Створено прилад для вимірювання теплопровідності рідин, принцип дії якого базується на методі прямого підігріву термістора. Надані результати експериментальних досліджень з використанням контрольних рідин за допомогою створеного приладу. Результати показали високу точність та ефективність використання приладу при визначенні теплопровідності рідин. Необхідна точність досягається за рахунок збільшення сеансу вимірювання з наступною обробкою їх результатів

Ключові слова: теплопровідність матеріалів, термістор, прямий підігрів термістора, прилад для визначення теплопровідності

Создан прибор для измерения теплопроводности жидкостей, принцип действия которого основан на методе прямого подогрева термистора. Представлены результаты экспериментальных исследований с использованием контрольных жидкостей с помощью созданного прибора. Результаты показали высокую точность и эффективность использования прибора при определении теплопроводности жидкостей. Требуемая точность достигается за счет увеличения сеанса измерения с последующей обработкой их результатов

Ключевые слова: теплопроводность материалов, термистор, прямой подогрев термистора, прибор для определения теплопроводности

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INCREASING ACCURACY OF MEASURING THERMAL CONDUCTIVITY OF LIQUIDS BY USING THE DIRECT HEATING THERMISTOR METHOD

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1. Introduction

The issue of energy saving and energy efficiency is quite acute in the modern world of science, technology and industry. That is why the newest designs and innovative projects have appeared lately, which are related to implementation of new efficient technologies in various fields of manufacturing. In the framework of implementation of such technologies, new materials and fluids that have special thermal insulating and thermal conducting characteristics are used. Development of new innovative cooling liquids for cooling systems of thermal power devices is carried out, based on two-phase systems, consisting of base medium (water) and nanoparticles [1], new liquid polymer materials are created that have increased thermal insulating and heat conducting properties compared to conventionally used materials.

In the food industry, when calculating refrigerating equipment, it is important to know thermal and physical characteristics (TPC) of food products [2, 3]. The quantity and range of products increases year in year out and the lack of or the use of unreliable TPC of products makes it difficult to conduct engineering calculations, leads to inaccuracies in the assessment of productivity of technological equipment for food production while performing design work. This, in turn, becomes the cause of violations of parameters of manufacturing process and additional unjustified expenditures, including electricity over-consumption, increase in costs and decrease in products quality [3].

Important are the studies of TPC of biological materials in biology and medicine. Thus, the availability and degree of immunologic reaction to allergen is determined by TPC [4, 5].

One of the priority tasks of the technique of thermal-physical research is the improvement of its performance. Only efficient measuring methods based on fundamental metrological approaches allow obtaining reliable results and may be applied in relation to a broad spectrum of new substances and solutions of organic fluids that are daily produced and synthesized both by domestic and global industry.

The range of instruments for the measurement of thermal and physical characteristics of liquids that are commercially available is extremely narrow while their price is rather considerable, which is why, in most cases, laboratory measuring installations of individual design are used, not industrial devices.

It is relevant to develop a device, owing to which the process of measuring thermal conductivity of materials by non-destructive method is simplified, and which makes it possible to simultaneously measure a large number of experimental samples with increased performance and accuracy of measurement.

2. Analysis of scientific literature and the problem statement

At present, the studies of thermal conductivity of liquids are carried out in a wide range of temperatures in stationary state and at laminar motion of liquid. When conducting studies, they use two groups of methods: stationary and nonstationary. Stationary methods, which are based on studying temperature fields, constant in time, are simpler, as a rule, compared to nonstationary [3, 6].

Nonstationary methods are based on examining temperature fields, changing in time by a particular law. They are more difficult to implement. The main difficulty is in the fact that it is difficult to implement in the experiment the conditions laid down in the theory of the method [3, 7].

To measure thermal conductivity of liquids and gases, the following methods are used, which are also used for solid bodies [1, 6, 7]: the method of a flat layer, the method of coaxial cylinders, the method of heat waves, the laser flash method, the hot filament method and the method of direct heating.

The peculiarity of implementing the method of a flat layer for the study of fluids is to control appearance of convection in the tested layer [1, 6, 7].

In the method of coaxial cylinders [1], the studied substance fills up the cylinder gap, formed by two coaxially located cylinders. The main heater is placed in the inner cylinder. A working difference in temperatures is measured by thermocouples.

The method of thermal waves is the excitation of thermal waves simultaneously in the studied and reference samples when measuring their characteristics and consequently comparing them. Thus, the paper [8] examines measuring installations that realize the method of temperature waves (regular mode method) by using laser radiation and electron flow.

The method of laser flash [9] (the laser pulse method) refers to a group of nonstationary methods that, unlike the stationary ones, do not require a long period of time for establishing thermal equilibrium. The essence of the laser flash method is that a short pulse of radiation energy is absorbed in a thin layer of the frontal surface of the sample.

In the hot filament method [1], the inner cylinder is replaced by hot wire (thread) that is both a source of heat and resistance thermometer to measure temperature.

The method of direct heating is in its essence similar to the hot filament method, the difference being that in the first case, the sensitive element is a platinum filament, and in the second – thermistor. The method of thermistor direct heating has a number of advantages over other methods. The essence of the method is in the use of the section of a volt-ampere characteristic of thermistor where its resistance decreases at the increase of current (for thermistors with a negative coefficient of dependency of resistance on temperature), and its voltage falls. In this section, the magnitude of drop in resistance will depend on the temperature of its heating, that is, on the medium it is in.

These methods of determining TPC of liquids and materials are the basis for the research into the magnitude of perfusion (transmission of solutions and biologically active substances through the vascular system of organs and tissues of the human body) by using thermistors [10], measurement of thermal conductivity of liquids and powders by using thermistor probe [11], as well as determining heat pulses with the help of thermistor probes [12].

At present, the installations that are used for measuring thermal conductivity of fluids and materials are produced in single copies, i.e., there is no industrial production of such devices (ITC-l-1, ITC-c-2, ITC-lc-3, ITC-c-4, ITC-c-5, ITC-q-6, Rezhim 1, KD2-PRO, DTC-25, DTC-300, LAMBDA, Thermal Constant Analyzer, C-Therm TCi, XFA-300, LFA 467 HyperFlash, FLASHLINE–3000/5000, THW-L1, TLS 100, THB-100). Majority of enterprises and scientific institutions use devices of their own design.

Based on the analysis of the methods of measuring TPC parameters of liquids and materials, it can be argued that the existing methods of measuring thermal and physical properties have various drawbacks.

1. When using a stationary method of measuring, characteristic drawbacks are long time period of measurements and the bulkiness of thermal measuring systems.

