A Simplified Method for Calibration of PRTs Used in Heat Meters

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Abstract. Many thousands of industrial platinum resistance thermometers are used in heat meters that are devices for measurement of the heat being spent in heat-exchange water systems. That is why it is important to develop an inexpensive, quick and simple method for calibration of the IPRTs. There are standard documents on verification of the heat meters, such as EN 1434 and OIML R75, adopted in several countries. It seems that the method of calibration of the temperature sensors, suggested in these documents is not the optimum one. When developing the method of calibration of the IPRTs, several important characteristics should be considered, such as IPRT's instability, hysteresis, and the small temperature range (0 to 170 °C), in which the IPRTs work. A method for calibration of the IPRTs was suggested, that made it possible to use only two calibration points: 0 °C and 100 °C. The technique was applied to more than a hundred of IPRTs of different designs, which were developed, manufactured and calibrated at Industrial Company "TESEY" (Russia). The main advantages of the two-point calibration of the IPRTs for heat meters over the method of the EN and OIML standards are its simplicity, quickness and a lower cost, as well as a satisfactory accuracy.

INTRODUCTION

The most of the thermometers that are used in the heat meters are industrial platinum resistance thermometers (IPRTs). To be employed in the devices intended for the measurements of quantity of the heat passing through heat-exchange water systems, these thermometers should meet some special technical requirements, such as to have a hermetic case, a special installation head, good resistance to vibrations, and good long-term stability. The maximum working range for the IPRTs is from 0 to 170 °C. The uncertainty of the difference between the temperatures of the heat conveying liquid at the flow and return of a heat-exchange circuit is one of the main parts of the combined uncertainty of the heat, measured by the heat meter. The tolerances for IPRTs of class A in International Standard IEC-751 are ±0.35 °C at 100 °C, and ± 0.49 °C at 170 °C. So if we use common IPRTs in heat meters and common methods for estimation of their accuracy, we might get an error in the temperature difference of about ±0.7 °C at 100 °C, and about ±1 °C at 170 °C. This situation does not satisfy the users of the heat meters, who realize that increasing of the accuracy of heat measurements in industry will give a direct economical effect. So, attempts were made to reduce the uncertainty of the temperature measurements, performed with pairs of IPRTs, used in heat meters. In the Standard of European Committee on Standardization EN 1434, as well as in Recommendation of OIML R75, it is suggested to calibrate IPRTs, which are supposed to be used in heat meters, in three calibration points over the working range, and then to calculate individual coefficients of Callendar-Van Dusen equation for each thermometer. The individual coefficients may be input in the secondary measuring devices, if the devices permit to do so. Most of the heat meter electronic devices, however, use for the temperature calculation standard coefficients defined for IPRTs by Standard Documents (IEC, DIN, GOST). In this case, the individual functions may help to choose pairs of IPRTs that will measure the temperature difference with the smallest uncertainty.

At the present time the problem of the individual calibration of IPRT used in heat meters are being discussed by Russian verification laboratories. The usual technique for calibration of the IPRTs in Russia employs measurements of the resistance at 0 °C and 100 °C in a water bath and calculation of the resistance ratio W(100). Calibration in three temperature points will require the application of an oil liquid bath, and, besides, this method is more time consuming and expensive. The question is whether the calibration in three temperature points can really improve the accuracy of the temperature difference measured with IPRTs in the range 0-170 °C, taking into account uncertainties of the measurements and instability of the IPRTs.

INTERPOLATION EQUATION FOR IPRTS IN THE RANGE 0-170 °C

According to the theory, the dependence of the resistivity of platinum on the thermodynamic temperature can be well described by a second-order polynomial in a wide temperature range above 0 °C. For IPRTs, CVD equation (1) is usually used as the interpolation function.

$$W(T) = (1 + AT + BT^2) \qquad (1)$$

where $W(T) = R(T)/R(0)$

To obtain coefficients $R(0)$, A and B, calibration at least at three points is required. However, it should be noticed that the curve $R(T)$ has a very small slope, the coefficient B in IEC-751 reference function is -5.775×10^{-7} °C^{-2}. So, it might not be so easy to get the precise slope of the curve making not very accurate measurements in a narrow temperature range. Calculations with using the law of uncertainty propagation showed that to obtain B for the range 0-170 °C with an uncertainty of about 1×10^{-8} °C^{-2}, it is necessary to have the uncertainty of the results at the temperature points being not worse than 0.02 °C.

