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DETERMINING FEATURES IN THE APPLICATION OF REDUNDANCY FOR THE THERMISTOR CUBIC TRANSFORMATION FUNCTION USING COMPUTER SIMULATION

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The object of research is the process of temperature measurement with a platinum thermistor. We have conducted studies on the cubic transformation function of the thermistor when using redundancy that yielded the equation of redundant measurements of the desired temperature. Owing to this, it became possible to directly apply the resulting equation without additional measures to linearize the function of the thermistor transformation. In addition, the obtained value of the desired temperature does not depend on the values of the parameters of the cubic transformation function and their deviations from the nominal values. Experimental studies have proven that the value of the normalized temperature T_0 has a greater influence on the result of redundant measurements and the value of the normalized temperature ΔT on the entire range of measured temperatures T_x is almost unaffected. The best accuracy results (value of relative error $\delta = 0.02$ %) were obtained at T_0 values lower than -60 °C. When the error of reproduction of normalized temperatures increased from ±0.02 °C to ±0.1 °C, the best accuracy results (value of relative error $\delta = 0.06$ %) were obtained at values of normalized temperature T_0 below -130 °C. Analysis of results of the absolute error Δ_T revealed that with an error of reproduction of normalized temperatures of ±0.02 °C and at $T_0 = -180$ °C, its value does not exceed 0.02 °C, that is, it is within the error of reproduction of normalized temperatures. This allows us to state that it is recommended to use sources of standardized temperatures of high accuracy during measurement control.

Thus, there are reasons to assert the prospect for redundant measurements when directly measuring temperature with a thermistor with a cubic transformation function with high accuracy

Keywords: redundant methods, instability of transformation function parameters, accuracy improvement, platinum thermistor

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1. Introduction

Modern technologies covering industry, science, ecology, and many other fields are constantly in need of measurement information of appropriate quality. One of the key factors affecting the reliability of the received information is the accuracy of the measurement. The efficiency of the technological or production process, the quality of products, and in some cases, the safety of technical systems depend on the accuracy of the measurement. In this regard, measuring transducers play a decisive role in measurements since the accuracy of the entire subsequent process would depend on how accurately the measured value could be converted into the output signal. The sensor must meet high requirements not only in terms of accuracy but also have a wide measurement range, metrological reliability, etc. One of the most common temperature sensors in industrial production is the thermistor; it is sensitive enough, it can work in a wide temperature range, and has a high temperature coefficient. However, the thermistor, like many other sensors, has a non-linear transformation function. This makes it necessary to carry out measures to linearize it, which leads to the occurrence of additional errors, or to work on a linear section of the input characteristic, which narrows the measurement range. Also, it should be noted that over time or under the influence of destabilizing factors, the parameters of the transformation function prematurely go beyond the nominal values or become unstable, which leads to obtaining unreliable measurement information. Thus, the application of known measurement approaches and methods becomes more complicated or requires their improvement.

Taking into account the need for constant improvement of methods and means of measurement, research aimed at increasing the accuracy of measurements with a non-linear and unstable transformation function of the sensor should be considered relevant.

