Int J Thermophys (2010) 31:1676–1684
DOI 10.1007/s10765-010-0821-x

The Hysteresis Characteristics of Some Industrial PRTs

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Received: 8 March 2010 / Accepted: 21 August 2010 / Published online: 19 September 2010

Abstract Hysteresis in industrial platinum resistance thermometers (IPRT) is caused by tension and compression induced in the wire due to differential thermal expansion of the platinum wire and the substrate. This article reports the measurement of hysteresis in a wide range of IPRTs including thin-film, glass-encapsulated, ceramic-encapsulated, and low-hysteresis partially-supported sensors, over the temperature range from −20 °C to 180 °C. The study confirms previous findings that the amount of hysteresis is very dependent on the design of the sensing element and the temperature range. In addition, some sensors exhibit a large change in resistance on first use, whereas others showed a slow increase in resistance with use. The observed hysteresis ranged between 0.2 % of the temperature range for one glass-encapsulated sensor and 0.002 % for the best of the partially-supported ceramic sensors.

Keywords Hysteresis · Industrial platinum resistance thermometer

1 Introduction

Hysteresis is a key performance parameter for industrial platinum resistance thermometers (IPRTs) used in high-accuracy applications. The main cause of hysteresis in IPRTs is tension and compression induced in the platinum wire due to differential thermal expansion of the wire and the substrate [1]. This mechanically-induced distortion of the wire is the main focus of performance and design compromises. A high level of mechanical support of the wire is required to minimize susceptibility to vibration and mechanical shock, whereas minimal support allows the wire to expand and

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contract with temperature without inducing strain on the wire. There are two general design classifications. In 'fully-supported' IPRT sensors, the full length of the wire is bonded to or embedded in the substrate, whereas in 'partially-supported' sensors, only a fraction of the wire is bonded to the substrate.

Although the hysteresis is a key performance parameter for high-accuracy applications, very little has been published on the effect, and much of what is known is probably proprietary. The most complete study of the mechanically-induced hysteresis in IPRTs was by Curtis [1], who developed a simple model of the effect and investigated the nature and magnitude of the effect in a wide range of different sensors. Nicholas and White [2] noted that hysteresis was one of the major sources of uncertainty for IPRTs and that this should be considered during calibration. More recently, Murdock and Strouse [3] followed a suggestion of Curtis and assessed the hysteresis in a large number of IPRTs by cycling them between −196 °C (liquid nitrogen) and 200 °C, and measuring the difference between the ice-point readings on the rising and falling temperatures. The observed differences provide indicative values for uncertainties to be included in the calibration uncertainty.

IPRTs used in laboratory measurements should be of the partially-supported type to minimize the effects of hysteresis. For many applications, a calibration uncertainty of 20 mK, due in large part to hysteresis, is not a major limitation. For this reason most calibration laboratories do not measure the hysteresis. However, as laboratory measurements are pushed to lower uncertainties, the need to measure and understand hysteresis effects becomes more pressing. For the calibration laboratory, hysteresis is a difficult problem. Hysteresis effects tend to be highly specific to different sensor types, depend greatly on the temperature range over which the sensor is cycled, and depend on the rate of change of temperature [1].

In some cases, an indication of the magnitude of the hysteresis effect can be gained by monitoring ice-point changes as the IPRT progresses through the calibration [2]; however, this seems to be applicable only when the ice point is not near the extreme of the calibration range. Ideally, a full performance assessment requires a full measurement of the resistance–temperature characteristic on both rising and falling temperatures over the range of use requested by the client. Such assessments double the time required for already expensive calibration procedures, and can be complicated by the need to rapidly move the IPRT between calibration baths or furnaces so that the IPRT is not subjected to additional rapid temperature changes. The motivation for this study is firstly to gain an improved understanding of the effect, and secondly to make preliminary investigations of strategies for assessing the hysteresis by means other than a complete measurement over rising and falling temperatures.

2 Survey

2.1 Experimental Setup and Analysis

Two groups of IPRTs were gathered for this study. Group 1 included a broad selection of different types of sensing elements. All were sent to a local manufacturer for assembly into a 4.5 mm stainless-steel sheath with four-wire connections to enable accurate resistance measurement. The sensors in this group included fully-supported glass, ceramic-encapsulated, and thin-film sensors. The instrument supplier was not able to advise if the ceramic sensors were either fully-supported or partially-supported elements.

