

Measurements of the selected thermal properties of insulating liquids used in the high voltage power transformers

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This article is devoted to the system which measures the thermal conductivity of insulating liquids used in the high voltage power transformers. It consists of six chapters. The first chapter is an introduction. The second section presents the functions that the electrical liquids perform in the electric power equipments. The third chapter is devoted to the thermal properties insulating fluids. The fourth chapter describes the general principle of thermal conductivity measurement and measuring system. The fifth chapter is devoted to the automation of the measurement procedure. Article ends with a summary.

KEYWORDS: mineral oils, natural esters, synthetic esters, thermal conductivity, measurement automation

1. Introduction

For over a hundred years, mineral oils, because of their numerous positive characteristics and very good recognition, are commonly used in high voltage power transformers. In recent years, great attention is paid to safety associated with the transformers operation and environmental properties of the electrical insulating liquids. Therefore, a few years ago, appeared the concept of using natural esters and synthetic esters in transformers, in place of conventionally used mineral oil as electro-insulating liquid. Thermal properties of these esters are not fully recognized, including thermal conductivity. Thus, this article is devoted to the authorial system for measuring the thermal conductivity of insulating liquids.

2. Functions of the insulating liquids

Due to their characteristics, electrical fluids are widely used in the power industry. They are used both in transformers, and in the capacitors, connectors and high voltage cables. The main objectives of the transformer oil are an effective heat dissipation and providing good electrical insulation. In addition, they reduce partial discharges, protect against air and moisture, as well as improve electric strength of cellulose insulation by the impregnation (saturation) [1, 2]. In the case of capacitors, insulating liquids are designed to provide a high electrical permittivity ϵ

and electrical insulation at a sufficiently high level. Also they function as a coolant and protection against moisture. They are used also in the connector, in which they are factors that facilitate the electric arc quenching. The use of insulating liquids in the high voltage cables is dictated by the need to ensure adequate electrical insulation, impregnation and cooling.

3. Thermal properties of the insulating liquids

This chapter describes the thermal properties of mineral oil, natural esters and synthetic esters. The viscosity, thermal conductivity and thermal expansion of presented insulating liquids are discussed. These values substantially affect the heat transfer coefficient α , which is essential from the point of view of heat transfer to the surroundings.

The main disadvantage of the natural esters, determining their ability to transport heat, as well as determining their thermal behavior of transformers, is their high kinematic viscosity. Figure 1 shows the dependence of the viscosity of mineral oils, natural esters and synthetic esters in terms of temperature. As is apparent from the figure, in the temperature range of 0 to 20°C the viscosity of natural esters is from 4 to 7 times higher than the viscosity of mineral oils. Further, in this temperature range, natural esters lose fluidity [3]. The viscosity of synthetic esters in the temperature range of 0 to 20°C is from 3 to 6 times greater than the viscosity of the mineral oils. In view of the fact, that one of the main tasks of the insulating liquids is to remove heat from the transformer, a large viscosity of the natural and synthetic esters in respect of mineral oils can slow the flow of fluid in its interior. This is due to reduced efficiency of heat transfer by convection. Consequently, this leads to an increase in the temperature inside the transformer, and in particular the hottest places (called hot spot), which negatively affects on the cooling efficiency of the transformer filled with natural esters or synthetic esters. It should be noted that from the viewpoint of thermal properties the viscosity plays an important role only in the high temperature (>50°C), where there is the need for intensive cooling of the transformer. This is due to the fact that the viscosity of the electro-insulating liquids is closely connected with its temperature. The electro-insulating liquid temperature is directly dependent on the transformer load and the ambient temperature. Thus, at low temperature is not necessary such intensive cooling, as in the case of a temperature greater than 50°C. However, the viscosity of the insulating liquid should be taken into account at the design stage of the cooling system transformer. It should also be noted that some of the natural esters have a viscosity similar to that of mineral oil, so its effect on the cooling conditions transformers filled with natural ester is small [9].

Another feature, which affects the heat transfer coefficient α is the thermal conductivity. Analyzing Table 2.1 it can be seen that the natural esters, unlike

mineral oils and synthetic esters, are characterized by a much higher coefficient of thermal conductivity for the temperature of 20°C.