2. Literature review and problem statement

The development of measuring and sensor technology presents scientists with the task of further increasing the accuracy of measurements. This applies to many applied issues, in particular, increasing the accuracy of measuring the voltage of an inharmonic signal under conditions of additive interference [1]. A schematic solution and improvement of the method of measuring the rms value of alternating current voltage were presented. However, the cited paper did not consider measurement issues with a non-linear transformation function. The increase in accuracy by structural methods is given in [2]. However, it should be noted that reference scales were used in the work, which requires increased material costs. The main factors affecting the accuracy of temperature measurement by non-contact methods were considered in [3]. In [4], the impact of methods of processing results on measurement accuracy was investigated. It is shown that owing to the improvement of the method of the middle line, the reduction of the absolute measurement error is ensured. However, the cited work did not consider ways to reduce the influence of other errors on the measurement result. In [5], the increase in accuracy was achieved due to the compensation of the influence of the reactive component of the shunt resistance on the measurement result. In the work, it is proposed to form a shunt with two identical shunts with resistances equal to half of the nominal resistance of the shunt or to create a middle point with the help of an additionally introduced resistive divider. However, such a solution requires the presence of shunts with the same parameters, which requires them to have a high class of accuracy and, as a result, leads to an increase in material costs. In addition, issues related to the influence of the surrounding environment on the measurement result remained unresolved. To overcome this problem, paper [6] proposed a compensation model for increasing the accuracy of the infrared thermal imager due to the influence of dust. To increase the accuracy of measurements in a wide frequency range, new technical solutions for generating test and reference signals, as well as for processing measurement signals in the impedance channel, were developed in [7]. However, the paper does not provide ways of correcting the nonlinearity of the sensor transformation function. To overcome this problem, the linearization method based on the formation of the compensating base measuring current was applied in [8]. In the cited work, the quadratic component of the transistor transformation function was compensated for in separate measurement temperature ranges. In [9], a method and device for linearizing analog output signals in the form of a sine or cosine is proposed. It was established that the reduction of the nonlinearity error occurs due to the use of a mathematical dependence, in which the formation of an additional signal equal to the square of the algebraic difference between the input and correction signals is assumed. In work [10], linear regression was proposed for the correction of nonlinear response. An increase in accuracy by measuring the nonlinear curvature correction for several reference temperature values was also reported in [11]. In those approaches to increase accuracy by means of calibration, reference samples are used, which are materially expensive, require high accuracy, and the issue of instability of sensor parameters caused by the action of the external environment was not considered. To overcome this problem, in work [12], the reduction of the influence of the instability of the sensor parameters on the measurement result was achieved through the use of the general equation of uncertainty propagation and the Monte Carlo method. Research aimed at determining the characteristics of the deviation of the waterproof sensor in accordance with the reference one was presented in [13]. The issue of increasing the accuracy of dynamic sensors in the presence of random interference was considered in [14]. It is shown that owing to the proposed sliding mode algorithm, it becomes possible to reconstruct true signals. The research reported in [15] proposed the use of artificial neural networks to stabilize the transformation function. However, the disadvantage of neural networks is the impossibility of achieving a non-zero estimation error and increasing the time for network training. Increasing accuracy by using a mathematical approach to processing measurement results and a built-in control and measurement system was considered in [16]. Despite the practical significance of the given results, the issue of comprehensively solving the problem of increasing accuracy when directly using a sensor with a nonlinear transformation function under the influence of the surrounding environment has not been sufficiently considered. The expediency of using redundant measurement methods in solving this issue is confirmed in [17]. According to the author, this is due to the use of the proposed equations of redundant measurements, which ensures the independence of the measurement result from the absolute values of the parameters of the transformation function and their deviations from the nominal values. Also, work [18] reported the use of redundant methods for a non-linear (logarithmic) function of the sensor with the possibility of determining the values of its parameters. Redundant measurements with a logarithmic transformation function were further developed in [19], in which ways of reducing the influence of the random component of the measurement error on the measurement result were considered. However, it should be noted that the cited work did not include studies of the influence of normalized radiation fluxes on the measurement result. This circumstance is due to the fact that in order to introduce redundancy, it is necessary to form value-normalized physical quantities of the same physical nature as the measuring one. Therefore, in work [20] regularities between normalized and sought values were established, which leads to the expansion of the range of high-precision measurements. The expediency of using redundant methods is also confirmed by their application with a quadratic sensor transformation function [21]. According to the authors of [21], the issue of increasing the accuracy of measurement with a quadratic transformation function with an extended measurement range was achieved by adjusting the values of normalized quantities. However, it should be noted that the above works did not investigate the use of redundant measurement methods (RMM) for the cubic transformation function that the platinum thermistor has. This is due to the fact that platinum temperature transducers have a cubic transformation function, as well as an average chemical resistance, which leads to the fragility of the material and the instability of the characteristics.

