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OPTIMIZING THE UNCERTAINTY DUE TO THE SELF-HEAT OF PLATINUM RESISTANCE THERMOMETERS IN PRACTICAL USE

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Abstract – Self-heat of platinum resistance thermometers (PRTs) is a well-known phenomenon that occurs when measurement current additionally heats up a PRT sensor. This temperature increase depends on measurement current, PRT design, operating temperature and surrounding medium. Self-heat temperature increase can be corrected with some residual uncertainty, but this applies mainly to calibration of PRTs, while in practical temperature measurements self-heat measurement or estimation is difficult due to poor temperature stability and/or short measurement time that does not allow temperature transient effects to fade away. If not handled properly, self-heat uncertainty can be one of the largest, but often neglected uncertainty contributions in temperature measurement. A study of uncertainty optimization is presented for a measurement system composed of up to twenty PRTs that are connected to the ohmmeter via a scanner and sequentially measured. The optimal measurement procedure is discussed and the uncertainty analysis is given.

Keywords: Self-heat, PRT, uncertainty.

1. INTRODUCTION

The self-heat effect is a well-known phenomenon that intrinsically affects all temperature measurements with platinum resistance thermometers (PRTs). When PRT resistance is measured, measurement current will dissipate power and therefore additionally heat up a PRT sensor. This temperature increase (self-heat error) can be corrected with some residual uncertainty, if the self-heat error can be measured or estimated.

The self-heat error can be measured by measuring temperature with two different measurement currents, [1]. If measurement currents are in 1:√2 ratio, the difference of the two measured temperatures is equal to the self-heat error at a lower measurement current. This procedure is only applicable when temperature stability is good, for example in fixed points or very stable calibration baths. Otherwise, the self-heat error measurement is possible with the use of another thermometer that is used to compensate temperature drifts, [2].

During calibration of PRTs, self-heat error can be corrected in two ways. In precision calibrations, especially in calibrations in fixed points, measurements are corrected for the self-heat error and results are given for 0 mA measurement current. User must measure or estimate the self-heat error for each measurement and correct the measured value with some residual uncertainty.

On the other hand, in calibration by comparison the results are usually given including the self-heat error at one measurement current (most commonly 1 mA). This kind of self-heat correction is good only, if the measurement current and the surrounding media are the same as during calibration. As this is often not possible, large self-heat errors may lead to increased uncertainty of measurement, where the self-heat uncertainty contribution is dominant. This paper presents methods for estimation and reduction of the self-heat uncertainty contribution in practical use of PRTs by using the optimal measurement method.

2. PRT SELF-HEAT PROPERTIES

Self-heat properties are very complex and depend on many factors. The first and most obvious is the PRT design. Manufacturers in general are trying to achieve low self-heat values and quick responses. A self-heat value is directly proportional to the square of a measurement current. This problem is usually avoided by using the same measurement current (typically 1 mA). Self-heat properties depend also on measured temperature. This dependence is partially taken into account during calibration.

The most problematic is the dependence of PRT self-heat properties on the medium, in which the PRT is immersed. This dependence can't be successfully anticipated during calibration and even manufacturers can only give approximate figures. Thermal properties of the surrounding medium are in general not known and are very difficult to measure or even estimate. Also, thermal properties are highly dependent on temperature, speed of surrounding liquid, etc.

Measurements of the self-heat response were performed in several media, but for the purpose of this paper only three most characteristic cases are presented. The highest self-heat value and the slowest response time in normal measurements can be achieved in still air. The lowest self-heat values can be achieved in liquids (especially if stirred). The properties for most such situations are quite similar, so only the self-heat in the ice-point bath is presented. Another common situation is to place the PRT in a glass test tube, to protect it from a surrounding liquid. The PRT self-heat properties are in this case somewhere in between the two extreme cases.