2. Existing nonstationary methods, though of high performance speed, also have the following drawbacks:

– the methods of laser and xenon flash have increased requirements to the conditions of experiment, in addition to it, in the measurement of thermal conductivity of liquids, many of which are transparent, a part of the light energy is not absorbed by the liquid, which leads to the error in determining TPC. It should be noted that the devices that use these methods are quite complex and their price is rather high;

– the method of monotonic heating requires a long-lasting process of calibration;

– practical implementation of most of the methods require bulky equipment that prevents simultaneous measurement of a large number of the studied samples.

The method of thermistor direct heating, due to small dimensions of the probe and simple design of the device, can be widely used in various industries, medicine and biology to determine TPC of different materials at low cost of the equipment.

The analysis of existing industrial and laboratory devices was conducted [13–15]. We can conclude that the instruments for determining thermal and physical characteristics of materials have large measuring errors that exceed 3 % and are characterized by long-lasting duration of measuring. The industrial devices are lacking, which are capable in a short period of time to measure thermal and physical characteristics of a large number of different materials. This fact predetermines a general necessity to create efficient methods of measuring thermal conductivity of fluids and materials to determine their thermal and physical properties. The need to control materials at all stages of manufacturing predetermines the search for, and improvement in, the means of non-destructive control of thermal conductivity of materials.

3. The purpose and objectives of the study

The aim of this work is designing a method for measuring thermal conductivity of liquids based on the method of thermistor direct heating.

To achieve the goal, the following problems were set:

– to carry out analysis of existing methods and instruments for measuring thermal and physical characteristics of materials that use the method of thermistor direct heating;

– to develop a mathematical model of determining thermal conductivity of liquids by using the selected method;

– to design a device for measuring thermal conductivity of liquids by the method of thermistor direct heating for

application in industry, which has increased accuracy and allows simultaneous measuring TPC of a large number of the studied materials, increasing in this way the measurements efficiency;

– to perform experimental studies using the newly created device to determine its metrological characteristics and develop practical recommendations for implementation of the proposed method and device for determining thermal conductivity of liquids and materials.

4. Materials and methods of research into measuring thermal conductivity of liquids by the method of thermistor direct heating

To solve the set task, it is proposed to use the method of the hot filament as the base of a would-be device for determining TPC.

In the industry they use, as a rule, thermocouples or resistive thermal converters that are made in the form of finished devices. The unsuitability of these thermosensitive elements for common use is due to high cost of the materials used and impossibility of remote control as a result of relatively low values of output parameters, which are largely sensitive to the impact of external factors. Often used are the sensors of integrated designs that have low non-linearity of initial characteristic on the temperature and considerably low price, but the integral design in itself is the "Achilles heel" of such elements, given the limitation of the working temperature range [16].

A thermistor, unlike the mentioned thermal converters, has a wide working temperature range, a capability of remote monitoring and relatively small dimensions of the sensor [16].

One of the efficient methods of measuring TPC of materials is the method of thermistor direct heating.

Determining TPC of substances by the method of thermistor direct heating that is located in the studied fluid, is based on measuring the temperature of self-heating of the thermistor under the action of the pulse of current.

For the explanation of the principle of action of measuring thermal conductivity, based on thermistor direct heating, Fig. 1 demonstrates a volt-ampere characteristic of the thermistor [17].

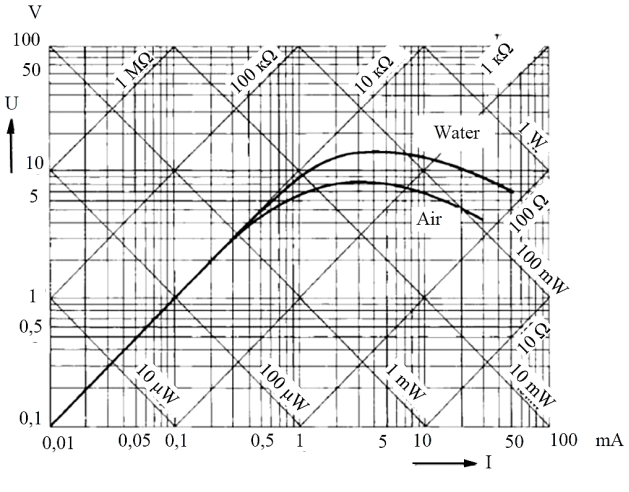

Fig. 1. Volt-ampere characteristic of thermistor at a constant temperature [17]

At a constant ambient temperature [18], volt-ampere characteristic of thermistor has three sections.

1. The section of direct increase where electrical power of thermistor does not lead to its significant self-heating. Voltage and current in this section comply with the Ohm's law. Thermistor resistance is determined by the temperature of the environment. In this section thermistors are used as temperature sensors (R=dV/dI=const).

2. The section of nonlinear increase to maximum voltage, where resistance starts to decline. At maximum voltage, relative decrease of the resistance $\Delta R/R$, as a result of self-heating, equals the relative increase in current $\Delta I/I$ ($R>dV/dI\geq 0$).

3. The section of voltage drop where the resistance decrease is larger than the relative increase in current. This section is used for the measurement of TPC of liquids in the method of thermistor direct heating. Here the effect of self-heating of thermistor manifests itself. In this section, ($dV/dI\leq 0$).

The volt-ampere characteristic of thermistor (Fig. 1) shows that it is affected not only by the resistance R(T) but by the coefficient of thermal conductivity of the environment. It depends on the dimensions, shape, and outputs of the thermistor. Fig. 1 displays the volt-ampere characteristics of the thermistor, which is located in different media:

– in water – the upper curve;

– in the air – the lower curve.

The curve V/I of the material that has larger thermal conductivity will be located above the curves of other materials with lower thermal conductivity. If the thermistor is put to the vacuum, its volt-ampere characteristic will be located lower. Thus, by the received volt-ampere characteristic one can define TPC of the medium the thermistor is in. This nature of dependency of V/I of thermistor is used in the method of its direct heating for determining TPC of the studied liquids.

A similar method of determining TPC of substances is also used when measuring by the method of the hot filament [19], but a thermistor probe has far smaller overall dimensions (the diameter of thermistor may be less than 0.3 mm) and is more simple in design. Despite its structural advantages, thermistor has a non-linear characteristic of dependency of its resistance on temperature and thermal inertia due to availability of a protective shell, which can lead to error in determining TPC of the studied liquids.

This method is efficient for creating a simple multi-probe device, which allows simultaneous measuring TPC of dozens of the studied samples with high precision, while the problems related to nonlinearity of characteristic of dependency of thermistor resistance on temperature and to the thermal inertia in the designed device are solved by approximation of the characteristic and selection of optimal mode of heating.

4. 1. Description of functional model of the developed device

On this basis we created device for measuring thermal conductivity of materials, the functional scheme of which is shown in Fig. 2.

The device has the following main components:

– six measuring units (MU), structurally combined in one measuring module (MM);

– device control unit (CU);

– thermostat, in which a container with the studied samples is put;

– power supply unit (PS) with external source of uninterruptible power supply (UPS).