Therefore, there are reasons to believe that the lack of certainty in research on increasing accuracy when using redundant measurements for the cubic function of the thermistor transformation predetermines the need for research into this area.

3. The aim and objectives of the study

The purpose of our study is to determine the features of the application of redundant measurement methods for the cubic transformation function (TF) of the thermistor. This will make it possible to increase the accuracy of the measurement over the entire range of the input characteristics of the sensor.

To achieve the goal, the following tasks were solved:

– to build a mathematical model of redundant measurements for the cubic TF of the thermistor in the form of a system of equations of quantities and the corresponding equation of redundant measurements;

– to carry out computer simulation of the constructed mathematical model to investigate the importance of the normalized temperatures T_0 and ΔT at different values of the normalized values and with changes in the TF parameters within ±10.0 %;

– to conduct a computer simulation of the influence of the values and errors of reproduction of values normalized by the value of T_0 and DT on the measurement result;

– to conduct computer modeling to establish the dependence between the values of T_x and T_0 temperatures on the absolute measurement error, which ensures an increase in accuracy over the entire measurement range.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is the process of temperature measurement with a thermistor with a cubic transformation function.

The research hypothesis assumes that the use of redundancy in temperature measurements using a thermistor could contribute to increasing the accuracy of the measurement over the entire range of measurement temperatures.

Simplifications adopted in the work accept that during eight measuring cycles, the changes in the parameters of the cubic transformation function remain constant.

Assumptions adopted in the work imply that the use of methods of redundant measurements (RMM) could help increase the accuracy of measurement with a non-linear transformation function of the sensor and its metrological reliability.

4. 2. Researched materials and modeling tools

During the study, a platinum thermistor PT100 (Ukraine) was chosen as a sensor with a cubic transformation function.

Mathcad15.0 software (USA) was chosen as a software tool for mathematical modeling and computer analysis of the results.

Computer modeling in the Mathcad15 environment was carried out with the following parameters of the thermistor PT100: coefficient A=3.9083·10^{-3} Ω/°C; coefficient B= =–5.775·10^{-7} Ohm/°C^2, coefficient C=–4.183·10^{-12} Ohm/°C^4, range of measured temperatures T_x=(–1÷–200) °C.

4. 3. Research method

To increase the accuracy in the entire range of measurements at the cubic TF of the thermistor, the method of redundant measurements was used. The essence of these methods is additional measurements, in addition to the desired value, of several normalized values of the same physical nature as the desired one. Moreover, the normalized and sought values must be related to each other according to the laws of arithmetic or geometric progression, depending on the possibility of their reproduction. Each such measurement cycle is described by the corresponding quantity equation. Moreover, the number of equations should be greater than the number of TF sensor parameters. A set of such equations of quantities (n) make up system (1), the solution to which makes it possible to obtain the equation of excess measurements of the desired quantity (2):

$$\begin{cases} y_{H1} = f\left(x_1, S'_H, S'_L\right) + \Delta y; \\ y_{H2} = f\left(x_2, S'_H, S'_L\right) + \Delta y; \\ \ldots \\ y_{Hn} = f\left(x_i, x_2, S'_H, S'_L\right) + \Delta y, \end{cases} \quad (1)$$

$$x_i = F\left(y_{H1}, \ldots, y_{Hn}, x_1, x_2\right), \quad (2)$$

where y_{H1}, y_{H2}, ..., y_{Hn} – sensor output signals; x_i – measurement value; x_1, x_2 – normalized values; S'_H, S'_L – the steepness of the transformation of the nonlinear and linear components of the sensor transformation function; Δy – parameter (displacement) of the transformation function, taking into account the additive error component.

It should be noted that when forming quantities normalized by value, one calibrated source normalized by value can be used.