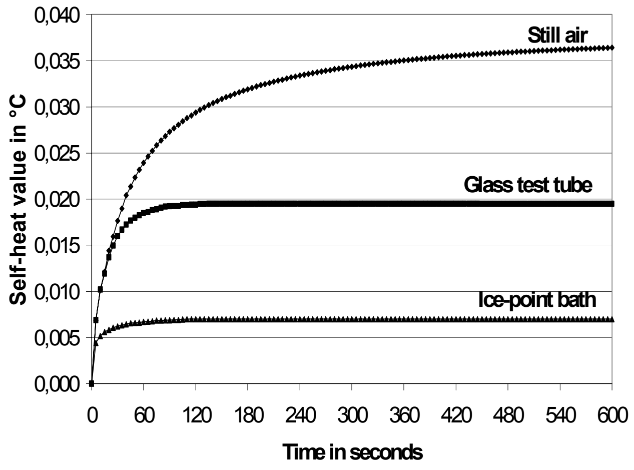

Fig. 1. Self-heat dynamic response for 0 mA to 1 mA measurement current step in different media at 0 °C

The self-heat responses in three different surrounding media at 0 °C are presented in Fig. 1. The PRT that was used for measurement was a small (100 mm) metal-sheathed Pt-100 industrial PRT, which is used in the example later in this paper.

3. SELF-HEAT DYNAMIC RESPONSE MODEL

To get a better insight in the dynamic behavior of the self-heat effect, the dynamic responses presented in Fig. 1 were thoroughly analyzed. Although there is a large difference between the dynamic responses in different media, the shape of the responses remains very similar. The responses were therefore normalized. The amplitude was divided with the self-heat value in the stable state and the time was divided with the rise time t_r, which is defined as the time required for the response to reach 90% of the maximum value. After normalization, several responses in different media were averaged, resulting in a standard self-heat dynamic response, presented in Fig. 2.

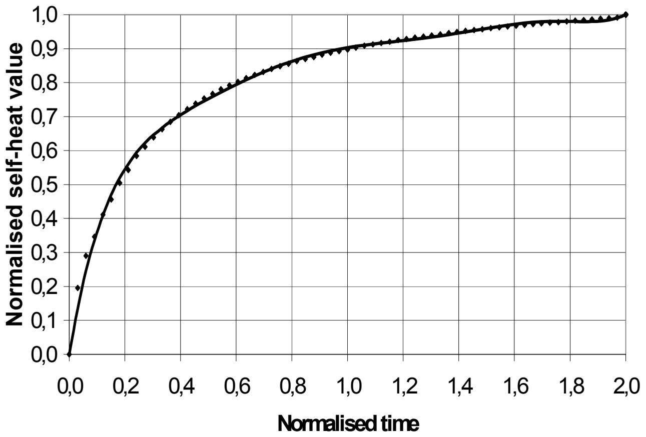

Fig. 2. Standard self-heat dynamic response and its polynomial approximation

To numerically analyze the self-heat effect, the response numerical model had to be approximated. The self-heat dynamic response might look like an exponential function, but approximation with (1) gives very poor results with errors larger than 20%, as the response in the beginning is too steep to be approximated with a first order exponential function.

$$f(t) = A\left(1 - e^{-\frac{t}{\tau}}\right). \tag{1}$$

A different approach was therefore used. A standard response was normalized with a seventh-order polynomial, as seen in (2).

$$p(\tau)=\begin{cases} 0;\tau<0 \\ a_1\tau+a_2\tau^2+a_2\tau^3+a_2\tau^4+a_2\tau^5+a_2\tau^6+a_2\tau^7;0\leq\tau\leq 2 \\ 1;\tau>2 \end{cases} \cdot \tag{2}$$

The polynomial coefficients a_1 to a_7 were calculated with the least-squares-fit method. The approximation polynomial gives a very good and simple approximation with fit error smaller than 10%, which is completely satisfactory for our purpose.

To approximate PRT self-heat responses in various media, one must provide only two parameters that can be easily determined from response curves presented in Fig. 1. Parameter SH is the maximum self-heat value with 1 mA measurement current and parameter t_r is the response rise time, defined as the time required for the response to reach 90% of the maximum value. These two parameters depend on a PRT design, PRT surrounding medium, temperature, etc. The PRT self-heat dynamic response $sh(t)$ for 0 mA to I measurement current step can therefore be expressed as:

$$sh(t) = SH \cdot I^2 \cdot p\left(\frac{t}{t_r}\right), \tag{3}$$

where I is the measurement current. The experiments have shown no significant difference between the heating and cooling response, so the dynamic response for I to 0 mA measurement current step can be expressed as:

$$sh(t) = SH \cdot I^2 \cdot \left(1 - p\left(\frac{t}{t_r}\right)\right). \tag{4}$$

In general, measurement current can change before the previous response has completed, so a more general self-heat response can be described with some simplifications as:

$$sh(t) = sh_0 + \left(SH \cdot I^2 - sh_0\right) \cdot p\left(\frac{t}{t_r}\right), \tag{5}$$

where sh_0 is the self-heat value at the moment of a measurement current step.