The people who are used to make precise calibrations of IPRTs in the range 0-170 °C might notice that the value of coefficient B obtained for the experimental CVD function, was, as a rule, for about 2×10^{-8} greater than the standard value of the IEC-751 function. It was published in several papers on developing methods for precise calibration of IPRTs, that the use of the same equation for calculating the temperature over the range from 0 to 650 °C will lead to a systematic error in the calculated values below 200 °C. That is why fourth or fifth order equations were suggested as improved reference functions for IPRTs in some works. The important result, published earlier in papers [1], [2], is that the systematic deviation of the quadratic interpolation function from the ITS-90 function does not depend on $W(100)$, that is the characteristic of the electrical purity of the platinum wire. The deviation is the same for SPRTs and IPRTs, but the value of the deviation is strongly depends on the temperature range. In Fig.1 we plotted the difference between ITS reference function and its CVD approximation for the range 0-170 °C. As seen from the graph, the maximum difference of - 2.5 m°C is observed at a temperature of about 40 °C. So, for the range 0-170 °C, the deviation of CVD from ITS is very small, as compared with uncertainties of IPRTs.

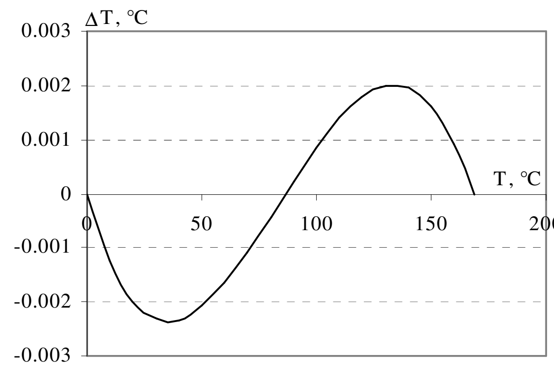

Figure 1. Deviation of ITS-90 reference function from its quadratic approximation in the range 0-170 °C.

A linear deviation function is used in ITS-90 for SPRTs in the range 0-156 °C. To get the individual interpolation equation for an IPRT, we can take the CVD quadratic approximation of ITS-90 reference function as a new reference function, calculate a linear deviation function, similar to that of ITS-90 in the range 0-156 °C, and obtain coefficients A and B, thus using the result at only one calibration point, besides 0 °C. The coefficients for the new reference CVD function $W_{r90}(T)$ are:

$A_{90} = 3.9881\times10^{-3}$ °C^{-1},

$B_{90} = -5.9773\times10^{-7}$ °C^{-2},

the deviation function is

$$\Delta W(T) = a\,(W_{r90}(T) - 1), \qquad (2)$$

where a is calculated from the result of calibration at the temperature T_1:

$$a = [W(T_1) - W_{r90}(T_1)]/[W_{r90}(T_1)-1]. \qquad (3)$$

Coefficients for the individual CVD interpolation function will be

$$A1 = (1 + a)\,A_{90}; \quad B1 = (1 + a)\,B_{90} \qquad (4)$$

Coefficients *A1* and *B1* depend on the value of *W(100)*. It is convenient to calculate the coefficients for the platinum of different purity used in commercially available IPRTs. The coefficients of CVD function calculated for thermometers with different *W(100)* values are given in Table 1. To get a better precision, it is worth to calculate *A1* and *B1* from the individual calibration result *W(100)* using equations (2), (3).

TABLE 1. Coefficients of CVD function for different W(100) in the range 0-170 °C

W(100)	A1 $\times 10^{-3}$ °C^{-1}	B1 $\times 10^{-7}$ °C^{-2}
1.385	3.9086	-5.8581
1.391	3.9695	-5.9494
1.392	3.9797	-5.9647
1.3922	3.9817	-5.9677

CALIBRATION OF IPRTS

IPRTs investigated in the present work were manufactured and calibrated at Industrial Company TESEY, Russia. All the thermometers had a hermetically sealed metal case and a standard connecting head. IPRTs from the first group (designated as S/N 1-1 to 1-65) had platinum wire sensing elements, IPRTs from the second group (designated as S/N 2-66 to 2-130) had a thin-film platinum sensing element, insulated from the metal case.