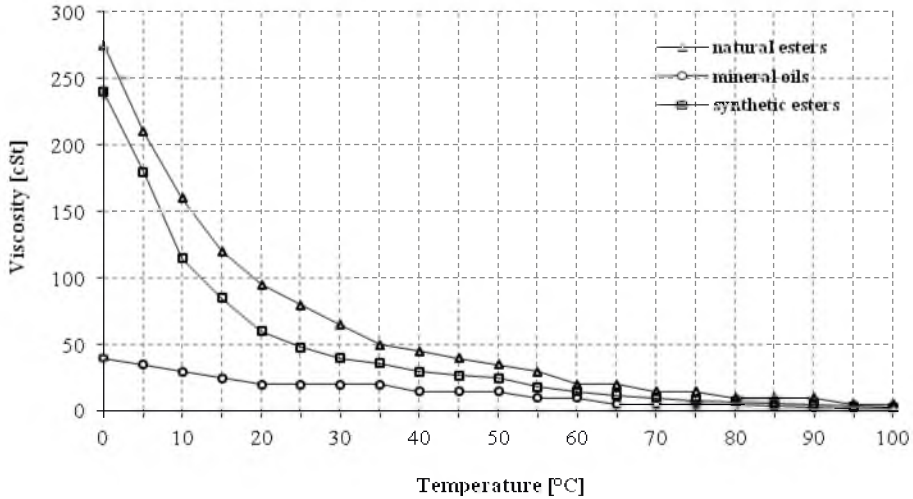


Fig. 1. The viscosity of the selected insulating liquids in a function of temperature [4]

Table 2.1. Chosen thermal properties of insulating fluids [4]

| Property | Mineral oil | Natural esters | Synthetic esters |
|---|-------------|-------------------|------------------|
| Thermal conductivity at 20°C [W/kgK] | 0,126 | 0,160 – 0,167 | 0,144 |
| Specific heat in 20°C [J/kg·K] | 1860 | 1883-1943 | 1880 |
| Thermal expansion coefficient [°C ⁻¹] | 0,00075 | 0,00068 – 0,00074 | 0,00075 |
| Kinematic viscosity at 0°C [mm ² /s] | 37,5 | 207 – 276 | 240 |
| Kinematic viscosity at 20°C [mm ² /s] | 22 | 78 – 97 | 70 |
| Kinematic viscosity at 40°C [mm ² /s] | 9 | 36 – 42 | 28 |
| Kinematic viscosity at 100°C [mm ² /s] | 2,6 | 8 – 9 | 8 |
| Density in 20°C [kg/m ³] | 880 | 910 – 920 | 970 |

Natural esters, in comparison to synthetic esters and mineral oils, are characterized by a similar, often even smaller, thermal expansion coefficient. Therefore, they can be used for vessel used in the case of mineral oils. It should however, be borne in mind that the natural esters exhibit poor oxidation resistance. Consequently, the construction of the transformer tank would need to be modified to ensure having adequate hermetic seal [10].

Other properties of listed thermal insulating liquids, such as, density and specific heat, are similar.

Summing up, the presented in the subsection thermal properties of mineral oils, natural esters and synthetic esters, it can be noted that it is not possible to exactly specify which of the analyzed liquids is characterized by a more desirable thermal characteristics. High viscosity of natural esters, as compared with mineral oils, may be compensated by a much greater thermal conductivity of the natural esters. There is therefore, a need to conduct a study to determine the effect of some factors (such as type of liquid, temperature, aging of insulation products) on the thermal properties of insulating liquids. In order to accurately define, which liquid is characterized by better cooling properties, these tests should be carried out on physical models of transformers [4, 11].

4. General principle of thermal conductivity measurement and concept of measuring system

This section presents the author's measurement system for the determination of the thermal conductivity coefficient λ of insulating liquids. It also presents the overall concept of measurement of the coefficient λ and the concept of the measuring system.

The following paragraphs will provide a definition and the general concept of determining the coefficient λ .