To verify this model numerous measurements were performed and compared with values calculated from a numerical model. The measurements were performed with the AC resistance bridge with selectable measurement current. The PRT was placed in a glass test tube inside the ice-point bath. The measurement current was switched from 1 mA to √2 mA and the dynamic response was observed. The dynamic response is the same as the response with 0 and 1 mA currents, but obviously we can't perform measurements with 0 mA measurement current. The results from measurement and numerical model are presented in Fig. 3.

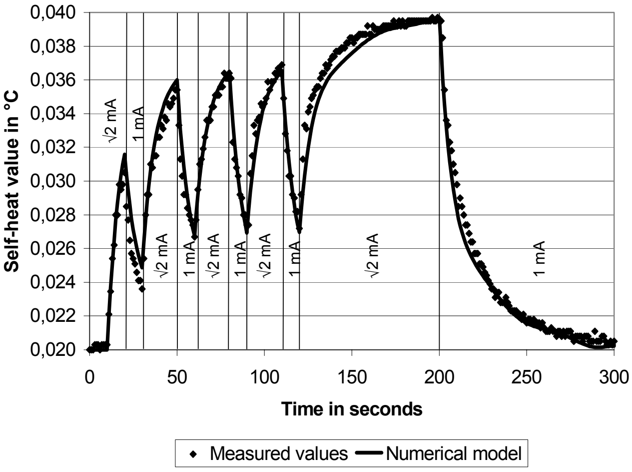

Fig. 3. Measured and calculated self-heat dynamic response

There is a noticeable difference between the measured values and the numerical model in Fig. 3. The difference is less than 0,002 °C or 10%, which is in agreement with the expected error presented in Fig. 2. Also, (5) gives a simplified solution, without taking into account any nonlinearity and assuming a first order system.

However, although the model is far from perfect, it gives a good basic insight in the self-heat dynamic behavior, which is completely sufficient for uncertainty optimization.

4. MEASUREMENT SYSTEM UNDER INVESTIGATION

The measurement system, used as the example in this paper, consist of up to twenty PRTs that are connected via a scanner to an ohmmeter. All instruments are connected with a personal computer via the GPIB bus and are controlled with the custom-made LabVIEW program. This measurement system is most commonly used in measurement of temperature gradients in climatic chambers.

The PRTs are Pt-100 thermometers in small (100 mm) metallic sheaths. They were calibrated by comparison in liquid baths in the calibration range from 0 °C to 150 °C. During calibration PRTs were measured with the AC resistance bridge ASL F700 with constant 1 mA measurement current. Uncertainty of calibration was 25 mK.

The PRTs are connected to Keithley 7001 scanner that sequentially connects PRTs to the ohmmeter HP 34420A. One PRT measurement duration is 10 seconds. Ohmmeter measures the resistance with 1 mA measurement current.

The PRT self-heat properties are highly dependent on the surrounding medium, as presented in Fig. 1. Another effect that causes self-heat problems is a value of the measurement current, which is 1 mA only for a limited period of time, as seen in Fig. 4. The measurement current can be applied to the PRT only when it is selected with the scanner. Since there can be from one and up to twenty PRTs in the measurement sequence, the active time period can vary from 5% to 100%.

The HP 34420A increases the measurement accuracy by using offset compensation procedure, [3]. This procedure separates each resistance measurement in two parts of the same time duration. In the first part, resistance is measured with 1 mA measurement current. In the second part the measurement current is set to 0 mA and parasitic voltage is measured. The measurement result is the difference of these two measurements, so any parasitic voltage is compensated. This procedure further decreases the time when measurement current is applied to the PRT.

The HP 34420A allows the selection of the A/D converter integration time, so the user can choose between the measurement speed and accuracy. An integration time selection directly defines the duration of the resistance measurement. However, duration of the complete PRT measurement cycle is fixed (in our case it was 10 seconds), so the time difference between the measurement cycle duration and the actual resistance measurement duration is compensated with a delay before the start of the resistance measurement. The measurement current during this delay can be set to 0 mA or 1 mA.

