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Determination of PRT Hysteresis in the Temperature Range from −50 °C to 300 °C

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Abstract This paper discusses the contribution of hysteresis to the measurement uncertainty of industrial platinum resistance thermometers (IPRTs). Hysteresis is one of the sources of uncertainty that has so far not been sufficiently researched and documented. The term hysteresis applies to any system that is path dependent; the output depends on the history of the input. In our case, thermal hysteresis results in different resistance values at the same temperature point, depending on whether the temperature was increasing or decreasing. The reason for such behavior is related to the construction of the thermometer (strain due to thermal expansion and contraction) and also to possible moisture inside the encapsulation. In the process of evaluation of the calibration and measurement capabilities (CMCs) of IPRTs within Working Group 8, the Consultative Committee for Thermometry (CCT WG8) concluded that the uncertainty due to hysteresis is not uniformly defined and not always added to the total uncertainty of the resistance thermometer under calibration. In order to estimate the uncertainty contribution due to the hysteresis and compare different procedures, resistance measurements were carried out on a number of IPRTs of different qualities and tolerance classes. The temperature span was between −50 °C and 300 °C, which is the most frequent temperature range in the practical use of IPRTs. The hysteresis was then determined in different ways (change of resistance at the ice point and at the midpoint temperature according to the ASTM International Standard E644 and according to the new version of IEC Standard 60751), and a comparison of results was made.

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1 Introduction

Resistance thermometers are secondary temperature measuring instruments that can be classified as contact electric thermometers. Temperature is determined indirectly by measuring the temperature-dependent electrical resistance of some materials. These materials would include nickel, copper, and platinum. The latter is by far the most common material for resistance thermometers, as it best fulfills all the required properties such as high resistance/temperature coefficient, high resistivity and melting temperature, stable physical properties, and sufficient mechanical strength. The electrical resistance increases with increasing temperature due to the higher probability of collisions between electrons and the thermodynamically vibrating crystalline structure of metals [1].

Different types of platinum resistance thermometers (PRTs) are used in the temperature range roughly between −260 °C and 1,000 °C [1]. Thermometers made of high-purity platinum and calibrated at specified temperature fixed points are used as interpolating instruments of the International Temperature Scale of 1990 (ITS-90) between 13.8033 K and 961.78 °C (standard platinum resistance thermometers, SPRTs) [2]. PRTs are also widely used in industrial environments where the highest possible accuracy is not needed. The emphasis is on withstanding mechanical shock, vibration, and also extraneous electromagnetic fields [3] in harsher operating conditions than those found in a laboratory (industrial platinum resistance thermometers, IPRTs) [4]. Furthermore, PRTs are commonly used as reference thermometers in systems for calibration of radiation thermometers below 961.78 °C (freezing point of silver) and in secondary systems for calibration by comparison [5].

There are two main IPRT designs. The first group employs wire sensors, where the sensing element is a thin platinum wire, supported by glass or a ceramic material of a preferably equal thermal expansion coefficient as platinum [1,4]. Such a construction should provide enough protection against vibration, and at the same time, should not introduce too much strain with changing temperature. As this goal cannot be achieved perfectly, this strain is one of the reasons for thermal hysteresis—change of resistance at a particular temperature that occurs with increasing or decreasing temperature [6–8]. This effect is even more pronounced with the second IPRT design that uses film sensors, where the resistance element is a platinum film deposited on a ceramic substrate. These sensors are cheap and robust, but normally achieve lower accuracies [4,9].

There are several sources of uncertainty that can be identified in the process of calibration and usage of PRTs and should be considered: standard deviation of readings, uncertainty of calibration equipment (i.e., reference thermometer, calibration enclosure, resistance bridge, and reference resistors), uncertainty due to immersion error, uncertainty due to self-heating, and uncertainty due to thermometer hysteresis [10]. The aim of this paper is to investigate the uncertainty source arising from hysteresis on thermal cycling.