Each of the six measuring units has 10 measuring probes, which are immersed in the studied liquid. Measuring probe has a conical shape with thermistor on the edge. It is switched on in one of the shoulders of the measuring bridge, the imbalance signal of which is boosted by differential (instrumental) amplifier and is fed through a multiplexer to the 12-bit analog-to-digital converter. Numeric values of the imbalance of all 10 measuring bridges from the analog-to-digital converter (ADC) output are memorized by turn by a microcontroller of the measuring unit.

The power of the measuring bridge is supplied by the source of the reference voltage of direct current +12 V ±2 %. The value of the voltage is selected so that it ensures the work of thermistor in the section of a voltage drop of the volt-ampere characteristic, where the decrease in resistance is larger than the relative increase in current.

Turning on power supply of the measuring bridge is carried out by a signal from the microcontroller for the time period, which is equal to the time constant of thermistor (6 sec). After this, a pause is kept to cool the thermistor (20 sec.). When one enables the key, the measuring bridge is fed with voltage and the thermistor heats up. The duration of the pulse is sufficient to measure the temperature of the thermistor self-heating, which is affected by TPC of the medium that surrounds the thermistor. The current process of thermistor's heating in the duration of the pulse is entered into the memory of the microcontroller.

The data obtained in the process of measurement after the end of the session are transmitted by the microcontroller of the control unit in the form of data file to the PC.

A container with test tubes is placed in the thermostat of the device to ensure constant temperature of samples when conducting research. It is heated up to the temperature of +40±0,5 °C. The power of the heater of the thermostat is defined by the temperature sensor of the container by using voltage regulator. The power supply of the units of the device is provided by a power supply unit, which is connected to the AC power network with the 220 V voltage and 50 Hz frequency via uninterruptible power source.

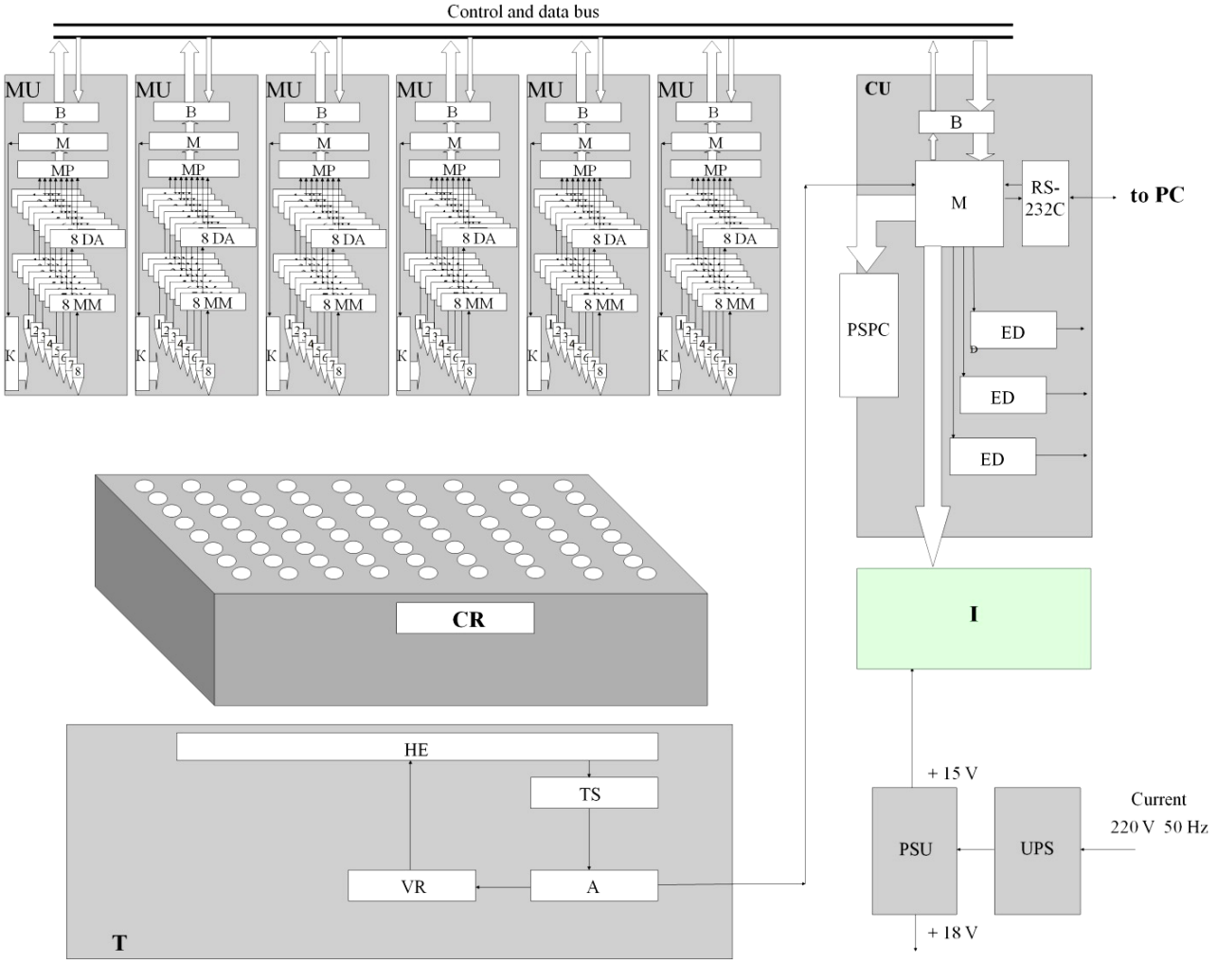

Fig. 2. Functional scheme of the device, where: MU is the measuring unit; B is the buffer; M is the microcontroller; MP is the multiplexer; DA is the differential amplifier; MM is the measuring module; 1...8 are the measuring probes; CR is the container; T is the thermostat; HE is the heating element; VR is the voltage regulator; TS is the temperature sensor; A is the amplifier; CU is the control unit; PSPC is the port of sensors of position of the container; ED is the driver of engine; I is the indicator; PSU is the power supply unit; UPS is the uninterruptible power supply; PC is the personal computer

The current status of the device and the temperature of the container with the studied samples are displayed in its indicator. The location of the measuring module and the thermostat is controlled by sensors (terminal switches) to prevent mechanical damage of the probes when moving the thermostat.

4. 2. Mathematical model of distribution of thermal energy

For the measurement of thermal conductivity of liquids, the designed device uses 60 probes of conical shape with the thermistors fixed on their edge.