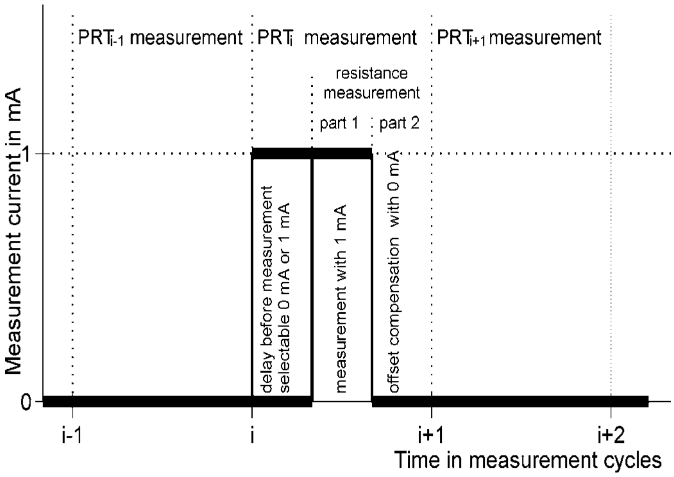

Fig. 4. Measurement current applied to one of the PRTs in the measurement sequence

4. OPTIMIZATION OF SELF-HEAT UNCERTAINTY

The presented measurement procedure applies the measurement current to the PRT for a relatively short time period, so in the most cases the self-heat will not reach its maximum value. Adjusting measurement parameters, especially integration time and value of measurement current during the delay before measurement, will directly affect this time period and therefore also the self-heat. It should also be taken in consideration, that reducing the integration time will also reduce noise rejection and therefore increase the measurement uncertainty.

In practice there are several approaches in reducing the measurement uncertainty due to the self-heat. One is to increase the delay before measurement and make a long measurement, so that the self-heat value will come close to its maximum value. The opposite approach is to use no delay before measurement and make a short measurement, so the PRT will not have time to heat-up. However, both methods are based on assumptions and not facts.

To objectively determine the optimal measurement procedure, the measurement was modeled using a numerical model presented in chapter 3. The measurement cycle presented in Fig. 4 and self-heat properties from Fig. 1 were used for model parameters.

The results of simulation are presented in Table I. The self-heat value was calculated for PRTs immersed in still air, glass test tube and ice-point bath. The number N of PRTs in the measurement was 1, 2, 3, 5, 10 and 20. The integration time was set to 10, 20 and 100 NPLC (Number of Power Line Cycles). The measurement current I_{delay} during the delay before measurement was set to 1 mA and 0 mA.

The results from the numerical model were verified with measurements performed with the actual measurement system and with the specified measurement settings. The measurement results showed good agreement with the numerical model. An example of simulated and measured data is shown in Fig. 5. The measurement system consisted of two PRTs, placed in glass test tubes and immersed in ice-point bath. The measurement current during the delay before measurement was 1 mA and the integration time was 100 NPLC. The part of the line that is integrated during measurement is drawn thicker. The corresponding self-heat value in Table I is printed in bold.

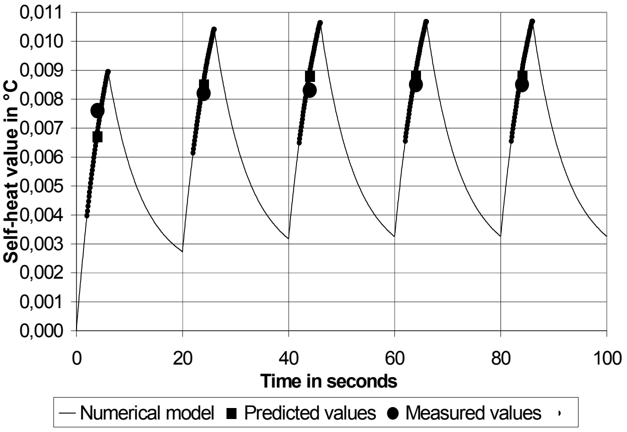

Fig. 5. Example of data simulated with numerical model and actual measured values

TABLE I. Self-heat value with different measurement settings and in various surrounding media