5. Results of computer simulation of the cubic transformation function of the thermistor to improve the accuracy of measurements

5. 1. Construction of a mathematical model of excess measurements for the cubic transformation function of the thermistor

At present, highly sensitive thermistors are being designed using solid-state electronics technologies [22]. Such structures are characterized by higher temperature coefficients of resistance, but their disadvantage is nonlinearity. Thus, the transformation function of a platinum thermistor, which determines the dependence between the resistance of the thermistor and temperature in the range from 0 to –200 °C, is described by the Callendar-Van Dusen formula:

$$R_{Tx} = R_0\left(1 + A\cdot T_x + B\cdot T_x^2 + C\cdot\left(T_x - 100\right)\cdot T_x^3\right), \quad (3)$$

where T_x is the measured temperature, °C; R_0 is the resistance of the thermistor at a temperature of 0 °C (R_0=100 Ohms for the PT100 sensor); A, B, C are temperature coefficients that depend on a specific type of thermistor.

When constructing a mathematical model of redundant measurements for the thermistor transformation function described by equation (3), the following normalized values were proposed: $\{T_1\}=\{T_0\}-\{\Delta T\}$, $\{T_2\}=\{T_0\}-2\{\Delta T\}$, $\{T_3\}=\{T_0\}+\{\Delta T\}$, $\{T_4\}=\{T_0\}+2\{\Delta T\}$. Thus, a system of equations of quantities describing eight measurement cycles was compiled:

$$\begin{cases} R_{Tx1}=R_0\begin{pmatrix}1+A\cdot(T_0-\Delta T)+B\cdot(T_0-\Delta T)^2+\\ +C\cdot(T_0-\Delta T-100)\cdot(T_0-\Delta T)^3\end{pmatrix}; \\ R_{Tx2}=R_0\begin{pmatrix}1+A\cdot(T_0-2\Delta T)+B\cdot(T_0-2\Delta T)^2+\\ +C\cdot(T_0-2\Delta T-100)\cdot(T_0-2\Delta T)^3\end{pmatrix}; \\ R_{Tx3}=R_0\begin{pmatrix}1+A\cdot(T_0+\Delta T)+B\cdot(T_0+\Delta T)^2+\\ +C\cdot(T_0+\Delta T-100)\cdot(T_0+\Delta T)^3\end{pmatrix}; \\ R_{Tx4}=R_0\begin{pmatrix}1+A\cdot(T_0+2\Delta T)+B\cdot(T_0+2\Delta T)^2+\\ +C\cdot(T_0+2\Delta T-100)\cdot(T_0+2\Delta T)^3\end{pmatrix}; \\ R_{Tx5}=R_0\begin{pmatrix}1+A\cdot(T_x+T_0-\Delta T)+\\ +B\cdot(T_x+T_0-\Delta T)^2+\\ +C\cdot(T_x+T_0-\Delta T-100)\times\\ \times(T_x+T_0-\Delta T)^3\end{pmatrix}; \\ R_{Tx6}=R_0\begin{pmatrix}1+A\cdot(T_x+T_0-2\Delta T)+\\ +B\cdot(T_x+T_0-2\Delta T)^2+\\ +C\cdot(T_x+T_0-2\Delta T-100)\times\\ \times(T_x+T_0-2\Delta T)^3\end{pmatrix}; \\ R_{Tx7}=R_0\begin{pmatrix}1+A\cdot(T_x+T_0+\Delta T)+\\ +B\cdot(T_x+T_0+\Delta T)^2+\\ +C\cdot(T_x+T_0+\Delta T-100)\times\\ \times(T_x+T_0+\Delta T)^3\end{pmatrix}; \\ R_{Tx8}=R_0\begin{pmatrix}1+A\cdot(T_x+T_0+2\Delta T)+\\ +B\cdot(T_x+T_0+2\Delta T)^2+\\ +C\cdot(T_x+T_0+2\Delta T-100)\times\\ \times(T_x+T_0+2\Delta T)^3\end{pmatrix}, \end{cases} \quad (4)$$

where R_{Txi} is the resistance value of the thermistor in each i-th ($i=(1\div8)$) measurement cycle; ΔT and T_0 are normalized by temperature values, which are formed using standard sources.

