A New Method For Temperature Measurement Using Thermistors

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This article considers the question of improving the accuracy of temperature measurement using thermistors. Improvement is carried out by binding the temperature to the inflection point T_{inf} of the functional dependence of the logarithm of the thermistor resistance $\ln R_C$ and measurement of the temporal drift of the decomposition coefficients $A_i(\tau_d)$.

A new method is proposed to derive a precise temperature of the thermistor since it provides a closer approximation to the actual temperature then simpler equations, and is useful over the entire working temperature range of the sensor.

Keywords: temperature measurement, inflection point of the functional dependence of the logarithm of the thermistor resistance, drift coefficients of decomposition.

Thermistors refer to equipment with a strong dependence of electrical resistance to temperature. At limiting high temperatures the thermistor resistance becomes almost constant and independent of temperature. This means that thermistor calibration has a constant at value at infinity, or has a reference point at very high temperature. This causes inconvenience in use and leads to significant errors at measurement and calculation of temperature using thermistors, at low and medium temperatures.

We offer to make a second constant value point, or reference point of thermistor calibration, which was determined by us to be at the inflection point of the functional dependence of the logarithm of the thermistor resistance $\ln R_C$.

The difficulty of temperature measurement using thermistors, which are used in the research of many thermal processes and in thermal equipment, is of high interest at this time, and improving the accuracy of measurements is considered very important.

In view of this, calibration of the thermistor CT3-19 within the temperature range of 0-200°C was made by verifying indicated values recorded in equilibrium thermodynamic conditions using the model platinum resistance temperature sensor [1, 2].

EXPERIMENTAL

Thermistors CT3-19 are represented as thermally sensitive elements [6-8], made of ceramic oxide materials based on nickel, magnesium and cobalt, denoted in composition by the formula $(Ni_{0.2}Mn_{0.7}Co_{0.1})_3O_4$, with negative temperature coefficient (NTC) and resistance of about 10 kOhm at room temperature. The thermistor bead of a CT3-19 is coated with a thin layer of molybdenum glass and welded on output traverses (0.3 mm) by thin platinum wires (0.01 mm).

The sensitive element of the standard Platinum Resistance Thermometer PRT-10 is used as a resistance temperature sensor. The quartz helicoid with platinum spiral is placed in a 4mm diameter thin-walled cylinder made of molybdenum glass. Before sealing, the cylinder with helicoid was filled with helium under a pressure a little less than atmospheric. After manufacturing, the resistance thermometer is calibrated again in temperature range 0-200°C at Siberian Scientific Research Institute of Metrology (SSRIM) in Novosibirsk. The absolute error of temperature measurement using the platinum resistance thermometer is ± 0.02 K.

The thermometer together with a thermistor are placed in a heavy copper cylinder, 100 mm in length and 70 mm in diameter, which is located in a vacuum chamber on rigid hangers fixed on the internal surface of upper flange of the chamber. Two pipes are welded to the upper flange of the vacuum chamber, through one of which the chamber is evacuated, though the other one all sensing wires exit. The pressure in the chamber is maximum $1.3 \cdot 10^{-3}$Pa (10^{-5}torr).

The vacuum chamber and copper unit are placed in liquid thermal bath with a capacity of 40 litres, which has is allowed to reach equilibrium temperatures in the range of 0-200°C with temperature gradients of less than $1 \cdot 10^{-3}$K/cm.

The cooling unit was a conditioner BK-1500, for which the standard flash-heat exchanger was replaced with a subdivided loop.

The working fluid in the thermal bath was silicone oil PES-V2, which allows operation at temperatures of 0-200°C. The temperature variation inside the bath over a period of several hours of monitoring was not more than $1 \cdot 10^{-3}$K, and rate of temperature drift was less than $1 \cdot 10^{-4}$K/h.