The second group of IPRT sensors included a range of partially-supported ceramic IPRTs commonly used in New Zealand for laboratory thermometry in the range from −40 °C to 200 °C. The group included two partially-supported sensors designed especially for low hysteresis. The remaining thermometers in this group were made by two different IPRT manufacturers, possibly using the same sensing elements. All of the Group 2 sensors were assembled in either 4 mm or 5 mm diameter stainless-steel sheaths.

Prior to the hysteresis measurements, all thermometers were subject to an insulation resistance test for the presence of moisture in the sheath assembly. A 100 V insulation tester was used to test for a connection between the sheath and one of the leads to the sensing element. All probes used in the tests had insulation resistances greater than 1 GΩ. This test ensures that the migration of moisture within the sheath of the IPRT does not contribute to the observed hysteresis.

The hysteresis assessments were carried out in two oil baths, covering a range of −20 °C to 50 °C and from 50 °C to 200 °C, with a stability and uniformity of better than 0.5 mK rms over the range of use. The rate of change of the bath temperature, for both rising and falling temperatures, was no faster than $10\,°\mathrm{C} \cdot \mathrm{h}^{-1}$, and the bath temperatures were held constant while the IPRTs were moved quickly from one to the other. The temperature in the baths was measured directly by an SPRT calibrated according to ITS-90. The temperature–resistance characteristics for Group 1 test thermometers were measured in four different assessments over the temperature ranges −20 °C to 180 °C, 50 °C to 180 °C, 50 °C to 120 °C, and finally −20 °C to 180 °C repeated. The Group 2 thermometers were cycled twice over the −20 °C to 180 °C range. The thermometers were tested at the same temperatures for both rising and falling temperatures. The test results for all temperature ranges for a single sensor were then collated and fitted to a quadratic equation of the form $R(t) = R_0(1 + At + Bt^2)$, and the residual resistance variations were plotted as temperature variations on a single graph. The use of a single equation for all data makes it possible to identify in a single graph, drift, hysteresis, and departures from the expected quadratic characteristoc.

2.2 Results

Figures 1 to 8 plot the measured hysteresis characteristics for a selection of the thermometers tested. In all figures, a solid line indicates measurements taken on a rising temperature, whereas the dotted line indicates measurements taken on a falling temperature. The entries in the legend for each graph have the most recent test runs uppermost. The legends were organized this way to correlate with the position of measurement on the graphs because a number of the thermometers showed a drift upwards in resistance with time.

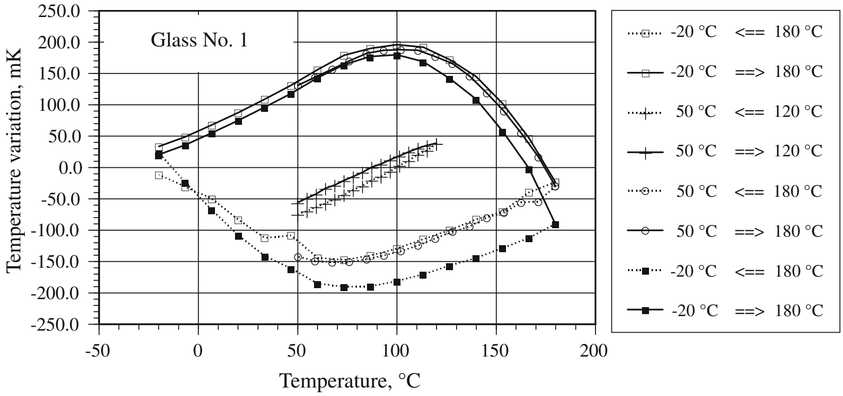

Fig. 1 Measured hysteresis for a glass IPRT showing classic hysteresis loop with peak-to-peak hysteresis approaching 0.2 % for a temperature range of 200 °C

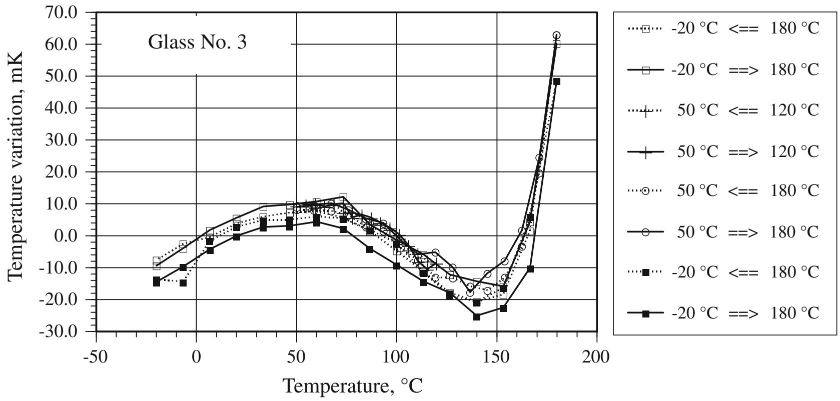

Fig. 2 A glass IPRT exhibiting negligible hysteresis and a strong departure from a quadratic resistance–temperature relation

2.2.1 Group 1: Assorted Sensor Types

Figures 1 to 5 show a sample of the measured hysteresis characteristics for the Group 1 IPRTs, including two different glass-encapsulated sensors, two different ceramic-encapsulated sensors, and a thin-film sensor.