The thermal conductivity coefficient λ determines the ability of the substance to the thermal conductivity. It is defined as amount of heat flowing through the edges of a cube of 1 m, at the time of 1 sec, with simultaneously temperature drop between the opposite faces of a cube equal to 1 K [5, 6]. This means that under the same conditions, more heat will pass through a substance which has a higher thermal conductivity coefficient λ .

The idea of measurement of the thermal conductivity coefficient λ is based on the introduction to a medium (solid, liquid, gas) and thermal disturbance observation of the temperature distribution. In other words, the measurement of the coefficient of λ is passed through the sample material and the specific heat flux observation of the temperature at a set flow formed on the surfaces of heat supply and heat removal (on both sides of the sample) [7].

Below the concept of measurement of the thermal conductivity coefficient λ of insulating liquids and the description of the measuring system are shown. The concept presents the formula for the coefficient λ , the main modules of which the measuring system shall consist of, the choice of a particular measuring system and its modifications introduced scheme.

Designed measurement system should facilitate the production of thermal disturbances (ΔT), and the measurement of the sample material with a predetermined thickness d and surface area S . The temperature drop of the tested sample of the material is usually achieved by using a heat source with a power P

and the cooling system. Knowing the parameters mentioned above it is possible to determine the coefficient λ based on the following formula:

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

Based on the assumptions it was stated that the measurement system should consist of three main segments, ensuring accurate and reliable results. One of the segments of the system should facilitate the production of thermal disorder in the material (segment A). Another segment of the system should provide a measurement of caused thermal disturbances (segment B). The last segment should include support components responsible for eliminating unwanted heat flow – heat loss (section C).

Segment A, causing thermal disturbances, should consist of the heat source and the cooling system. As a heat source used the heater with properly chosen power and size, and power supply, which attached to the heater. The cooling system is a bath radiator and thermostat. The cooling medium is water. Bath is equipped with a cooling loop, fed with tap water (outer loop). The combination of the cooler and bath provides internal circuit.

Segment B, used to measure the thermal disturbances. It should consist of a probe (thermal), temperature recorder, computer and auxiliary circuits, in which will be placed the probe.

Segment C, which is responsible for eliminating unwanted heat flow should be built with an auxiliary heater and the power supply and isolation.

The above conditions are feasible, for example using a single-plate camera Poensgen [8]. In order to improve the measurement of single-board camera Poensgen undergone certain modifications. The first one was to change the location of the main heater to cooler. Main heater, which in Poensgen single-board camera is placed under the radiator, in the present system, was placed above the cooler. This made it possible to eliminate any phenomena of convection heater to the main cooler. Another modification was to replace the side heaters insulation by up to high thermal resistance and appropriate thickness, which allows to excluding unwanted heat flow.

The diagram of a measurement system of the thermal conductivity coefficient λ of liquids is shown in figure 2. The measurement involves placing a sample of the liquid, with a certain thickness d and surface area S , between the main heater and cooler. Main heater with power P and surface area S produces a heat flux flowing through the test fluid to the cooler. As a result of the heat flow, the temperature drop $\Delta T_{measuring}$ is generated in the liquid. Cooler is designed to provide a constant temperature on the bottom surface of the liquid. The measurement is based on recording temperature drop $\Delta T_{measuring}$ and main heater power P at a fixed heat flow (after stabilization of the temperature). Knowing the main heater power P , the thickness d and surface area S of the sample liquids and the generated temperature

drop $\Delta T_{measuring}$, the thermal conductivity coefficient λ is determined using the formula (1). So determined value of the coefficient λ is correct, if the heat losses will be eliminated at both sides and heat flows vertically upward. The heat generated by the main heater should flow at right angles downwardly through the liquid sample. In the illustrated measuring arrangement, the heat flow orthogonally upwards is eliminated by the use of auxiliary heaters. Auxiliary heater is designed to produce such a heat flow, which causes that the temperature values recorded directly above the main heater and under the auxiliary heater will be equal. This requirement will be met if the temperature drop $\Delta T_{auxiliary}$ between them is 0 K, which means there is no heat transfer between heaters.