MEASURING

Calibration of the thermistor CT3-19 was carried out over more than two years. Measurements were made in stable conditions under an isothermal cover [9-10], with gradual increase of temperature from 0°C to 200°C in increments of 10°C. The duration of one continuous cycle of temperature rise and measuring run was up to 48 hours. In total there were 21 cycles of measurements .

Calibration of the thermistor is in the precise measuring of the thermistor resistance R_C, (Ohm), using the standard potentiometric method, in a stationary state under fixed temperature T, (K), determined by the platinum resistance temperature thermometer PRT-10. A high quality voltage comparator P3003, accuracy class 0.0005, is used, coupled with standard resistance coil P321 accuracy class 0.01, located in a temperature-insulated box. A pack of batteries “Backen” in a grounded metal enclosure worked as a current source.

A total of 500 experimental points were obtained, which were formed into a source data array of temperatures T, and the logarithms of the resistance of the thermistor $\ln R_C$. The maximum random error of measurement of temperature with thermometer PRT-10 does not exceed $(2\text{-}3)\cdot10^{-3}$K, thermistor resistance $5\cdot10^{-4}$Ohm.

All temperature measurements, conducted using platinum resistance thermometer PRT-10, including calibration at SSRIM, were made when measuring a current value of 1 mA ($1\cdot10^{-3}$A), and sensor dissipation is $W_{PRT} = (10\text{-}17)\cdot10^{-6}$ W.

Fig. 1 shows the results of one cycle of thermistor resistance R_C measurement, against temperature. For easier viewing, the graphic is presented as a reciprocal temperature function $10^4/T$, 1/K, of $\ln R_C$. This relationship is close to linear, but at high temperatures around T~473K, where $\ln R_C$ ~4-5, and at low temperatures around T~273K, where $\ln R_C$~9-10, some deviations are noticed. At moderate temperature, at the range of $\ln R_C$ ~6-8, an inflexion point possibly exists.

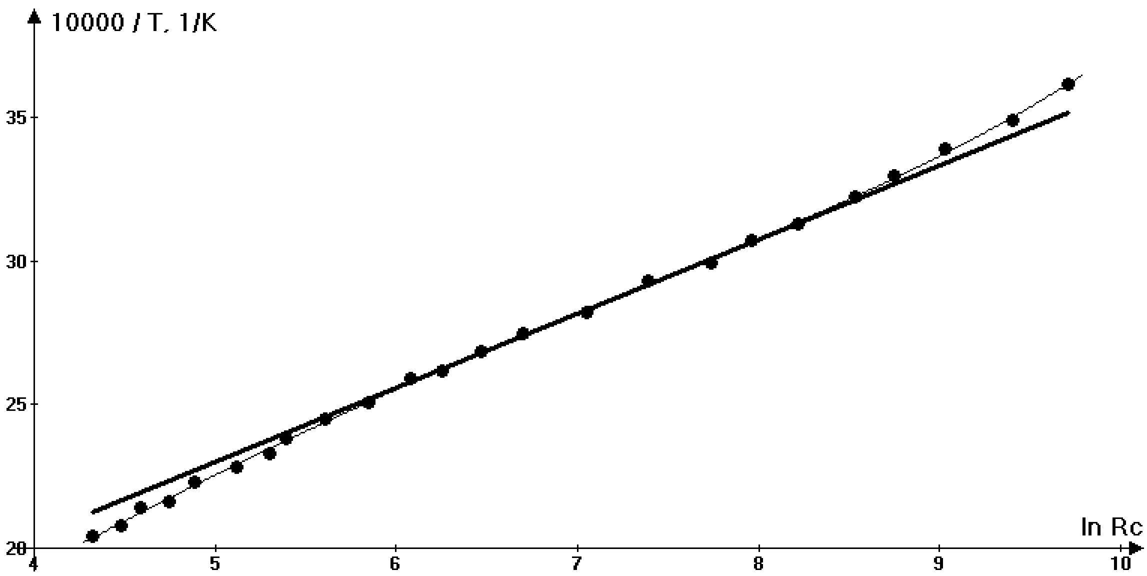

Fig.1. Experimental dependence of the logarithm of thermistor CT3-19's resistance on the reciprocal temperature 10^4/T, 1/K. The straight line is the calculation according to equation (6), the curve -calculation according to equation (9).