During thermistor's self-heating by electric pulse, the heat flow q (Fig. 3) spreads towards the thermostat cartridge through the walls of the tube. Along the way of heat distribution, the heat flow consecutively meets thermal resistance [20] of the thermistor shell $R_{sh.}$, of the studied liquid $R_{s.ld.}$ of the test tube $R_{t.}$, of the air gap between the tube and the wall of the thermostat cartridge $R_{a.g.}$ and thermal resistance of the thermostat cartridge $R_{crtg.}$. In addition, from the thermistor shell, the outflow of heat will occur through the holder of the thermistor in the direction of the thermistor probe mount, which has the temperature of the environment. Thermal resistance of the holder $R_{hld.}$ is determined by TPC of the material it is made of and its dimensions.

Thermal resistances, presented in the scheme of distribution of thermal energy, are determined by the formulas:

$$R_{sh.}=\frac{1}{k_{sh.}}=\frac{1}{\alpha_1\cdot d_1}+\frac{1}{2\lambda_{sh.}}\cdot\ln\left(\frac{d_1}{d_2}\right)+\frac{1}{\alpha_2+d_2}, \quad (1)$$

$$R_{s.ld.}=\frac{1}{k_{s.ld.}}=\frac{1}{\alpha_2\cdot d_2}+\frac{1}{2\lambda_{s.ld.}}\cdot\ln\left(\frac{d_2}{d_3}\right)+\frac{1}{\alpha_3+d_3}, \quad (2)$$

$$R_{t.}=\frac{1}{k_{t.}}=\frac{1}{\alpha_3\cdot d_3}+\frac{1}{2\lambda_{t.}}\cdot\ln\left(\frac{d_3}{d_4}\right)+\frac{1}{\alpha_4+d_4}, \quad (3)$$

$$R_{a.g.}=\frac{1}{k_{a.g.}}=\frac{1}{\alpha_4\cdot d_4}+\frac{1}{2\lambda_{a.g.}}\cdot\ln\left(\frac{d_4}{d_5}\right)+\frac{1}{\alpha_5+d_5}, \quad (4)$$

$$R_{crtg.}=\frac{1}{k_{crtg.}}=\frac{1}{\alpha_5\cdot d_5}+\frac{1}{2\lambda_{crtg.}}\cdot\ln\left(\frac{d_5}{d_6}\right)+\frac{1}{\alpha_6+d_6}, \quad (5)$$

$$R_{hld.}=\frac{1}{k_{hld.}}=\frac{1}{\alpha_7}+\frac{l_{hld.}}{2\lambda_{hld.}}+\frac{1}{\alpha_8}, \quad (6)$$

where $k_{sh.}$, $k_{s.ld.}$, $k_{t.}$, $k_{a.g.}$, $k_{crtg.}$, $k_{hld.}$ are the thermal conductivities of the thermistor shell, the studied fluid, the tube, the air gap between the tube and the thermostat cartridge, thermostat cartridge and the thermistor holder; $\lambda_{sh.}$, $\lambda_{s.ld.}$, $\lambda_{t.}$, $\lambda_{a.g.}$, $\lambda_{crtg.}$, $\lambda_{hld.}$ are the coefficients of thermal conductivity of the thermistor shell, the studied fluid, the tube, the air gap between the tube and the thermostat cartridge, the thermostat cartridge and the thermistor holder; d_1, d_2, d_3, d_4, d_5, d_6 are the diameters of thermistor and the thermistor shell, the inner diameter of the tube, outer diameter of the tube, diameter of the hole in the thermostat cartridge and diameter of the thermostat cartridge; $l_{hld.}$ is the length of the holder.

Coefficient of thermal conductivity is determined by the formula [21]:

$$\lambda=\frac{P_T}{4\pi r\Delta T}, \quad (7)$$

where λ is the coefficient of thermal conductivity of the studied liquid, W/(m·K); P_T is the power of thermistor, W; r is the radius of the thermistor, m; ΔT is the temperature of heating up the thermistor, °C.

The crystal of thermistor is covered with protective shell mostly of glass or epoxy resin. These materials have coefficient of thermal conductivity from 0.3 to 0,5 W/(m·K) and that is why create additional thermal resistance on the way of warming the studied substance by thermistor. If the thermal conductivity of the studied substance is fairly low compared to the thermal conductivity of the shell, then this factor hardly affects the value of temperature of thermistor heating. If the thermal conductivity of the studied material equals or exceeds the thermal conductivity of the thermistor shell, then this leads to additional self-heating of thermistor.

The temperature of additional self-heating of thermistor decreases with a decrease in thermal conductivity of the studied liquid.

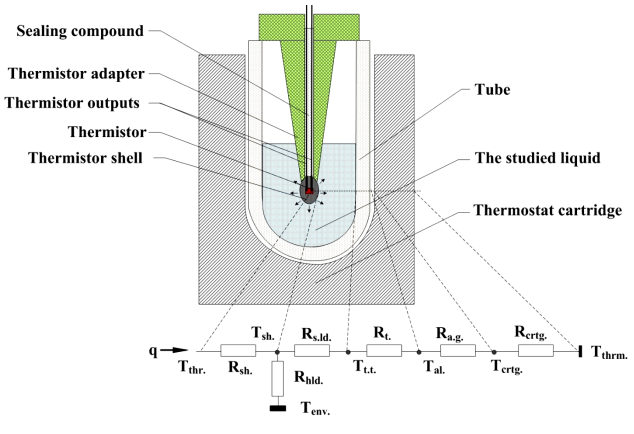

Fig. 3. The scheme of distribution of thermal energy from the thermistor probe: $R_{sh.}$, $R_{s.ld.}$, $R_{t.}$, $R_{a.g.}$, $R_{crtg.}$, $R_{hld.}$ are the thermal resistances of thermistor shell, of the studied liquid, of the tube, of the air gap between the tube and the thermostat cartridge, thermostat cartridge and the thermistor holder, $T_{sh.}$, $T_{al.}$, $T_{t.}$, $T_{thr.}$, $T_{crtg.}$ are the temperature of the thermistor shell, of the studied liquid, of the tube, of the air gap between the tube and the thermostat cartridge, of the thermostat cartridge and the thermistor holder, q is the direction of heat flow

This fact necessitates introduction to the calculation formulas for determining thermal conductivity of the studied liquids of additional coefficients of proportionality, which are determined by testing thermistors with the use of reference liquids with known TPC.

Therefore, the formula for the calculation of coefficient of thermal conductivity with regard to these circumstances takes the form:

$$\lambda_{s.ld.}=\frac{P_T}{4\pi r(\Delta T_m-\Delta T_0)\cdot\dfrac{1}{K_{p.f.}}}, \quad (8)$$

where $\lambda_{s.ld.}$ is the coefficient of thermal conductivity of the studied liquid, W/(m·K); P_T is the thermistor power, W; r is the radius of the thermistor, m; ΔT_m is the temperature of thermistor heating that is measured by experimental installation, °C; ΔT_0 is the temperature of thermistor self-heating that is determined by the results of the tests with the use of reference substances, °C. The self-heating of thermistor is caused by availability of the shell; $K_{p.f.}$ is the coefficient of proportionality, which is determined by the results of the tests using reference liquids. It characterizes sensitivity of a thermistor probe to the value of thermal conductivity of the studied liquid that surrounds it.

