Determination thermal and physical characteristics of liquids using pulse heating thermistor method

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Abstract— *This work addresses of the research thermal and physical characteristics of different liquids by non-destructive method. Proposed to determine the thermal conductivity of liquids used by pulse heating thermistor method. Considered calculation the unit to determine thermal and physical characteristics of liquids. Presented scheme thermistor probe design and block diagram the device for research. The results of experimental studies with control materials using established device based on pulse heating thermistor method showed high accuracy and efficiency of use to determine the thermal conductivity of liquids. Describes possibility of using proposed method for measuring the thermal conductivity of solid, conditional-solid and friable materials in biology and medicine.*

Keywords— ***thermal and physical characteristics of liquids, pulse heating thermistor method.***

I. INTRODUCTION

Relevance of the research is that the thermal and physical characteristics of materials according to requests of scientific and industrial organizations, most interest are the thermal conductivity, heat capacity and thermal diffusivity. Thus, for through the presence of functional relationship between these characteristics and because the vast majority of stationary thermal processes defined methods, the greatest number of requests concerning heat. This is due to the fact that the thermal conductivity is sensitive to the chemical composition and structure of the material varies widely values.

The widespread introduction of new materials industry requires the development of instruments for research of thermal and physical characteristics (TPC), and in particular the thermal conductivity and thermal diffusivity, due to several reasons. First, the thermal conductivity is passport characteristic of existing and emerging new substances and materials, whose number is constantly growing. With thermal conductivity closely related issues saving energy and resources, calculations of thermal regimes of complex structures, optimization of manufacturing processes and many others. In addition, the thermal conductivity as structurally sensitive parameter is an effective tool in research [1].

Research TPC engaged in various materials are Burova S. A., Vorobiev L. Y., Dekusha L. V., Dekusha O. L., Varhaftyk V. P., Tahoev S. A., Kubičár Ľ., Bágeľ Ľ., Vretenár V., Štofanik V, Simankov D. S., Selivanova Z. M. and many other scientists.

The analysis of these studies showed that primary in determining the properties of various materials are thermal characteristics on which they then determine other parameters.

Available today instruments for determining thermal characteristics of materials have significant measurement error up to ± 10%, greater length measurements and virtually no industrial devices that are able in a short time to measure the thermal characteristics of many different materials [2].

II. MATERIAL AND METHODS

To achieve this goal were analyzed pulse methods for determining thermal characteristics, and selected and reasonably pulse method of heating thermistor for research. On the basis of experimental research, a new instrument for determining TPC liquids and discussed settlement of the unit to determine the thermal characteristics of fluids. The method of measurement and calculation TPC fluids and additionally developed software to control the device and calculate the required values of thermal conductivity and thermal diffusivity.

Thermal conductivity is a physical parameter of a substance that is characterized by its ability to conduct heat, and is defined as:

$$\lambda = \frac{d^2 Q_\tau}{\left({dt}/{dn} \right) dF d\tau} \tag{1}$$

Numerically, the thermal conductivity λ is the amount of heat Q_τ that stands pulse duration τ and a frequency *F* passes per unit time *(dt/dn)* across the surface isothermal unit, provided that $gradQ_\tau = 1$. Its dimension W/(m*°K). The coefficient of thermal conductivity for various substances defined with reference tables that based on experimental data.

One of the most accurate methods of determining thermal conductivity of liquids, gases and dispersive materials is method linear constant power source [3,4]. This method is absolute, because it makes measurements of current and voltage at the source of heat, which allows calculating the power source line-probe. This probe is included in one of the shoulders measuring bridge, which is supplied electrical impulse voltage. From the moment you turn the probe is heated by passing it through an electric current. During the action the pulse voltage on the probe measuring device recorded using analog-to-digital converter. So get thermograms of heating probe that determines TPC the substance. It makes transient method; the advantage is compared with other methods of measurement TPC is that testing time is reduced to a few seconds. This method also allows for a test to determine thermal diffusivity.