		I_{delay} = 1 mA			I_{delay} = 0 mA		
		NPLC=10	NPLC=20	NPLC=100	NPLC=10	NPLC=20	NPLC=100
N=1	still air	35,3 mK	33,9 mK	22,1 mK	1,1 mK	2,7 mK	14,5 mK
	glass test tube	18,6 mK	18,0 mK	12,3 mK	0,7 mK	1,7 mK	8,0 mK
	ice-point bath	6,8 mK	6,6 mK	4,7 mK	0,3 mK	0,7 mK	3,1 mK
N=2	still air	19,8 mK	19,0 mK	11,9 mK	0,6 mK	1,4 mK	7,6 mK
	glass test tube	13,3 mK	13,0 mK	**8,7 mK**	0,5 mK	1,2 mK	5,5 mK
	ice-point bath	5,2 mK	5,1 mK	3,6 mK	0,2 mK	0,5 mK	2,3 mK
N=3	still air	14,8 mK	14,1 mK	8,6 mK	0,4 mK	1,0 mK	5,3 mK
	glass test tube	12,4 mK	12,1 mK	7,9 mK	0,4 mK	1,0 mK	4,8 mK
	ice-point bath	5,0 mK	4,9 mK	3,3 mK	0,2 mK	0,4 mK	2,0 mK
N=5	still air	11,1 mK	10,6 mK	6,1 mK	0,3 mK	0,7 mK	3,6 mK
	glass test tube	11,7 mK	11,3 mK	7,0 mK	0,4 mK	0,8 mK	4,0 mK
	ice-point bath	4,8 mK	4,7 mK	3,1 mK	0,2 mK	0,4 mK	1,8 mK
N=10	still air	9,0 mK	8,5 mK	4,6 mK	0,2 mK	0,5 mK	2,6 mK
	glass test tube	11,2 mK	10,9 mK	6,5 mK	0,3 mK	0,7 mK	3,6 mK
	ice-point bath	4,7 mK	4,6 mK	3,0 mK	0,2 mK	0,4 mK	1,7 mK
N=20	still air	7,7 mK	7,3 mK	3,7 mK	0,2 mK	0,4 mK	2,0 mK
	glass test tube	11,2 mK	10,8 mK	6,5 mK	0,3 mK	0,7 mK	3,6 mK
	ice-point bath	4,7 mK	4,6 mK	3,0 mK	0,2 mK	0,4 mK	1,7 mK

Based on Table I we can conclude that it is the best to use the integration time 10 NPLC and no measurement current during the delay, since the difference in self-heat is less than 1 mK. However, this is true only, if the PRTs were also calibrated using this system. If the PRTs were calibrated using a constant 1 mA measurement current, the error will be close to 10 mK. Also, it is more difficult and more susceptible to errors to set the delay current to 0 mA than to 1 mA.

If we choose to set the delay measurement current to 1 mA, it is optimal to choose the integration time 100 NPLC. The largest difference in self-heat values is 19 mK. If we assume rectangular distribution, the standard uncertainty contribution due to the self-heat u_{SH} will be:

$$u_{\mathrm{SH}} = \frac{\Delta sh}{2\sqrt{3}} = 5{,}5\,\mathrm{mK}\,. \tag{6}$$

With this procedure PRTs could be calibrated using a constant measurement current (on the AC resistance bridge with a scanner with standby current on unused channels) or using this measurement system.

The example above assumed that we could have from one up to twenty PRTs. If the number of PRTs is fixed to 10 PRTs, for example, the difference in self-heat values is only 3,5 mK with the resulting uncertainty contribution 1 mK. In our case this was found to be an optimal solution, ten PRTs were permanently connected to the scanner and the ohmmeter and the whole system was then calibrated as an indication thermometer with ten channels.

5. CONCLUSIONS

Reducing measurement uncertainty of practical temperature measurements significantly improves the quality of our work. The self-heat is often neglected uncertainty source that can become in some situations one of the largest measurement uncertainty contributions and if not handled properly may cause unreliable results. The work presented in this paper showed that even where the self-heat problem is critical, detailed analysis could be used to optimize the measurement system and measurement procedure, which results in the reduced and more objective measurement uncertainty.

The numerical model that was presented in the paper is very useful to get an insight in the self-heat behavior and can be used to optimize the measurement system and measurement procedure, but its accuracy and reliability is not sufficient to be used for the direct correction of the self-heat error in practical measurements. Instead, the differences in self-heat value should be taken into account in the uncertainty contribution due to the self-heat.

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