The coefficient of proportionality $K_{p.f.}$ is defined by the formula:

$$K_{p.f.} = \frac{(\Delta T_{r.2m.} - \Delta T_{r.1m.})}{(\Delta T_{r.2c.} - \Delta T_{r.1c.})}, \quad (9)$$

where $\Delta T_{r.2\ m.}$ and $\Delta T_{r.1\ m.}$ are the values of temperature of thermistor heating that are defined by the results of the tests using reference substances in accordance with the lowest coefficient of thermal conductivity, for example, the 96 % ethyl alcohol solution ($\Delta T_{r.2\ m.}$) and the largest coefficient of thermal conductivity, such as distilled water ($\Delta T_{r.1\ m}$); $\Delta T_{r.2\ c.}$ and $\Delta T_{r.1\ c.}$ are the values of temperature of thermistor heating for reference substances in accordance with the lowest coefficient of thermal conductivity, for example, the 96 % ethyl alcohol solution ($\Delta T_{r.2\ m.}$) and the largest coefficient of thermal conductivity, such as distilled water ($\Delta T_{r.1\ m}$). These magnitudes are calculated by the formula (7), using the values of coefficients of thermal conductivity of reference liquids from the materials of a reference book [22, 23].

The temperature of thermistor self-heating ΔT_0, which is caused by availability of the shell, is determined by the formula:

$$\Delta T_0 = \Delta T_{r.2m.} - (\Delta T_{r.2m.} - \Delta T_{r.1m.}) \cdot \frac{\Delta T_{r.1c.}}{(\Delta T_{r.2c.} - \Delta T_{r.1c.})}, \quad (10)$$

General temperature of thermistor heating is determined by the thermogram, obtained in the process of measurement. Numerical values are obtained during testing by the data presented in conventional units at the ADC output of the device. Therefore, it is necessary to have the dependency $T=f(N_{ADC})$ for the calculations, where T is the temperature of thermistor, N_{ADC} is the numeric value at the ADC output. Since this dependency is nonlinear, then to simplify the calculations, one must perform approximation of this function and replace it with the linear $T=To+N_{ADC} \cdot K_T$.

To determine the function $T=f(N_{ADC})$, one should take into account electrical characteristics of the measuring channel of the device, the structural scheme of which is presented in Fig. 4.

Thermistor is turned on in one of the shoulders of the measuring Winston bridge. The study of thermal conductivity of liquids is carried out at the temperature of +40 °C. That is why the measuring bridge consists of three resistors of 1.15 kOhm ±1 % (estimated value of thermistor resistance at the temperature of +40 °C equals 1.15 kOhm) and the thermistor. The voltage in the diagonal of the bridge is amplified by the amplifier and supplied through the divider $R_{c1}/(R_{c1}+R_{c2})$ to ADC. At the ADC output, we receive a numeric value that is proportional to the voltage of imbalance of the bridge, which is measured by microcontroller for 6 sec. of the duration of the heating pulse and is transmitted to PC. By the obtained thermogram of thermistor heating (Fig. 5), one determines the temperature of thermistor heating under the action of current pulse, as $\Delta N=N_3 - N_1$, where N_3 and N_1 are the final and the starting points of the heating thermogram, respectively.

In the chart (Fig. 5), point 1 is the starting point of thermistor heating (numeric value at the ADC output – N_1), point 2 is the middle of the pulse of thermistor heating (numeric value at the ADC output – N_2), point 3 is the final point of thermistor heating (numeric value at the ADC output – N_3). The values of N_3, N_1 are shown in the chart (Fig. 5).

The dependency $T=f(N_{ADC})$

$$T(N_{ADC}) = \frac{1}{\frac{B}{\ln\frac{R_M}{R_{25}}\left(\frac{U_i \cdot N_{ADCmax} \cdot R_{C1}(K_\alpha+1) - 2N_{ADC} \cdot U_{ADCmax} \cdot (R_{C1}+R_{C2})}{U_i \cdot N_{ADCmax} \cdot R_{C1}(K_\alpha-1) - 2N_{ADC} \cdot U_{ADCmax} \cdot (R_{C1}+R_{C2})}\right)} - \frac{1}{298{,}5}} - 273{,}15, \quad (11)$$

where N_{ADC} is the received numeric value of imbalance of the measuring bridge, c.u.; U_{ADC} is the voltage at the ADC input, W; $N_{ADC\ max}$ is the maximum numeric value at the ADC output, c.u.; $U_{ADC\ max}$ is the maximum voltage at the ADC input, W; U_i is the pulse amplitude, W; K_a is the amplifier's amplifying coefficient; R_{C1} and R_{C2} are the resistances of voltage divider at the output of the amplifier, respectively, Ohm; $R_м$ are the permanent resistances of the measuring bridge, Ohm; U_a is the voltage at the output of the amplifier, W; $U_м$ is the voltage in the diagonal of the measuring bridge, W; U_T is the voltage on thermistor, W; T_{25} is the temperature of + 25 °C in K, at which resistance of the thermistor R_{25} is standardized; R_{25} is the resistance of thermistor at the temperature of 25 °C (characteristic of thermistor), Ohms; B is the technological coefficient, which depends on the technology of manufacturing a thermistor.

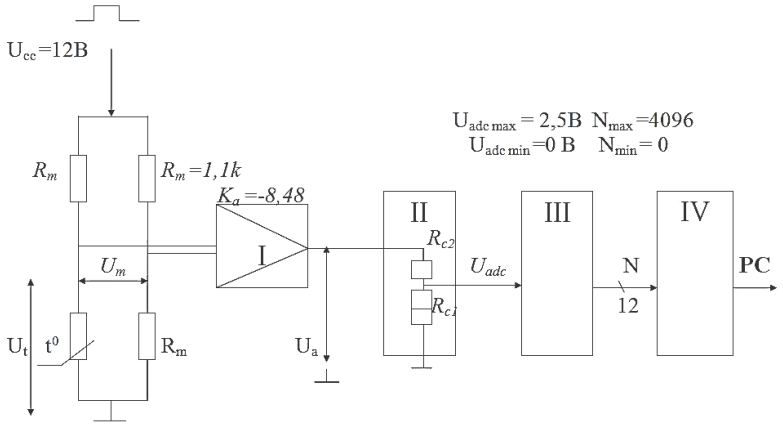

Fig. 4. Structural scheme of measuring channel of the device: I is the amplifier, II is the divider, III is the ADC, IV is the microcontroller

The dependency, shown in Fig. 6, is close to linear. That is why we present it as a straight line (straight line $T=To+N_{ADC}\cdot K_T$, Fig. 6), which crosses the lowest value in the range of temperatures (the value at the ADC output N=0) and the point, which by the calculations matches the temperature value of +40 °C (the value of N at the ADC output will equal 1394,1).

