research to determine the impact of various factors on the thermal properties of insulating liquids. These results will be used to specify which of the insulating liquids is characterized by the desired thermal properties.

4. Summary

Built and designed measurement system can accurately determine the thermal conductivity coefficient λ of liquids. Due to the materials from which it has been made, as well as safety measure, it is possible to determine the thermal conductivity of the liquid in the temperature range from 20°C to about 100°C

Tests of designed and built measuring system was conducted on the insulating liquids with known from the literature data value of the thermal conductivity coefficient. On the basis of these tests, it can be concluded that the measurements' results obtained during the measurements of the authoring measurement system do not differ by more than 10% from the literature data.

On the basis of the obtained results, it can be concluded that the natural esters have the highest thermal conductivity coefficient within a temperature range from 20°C to 100°C. The thermal conductivity of the examined natural esters is more than 35% greater than the thermal conductivity of the tested mineral oil, and more than 15% greater than the thermal conductivity of the examined synthetic esters. In turn, the thermal conductivity of the tested natural esters is more than 17% greater than the thermal conductivity of the examined mineral oil. Moreover, presented results show correlation of thermal conductivity coefficient and temperature, which certainly facilitates designing and simulating the operation of power devices.

In order to clarify which of insulating liquids are characterized by greater ability to the heat transfer to ambient the measurements of thermal conductivity coefficient of insulating liquids should be supplemented with data concerning other properties that impact on the heat transfer coefficient α. These studies should determine the impact of temperature, moisture and aging products of insulating liquid and solid insulation on each of analyzed thermal properties.

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