III. PROPOSAL METHOD FOR MEASURING HEAT-CONDUCTING FLUID

The essence of the proposed method is solving a differential equation of thermal conductivity:

$$\frac{dT}{d\tau} = \alpha * \left(\frac{d^2T}{dr^2} + \left(\frac{dT}{dr}\right) * \frac{1}{r}\right), \quad (2)$$

where:

T- temperature of probe, °C;

τ – time, s;

r - radius of probe, m;

$\alpha = \frac{\lambda}{\rho * c}$ – coefficient of thermal diffusivity, m^2/s;

λ – coefficient of thermal conductivity, W/(m*°K);

ρ – density, kg/m^3;

C – specific heat capacity, J/kg* K.

In this capacity, which stands thermistor is constant?

$$P_t = 2\pi r\lambda * \frac{dT}{dr} = const \quad (3)$$

Solving differential equation (2) using a thermistor sensor probe with a shell in the form of balls is:

$$T = \left(\frac{P_t}{4\pi r\lambda}\right) * \left[\frac{ln4\alpha\tau}{r^2 - \gamma}\right] \quad (4)$$

where γ=0,5772 – Euler's constant.

Since the test material is unknown thermal conductivity and thermal diffusivity, thermal conductivity is given by:

$$\lambda = \frac{P_t}{4\pi r\Delta T_\lambda} \quad (5)$$

where:

λ– coefficient thermal conductivity of liquid, that tested, W/(m*°K);

P_t – power that is allocated thermistors, W;

r – thermistor shell radius, m;

ΔT_λ – heating temperature thermistor, °C.

The technique of determining TPC substances used in the measurement by heated filaments, but unlike the thermistor measuring threads covered with a protective glass or epoxy. Materials for shells with thermal conductivity of 0.3-0.5 W/(m*°K), therefore creating additional thermal resistance towards thermistor heating of the substance. The thermal conductivity of substance rather small compared to conduction membrane, so this factor doesn`t affect the heating temperature thermistor. The thermal conductivity of the test material heat conductivity equal to or more shell thermistor, and this leads to additional self-heating thermistor, which was confirmed by measurements.

Graph of thermal conductivity on temperature thermistor heating, built by the formula (4), and according to the measurements shown in Fig. 1.

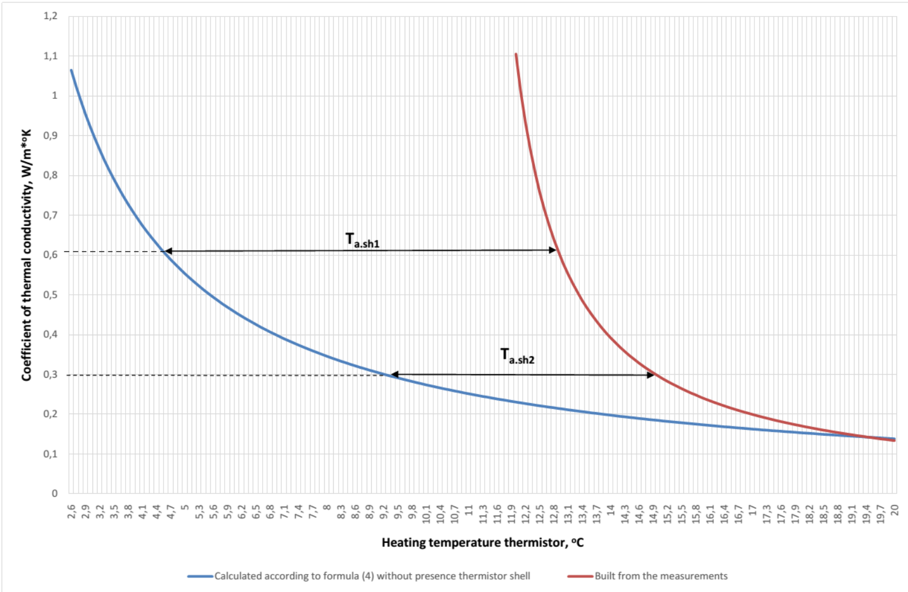

FIG.1. DEPENDENCE OF THERMAL CONDUCTIVITY ON TEMPERATURE THERMISTOR HEATING, BUILT BY THE FORMULA (4) AND ACCORDING TO THE MEASUREMENTS