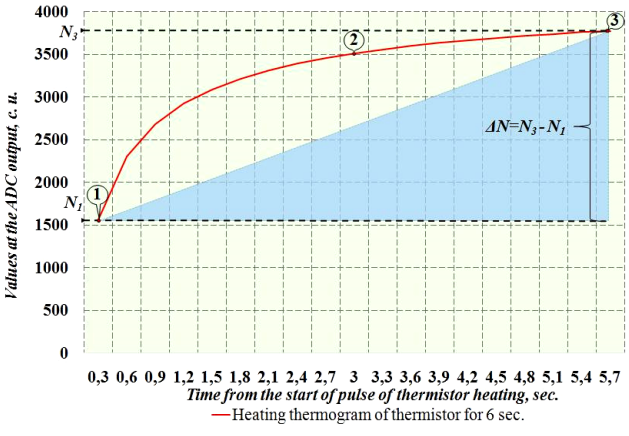

Fig. 5. Heating thermogram of thermistor

After substitution of numerical values into the components of the formula, we obtain the dependency in the form of the curve T=f(N) (Fig. 6).

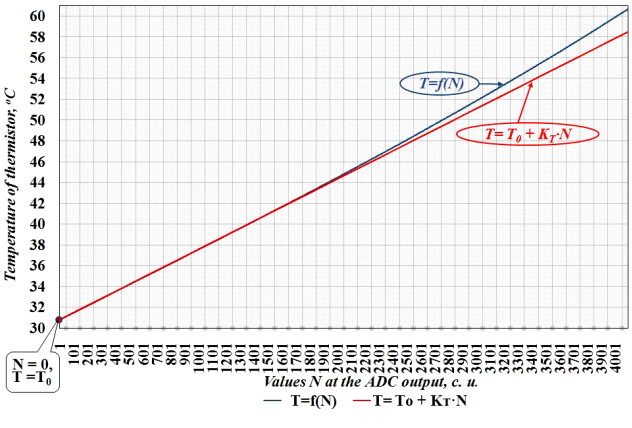

Fig. 6. Dependency of temperature of thermistor heating on the corresponding numeric value at the ADC output of measuring unit

With this purpose, when performing calculations of coefficient of thermal conductivity, we will introduce appropriate amendments. Then the formula (8) will take the following form:

$$\lambda_{s.ld.} = \frac{P_T}{4\pi r\left(\left((N_{3mi}-N_{1mi})-(N_{(+40)}-K_{ni}N_{1mi})\cdot K_{pi}\right)\cdot K_{ki}\dfrac{T_{(+40)}-T_0}{N_{(+40)}}-\Delta T_0\right)\cdot\dfrac{1}{K_{p.f.}}}, \quad (12)$$

where $\lambda_{s.ld.i}$ is the coefficient of thermal conductivity of the studied liquid, which is defined by the data of measuring by the i-th thermistor probe; $N_{3m\,i}$ is the numeric value in the final point of thermistor heating in the thermogram, obtained as a result of measuring by the i-th thermistor probe; $N_{1m\,i}$ is the numeric value in the starting point of thermistor heating in the thermogram, obtained as a result of measuring by the i-th thermistor probe; K_{ni} is the coefficient that corrects the error of measuring by the i-th thermistor probe of the studied sample temperature; K_{pi} is the coefficient that corrects the dependency of the value of the difference $N_{3m\,i}-N_{1m\,i}$, measured by the i-th thermistor probe, on the temperature of the studied sample; K_{ki} is the coefficient that adjusts the sensitivity of the i-th thermistor probe (compensates for the error of value of the difference $N_{3m\,i}-N_{1m\,i}$, measured by the i-th thermistor probe, to the average value); $T_{(+40)}$ is the thermistor temperature that equals +40 °C; T_0 is the temperature of thermistor, at which $N_{ADC}=0$; $N_{(+40)}$ is the numeric value at the ADC output at the probe's temperature +40 °C, which is calculated under condition of linear dependency N=f(T).

The coefficients K_{ni}, K_{pi}, K_{ki} are determined individually for each thermistor in the course of calibration tests, by using reference fluids with known TPC as the studied ones. These coefficients are the characteristics of a thermistor probe. The coefficients ΔT_o, $K_{p.f.}$ are defined by the data of calibration tests, by using reference fluids with known TPC as the studied ones, but they are the mean values for all probes.

5. Results of the study of measuring thermal conductivity of liquids by the thermistor direct heating method

For the verification of the proposed method for determining thermal conductivity of liquids and efficiency of using the device, designed for it, we carried out the study of the following liquids [22]:

– distilled water;
– saline solution (the 0.9 % NaCl solution in distilled water);
– 2.5 % fat milk;
– the 25 % ethyl alcohol solution in distilled water;
– the 60 % glycerol solution in distilled water;
– the 80 % glycerol solution in distilled water;
– the 85 % glycerol solution in distilled water (cutaneous solution, 85%, medical);
– the 70 % ethyl alcohol solution in water ("Septol");
– the 75 % ethyl alcohol solution in water;
– ethyl alcohol, medical 96-Extra (the 96 % ethyl alcohol solution in water).

The calculation of coefficients of thermal conductivity of the studied liquids was carried out by the formula (9). In the calculations we used coefficients of proportionality $N_{3m\,i}$, $N_{1m\,i}$, K_{ni}, K_{pi}, K_{ki}, determined by the control measurements of temperature of thermistor heating in reference liquids with known TPC. Distilled water and the 96 % ethyl alcohol solution in water were used as reference liquids. The results of calculations based on the measuring data are given in Table 1.

When performing calculations of coefficients of thermal conductivity of the studied liquids, we used mean values for each of the probes for each 10-minute measuring session. The density of probability distribution of average values of the coefficients of thermal conductivity of various studied liquids, measured in one session of measurements of 10 minutes each, is shown in Fig. 7. To determine the error of measurement, each liquid was exposed to 10 measuring sessions; the analysis of error

was run for several sessions and the analysis of error performed, while measuring, simultaneously by all the probes of the same studied fluid. The results of the analysis are presented in the form of graphs in Fig. 8. The density of probability distribution of the average values per session of the coefficients of thermal conductivity of the same liquid, defined over 10 measuring sessions of 10 minutes each, is given in the diagram (Fig. 9).

Based on the measurement results, one can argue that:

1. The mean value of measurement error per one measuring session of 10 min. by different probes amounted to no higher than 2 %.