As a result of the solution of system (4), the equation of excess measurements of the desired temperature T_x was obtained:

$$T_x=\frac{\left(\begin{pmatrix}R_{Tx8}-R_{Tx6}-\\ -2(R_{Tx7}-R_{Tx5})\end{pmatrix}-\begin{pmatrix}R_{Tx4}-R_{Tx2}-\\ -2(R_{Tx3}-R_{Tx1})\end{pmatrix}\right)(4T_0-100)}{4\left((R_{Tx4}-R_{Tx2}-2(R_{Tx3}-R_{Tx1}))\right)}. \quad (5)$$

As can be seen from the equation of redundant measurements (5), the value of the desired temperature does not depend on the values of the parameter R_0, the coefficients A, B, C, and their deviations from the rated values.

5. 2. Investigating the significance of temperatures T_0 and DT normalized by value

Based on the excess measurements equation (5), calculations were performed to check the high accuracy of the measurements and the effect of the normalized temperature values T_0 and ΔT on the result.

Initially, the research was aimed at establishing the significance of each of the normalized temperatures T_0 and ΔT for the measurement result. For this, the values of normalized values were set: T_0=–100 °C and ΔT =5 °C. During the calculations, the deviations of the TF parameters were set within ±10 %, and the reproduction errors of the normalized values T_1,...,T_4 were set within ±0.02 °C. It should be noted that such accuracy of reproduction of values normalized by value T_1,...,T_4 is due to the fact that they are formed by a calibrated source with normalized characteristics. As a result of the calculations, a relative error of 0.02 % was obtained over the entire working range of T_x measuring temperatures from –1 °C to –200 °C. This gives grounds for asserting the high accuracy of RMM, as well as the independence of the result of redundant measurements on changes in the TF parameters. In addition, the proposed equation of redundant measurements can be directly used for cubic TF without additional measures for its linearization.

In the further study, «cross» values were set: T_0=–5 °C and ΔT =100 °C for the specified deviations of the TF parameters within ±10 %. As a result, a relative error of 0.07 % was obtained over the entire operating range of T_x from –1 °C to –200 °C. The results show that the value of the normalized value T_0 is more significant compared to the value ΔT.

In order to confirm the established statement that the value of the normalized temperature T_0 has a greater influence on the accuracy of excess measurements, further research was directed at establishing the relationship between its values and the measurement result. During the calculations, the following ranges of changes in the values of normalized values were set: T_0=(–1÷–100) °C and ΔT=(–1÷60) °C. The results of dependence of the relative measurement error δ (%) on the values of the normalized values T_0 and ΔT at the beginning of the working range at T_x=–1 °C are given in Table 1.

Table 1

Relative measurement errors (%) when the values of normalized temperatures T_0 and ΔT change

ΔT, °C / T_0, °C	–1	15	30	45	60
–1	0.08	0.08	0.08	0.08	0.08
–10	0.06	0.06	0.06	0.06	0.06
–21	0.04	0.04	0.04	0.04	0.04
–30	0.04	0.04	0.04	0.04	0.04
–40	0.03	0.03	0.03	0.03	0.03
–50	0.03	0.03	0.03	0.03	0.03
–60	0.02	0.02	0.02	0.02	0.02
–70	0.02	0.02	0.02	0.02	0.02
–80	0.02	0.02	0.02	0.02	0.02
–90	0.02	0.02	0.02	0.02	0.02
–100	0.02	0.02	0.02	0.02	0.02

Identical results, as in Table 1, for values of the relative measurement error δ (%) were obtained over the entire range of measured temperatures T_x from –1 °C to –200 °C.

5. 3. Influence of values and errors of reproducing normalized temperatures on the measurement result

In order to establish the effect of reproduction errors on the measurement result, the reproduction errors of normalized values $T_1,...,T_4$ were increased from ±0.02 °C to ±0.1 °C during computer simulation. The studies were carried out at the values of normalized values $T_0=(-60\div-140)$ °C and $\Delta T=(-1\div60)$ °C, as well as at specified deviations of the TF parameters within ±10 %. The results of dependence of the relative measurement error δ (%) on values of the normalized values T_0 and ΔT at the beginning of the working range at $T_x=-1$ °C are given in Table 2.