The first of the glass sensors, Fig. 1, shows a very large hysteresis loop with a peak-to-peak hysteresis of 0.19 % for the −20 °C to 180 °C cycle, much larger than for any of the sensors investigated by Curtis [1]. The much reduced hysteresis for the cycle over the 50 °C to 120 °C range also demonstrates that the hysteresis is range dependent. The second glass sensor, Fig. 2, shows quite different behavior from the first. The amount of hysteresis is very much reduced, but there is instead a very large departure from the quadratic curve expected for an IPRT. In particular, the resistance rises very rapidly for temperatures above 150 °C. The large departure from quadratic behavior presumably arises because the resistance–temperature characteristic for sen-

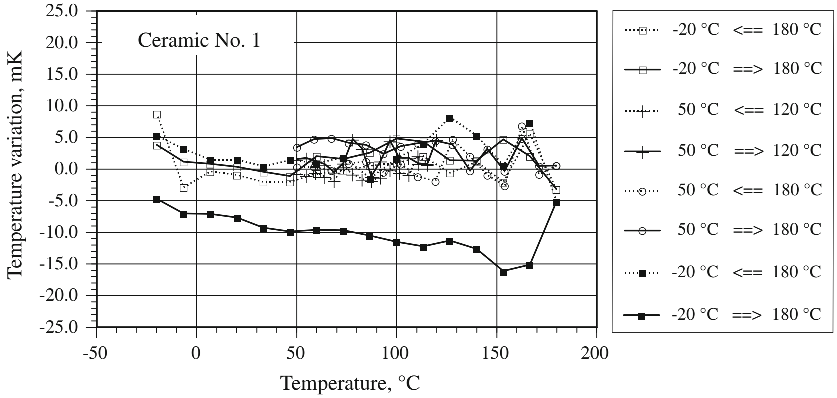

Fig. 3 A ceramic IPRT exhibiting little hysteresis, except for the first set of measurements

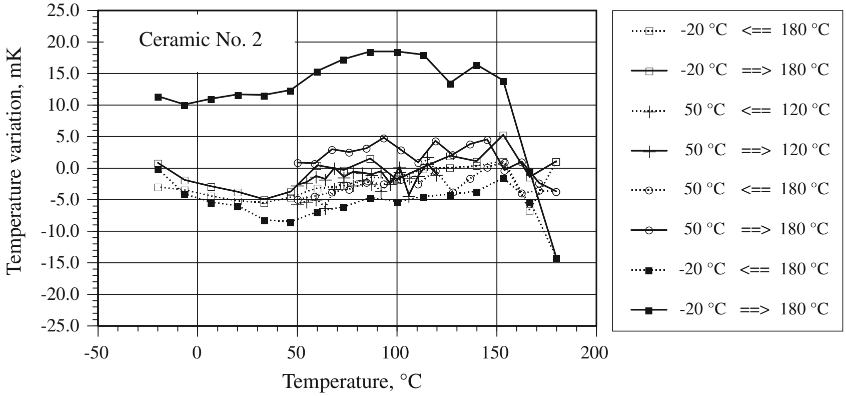

Fig. 4 A ceramic IPRT exhibiting similar effects to those of Fig. 3, except that the effects are of opposite sign

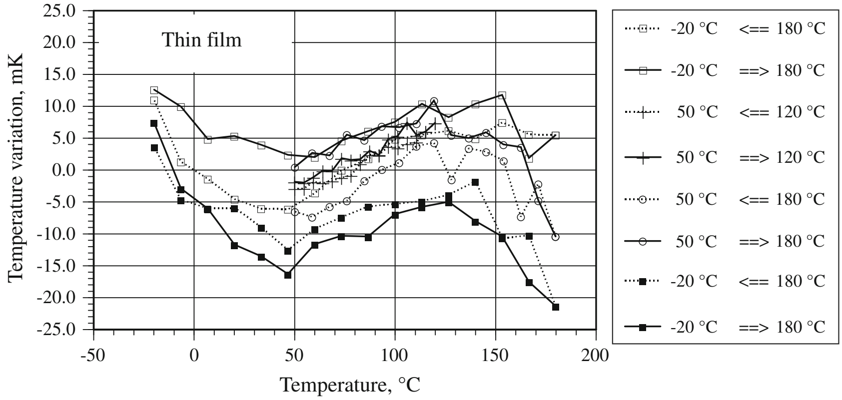

Fig. 5 A thin-film IPRT showing a drift upwards in resistance with time, and a weak cubic error