2. Prolongation of the measuring session with consequent averaging of the results of measurement increases the accuracy of measuring by almost two times while in this case the period of the research increases, too.

3. When measuring the same studied liquid simultaneously by 60 probes, the error will not exceed 1.5 %.

Table 1

Results of measuring coefficient of thermal conductivity of the examined liquids

Mode	The value of thermal conductivity and magnitude of error	Distilled water	0.9 % NaCl solution in water	Milk	25 % ethyl alcohol solution in water	60 % glycerol solution in water	80 % glycerol solution	70 % ethyl alcohol solution in water (Septol)	75 % ethyl alcohol solution in water	96 % ethyl alcohol solution in water
1 session, 10 min	Value, W/(m·K)	0,6288	0,6097	0,5632	0,4753	0,4001	0,3428	0,2671	0,2445	0,1741
	Error, %	1,09	1,64	1,25	0,92	1,24	1,22	1,23	1,19	1,8
2 sessions by 10 min.	Value, W/(m·K)	0,6296	0,6113	0,5632	0,4751	0,3998	0,3428	0,267	0,2444	0,174
	Error, %	0,67	1,06	0,9	0,65	0,91	1,05	1,02	0,96	1,47
3 sessions by 10 min.	Value, W/(m·K)	0,6295	0,6112	0,5632	0,4752	0,4001	0,3429	0,2672	0,2445	0,174
	Error, %	0,58	0,79	0,70	0,60	0,84	0,88	0,93	0,86	1,40
5 sessions by 10 min.	Value, W/(m·K)	0,63	0,6109	0,5634	0,4753	0,4002	0,343	0,2672	0,2445	0,1740
	Error, %	0,55	0,66	0,58	0,52	0,78	0,74	0,83	0,78	1,25
1 sessions by 10 min. (one liquid)	Value, W/(m·K)	0.6288	0.6097	0.5632	0.4753	0.4001	0.3428	0.2671	0.2445	0,1741
	Error, %	0.38	0.4	0.38	0.46	0.48	0.44	0.48	0.65	0,99
Data from reference books *, W/(m·K)		0,628	–	0,564	0,477	0,399	0,336	0,259	0,245	0,175

*Note: * – tabular data are prepared based on the materials of a reference book [23]*

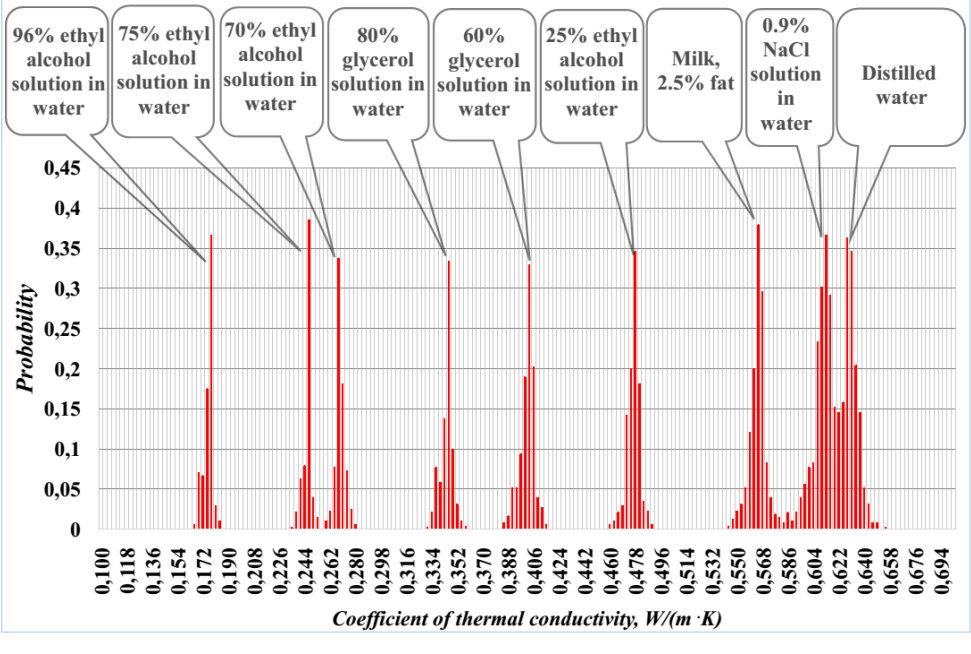

Fig. 7. Density of probability distribution of the mean values of coefficients of thermal conductivity of different studied liquids, measured in one session of 10 minutes each

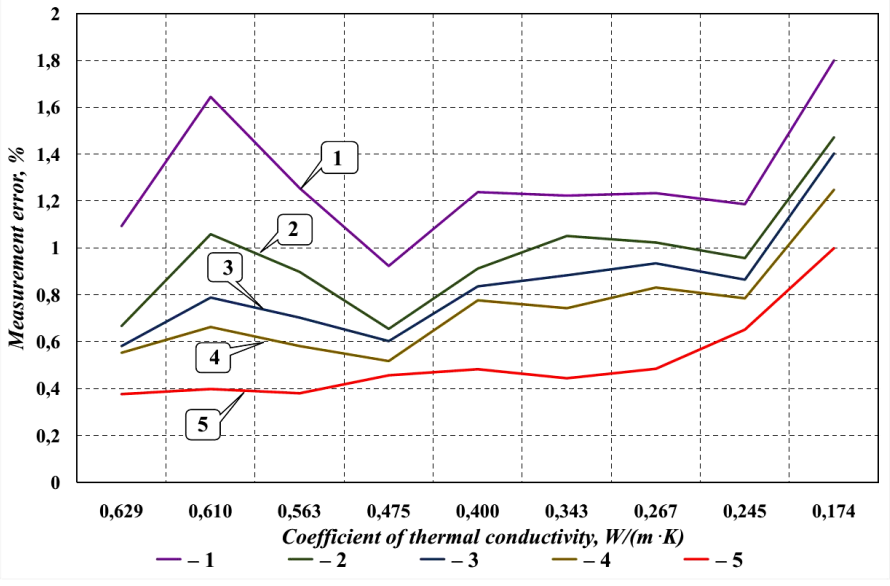

Fig. 8. Measurement errors of coefficient of thermal conductivity by the results of the study: 1 – error of determining coefficient of thermal conductivity during one 10-minute measuring sessions; 2 – error of determining coefficient of thermal conductivity during two 10-minute measuring sessions; 3 – error of determining coefficient of thermal conductivity during three 10-minute measuring sessions; 4 – error of determining coefficient of thermal conductivity during five 10-minute measuring sessions; 5 – error of determining coefficient of thermal conductivity during one 10-minute measuring session when measuring the same studied fluid by all 60 probes