The thermometers were calibrated at 0 °C in an ice bath, and at 100 °C and 167 °C in an oil temperature controlled bath by comparison with an SPRT. The expanded uncertainty of the calibration, that includes components from the measuring apparatus, the SPRT calibration, and the bath instability was within 0.01 °C at 0 °C and within 0.03 °C at the other temperatures. The measurement procedure included four cycles of comparisons at the three calibration points. The experimental CVD function $R_{III}(T)$ was generated from all the results by least-square procedure. The coefficients for the second CVD function $R_{II}(T)$ were calculated using the results at 0 °C and 100 °C and the method described above. The difference between functions $R_{III}(T)$ and $R_{II}(T)$, expressed as the equivalent change in temperature, is plotted in Fig.2 for the first group of the IPRTs and in Fig.3 for the second group of the thermometers.

As seen from Fig.2, wire-type IPRTs may exhibit both positive and negative difference between the two and three-point functions. 74% of the IPRTs showed the difference between the two functions smaller than 0.05 °C. The most of the film-type thermometers exhibited a deviation of about 0.1-0.15 °C at the end of the range. To explain the observed phenomenon we can suggest that some internal change occurs in the platinum films, which leads to a distortion of the coefficients of the CVD function. This effect was also observed for the film sensing elements in paper [1].

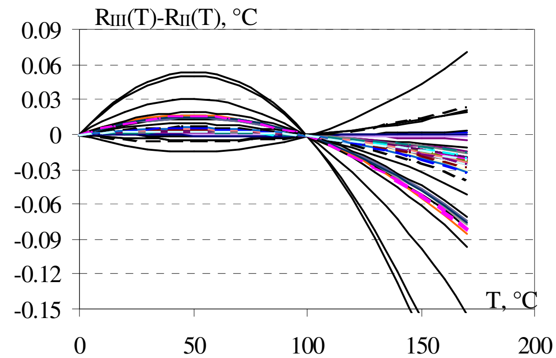

Figure 2. Difference between functions calculated from three and two calibration points for IPRTs S/N 1-1 to 1-65 (wire type).

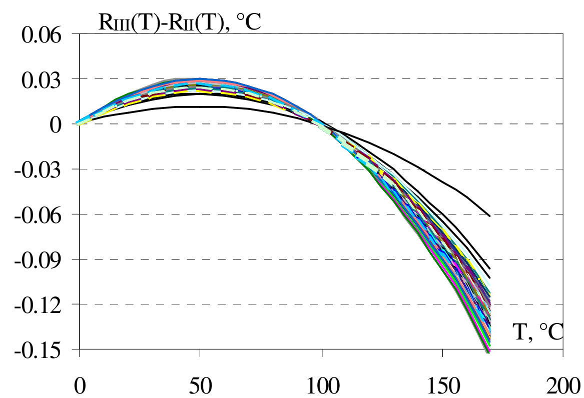

Figure 3. Difference between functions calculated from three and two calibration points for IPRTs S/N 2-66 to 2-130 (film type).

In a heat meter, the difference between two temperatures of the input and output water is measured with two thermometers of the same design. So, the systematic interpolation error will be excluded from the result. To asses this, we arbitrarily divided all of 65 wire-type IPRTs in 32 pairs and for each pair we calculated the difference between functions $R_{III}(T)$ for two thermometers of the pair, $\Delta R_{III}(T)$, and the difference between functions $R_{II}(T)$, $\Delta R_{II}(T)$. Then we estimated difference $\delta R(T) = \Delta R_{III}(T) - \Delta R_{II}(T)$. The same was done for 65 film-type IPRTs. The maximum difference between the two and three point functions is observed at the end of the range, at 170 °C, which is due to the extrapolation of the two-point function beyond the last calibration point 100 °C. The histogram in Fig.4 shows the percentage of the IPRT pairs, the difference between values of $\Delta R_{III}(170)$ and $\Delta R_{II}(170)$ for which was smaller than the value, given on the horizontal axis of the graph.