sors with the platinum fully bonded to the substrate depends on the combination of the temperature coefficient of the platinum and the strain-gauge effect due to the substrate stressing the wire. The lack of a hysteresis effect may indicate that the wire is firmly bonded to the substrate and not subject to relaxation effects.

A number of ceramic-encapsulated sensors were evaluated, with all exhibiting a relatively low level of hysteresis (0.01 % or lower), suggesting that they may have all been partially-supported types. The characteristics shown in Figs. 3 and 4 showed two interesting features. Firstly, the very first set of measurements show a distinctly different resistance–temperature characteristic from all subsequent measurements. The thermal-cycling testing guidelines of the EN 60751 and ASTM 644 documentary standards imply that such behavior should be expected [4,5]. This further suggests that for the best accuracy and repeatability, new sensors should always be cycled over the required temperature range before they are used or calibrated. The second feature of Figs. 3 and 4 is that they are almost mirror images, but not just on the first-measurement effect just described. In Fig. 3, the reading on rising temperatures is always low, whereas in Fig. 4, it is always high. This is consistent with the fact that the sign of the hysteresis depends on the relative thermal expansion of the platinum wire and the substrate, and the two sensors here having opposite signs in the differential temperature coefficients.

Figure 5, the results for the thin-film IPRT sensor, shows a steady rising in the sensor resistance with use. This effect occurred to a lesser degree in some of the other sensors. Note too, a residual cubic shape in the error curves, though not as extreme as in Fig. 2.

2.2.2 Group 2: Assorted Partially-Supported Ceramic IPRTs

Figures 6 to 8 show the measured characteristics of a selection of partially-supported sensing elements. The three figures have been selected because they exhibit, distinctly, different features that were observed on most of this group of IPRTs.

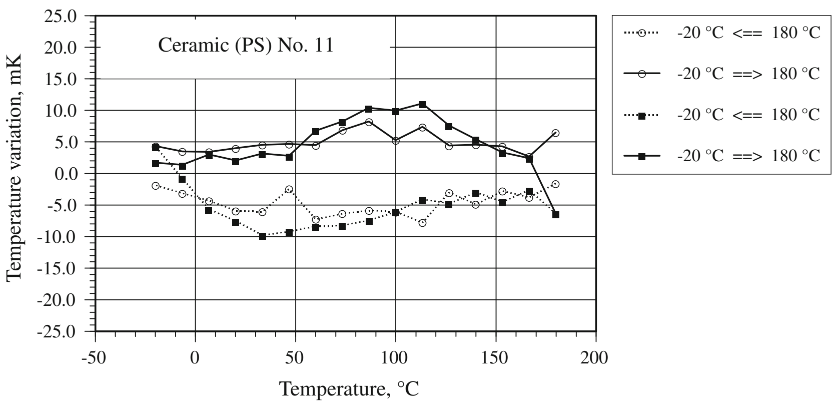

Fig. 6 A partially-supported ceramic IPRT with a large amount of hysteresis

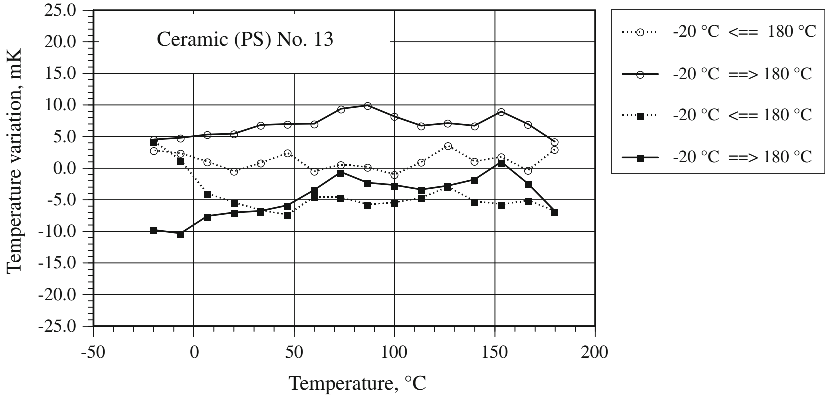

Fig. 7 A partially-supported ceramic IPRT exhibiting drift upwards in resistance with use