Considering the temperature detector as a system with lumped parameters, the thermistor's equation is written as follows [1,2]

$$T_C + \tau_C \cdot \dot{T}_C = \frac{W_C}{K_C} + T_0 \;;\; \tau_C = \frac{C_C}{K_C} \quad (1)$$

Where T_C — thermistor temperature, K; $\dot{T}_C$ — derivative with respect to thermistor's time-temperature in dynamic conditions of measurement; τ_C — thermistor's characteristic lag time, s; W_C — electrical heating output, W ; K_C — heat-transfer coefficient between thermistor and copper unit, W/K; T_0 — measurement with thermometer PRT-10 temperature of copper unit or, for example, heat pipe; τ — time, s; C_C - thermistor's heat capacity, J/K.

Solution of equation (1) is the following formula [3], in which at moment in time $\tau = \tau^*$ the thermistor's temperature is considered to be equal to T_C^*.

$$T_C(\tau) = T_C^* \cdot \exp\left(-\frac{\tau-\tau^*}{\tau_C}\right) + \left(\frac{W_C}{K_C} + T_0\right) \cdot \left[1 - \exp\left(-\frac{\tau-\tau^*}{\tau_C}\right)\right] \quad (2)$$

The electrical heating output W_C, generated on the thermistor by the act of measuring the current, is constant during all calibration tests and equals $20 \cdot 10^{-6}$W, and the thermistor's overheating ΔT_C is calculated by the formula:

$$\Delta T_C = \frac{W_C}{K_C} = \tau_C \cdot \frac{W_C}{C_C} \quad (3)$$

To define the thermistor's overheating special tests were performed: when in a stationary state at temperatures from 2°C to 195°C, the thermistor's (and thermometer's) heating and cooling temperature was measured during a staged evolution of the electrical heating output W_C. With the help of a measuring system liquid calorimeter, described in [9,10], detailed measurements of the relaxational characteristics of the sensors were made. Calculation of the thermistor's response (lag) time τ_C, according to equation (2) using ordinary least squares technique (OLS) [11-14], gave the results shown in Figure 2.