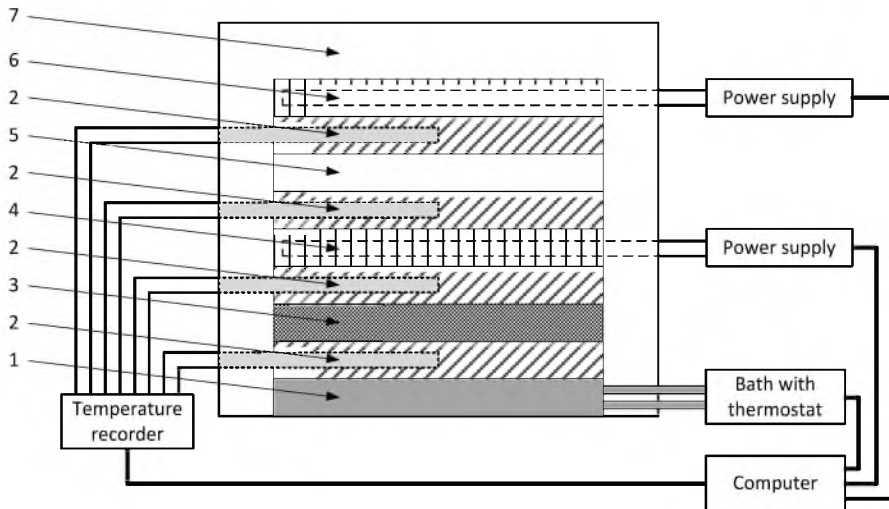


Fig. 2. Scheme of the thermal conductivity fluids λ with associated measuring instruments and power supply, 1 - cooler, 2 – Secondary electrode with probes (thermal), 3 - sample of the fluids, 4 – central heater, 5 - secondary insulation, 6 - secondary heater, 7 - isolation

The selection of the value of temperature drop on a sample liquid ($\Delta T_{measuring}$) was determined by the fulfillment of two basic criteria. It is required to establish the possible small value of temperature drop in order to accurately determine the effect of temperature on the measurement of the coefficient λ . At the same time, this value should be relatively large, which is limited by the measurement uncertainty factor λ . It was decided that the above criteria are met if the value of temperature drop $\Delta T_{measuring}$ will be 5 K.

Systems for measuring the thermal conductivity λ by fixed methods (measured in steady state) are characterized by high accuracy of the results obtained and simple construction, which are called standard systems. The only disadvantages of the application of the fixed methods are relatively long time of measurement, due

to the time constant of the measuring system and the difficulty in maintaining the same thermal conditions on the surface of the sample material [7].

5. Measurement automation

This chapter discusses the possibilities of automation system for measuring the thermal conductivity coefficient λ of liquid. It describes the modules responsible for individual tasks. There is also presented flowchart of algorithm, on the basis of which a computer program used to manage the automation of measuring thermal conductivity λ of appropriate liquid will be constructed.

The procedure for measuring the thermal conductivity coefficient λ of liquids is a long process. This is due to the need to dispatch the thermal disorder ($\Delta T_{measuring} = 5$ K) of the sample liquids and elimination of heat flow perpendicular upwards ($\Delta T_{auxiliary}$ equal to 0 K) by using an auxiliary heater. As a result during the measurement it is necessary to change the power settings of heaters, and proper thermostat temperature stabilization. Consequently it was decided to automate the process of measuring the coefficient λ .

Due to the need for automatic temperature control of the various components of the measurement system (cooler, heater main, auxiliary heater) found that the automation of measurement should be carried out using three independent control systems. Therefore, three modules of automation control, providing temperature control of the various parts of the system are listed. Featured are cooler temperature control module, power control module of the main heater, and power control module of auxiliary heater.

Cooler temperature control module is responsible for the evenly and efficient heat transfer from the lower surface of the sample. It consists of the cooler bath with thermostat, temperature recorder, and thermal probes responsible for measuring the surface temperature of heat dissipation from the sample. Cooler provides heat dissipation from the bottom surface of the sample. The thermostat allows adjusting the temperature of coolant (water) in the full range of measurements (from 293.15 K to 373.15 K), with an accuracy of ± 0.01 K. In order to improve the temperature stability, the bath has been equipped with the cooling loop in the form of an external circuit supplied with tap water. The input information initiating temperature control of the cooler is temperature T , for which the coefficient λ of the liquid is determined. Depending on this temperature at the thermostat the cooling temperature (T_1) is set. The algorithm controls the operation of the system will be described later in this article.