2 Measurements

2.1 Specimens

There were two groups of specimens, as the aim was to test both designs: film and wire platinum resistance elements. The first group consisted of nine thin film sensors (numbered from #01 to #09), made by a UK company for the temperature range between −70 °C and 500 °C:

- 3 Pt100 sensors, Class B, dimensions 2 mm × 2.3 mm (#01–#03),
- 3 Pt100 sensors, Class A, dimensions 2 mm × 2.3 mm (#04–#06),
- 3 Pt1000 sensors, Class A, dimensions 2 mm × 10 mm (#07–#09).

The thermometer classes refer to tolerance classes as defined by the standard IEC 60751. The tolerance value of Class A is $\pm(0.15 + 0.002|t|)$ °C and of Class B is $\pm(0.3 + 0.005|t|)$ °C, where $|t|$ is the absolute value of temperature in °C. In order to use these small sensors as thermometers, they were inserted into glass protective sheaths and four PVC insulated copper wires were soldered to two short sensor leads. That imposed a maximum allowable temperature of 150 °C, as the PVC insulation of copper wires would start to melt at any higher temperature.

The second group consisted of two IPRTs with wire platinum sensing elements (Pt100, numbered #10 and #11), assembled by a local company. Thermometers were marked as B class with a temperature range from −200 °C to 600 °C and featured stainless steel sheath and four leads.

2.2 Procedures

In practice, different measuring procedures can be used to assess the thermometer's hysteresis in a certain temperature range. At least two relevant standards can be found. The first is the International Electrotechnical Commission's (IEC) Standard 60751 titled "Industrial Platinum Resistance Thermometer Sensors." The first edition (now withdrawn) that was published in 1983 with its two amendments does not mention hysteresis [11]. However, in the new edition of the standard, published in 2008, a type test for thermometers named "Effect of Hysteresis" can be found under subtitle 6.5.6. It states that the resistance is measured in the middle of the temperature range after the thermometer is exposed to a temperature at the lower limit of the range, and then again at the same midpoint temperature after exposure to the upper limit temperature. The difference between measured resistances should not be larger than the tolerance value at the test temperature for the respective class [12].

The second standard that deals with hysteresis determination is the ASTM E644 titled "Standard Test Methods for Testing Industrial Resistance Thermometers." Under subtitle 16, "Thermal Hysteresis Test" is described. It defines hysteresis testing as a means to quantify the amount of change in a PRT when exposed to thermal cycling. The procedure is as follows: starting at room ambient, the temperature of the test thermometer is raised to the specified maximum temperature (±5 °C), then reduced to a temperature midway between the specified maximum and minimum when the resistance reading is taken. The temperature is further reduced to the specified minimum (±5 °C) and raised to the midpoint temperature when the second reading is taken. In this manner several cycles should be made. The average of measured resistance differences quantifies the thermometer's hysteresis [13].

Besides these two standard hysteresis testing procedures, another procedure that is very similar to the one that IEC/ASTM standards describe was also employed (ice-point procedure). The difference is that the resistance readings, before and after, were always made at 0 °C. Such a procedure is usually used to determine hysteresis by a number of national temperature laboratories around the world.

2.3 Actual Measurements

The first group of thermometers (with film sensors) was tested for hysteresis following all three previously presented procedures. The temperature range selected was from −50 °C to 150 °C, so the temperatures needed for the measurements were: −50 °C (methanol bath), 0 °C (mixture of water and ice), 50 °C (water bath), and 150 °C (light viscosity oil bath). The temperature and its stability were constantly monitored with calibrated reference SPRTs with a measurement uncertainty of 2 mK. Four wire resistance measurements were done using a calibrated reference AC bridge and logged in custom-made LabVIEW software [14]. The uncertainty of the resistance measurement was 3.1 ppm (≈0.8 mK). The stability of the thermometer output before taking the actual reading was within 5 mK. Any possible heat leaks through the thermometer stem were proven constant and therefore did not affect measurement results. Nine separate experiments were performed; each group of three thermometers was tested three times following all three procedures described earlier (Fig. 1).

The second group (wire thermometers) was tested according to the IEC 60751 and ASTM E644 procedures in the temperature range from 50 °C to 300 °C. The temperature enclosure used was a dry-well calibrator with a specified 10 mK stability. This realization differs from the previous one as the temperature in this case was a continuous function. The test was fully automated as the calibrator temperature was set through its RS-232 interface, and that enabled us to run 55 full cycles. Otherwise, the same equipment was used.