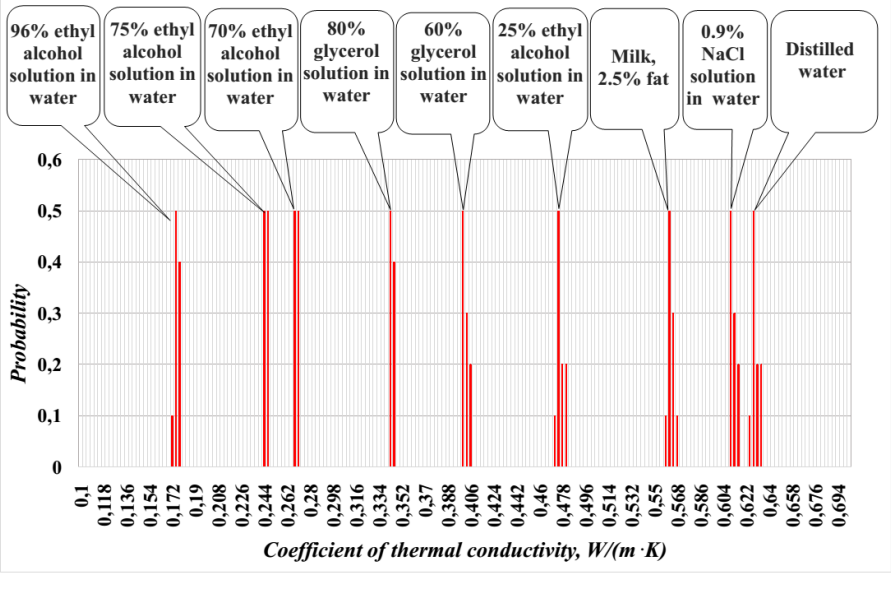

Fig. 9. Density of probability distribution of the mean values per session of coefficients of thermal conductivity of the same studied liquid, measured during 10 measuring sessions of 10 min. each

6. Discussion of results of the study of possibilities to increase the accuracy of measuring thermal conductivity of liquids by the thermistor direct heating method

The use of the designed device for determining thermal conductivity of the studied liquids made it possible to define the following characteristics and peculiarities of its application.

1. The range of temperature when measuring by thermistor is from +30,5±1 °C to +60,5±1 °C. To reduce the measurement error, it is necessary to perform calibration of the device on reference liquids with determining correcting coefficients.

2. The warm-up time to reaching the initial temperature of +30,5 °C is no longer than 30 minutes at the ambient temperature of +22 °C. With the increase in ambient temperature, the warm-up time will decrease, but it should be noted that the ambient temperature must not exceed +28,5 °C. To accelerate the process of measurement, it is expedient, at the ambient temperature lower than +22 °C, for the cartridge with the studied substances to warm up additionally in the thermostat.

3. The range of values of the coefficient of thermal conductivity $\lambda_{s.ld.i}$ of the studied liquids ranges from 0.1 to 1.0 W/(m·K) with an average value of measurement error not exceeding 2 %.

4. The resolution of the device is not less than 3σ, i. e., larger than 0.03 W/(m·K) at the value of thermal conductivity 0,6–1.0 W/(m·K) and decreases to the value of 0.01 W/(m·K) at the value of thermal conductivity 0.1–0.2 W/(m·K).

5. It was found that the error of the device when measuring the temperature of heating a thermistor, that occurs due to the action of destabilizing factors on electronic components of the device (pulse and fluctuating interference), is eliminated by introducing an algorithm of preliminary processing of measuring data.

6. In the course of the study, we defined the factors that affect the probe and measurement area:

– probe contamination;

– fluctuations in the voltage supply to the device;

– emergence of air balls or grease stains on the surface of the probe.

These factors that cause errors of measurement can be eliminated. With this purpose, power supply to the device must come from a high-quality uninterruptible power source, as well as additional cleaning and degreasing of the probe and lubricating the probes with special substances is needed.

7. With a decrease in thermal conductivity of the studied fluid from 1.0 to 0.1 W/(m·K), the temperature of

thermistor self-heating increases from 12 °C to 20 °C. The increase in the temperature of thermistor self-heating is due to availability of the thermistor's protective shell, the material of which, compared with the studied liquids, has lower thermal conductivity, which necessitates introduction of additional coefficients to the formula of calculations, which are determined experimentally using reference liquids with known TPC.

8. For the selected thermistor with resistance of 2 kOhm, sufficient amplitude of heating pulse in the measuring bridge is 12 V. This will provide heating the thermistor from 12 °C to 20°C with the coefficient of thermal conductivity of the studied liquid from 1.0 up to 0.1 W/(m·K).

9. Minimum duration of the thermistor warm-up pulse must equal the thermistor's time constant (for the thermistor RH16 Mitsubishi – 6 sec.) with the cooling pause for 20 sec. And for the alignment of temperature of the studied fluid and the thermistor, the first two pulses are not measured because stabilization of thermal mode takes place in the studied fluid during their action. Thus, before measuring thermograms, the thermistor temperature is stabilized due to the action of the first two pulses and further measurements are carried out at the constant temperature. During heating pulse duration equal to the time constant of the thermistor, it is heated up to 62.9 % of its maximum heating temperature.

10. Minimal volume of the studied in the tube with a diameter of 8 mm is 165 ml, in the tube with a diameter of 10 mm – 380 ml. When measuring larger volumes of the studied liquid, one should use tanks of corresponding dimensions. As a result of moving warm and cold layers of liquids in containers with a diameter larger than 30 mm, the measurement of thermal conductivity by such method is impractical.

7. Conclusions

1. Based on the performed analysis of existing industrial and laboratory instruments for determining thermal and physical characteristics of materials, it was found that they have large errors of measurement that exceed 3 %, are characterized by long period of measurements, while the industrial devices that are capable to measure thermal and physical characteristics of a large number of different materials in a short period of time are lacking.

2. We developed a mathematical model for determining thermal conductivity of liquids, based on its dependency on the temperature of thermistor self-heating. While calculating thermal conductivity of the studied fluid, the data on imbalance of the measuring bridge are used, proportional to the temperature of thermistor heating, and additional coefficients of proportionality, which are determined by testing thermistors with the use of reference liquids with known TPC.

3. We created a device whose shoulder of bridge scheme includes a thermistor. It allows measuring thermal conductivity coefficients of 60 liquids at a time, within a range of their values from 0.1 W/(m·K) to 1.0 W/(m·K), increasing in this way the efficiency and accuracy of the studies.

4. Approbation of the method and the device was carried out. The conducted studies revealed that the value of a measurement error per one session of 10 minutes by different probes amounted to not larger than 2 %, while in the course of measuring the same studied fluid by 60 probes simultaneously the error did not exceed 1.5 %. Application of the proposed method of thermistor direct heating allows using it in a variety of industries, medicine and biology for determining TPC of different materials with high accuracy of measurements.

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