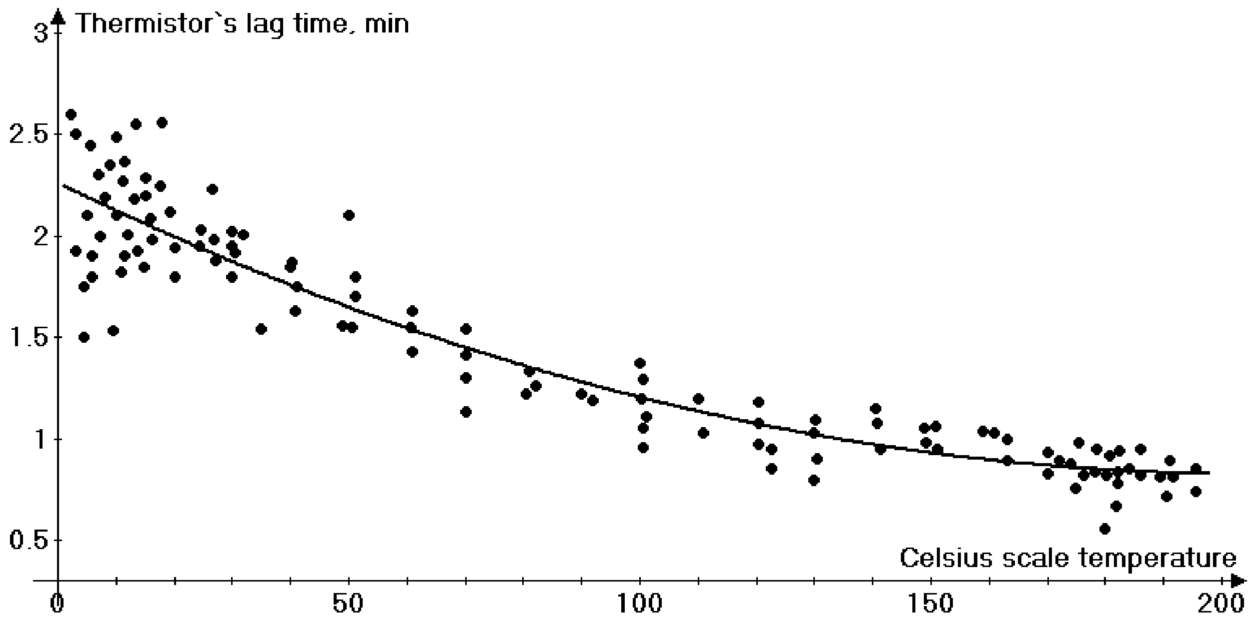

Fig.2 . Experimentally defined thermistor's CT3-19 lag time τ_C.

An approximation to the curve in Figure 2 is given by a polynomial formula

$$\tau_C(t) = 3.3963027 \cdot 10^{-5} \cdot t^2 - 1.39779 \cdot 10^{-2} \cdot t + 2.261388 \text{ minutes} \quad (4)$$

where t — temperature Celsius, experimental points' mean squared departure $\sigma \sim 0.18$ min.

The heat capacity of the thermistor $C_C \sim 0.3$ J/K, weak dependence of the heat capacity of the thermistor temperature; heat-transfer coefficient $K_C \sim (2 \div 5) \cdot 10^{-3}$ W/K; and the overheat value caused by the measurement current not more than $\Delta T_C \sim (10\text{-}4) \cdot 10^{-3}$K, and is considered in all measurements. The temperature difference between the copper cylinder and its isothermal cover, was not more than 0.05-0.1 K; temperature change during calibration was less than 10^{-7}K/s. Therefore, the thermodynamic state of the temperature sensors inside the copper unit during this period was quasi-stationary.

ELABORATION

The functional dependence of the electrical resistance of the oxide semiconductor thermistor R_C on temperature T is quite difficult, and at first approximation it is represented as a resistance of an ideal semiconductor with strictly the same number of holes and charge carriers in the exponential form:

$$R_C = A \cdot \exp\left(\frac{B}{T}\right) \quad (5)$$

where R_C — electric resistance of thermistor, Ohm, at temperature T, K;

A — thermistor's resistance value, Ohm, at infinite temperature;

B — thermistor's sensitivity parameter, dependent upon temperature in general way, K.

At temperature T=1°C thermistor's CT3-19 resistance R_C~30 kOhm; at temperature T=200°C R_C~50 Ohm; B~4000 K, A~0.013 Ohm. Taking logs in equation (5):

$$\frac{1}{T} = -\frac{1}{B} \cdot \ln A + \frac{1}{B} \cdot \ln R_C \quad (6)$$

To clarify the question of inflection of the experimental curve in Fig.1, the derivative was calculated $d(1/T)/d(\ln R_C)$, and analyzed with the whole array of experimental points. Derivative value $d(1/T)/d(\ln R_C)$, calculated according to the results of one cycle of thermistor's resistance measurement dependent upon $\ln R_C$, are shown in Fig.3.

According to the results of numerical differentiation [15] of the entire array of experimental points, curve minimum was defined for the value $\ln R_C$ min=7.63±0.01, which corresponds to the temperature of inflection point, T_{inf} = 336.34K or 63.19°C.