3 Results

Ideally, the temperature of our enclosures where the resistance was measured (ice, water, and calibrator) would be exactly the same the whole time when measurements were performed. As this is practically impossible, especially for the dry block and the baths, correction of the measured difference in resistance due to a change in temperature was made for each cycle. At the times when resistance readings were taken, the temperature was also simultaneously measured with an SPRT that did not show any significant hysteresis. The difference in temperature was then converted into an equivalent resistance difference that cannot be assigned to hysteresis. The well-known temperature/resistance relationship from IEC 60751 was used [12]:

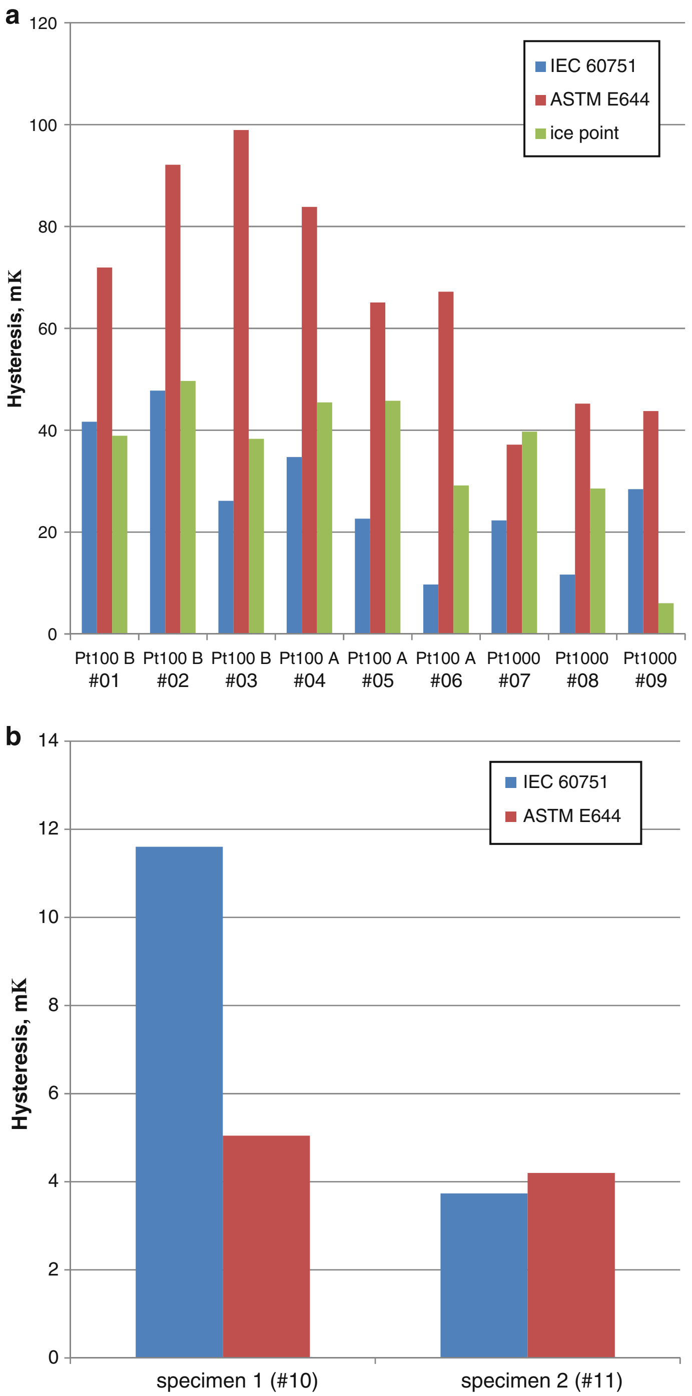

Fig. 1 Column diagram of the hysteresis of (a) film sensors and (b) wire sensors

Table 1 Summary of measurements of hysteresis for film sensors (in mK) for different types of sensors, different nominal values, and different hysteresis determination procedures