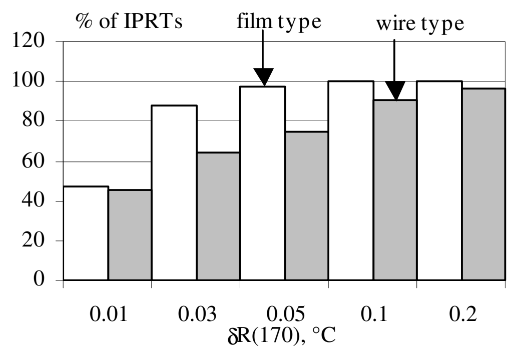

Figure 4. Difference between values $\Delta R_{III}(170)$ and $\Delta R_{II}(170)$ calculated for the pairs of wire and film-type IPRTs, expressed as the equivalent change in temperature.

As seen from the histogram, the range of $\delta R(170)$ values for the pairs of wire type IPRTs is larger than that for the film-type thermometers. This probably is related to change in strains developed in the platinum wire during heating and cooling of the thermometers. However, for almost a half of wire and film-type IPRTs the difference $\delta R(170)$ was smaller than 0.01 °C.

INVESTIGATION ON THE STABILITY OF IPRTS IN THE RANGE 0-170 °C

The purpose of the application of the individual functions to the IPRTs used in heat meters is to reduce the uncertainty of the temperature difference measured by a pair of these thermometers. If the standard coefficients are used in a secondary electronic device for the calculation of temperature difference, the error in the calculated difference will be equal to the difference between the individual functions of the IPRTs of the pair. The reduction of the error may be provided by choosing a pair of IPRTs with close functions R(T).

To decide if the selection of the IPRTs pairs would result in a real decrease of uncertainty of the temperature difference measured by a pair of IPRTs, we have to investigate the stability of the difference over the time between the verifications.

To study the stability of the IPRTs, they were exposed to thermal cycling in the range from 20 to 160 °C. The number of the cycles in the experiment was 365, the time of exposure of the IPRTs to the highest temperature at each cycle was 35 min. This treatment was a very serious test for the IPRTs, the number of the thermal cycles exceeding that normally received for two-year period. The difference in the values of temperature, calculated using equations $R_{III}(T)$ obtained before and after the stability test for 65 wire IPRTs, $\Delta T(T)$, is plotted in Fig. 5.

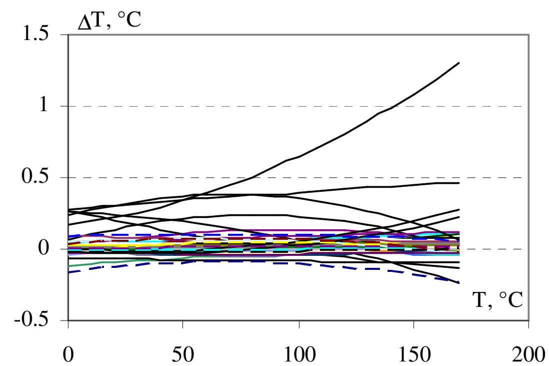

Figure. 5 Change in the temperature, calculated using the interpolation functions obtained before and after the stability test.

The change in $R_{III}(T)$ functions for most of the IPRTs was within ±0.25 °C. To asses the number of stable and unstable thermometers, we give in Fig. 6 and Fig.7 the histograms, showing the percentage of the IPRTs, the change in the values of $R_{III}(0)$ and $R_{III}(100)$ for which, expressed as the equivalent change in temperature, was greater than values given on the horizontal axis.

As seen from the histograms, the stability of 0.03 °C or better at 100 °C was observed for more than 60% of the wire-type IPRTs and only for about 30% of the film-type IPRTs. 90% of the wire-type IPRTs and 75% of the film-type thermometers exhibited the stability better than 0.1 °C. The stability at 0 °C is better than that at 100 °C. About 80 % of the wire and film thermometers had a change at 0 °C less than the equivalent of 0.05 °C. The stability at 170 °C is slightly worse than that at 100 °C.

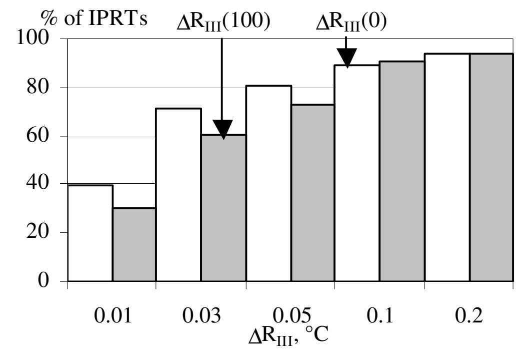

Figure 6. Difference between $R_{III}(T)$ functions obtained before and after the stability test for the wire-type IPRTs at 0 °C and 100 °C.