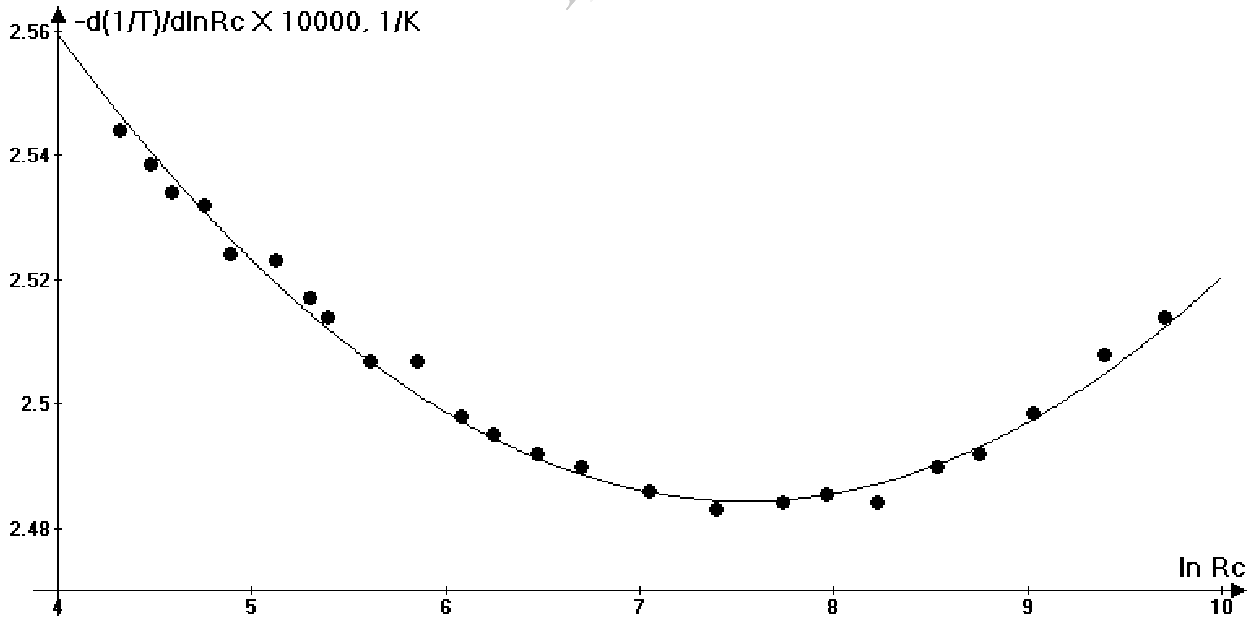

Fig.3. Calculated derivative dependence — $d(1/T)/d(\ln R_C)\cdot 10^4$, 1/K dependent upon logarithm of thermistor's CT3-19 resistance $\ln R_C$.

Expanding the derivative $d(1/T)/d(\ln R_C)$ to a series form at a point minimum:

$$\frac{d(1/T)}{d\ln R_C} = a_1 + a_2 \cdot (lnR_C - 7.63)^2 + a_3(lnR_C - 7.63)^3 + \dots \quad (7)$$

where a_i — the expansion coefficients.

After integration the expansion (7) leads to the following form

$$\frac{1}{T} = A_0(\tau_d) + A_1(\tau_d) \cdot (\ln R_C - 7.63) + A_2(\tau_d) \cdot (\ln R_C - 7.63)^3 + A_3(\tau_d) \cdot (\ln R_C - 7.63)^4 \quad (8)$$

where $A_i(\tau_d)$ — the expansion coefficients, τ_d — time drift of the coefficients.

Thus, the calibration of the thermistor CT3-19 essentially consists of determining the numerical values of polynomial (8) $A_i(\tau_d)$ coefficients and taking account of their drift through time τ_d.
The main feature of the calculation according to the equation (8) is in binding the temperature to the inflection point T_{inf} of the functional dependence of the logarithm of thermistor's resistance.

Calculation of coefficients $A_i(\tau_d)$ was made using ordinary least squares technique (OLS) [11-14]. The absolute errors of calculation coefficients $A_i(\tau_d)$ are following:
$\delta A_0 \sim 1\cdot10^{-3}$, $\delta A_1 \sim 1\cdot10^{-3}$, $\delta A_2 \sim 1\cdot10^{-4}$, $\delta A_3 \sim 1\cdot10^{-5}$.