From the dependency follows that the thermistor, due to the presence of containment, in addition self-heating. Self-heating additional temperature – $T_{a.sh}$, provided $T_{a.sh1} > T_{a.sh2}$, where $T_{a.sh1}$ - additional self-heating temperature at high thermal conductivity of the environment and $T_{a.sh2}$ - additional self-heating temperature at low thermal conductivity of the environment. This is because with a decrease in thermal conductivity test liquid impact existing containment decreases. For a graph can estimate the value of thermal conductivity when the temperature further self-heating $T_{a.sh}$ will be equal thermistor temperature heating, which is calculated using the formula (4). In this case, RH16 Mitsubishi thermistor type that was used in the measurement, thermal conductivity of the membrane is approximately 0.35 W/(m*°K), [5].

This fact necessitates the introduction of the additional formulas Aspect Ratio, defined by standard test liquids with known TVH.

Taking into account this formula to calculate the thermal conductivity becomes the following:

$$\lambda_{t.s.} = \frac{P_t}{4\pi r(\Delta T_m - \Delta T_{sh}) * \frac{1}{K_p}} \quad (6)$$

where:

$\lambda_{t.s.}$ – coefficient thermal conductivity of liquid, that tested, W/(m*°K);

P_t – power that is allocated thermistors, W;

r– thermistor radius, m;

ΔT_m – heating temperature thermistor, that measured by device, °C;

ΔT_{sh} – self-heating temperature of thermistor which defined by the results of tests using reference substances, °C. The self-heating thermistor caused by the presence of membranes;

K_p – proportionality factor that determined the results of tests using reference materials. He describes thermistor probe sensitivity to the value of thermal conductivity experimental substances with which it has a thermal contact.

Thermal diffusivity is given by:

$$\alpha = \left(A * \frac{r^2 \gamma}{4\Delta\tau_\alpha}\right) * \left(\frac{dln\Delta\tau_\alpha}{d\Delta T_\alpha} * \Delta T_\alpha\right) \quad (7)$$

where:

A – proportionality factor, determined by standard test liquids with known TPC;

$\Delta\tau_\alpha$ - warm-up time of the thermistor, s;

ΔT_α – heating temperature thermistor during $\Delta\tau_\alpha$, ^oC.

The design of thermistor probe is used to measure the thermal conductivity of liquids shown in Fig. 2.

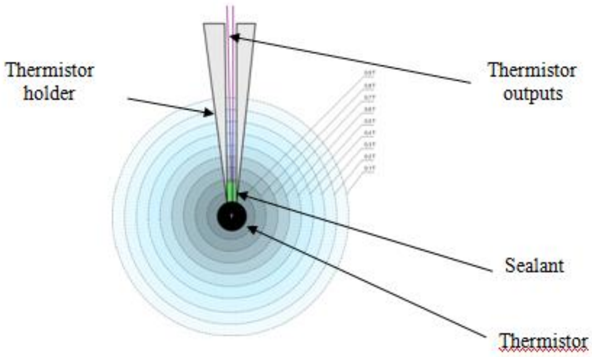

FIG. 2. THE DESIGN OF THE THERMISTOR PROBE TO MEASURE THE THERMAL CONDUCTIVITY OF LIQUIDS

3.1 Block diagram of the developed device

Based on the proposed method developed measuring device for determining the thermal conductivity of liquids, a block diagram is shown in Fig. 3.