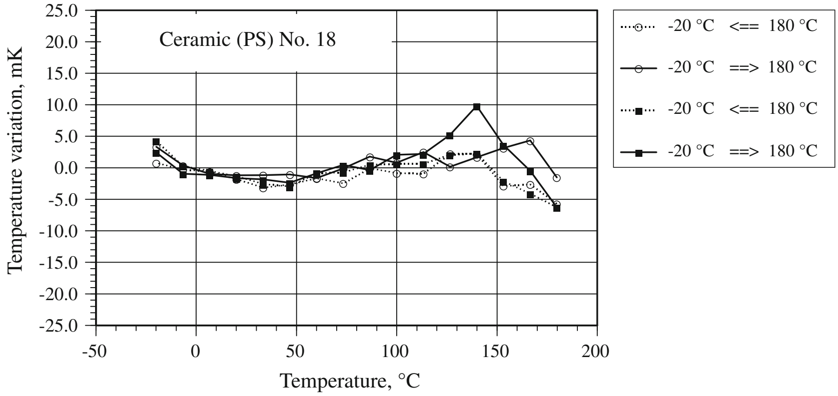

Fig. 8 The best of the partially-supported ceramic IPRTs

Figure 6 shows the characteristic of the IPRT exhibiting the largest hysteresis loop of any of the partially-supported sensors we tested. The peak-to-peak error is about 20 mK (about 0.01 % of temperature range).

Figure 7 shows a partially-supported IPRT exhibiting drift upwards in resistance with use. This behavior was usually absent, or at most a weak tendency, for most of the IPRTs in Group 2. This sensor was also slightly peculiar in that the second cycle of measurements produced a larger hysteresis loop.

Figure 8 shows one of the best of the partially-supported ceramic IPRTs tested, with hysteresis over most of its range near or below 0.002 %, although there are perhaps indications of hysteresis affecting some of the measurements at temperatures above 150 °C. About a third of the IPRTs tested in Group 2 had hysteresis effects demonstrably better than the others in the group. Unfortunately, in contrast to the observations of Murdock and Strouse [3], there did not seem to be a strong correlation between the maker or model and performance.

3 Conclusions

The measurements and observations here broadly support the general observations of Curtis [1]. For the sensors evaluated here the hysteresis effects ranged from 0.002 % to 0.2 % of the temperature range. Amongst the sensors tested, those most susceptible to strain effects were glass-encapsulated sensors, and the best were partially-supported ceramic-encapsulated sensors. The observed strain-related effects included hysteresis loops, an initial rise or fall in resistance on first use, a cubic resistance–temperature dependence, and a steady rise in resistance with use. Although no quantitative assessment has been made, partially-supported sensors exhibiting the largest hysteresis effects also exhibited greater non-repeatability of the resistance–temperature characteristic. For the very limited selection of partially-supported ceramic sensing elements tested here, there was no strong correlation between manufacturer/model and the magnitude of the observed hysteresis.

This collection of diverse strain- and hysteresis-related effects greatly complicates the assessment of hysteresis in the calibration environment. To achieve an accurate assessment of the uncertainty caused by hysteresis, the temperature range of the tests should, ideally, reproduce the temperature range in use. In addition, it may be necessary to reproduce during calibration the rate of change of temperature expected in use. Unfortunately, calibration baths are typically slow to change temperature, much slower than, for example, direct immersion into a medium of interest.

One important observation is that some sensors exhibit an initial rise or fall in resistance on first use. This effect means that new thermometers should be cycled over the temperature range of expected use before they are subject to calibration or hysteresis assessment.

For most of the partially-supported ceramic-encapsulated sensors tested here, including the ceramic sensors of Group 1, the variations in measurements largely fell within a rectangular block, much as seen in Fig. 7. This observation suggests that a pair of measurements taken on rising and falling temperatures and over a sufficiently wide range might characterize the amount of hysteresis quite well. The test suggested by Curtis, of cycling rapidly between −196 °C and 200 °C and measuring the change in the ice-point reading, may provide a suitable measure of hysteresis for some applications. Limitations in tests for hysteresis include a high level of non-repeatability in partially-supported IPRTs exhibiting hysteresis, so that the confidence (equivalent number of degrees of freedom [6]) in the uncertainties used to characterize the measured hysteresis might not be as high as desirable. Any tests would have to be designed to detect the occasional sensor exhibiting the classic loop shape, as in Fig. 6. For these sensors, measurements near either end of the temperature range would underestimate the hysteresis occurring elsewhere.

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