For quality control and calibration and long term stability, after each of the 21 defining set of coefficients $A_i(\tau_d)$ from formula (8), the derivatives $d(1/T)/d(\ln R_C)$ were calculated. With dispersion of not more than $\Sigma \sim 5\cdot10^{-7}$ all the values of derivatives lie on the curve in Fig. 3. In the low temperature area at values of the logarithms $\ln R_C \sim 9$-10, the dispersion of calibration is a bit higher, and reaches $\Sigma \sim (5\text{-}7)\cdot10^{-7}$. This is due to the higher thermistor resistance $R_{C,}$ and the steeper temperature dependence dR_C/dT, then the lower density of experimental points, since the calibration of the thermistor was mostly performed at intervals of 10°C.

Fig.4 shows the time history of coefficients $A_i(\tau_d)$, and the temporal drift of the thermistor's calibration. The first eight measurement cycles were made when heating the thermistor up to 200°C. As a result of such heating there was significant calibration drift and change of coefficient $A_i(\tau_d)$, for example: $dA_0/d\tau \sim 6\cdot10^{-4}$ 1/month. After the limiting high temperature was decreased to 190°C, temporal drift of coefficients decreased notably, for example the rate of change of coefficient $A_0(\tau_d)$ became only $dA_0/d\tau \sim 1.5\cdot10^{-4}$ 1/month. Values of temporal coefficients drift $A_i(\tau_d)$ are shown below, τ_d — months.