TPC device for measuring liquid consists of thermostat, which is a container (vial) with the investigated liquid thermistor measuring probe, the measuring device and personal computer (PC). On the PC set of programs for process control measurements, read data from the measuring device and the calculation TPC test substances according to measurement.

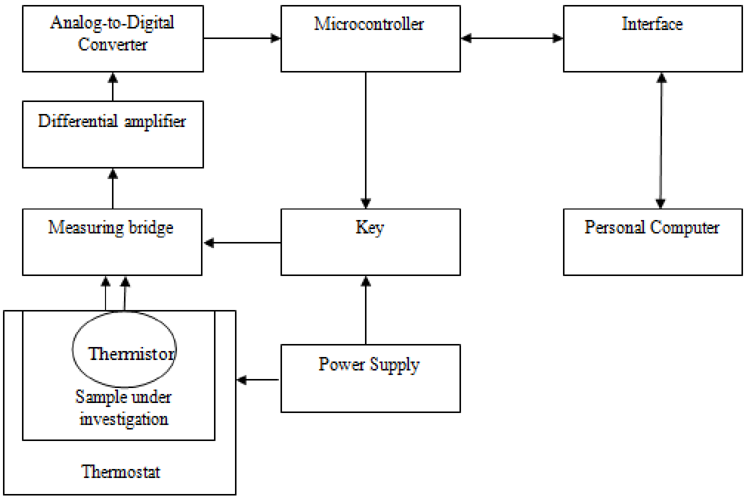

FIG. 3 BLOCK DIAGRAM OF THE DEVICE FOR MEASURING TPC LIQUIDS

3.2 The principle developed device and determination thermal conductivity and thermal diffusivity of materials

The tested material (liquid) is placed in an incubator with constant temperature. When conducting research thermistor probe immersed in the test liquid. Microcontroller with the key delivers voltage to measuring bridge with thermistors. When an electric current thermistor is heated and its resistance decreases and voltage unbalance measuring bridge is increased. During the heating pulse action every 0.3 seconds by using the analog to digital converter and microcontroller conducted measure unbalance of the bridge. These measurements after the heat pulse recorded in file on the hard disk of personal computer. The numerical value the voltage unbalance of bridge are in conventional units values at the ADC output device, which is proportional to the voltage unbalance measuring bridge, and thus proportional to temperature thermistor. A value of 1 (one) standard unit in the ADC output corresponds to increase in temperature thermistor 0.00725 ^{o}C. This value is determined using the design characteristics of the unit and adjusted for test results. The experimental data can be written thermohram heating thermistors, which is determined by the temperature of heating, which is used to calculate the thermal conductivity of material. Number of thermohram obtained depends on the measurement session. Thermogram, indicating temperature thermistor, expressed in standard units at ADC output for the duration of pulse and is obtained from studies shown in Figure 4.