Another module – power control module of main heater – is designed to produce an appropriate heat flux flowing through the sample liquid into the cooler. It is composed of the main heater, power supply, temperature recorder, and probes. At the start of testing the power supply voltage is dependent on the temperature T , for which we want to determine the coefficients λ ($U_{G1} = f_1(T_\lambda)$). During the

measurement, the main heater power control according to the used algorithm, thereby generating the desired temperature at the top surface of the sample liquid.

The last module – power control module of auxiliary heater – is responsible for the compensation of heat losses resulting from heat flow vertically upward. It is composed of identical devices such as power control module of main heater. Probes are responsible for the temperature measurement just below the surface of the auxiliary heater. After the start of measurement, power supply is energized to a voltage depending on predefined in the temperature T ($U_{G2} = f_2(T)$). Adjusting the temperature is achieved by automatic power control of auxiliary heater during the measurement.

Figure 3 shows flowchart of algorithm for measuring the thermal conductivity coefficient λ of insulating liquids. Input information is the temperature T for which it should be determined the value of the coefficient λ . Depending on this temperature, through appropriate thermostat setting, the temperature on the cooler is set $T_1 = T - 2.5$ K. This is due to the need to maintain a pre-set temperature drop (5 K) in the sample liquid. The values of the power supply of main heater and auxiliary heater also depend on the desired temperature T . Consequently the main heater voltage G_1 is selected based on the relationship $U_{G1} = f_1(T)$, and an auxiliary heater voltage according to the relationship $U_{G2} = f_2(T)$. In subsequent steps, measurements of the temperature recorded by the probe T_1, T_2, T_3 and T_4 follow. Due to the long time of to stabilize the temperature T_2, T_3, T_4 measurement is performed every 10 minutes. The temperature is considered to be stable if, during the 40 minutes more registered by the sensor values do not differ from each other.

The main task of the algorithm for determining the thermal conductivity coefficient λ of liquids is to estimate the value of change (increase or decrease) of the main heater voltage and auxiliary heater voltage during the automatic adjustment of heat flow. In the case of the main heater the determination of the value by which the voltage should be change is based on the last measured temperature differences (ΔT) at the top (T_2) and bottom (T_1) of the surface of the sample liquid. The algorithm verifies whether these differences are within the accepted limits of acceptable deviation ($4.9 \text{ K} < \Delta T < 5.1 \text{ K}$). If the values of temperature drop do not fall within the accepted limits, the change of the main heater power supply follow. Estimating the value by which to change the voltage of auxiliary heater is based on the last measured temperature differences (ΔT_p) recorded by probes placed on opposite faces of the heaters (the auxiliary heater (T_4) and the main heater (T_3). The algorithm checks whether these differences are within the acceptable limits of deviation ($-0.1 \text{ K} < \Delta T_p < 0.1 \text{ K}$). If registered differences go beyond the accepted limit of deviation, the change of the supply voltage auxiliary heater follows. Next, verify the correctness of the key assumptions ($\Delta T = 5 \pm 0.1 \text{ K}$ and $\Delta T_p = \pm 0.1 \text{ K}$). If these conditions are fulfilled, then on the basis of the formula (1) the thermal conductivity coefficient λ is assigned.

The presented flowchart of algorithm to determine the thermal conductivity coefficient of insulating liquids λ is the basis for the creation of a computer program controlling the process of defining the coefficient λ . The used algorithm

allows estimating the changes values in supply voltage of the main and auxiliary heater, which can be relevant modules set to control the operation of the system. The result is shortened relative time of measurement.