Table 2

Relative errors of measurements (%) with increased errors of reproduction of normalized values up to ±0.1 °C

T_0, °C \ ΔT, °C	–1	15	30	45	60
–60	0.12	0.12	0.12	0.12	0.12
–70	0.10	0.10	0.10	0.10	0.10
–80	0.09	0.09	0.09	0.09	0.09
–90	0.09	0.09	0.09	0.09	0.09
–100	0.08	0.08	0.08	0.08	0.08
–110	0.07	0.07	0.07	0.07	0.07
–120	0.07	0.07	0.07	0.07	0.07
–130	0.06	0.06	0.06	0.06	0.06
–140	0.06	0.06	0.06	0.06	0.06

Identical results, as in Table 2, for the values of relative measurement error δ (%) were obtained over the entire range of measured temperatures T_x from –1 °C to –200 °C.

5. 4. Establishing a dependence between the values of temperatures T_x and T_0 on absolute measurement error

In addition to the relative measurement error, the absolute measurement error Δ_T (°C) is of scientific interest during measurement control. Therefore, further research was aimed at establishing such a value of the normalized temperature T_0, which provides the best results in terms of accuracy over the entire measurement range. During the calculations, the deviations of TF parameters were set within ±10 %, and the reproduction errors of the normalized values $T_1,...,T_4$ were set within ±0.02 °C. The results of the values of the absolute measurement error Δ_T (°C) are given in Table 3.

Analysis of results of the absolute measurement error Δ_T confirmed that it is better to choose the value of the normalized temperature $T_0\geq-130$ °C during measurement control.

To establish the relationship between the values of temperatures T_x and T_0 on the absolute measurement error Δ_T, this dependence was plotted in Fig. 1.

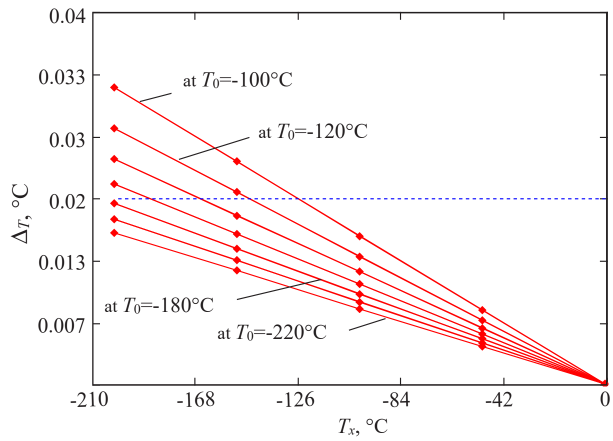

Fig. 1. Dependence plot: influence on the value of the absolute error Δ_T exerted by temperatures T_x and T_0

As the above plot demonstrates (Fig. 1), an increase in the normalized temperature T_0 from –100 °C to –220 °C does not significantly affect the absolute error. However, it should be noted a general trend: a decrease in the normalized temperature T_0 leads to a decrease in the absolute measurement error Δ_T.

Over the entire working range of the input characteristic of the thermistor at the values of the normalized temperature $T_0=(-100\div-220)$ °C, the value of the absolute error of RMM measurement is in the range of $(0.08\cdot10^{-3}\div0.03)$ °C.

The next step of the computer simulation was studying the influence of the error of reproduction of normalized values on the measurement result. Thus, with an increase in the reproduction error of the normalized values $T_1,...,T_4$ from ±0.02 °C to ±0.1 °C, values of the absolute reproduction error were obtained, which are within the range of up to $(0.40\cdot10^{-3}\div0{,}16)$ °C.