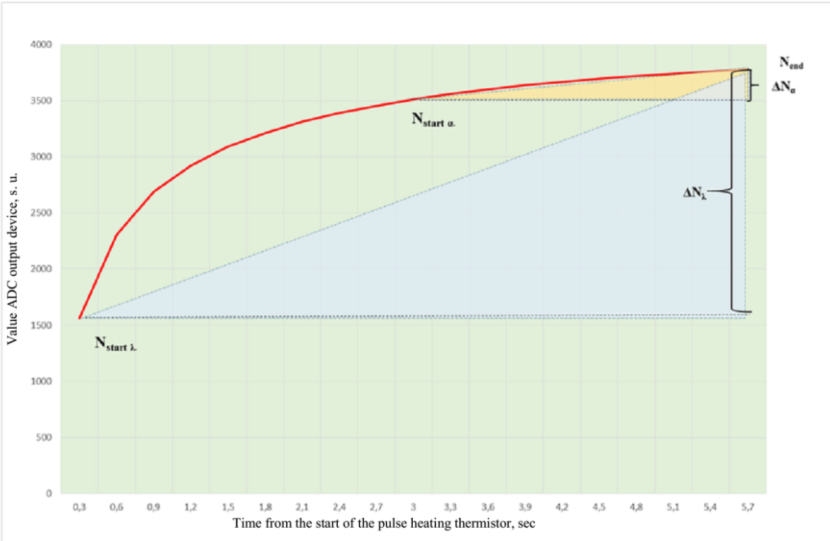

FIG. 4 HEATING THERMOGRAM OF THERMISTOR

In determining the thermal conductivity test liquid according to the measuring probe thermohram calculated averages ΔN_{λ} at the ADC output in standard units:

$$\Delta N_{\lambda} = N_{end} - N_{start\ \lambda} \tag{8}$$

where:

N_{end} – endpoint pulse heating thermistor;

$N_{start\ \lambda}$ – starting point heating thermistor.

ΔN_{λ} value is proportional to temperature by heating thermistor duration of the pulse. Using ΔN_{λ}, determined heating temperature thermistor ΔT_m that the measured device:

$$\Delta T_m = K_{\lambda} * \Delta N_{\lambda} \tag{9}$$

where:

K_{λ} - proportionality factor characterizing the dependence unbalance value in standard units at the ADC output to changes in temperature thermistor probe;

ΔN_λ - average of the unbalance measuring bridge at the ADC output in standard units of measurement for the session. Average ΔN_λ used to reduce measurement error as error during session may make several standard units.

Also, the value $N_{start\lambda}$ calculated temperature test liquid to start of the pulse, which corresponds to the temperature test. Taking into account these value adjustments made thermal conductivity at + 40°C, which is calculated using the formula (5).

With the developed measuring device and the software is the ability to determine the thermal diffusivity of the material.

In carrying out calculation thermal test liquid is calculated according thermohram probe for measuring average values ΔN_α at the ADC output in conventional units:

$$\Delta N_\alpha = N_{end} - N_{start\ \alpha} \tag{10}$$

where:

N_{end} – endpoint heating thermistor;

$N_{start\ \alpha}$ – middle pulse heating thermistor.

ΔN_α value is proportional to the velocity thermistor heating during the pulse. To determine the effects ΔN_α by self-heating thermistor and availability of containment selected the most linear plot of thermogram - the second half of the heating pulse, which "most sensitive" to the coefficient of thermal test liquid.

With values determined ΔN_α heating temperature thermistor ΔT_α the linear section of thermogram, measured using the device:

$$\Delta T_m = K_\alpha * \Delta N_\alpha \tag{11}$$

where K_α - proportionality factor that is calculated by the design characteristics of the device. This ratio determines the dependence unbalance value in standard units at the ADC output to changes in temperature thermistor probe.

ΔN_α - average of the unbalance measuring bridge at ADC output in standard units of measurement for the session. Average ΔN_α calculated to reduce measurement error as error during a session may make several standard units.

Also calculated value $N_{start\lambda}$ is determined by temperature of test liquid to start of pulse, which corresponds to temperature at the process of testing. Given the value adjustment is made to established thermal diffusivity values at + 40 °C, is calculated using the formula (6). Value ${dln\Delta\tau_\alpha}/{d\Delta T_\alpha}$ in the formula (7) is determined by thermogram as quantity that is inversely proportional to average rate of increase temperature in the second half of pulse, and proportionality K_α determined experimentally - by testing with known reference liquids TPC.

3.3 Progress in research and the results of experimental research

To determine the effectiveness proposed methodology for determining the thermal conductivity and thermal diffusivity material created using unit conducted experimental studies using the following liquids:

- distilled water;
- saline (0,9% NaCl solution in distilled water);
- 2,5% milk fat content;
- 25% ethanol solution in distilled water;
- 60% glycerol solution in purified water;
- 80% glycerol solution in purified water;
- 85% glycerol solution in purified water (85% cutaneous solution, medical);
- 70% solution of ethanol in water ("Septol");
- 75% solution of ethanol in water;
- ethyl alcohol Extra medical (96% solution of ethanol in water).