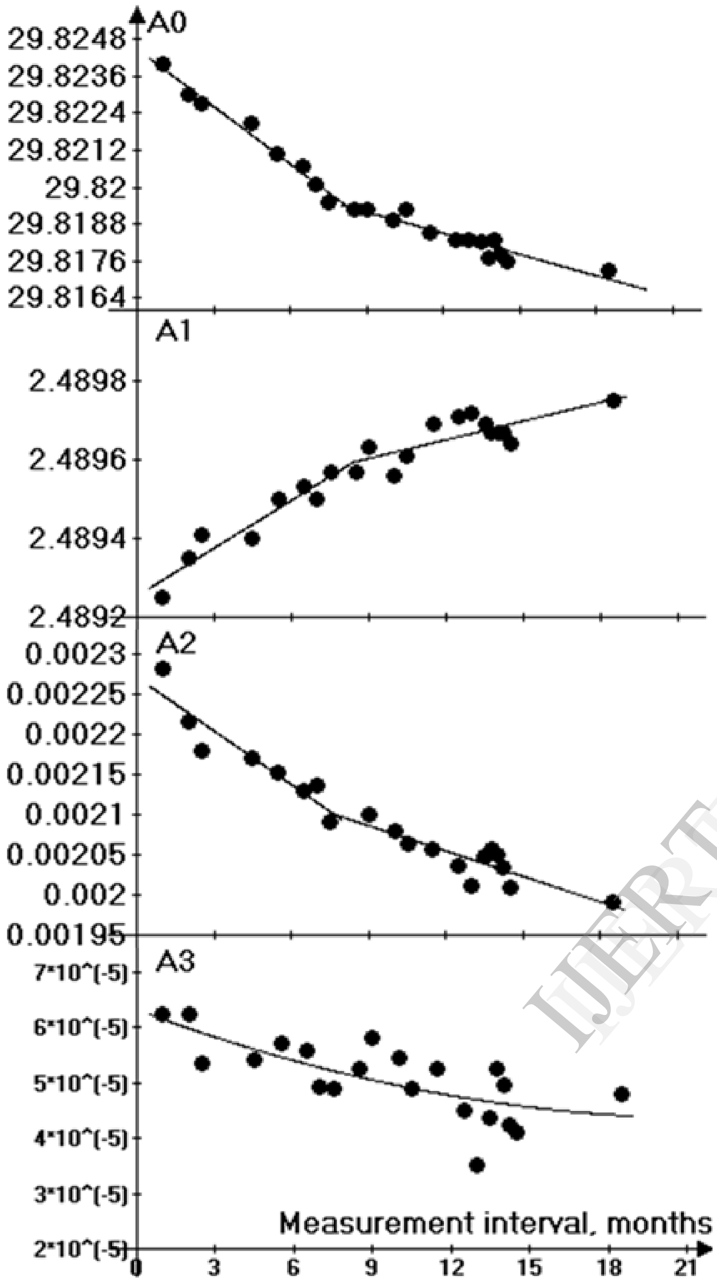

Fig.4. Time history of coefficients $A_i(\tau_d)$ at heating up to 200°C — left part of graphics, heating up to 190°C — right part of graphics.

Coefficients $A_0(\tau_d)$

$A_0 = -6.21997 \cdot 10^{-4} \cdot \tau_d + 29.824488$ at heating up to 200°C

$A_0 = -2.3075444 \cdot 10^{-4} \cdot \tau_d + 29.8213$ at heating up to 190°C

Coefficients $A_1(\tau_d)$

$A_1 = 4.051207 \cdot 10^{-5} \cdot \tau_d + 2.4893$ at heating up to 200°C

$A_1 = 1.5876991 \cdot 10^{-5} \cdot \tau_d + 2.4895$ at heating up to 190°C

Coefficients $A_2(\tau_d)$

$A_2 = -2.2266277 \cdot 10^{-5} \cdot \tau_d + 0.00227$ at heating up to 200°C

$A_2 = -1.0559017 \cdot 10^{-5} \cdot \tau_d + 0.00218$ at heating up to 190°C

Coefficients $A_3(\tau_d)$

$A_3 = - 3.98635 \cdot 10^{-8} \cdot (\tau_d)^2 + 1.771915 \cdot 10^{-6} \cdot \tau_d + 6.3241 \cdot 10^{-5}$ at heating up to 190°C and to 200°C

Substitution of the coefficients $A_i(\tau_d)$, calculated when heating the thermistor up to 190°C, into equation (8) reduces the dispersion of derivatives $d(1/T)/d(\ln R_C)$ of the curve in Fig.3 to the value $\Sigma \sim (2\text{-}3) \cdot 10^{-7}$, and allows to define the minimum point more accurately: $\ln R_{C\ min} = 7.63_2 \pm 0.01$, thus reducing the calculation error when temperature measurement using thermistor CT3-19.

Thus, the recommended equation for calculating temperature using the thermistor CT3-19, taking account of both inflection point $T_{inf} = 336.34K$ to functional dependence of the logarithm $\ln R_C$ of thermistor's resistance, and temporal drift of the polynomial decomposition coefficients $A_i(\tau_d)$, at periodic heating thermistor up to 190°C, is as follows:

$$\frac{1}{T} = A_0(\tau_d) + A_1(\tau_d) \cdot (\ln R_C - 7.63) + A_2(\tau_d) \cdot (\ln R_C - 7.63)^3 + A_3(\tau_d) \cdot (\ln R_C - 7.63)^4 \quad (9)$$

DISCUSSION OF THE RESULTS

There is the well-known cubic polynomial Steinhart-Hart equation [4], designed to calculate temperature using thermistors, by incorporating linear and cubic components using the logarithm of the resistance $\ln R_C$:

$$\frac{1}{T_{SH}} = A + B \cdot \ln R_C + C \cdot \ln R_C^3 \quad (10)$$

where A, B, C — the expansion coefficients.

The useful temperature range of this equation with one set of coefficients is not more than 50-75K [4,5]. Using sets of numerical coefficients of the Steinhart-Hart equation, available in internet publications, a comparison of temperature calculation data was made based on the Steinhart-Hart equation and on our biquadratic equation of logarithms of thermistor resistance (9). Fig.5 shows temperature relative differences $\delta = (T_{SH} - T)/T \cdot 100\%$, dependent upon $\ln R_C$. Comparison of results shows that temperature differences δ, depending upon $\ln R_C$, have an alternating-sign nature. Minimum values of temperature differences δ on the order of 0.25% are observed at a value $\ln R_C \sim 6$ of thermistor CT3-19. Maximum values of differences δ, reaching 0.8-1%, occur at the edges of applicability of the equation interval (9).