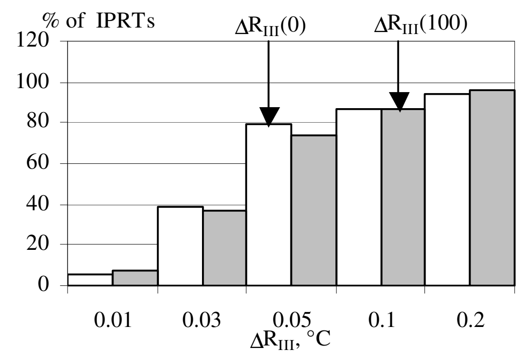

Figure 7. Difference between $R_{III}(T)$ functions obtained before and after the stability test for the film-type IPRTs at 0 °C and 100 °C.

It is interesting to compare the results on the stability of the IPRTs obtained in the present study with those reported previously in papers [3], [4]. In paper [3] Mangum investigated a large group of small wire IPRTs. The thermometers were submitted to 10 heat treatments, each of them included exposing of the IPRTs to 235 °C for 24 hours. From the 92 IPRTs that did not fail during the test, 71% had changes in R(0) of the equivalent of 0.05 °C or less, 13% had changes of the equivalent of greater than 0.1 °C. These results are in a good agreement with those obtained in the present work for the IPRTs at 0 °C.

In paper [4] Hashemian and Petersen performed laboratory tests on two groups of industrial platinum Resistance Temperature Detectors (RTDs) over the range 0-300 °C. One group involved 30 nuclear RTDs, and the other group involved 17 commercial-grade RTDs. The tests consisted of thermal aging, humidity aging, temperature cycling and exposure to the highest temperatures. The thermal aging of the RTDs lasted for 18 months. The average drift observed for the nuclear grade RTDs was about 0.1 °C. The application of the five aging processes on the 30 nuclear grade thermometers produced five failures (17%), six cases (20%) of drift in the range of 0.6 to 3.0 °C. The remaining 19 RTDs (63%) performed well with their aging drifts contained within a ± 0.2 °C band.

Based on the data obtained in this study and the results reported earlier, it is natural to suggest that the optimistic estimation of the two-year stability of wire IPRTs should be 0.1 – 0.2 °C.

INTERPOLATION UNCERTAINTY OF THE TEMPERATURE DIFFERENCE MEASURED BY A PAIR OF IPRTS

Uncertainty of the temperature difference measured by a pair of IPRTs includes three main components: the calibration uncertainty of the IPRTs; the user's uncertainty, which depends on the conditions under which the IPRTs work, especially on the depth of immersion of the thermometers in the heat conveying liquid; and the instability of the IPRTs over the time between two subsequent verifications. The calibration uncertainty includes uncertainties of the measuring equipment, calibration uncertainties of the SPRT, stability and uniformity of temperature in the calibration bath, immersion uncertainty of the IPRTs, and interpolation uncertainty, which depends on the choice of the equation for calculation the temperature difference measured by the IPRTs. There are two methods for calculation of the temperature difference. The first one is to apply the individual interpolation functions to the IPRTs of a pair. The interpolation uncertainty, arising when we use the two-point calibration, may be estimated as the difference between functions calculated using three or two calibration points. The second way is to apply CVD equation with the standard coefficients to each of the IPRTs. In this case, which is usual for heat meters, the interpolation uncertainty of the temperature difference will be equal to the difference between individual interpolation functions of the IPRTs. Thus, the interpolation uncertainty will be different if we use a random pair of IPRTs that meet the requirements of IEC or GOST, or we select a pair of the IPRTs with close individual functions.

The major part of the uncertainty of the temperature difference is that coming from the instability of the

IPRTs. In order to decide if the selection of IPRT pairs or the using of three calibration points will lead to a remarkable reducing of the uncertainty of the temperature difference, we have to compare interpolation uncertainties of the methods described above and the instability of the temperature difference measured with the pairs of IPRTs under investigation.