As reference liquids to determine additional proportionality factor used distilled water and 96% solution of ethanol in water.

Before the researches carried out to prepare the material. For this test-tube test liquid is poured. This is the minimum required volume in test-tube diameter 8 mm and diameter 0.9 mm thermistor. The error was in dosage doesn`t exceed 3%. Liquids for research prepared just before their execution. Here, the following liquids:

- 25% ethanol solution in distilled water;
- 60% glycerol solution in purified water;
- 80% glycerol solution in purified water;
- 75% solution of ethanol in water.

In addition to testing of test solutions fueled to temperature of + 40^{o}C and mixed in a medical shaker for 20 minutes to obtain a homogeneous solution.

Test-tube with solution for determined in thermostat and heated to temperature +40^{o}C ±1^{o}C. The team at the beginning of the measurement was given by PC with appropriate software. After the measurements obtained session data is automatically copied from the device to file on your PC hard drive.

Recorded files are stored in your heating thermistor probe measuring device for the duration of the pulse measurement during the session.

For each test liquid measurement was conducted 50 times in sessions of 10 minutes. For each measurement session received 20 thermohrams. Measurements were carried out in the mode 6-second pulse heating and 20-second interval cooling thermistor.

Using ratios as defined in the standard test liquids with known TPC, these design characteristics of the device and software processing, carried out the necessary calculations, data obtained by each of sessions ΔN_{λ} calculated mean values and formula (4) is calculated studied the thermal conductivity of liquids.

Comparative value of thermal conductivity investigated liquids derived from experimental studies suggested method for determining thermal conductivity using established device and for reference data shown in Table 1. In Figure 5 a value of thermal conductivity for distilled water, saline solution (solution 0,9 % NaCl in distilled water), 2.5% milk fat content, 25% ethanol solution in distilled water, 60% glycerol solution in purified water, 80% glycerol solution in purified water, 85% glycerol solution in purified water (85% cutaneous solution, medical), 70% solution of ethanol in water ("Septol"), 75% solution of ethanol in water, ethanol Extra medical (96% solution of ethanol in water), which is calculated based on the results of experimental measurements.