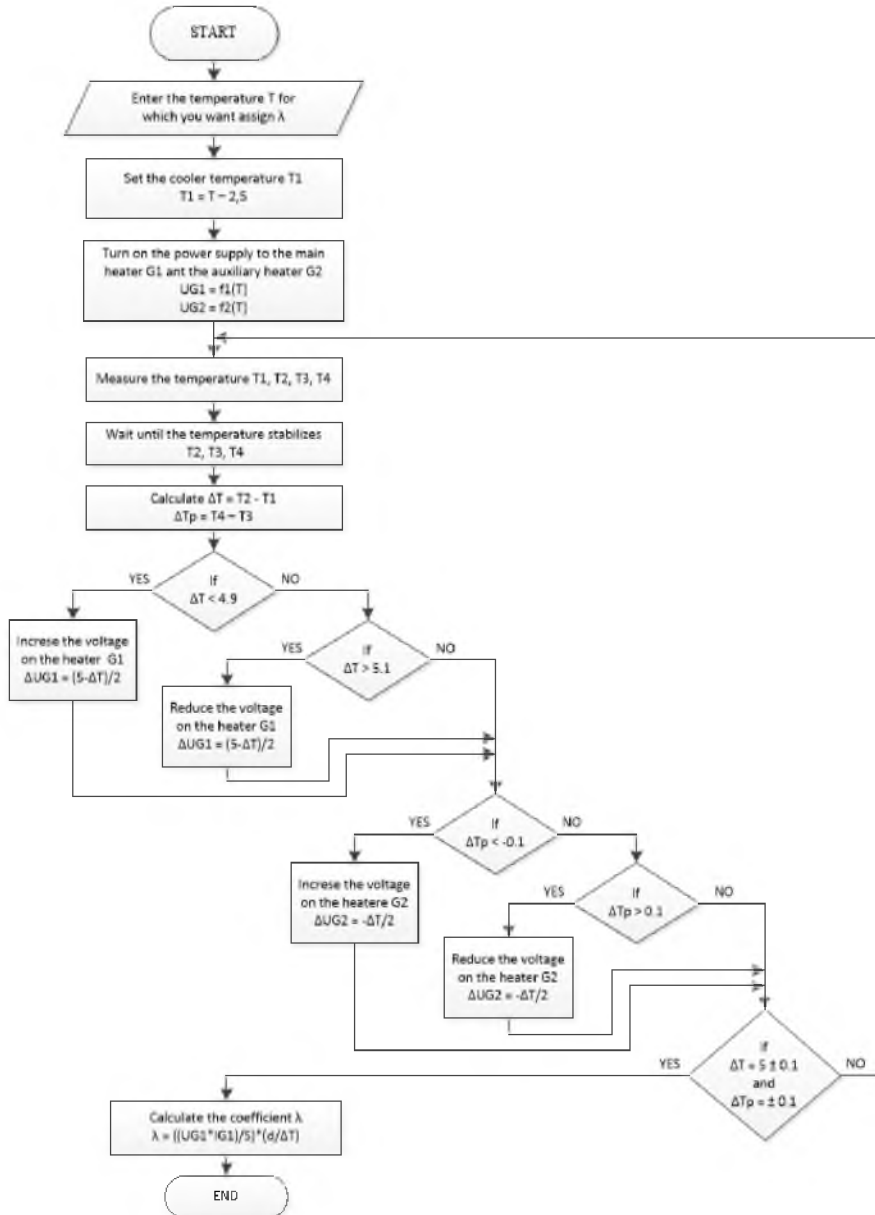


Fig. 3. The flowchart of algorithm to determine thermal conductivity coefficient λ

6. Summary

Comparison of the thermal properties of insulating liquids is essential to their use in high-voltage transformers. Not an easy task is to determine which of the insulating liquids are more or less suitable for use in transformers. Both mineral oils and natural and synthetic esters have a number of desirable properties. Unfortunately, they have some disadvantages. Furthermore, there is a need to define the influence of selected factors on the thermal properties of insulating liquids. This impact will determine the efficiency of heat transfer to the ambient by electrical equipments, which significantly determines the lifetime of these devices and their safety.

The designed system to measure the thermal conductivity coefficient of liquid λ is equipped with a measuring algorithm. The algorithm used allows automating the measuring process and significantly reducing the measurement time, and will positively affect the accuracy of the results.

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