We calculated the change $\Delta R(T)$ of the difference $\Delta R_{III}(T)$ between functions of two IPRTs of each pair arisen after the stability test. The histogram in Fig.8 shows the percentage of the pairs that exhibited a change in the temperature difference coming from the instability, $\Delta R(T)$, and coming from the use of three or two-point calibration, $\delta R(T)$, smaller than values on the horizontal axes of the graph. At the same graph we plotted the uncertainty U(T) of the temperature difference between two thermometers of a pair, if the coefficients of GOST 6651 (IEC-751) function are used for the temperature calculations.

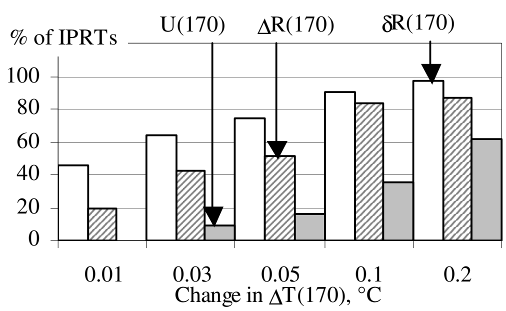

Figure 8. The change in the temperature difference measured by a pair of IPRTs as a result of instability, or the use of two or three calibration points, or the use of the standard coefficients for wire-type IPRTs at 170 °C.

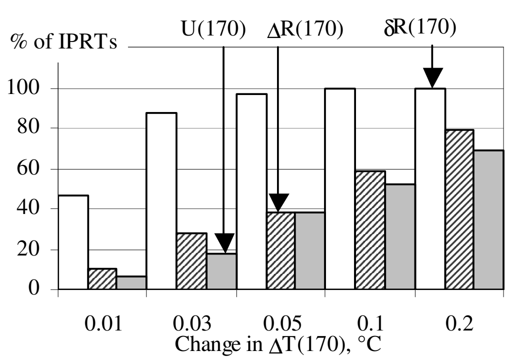

Figure 9. The change in the temperature difference measured by a pair of IPRTs as a result of instability, or the use of two or three calibration points, or the use of the standard coefficients for film-type IPRTs at 170 °C.

As seen from the graphs, the interpolation uncertainty coming from the application CVD equation with standard coefficients to a random pair of IPRTs is larger than the instability of the temperature difference. The uncertainty coming from the use of two or three calibration points is much smaller than the instability. So, to increase the accuracy of the temperature difference measurements, it is worth to select the pairs of IPRTs with close interpolation functions. Individual calibration of the IPRTs can be performed in two calibration points.

CONCLUSION

Selecting the pairs of thermometers with close interpolation functions (determined by W(100) and R(0)) can help to reduce the uncertainty of the temperature difference measured by a pair of IPRTs. The method of three-point calibration in the range 0-170 °C, suggested in EN 1434 and R 75 has advantages over the calibration at 0 °C and 100 °C only when being applied to very stable IPRTs, while the calibration and user's uncertainty are within ±0.05 °C. The requirements of the Standards on the IPRTs uncertainties and stability are much lower. The evaluation of the achievable stability of the IPRTs commonly used in heat meters proved that the verification can be successfully made at two calibration points 0 °C and 100 °C.

REFERENCES

1. N.P. Moiseeva, "Investigation of Functions W(T) for Low-α PRTs in the Sub-ranges above 0 °C", in *Temperature: Its Measurement and Control in Science and Industry*, Vol. 7, New York, AIP, 2002.

2. P. Marcarino, P.M. Steur, G. Bongiovanni, B. Cavigioli, "ITS-90 Approximation by means of non-standard platinum resistance thermometers", in *TEMPMEKO-2001: 8-th symposium on temperature and thermal measurements in industry and science*, Berlin, 2001, pp.85-90.

3. B.W. Mangum, "Stability of Small Industrial Platinum Resistance Thermometers", in *Journal of Research of the NBS*, Vol. 89, No. 4, 1984, pp. 305-316.

4. H.M. Hashemian, K.M. Petersen, "Achievable accuracy and stability of industrial RTDs", in *Temperature: Its Measurement and Control in Science and Industry*, Vol. 6, New York, AIP, 1992, 427-432.