Table 3

Dependence of the absolute measurement error (°C) on values of the normalized temperature T_0

T_x, °C	–1	–20	–40	–60	–80	–100	–120	–140	–160	–180	–200
T_0=–200 °C	$8.9\cdot10^{-5}$	0.002	0.004	0.005	0.007	0.009	0.01	0.01	0.01	0.02	0.02
T_0=–130 °C	0.0001	0.003	0.005	0.008	0.010	0.013	0.015	0.018	0.02	0.023	0.025
T_0=–100 °C	0.0002	0.003	0.006	0.009	0.012	0.015	0.019	0.022	0.026	0.029	0.032
T_0=–60 °C	0.00023	0.005	0.010	0.014	0.019	0.024	0.028	0.033	0.038	0.043	0.047

6. Discussion of results of computer modeling with a cubic transformation function

In the study of RMM for the cubic TF, a system of redundant equations of quantities (4) was compiled, describing eight measurement cycles both normalized by the value of the quantity and their combination with the desired quantity. This does not differ from the approaches that were used in works [2, 7, 9], in which the formation of additional signals was also assumed. As a result of the solution of system (4), the equation of excess measurements (5) was built, in which the additive component of the measurement error is excluded owing to the subtraction operation, and the multiplicative component is eliminated owing to the division operation. This does not differ from the practical data given in [2, 16], in which an increase in accuracy was also achieved due to the processing of measurement results according to the proposed algorithms. Thus, equation (5) can be directly used for temperature measurements with a thermistor without additional measures to linearize the transformation function. Also, it was established that the measurement result is not affected by a change in the parameters of the transformation function (from

±1 % to ±10 %), which negates the need to set exact parameter values for each specific type of thermistor. Thus, equation (5) can be used for any sensor with a cubic TF described by equation (3), which testifies to the universality and flexibility of RMM.

A study was conducted to determine the influence of values of normalized values T_0 and ΔT on the measurement result over the entire range of measured temperatures T_x. This does not differ from the approaches that were reported in [20], in which regularities between normalized and sought values were also taken into account. As a result, it was established (Table 1) that the value of the relative error decreases when the value of the normalized temperature T_0 increases and remains constant when the values of the normalized temperature ΔT change. Thus, the value of the normalized value T_0 has a greater influence on the result of redundant measurements, and the value of ΔT is almost unaffected. We believe this is due to the type of excess measurement equation (5), in which the T_0 value is present and ΔT is not included. When analyzing the values of relative errors, it was established that the best results in terms of accuracy (values of relative error δ=0.02 %) were obtained at T_0 values below –60 °C.

Further studies were aimed at establishing the influence of errors in the reproduction of normalized values T_0 and ΔT on measurement result at the values of normalized values $T_0=(-60\div-140)$ °C and $\Delta T=(-1\div 60)$ °C. As a result, it was established (Table 2) that when the error of reproducing normalized temperatures increased from ±0.02 °C to ±0.1 °C, the best results in terms of accuracy (δ=0.06 %) were obtained when the value of the normalized value changed from $|T_0|>-60$ °C to $|T_0|\geq-130$ °C. Thus, with increased errors in the reproduction of normalized temperatures, it is necessary to increase the value of T_0 to obtain the best results in terms of measurement accuracy. This indicates that, on the one hand, RMM is sensitive to the accuracy of reproducing the normalized temperatures, and on the other hand, it makes it possible to increase the accuracy by increasing the value of the normalized value T_0. Since modern technologies allow the use of sources of high-precision normalized temperatures, the use of redundant measurement methods is quite promising.