Procedure/ specimen	Pt100 B #01	Pt100 B #02	Pt100 B #03	Pt100 A #04	Pt100 A #05	Pt100 A #06	Pt1000 #07	Pt1000 #08	Pt1000 #09
IEC 60751	41.688	47.795	26.162	34.736	22.646	9.714	22.305	11.659	28.421
ASTM E644	71.940	92.119	98.928	83.843	65.069	67.209	37.172	45.234	43.754
Ice point	38.928	49.675	38.302	45.474	45.767	29.143	39.730	28.564	6.050

$$R_t = R_0(1 + At + Bt^2); \quad t > 0\,^\circ\mathrm{C} \tag{1}$$

where t is the temperature, R_t is the resistance at temperature t, R_0 is the resistance at $t = 0\,^\circ\mathrm{C}$, and A and B are constants: $A = 3.9083 \times 10^{-3}\,^\circ\mathrm{C}^{-1}$, $\mathrm{B} = -5.775 \times 10^{-7}\,^\circ\mathrm{C}^{-2}$.

This correction for film sensors was never larger than 3 mΩ for Pt100 and 30 mΩ for Pt1000, so the worst stability of the water bath was roughly 8 mK. The temperature of ice was very stable and never changed for more than 0.5 mK.

With the calibrator, the automation cycle is controlling the sensor of the dry block calibrator, but the stability and actual temperature is determined with the SPRT as in the case of the liquid bath; the corrections were 4 mΩ to 5 mΩ at most, so the temperature stability was up to 10 mK to 15 mK. There were some extreme cases when the stability was as poor as 60 mK, but results from those cycles were discarded. A cycle was valid if the calculated correction was less than the measured resistance difference.

Results of our measurements clearly show an obvious hysteresis of platinum film temperature sensors, even in a quite narrow temperature span (200 °C), as shown in Table 1. In all cases, the measured resistance was higher when the temperature was decreasing than when the temperature was increasing. Also, the resistance differences we got with the second method (ASTM) are significantly larger than those of the other two methods. For Pt100 sensors, the largest hysteresis measured was approximately 40 mΩ. If we convert that to a temperature equivalent, the thermometer shows a difference in temperature of about 100 mK after a thermal cycle. That is still within the allowable tolerance for both IEC 60751 classes: 150 mK for Class A and 300 mK for Class B. For Pt1000 sensors, the maximum hysteresis measured was 175 mΩ, again following the ASTM procedure. That is equivalent to a 45 mK temperature difference and is also well within tolerance.

Valid measurement results for wire thermometers are shown in Table 2. The hysteresis effect is less pronounced, but resistance differences can still be detected. With a temperature span of 250 °C, the measured hysteresis was typically just a few mΩ. The maximum value was 9 mΩ, equivalent to 23 mK.

4 Conclusion

Hysteresis is a complex phenomenon. Its effect can vary depending on sensor design and on the environment in which it is used. As results show, film sensors exhibit larger

Table 2 Summary of valid measurements of hysteresis for wire sensors (in mK)

Specimen 1 (#10)		Specimen 2 (#11)	
IEC 60751	ASTM E644	IEC 60751	ASTM E644
19.011	1.361	4.905	3.334
7.494	4.770	2.379	4.599
5.588	0.096	7.001	5.734
22.841	6.185	0.608	3.129
3.069	7.318	2.137	
	6.030	4.983	
	5.092	4.129	
	8.151		
	4.111		
	5.801		
	3.747		
	7.889		
Mean values			
11.601	5.046	3.735	4.199

hysteresis than wire sensors. Such a result is understandable if we take into account that the main reason for hysteresis is strain due to thermal expansion and contraction. Such strain effects are less present with wire sensors than with film sensors, where platinum is in direct contact with another material. The best wire sensors, found in SPRTs, are virtually strain free and their hysteresis is consequently negligible. An additional reason for hysteresis can also be moisture, as many sensors are not completely sealed. Moisture causes shunting effects and can have a significant impact on the actual resistance of platinum [9].

Thermal hysteresis also cannot be uniformly quantified and thus corrected for, but only estimated as one of the uncertainty components. As shown, different procedures exist and give different results. Another important aspect is the temperature span and the temperature point where the resistance difference is observed. Hysteresis can be different if a broader or narrower temperature span is used.

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