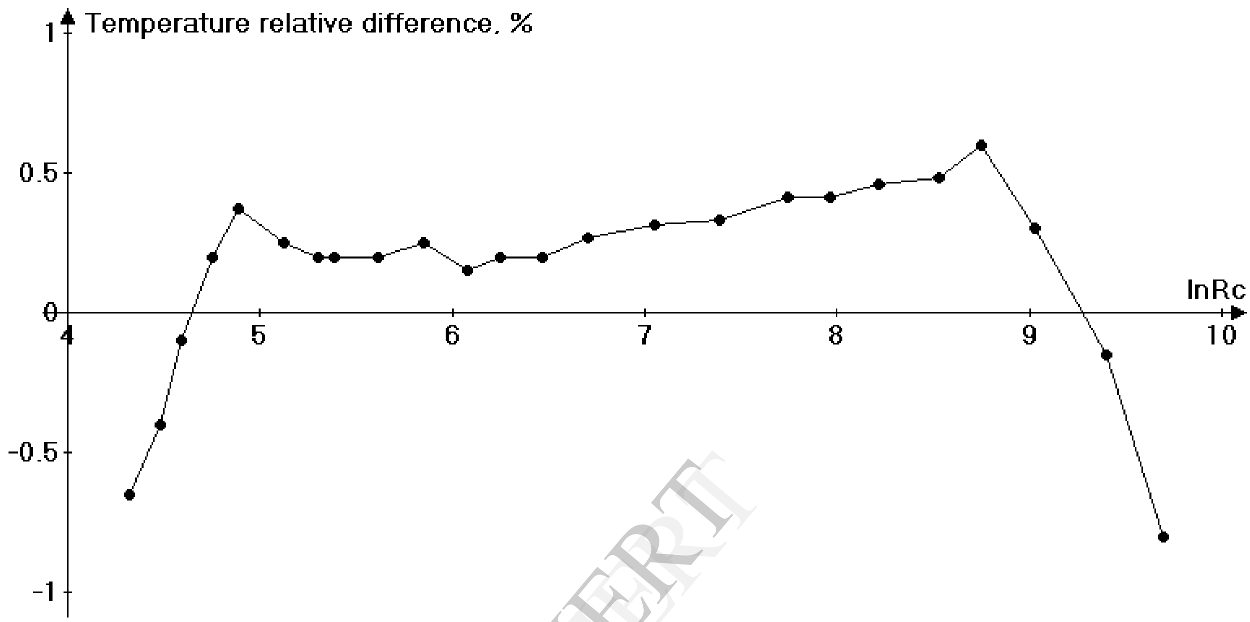

Fig.5. Temperature relative difference δ, calculated according to the Steinhart-Hart equation and biquadratic equation under point of inflection of thermistor characteristic (9).

The error, when defining temperature (temperature differences) using thermistor CT3-19 with the biquadratic equation (9) subject to the inflection point at $\ln R_C = 7.63_2$, is not more than $(3\text{-}5) \cdot 10^{-4}$ K.

CONCLUSIONS

The use of the biquadratic polynomial equation (9) with temperature binding to the inflection point of the functional dependence logarithm of thermistor resistance, can extend the range and increase accuracy of the temperature definition.

Account of temporal drift decomposition coefficients polynomial (9) $A_i(\tau_d)$, allows to improve the accuracy of the minimum point definition $\ln R_{C\ min} = 7.63_2 \pm 0.01$ of thermistor characteristics, and thus the accuracy of the temperature definition.

The use of Steinhart-Hart cubic polynomial equation increases temperature calculation error, using thermistor, at range limits 273K - 473K to 1.5-2K.

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