The dependence of absolute error Δ_T on the ratio of temperatures T_x and T_0 was investigated. It was established (Table 3) that with a reproduction error of normalized temperatures of ±0.02 °C, the change in the value of T_0 normalized from –100 °C to –220 °C at each point of measuring temperatures T_x does not significantly affect the absolute measurement error. To establish the nature of the influence of changes in the normalized temperature T_0 on the absolute measurement error Δ_T over the entire range of T_x measurements, this dependence was plotted in Fig. 1. As a result of the study, it was established that at values of the normalized temperature T_0 lower than –180 °C, the value of the absolute measurement error is $(0.097\cdot10^{-3}\div0.019)$ °C, which does not exceed the error of reproducing the normalized temperatures ±0.02 °C. With increased errors of reproduction of normalized temperatures from ±0.02 °C to ±0.1 °C, the value of the absolute measurement error at $T_0=-180$ °C will be $(0.487\cdot10^{-3}\div0.098)$ °C over the entire range of measured temperatures T_x. The comparison of the obtained results of absolute measurement errors with the error of reproduction of normalized temperatures within ±0.02 °C and ±0.1 °C shows that the result of redundant measurements depends on the error of reproduction of normalized temperatures $T_1,...,T_4$. Therefore, in order to ensure a measurement error that does not exceed the error of reproduction of normalized temperatures, it is advisable to set the value of the normalized value T_0, which is equal to or lower than –180 °C. Thus, in order to increase the accuracy of measurements when using RMM, it is advisable to set the temperature value T_0 of the normalized value.

Such conclusions can be considered appropriate from a practical point of view as they allow a reasonable approach to setting T_0 below –180 °C. At the same time, it becomes possible to ensure an absolute measurement error that does not exceed the error of reproduction of normalized temperatures. From a theoretical point of view, our conclusions allow us to assert the possibility of direct use of RMM in cubic TF, which are certain advantages of this study. In addition, it should be noted that the measurement result is not affected by the values of TF parameters, and the need to set the exact values of the coefficients for each specific type of thermistor disappears. However, it is impossible not to note that such results are obtained under the condition that during the 8 measuring cycles, the TF parameters must remain constant. In addition, there is a methodical error inherent in RMM, which is due to the error in reproducing normalized temperatures. Such uncertainty imposes certain restrictions on the use of our results, which can be interpreted as the shortcomings of this study. The impossibility of removing the mentioned shortcomings within the framework of this study gives rise to a potentially interesting direction of further research. It, in particular, could focus on the use of high-precision standardized temperature sources.

7. Conclusions

1. A mathematical model of excess measurements for the cubic TF of the thermistor was built in the form of a system of equations of quantities describing 8 cycles of measurements. As a result of the system solution, the equation of redundant measurements was obtained, which ensures the independence of the measurement result from the absolute values of the parameters of the transformation function and their deviations from the nominal values. This allows us to assert the effectiveness of RMM in cubic TF.

2. Based on the mathematical model, a computer simulation of the reported mathematical model was carried out to investigate the importance of values T_0 and ΔT normalized by value with changes in the TF parameters within ±10.0 %. Owing to this, it was established that the value of the normalized value T_0 has a greater influence on the measurement result, and the value ΔT is almost unaffected. The best results in terms of accuracy were obtained at a value of T_0 below –60 °C.

3. We have conducted computer simulation of the influence of values and errors of reproduction of T_0 and ΔT normalized by value on relative measurement error. Studies have shown that in order to ensure the best results in terms of accuracy when the error of reproduction of normalized values increases from ±0.02 °C to ±0.1 °C, it is necessary to increase the value of the normalized value from $|T_0|\geq-60$ °C to $|T_0|\geq-130$ °C.

4. We have conducted computer simulation to establish the dependence between T_x and T_0 temperature values on the absolute measurement error. It was established that an increase in the normalized temperature T_0 from –100 °C to –220 °C at each point of measuring temperatures T_x does not significantly affect the absolute error, especially at the

beginning of the measurement range. Computer modeling showed that at T_0 values lower than −180 °C, the value of the absolute error does not exceed 0.02 °C, that is, it is within the error of reproducing normalized temperatures. It was also established that at T_0 values lower than −180 °C, an increase in the error of reproducing normalized values from ±0.02 °C to ±0.1 °C leads to an increase in the absolute error, but within the error of reproducing normalized temperatures. The comparison of the obtained results of the absolute measurement errors with the error of reproducing normalized temperatures within ±0.02 °C and ±0.1 °C indicate the feasibility of setting the normalized T_0 value below −180 °C.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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