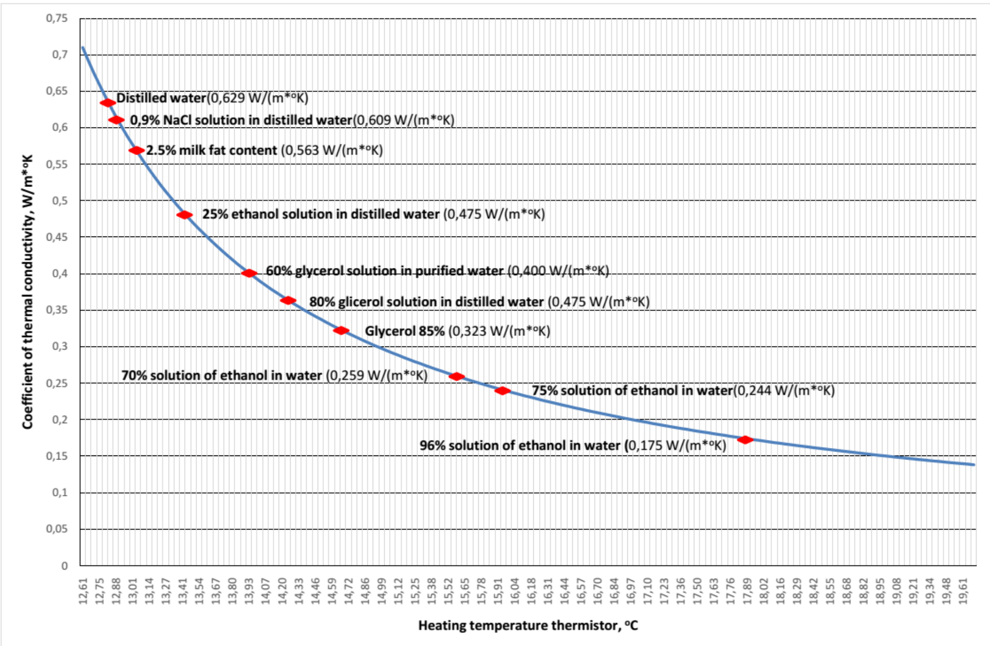

FIG. 5 GRAPH OF THE THERMAL CONDUCTIVITY OF LIQUIDS EXPERIMENTAL HEATING TEMPERATURE THERMISTOR ACCORDING TO MEASUREMENTS AT THE RESEARCH SAMPLE OF +40 ^{o}C

TABLE 1
COMPARATIVE VALUE OF THERMAL CONDUCTIVITY TEST LIQUIDS

Test liquid	Coefficient of thermal conductivity			
	Coefficient of thermal conductivity, W/(m*°K)	Standard deviation, W/(m*°K)	Measurement error,%	Data from the directory [6], W/(m*°K)
Distilled water	0,6288	0,00688	1,093	0,628
Saline (0,9% NaCl solution in distilled water)	0,6097	0,01003	1,645	-
2.5% milk fat content	0,5632	0,00707	1,255	0,564
25% ethanol solution in distilled water	0,4753	0,00918	1,936	0,477
60% glycerol solution in purified water	0,4001	0,00501	1,25	0,399
80% glycerol solution in purified water	0,3408	0,00412	1,20	0,336
85% glycerol solution in purified water	0,3233	0,005343	1,65	0,323
70% solution of ethanol in water ("Septol")	0,2601	0,003295	1,26	0,259
75% solution of ethanol in water	0,2445	0,002901	1,19	0,245
Ethyl alcohol 96 Extra medical (96% solution of ethanol in water)	0,1741	0,003134	1,80	0,175

IV. CONCLUSION

- By using the device, whose work is based on pulse heating thermistor method can be measure thermal conductivity λ in the range of 0.1 to 1.0 W/m*°K with an error not exceeding 3%. Also, using the device is the ability to measure thermal diffusivity α and the measurements obtained by the value of λ and α can calculate the thermal characteristics of experimental fluids - heat capacity C_p and thermal activity ε.
- The advantage of this method is use small volumes of liquids investigated by small size of thermistor probes and simultaneously test a large number of test liquid by increasing the number thermistor probes.
- The probe affects thermal performance, availability containment chip thermistor (glass or epoxy), rejecting the electrical characteristics of various design and thermistor measuring probe.
- If you are measuring static and dynamic errors. The statistical error is due to slow temperature variations experimental fluid contamination of surface thermistor probe formation on surface of balloons air stratification components of liquids research solutions and more. Reduction is achieved by statistical error correction values obtained based test liquid temperature, ensuring purity and homogeneity research probe liquids. Dynamic measurement errors that occur due to different kinds of vibrations measuring electrical signals in circuits, offset accumulation values and their subsequent statistical processing. To ensure the required accuracy of measurement TPC, advisable to increase the term measurement session and sessions measurement.
- The proposed device can be modified with minimal time and material costs to significantly increase the number of thermistor probes. This allows both to test large number of experimental fluids that reduces testing time and measurement error.

- This method can be used in biology to measure TPC biological materials, in medicine - to determine the immunological reactions in biological fluids, where limited volume of research material and requires a large number of investigated materials, food and oil industry.
- The proposed method can be used to measure TPC solid, opportunistic solid, plastic, bulk materials. Thus to ensure reliable thermal contact with the research material enough to change the design thermistor probe.

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