Int J Thermophys (2008) 29:1817–1827
DOI 10.1007/s10765-008-0463-4

Approximating the ITS-90 Temperature Scale with Industrial Platinum Resistance Thermometers

V. C. Fernicola · L. Iacomini

Published online: 10 June 2008

Abstract Platinum resistance thermometers (PRTs) are widely used for accurate temperature measurements in industrial process control as well as in testing and calibration laboratories. Industrial-type PRTs (IPRTs) are available with platinum wires of different purity and can attain measurement accuracy at the level of few tens of millikelvin in a broad temperature range from −196 °C to 550 °C and above. For such IPRTs, the most-used interpolation model (resistance versus temperature) is based on the Callendar–Van Dusen (CVD) equation, which is also recognized in several industrial standards including IEC 60751 and the corresponding national standards. In recent years, several studies have shown that systematic differences exist between the ITS-90 temperature (T_{90}) and the temperature calculated by the CVD function. When the CVD equation is used to fit experimental data, the difference can be as large as several tens of millikelvin, even near a calibration point, i.e., of the same order of magnitude as the experimental uncertainty routinely achieved in laboratory calibrations. In order to overcome the above limitations, many interpolation models were proposed. The aim of this work is to assess the use of ITS-90 defining equations in precision laboratory calibrations of IPRTs in the temperature range from −196 °C to 420 °C. Twenty IPRTs with $W(100)$ ranging from 1.384 to 1.392 were calibrated by comparison against a standard PRT, and the experimental data were processed using several interpolation schemes based on ITS-90 deviation functions with different degrees of freedom. The overall results showed that any ITS-90-based scheme performs better than the CVD equation, suggesting that it be applied to a broad spectrum of industrial and laboratory applications.

V. C. Fernicola (✉) · L. Iacomini
Thermodynamics Division, Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
e-mail: v.fernicola@inrim.it

Keywords Callendar–Van Dusen equation · Deviation functions · Industrial platinum resistance thermometer · Interpolation model · ITS-90 approximation

1 Introduction

Temperature measurements are vital to many industrial processes including, e.g., energy conversion, metallurgy and steel production, plastic and food industries, basic chemical production and, of course, in several environmental and life science areas. Various temperature measurement principles and instruments are available, but the platinum resistance thermometer (PRT) affords the lowest uncertainty over a wide temperature range. It is also the standard interpolation instrument (SPRT) defining the International Temperature Scale of 1990 (ITS-90) in the temperature range from 13.8033 K to 961.78 °C [1].

PRTs used in the industrial field (IPRTs) do not comply with SPRT constraints, but can be reproducible to within a few tens of millikelvin from −200 °C to about 600 °C. IPRTs are widely used in industrial process applications and in testing and calibration laboratories. Different IPRT interpolation schemes were developed; however, the most common is still based on the Callendar–Van Dusen (CVD) equation, which is also recognized in several international standards and the corresponding national standards [2].

The CVD equation was used, before 1968, both for SPRTs and for IPRTs, although they differed in the purity of the platinum wires used to make the sensing element and in their thermometer resistance at 0 °C (SPRTs are usually 25.5 Ω, whereas IPRTs are usually 100 Ω). After the introduction of the IPTS-68, the interpolation equation of the SPRT changed, and the CVD equation continued to be used for IPRTs that complied with the IEC 60751 standard. This approach was largely justified by the lower accuracy needed by IPRT applications and by the advantage of sensor interchangeability offered by IPRTs that comply with the standard. Although the temperature deviation with respect to the ITS-90 temperature obtained by using the CVD equation is small when compared with the Pt-100 tolerances set by the IEC 60751 standard, it cannot be neglected in precision measurements, e.g., in PRT calibrations carried out by many accredited laboratories that have best measurement capabilities of 0.03 °C or lower in the temperature range from 0 °C to 250 °C. Figure 1 shows the difference, i.e., the fitting residuals $t_{\mathrm{CVD}} - t_{90}$, between the temperature calculated by means of the following CVD equation and the corresponding ITS-90 temperature:

$$\frac{R_t}{R_0} = 1 + At + Bt^2 + C\left(t - 100\,^{\circ}\mathrm{C}\right)t^3 \quad (C = 0 \text{ above } 0\,^{\circ}\mathrm{C}). \tag{1}$$

The difference represents the fitting residuals obtained with the CVD equation applied to a data set of equally spaced temperatures (1 °C) generated using the ITS-90 reference function.

From Fig. 1, any improvement in IPRT sensor technology, e.g., with platinum wires of higher purity ($\alpha \approx 0.00392\,^{\circ}\mathrm{C}^{-1}$), that may result in a measurement uncertainty of a few millikelvin can be offset by the interpolation error. Results from several works

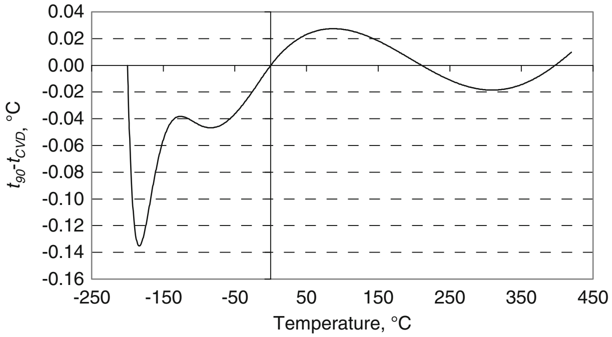

Fig. 1 Difference between the temperature calculated by means of the CVD function and the corresponding ITS-90 temperature ($t_{\mathrm{CVD}} - t_{90}$) in the range from −196 °C to 420 °C

have shown that the CVD fitting residuals can be as large as several tens of millikelvin, even at the calibration point, i.e., the same order of magnitude of the experimental uncertainty routinely achieved in laboratory calibrations.

In the literature, several studies suggested the inadequacy of second- and third-order polynomial models as well as the CVD function to describe the IPRT behavior [3]. Hasheiman and Petersen [4] pointed out that polynomials of sixth to eighth order provide a better approximation of ITS-90 than the CVD model for the temperature range from 0 °C to 300 °C. Zhang et al. [5] used polynomials of second to ninth order for the 0 °C to 800 °C range; they found that even fourth- and fifth-order polynomials are not appropriate for this interpolation. Kaiser [6] suggested that the set of equations of the ITS-90 should be used when working in the temperature range from −50 °C to 420 °C; on the other hand, he also proposed the use of a second-order polynomial to correct the deviation from the ITS-90 found in Fig. 1. He also concluded that a model based on less than a fourth-order polynomial is unsuitable for IPRTs. Mèndez-Lango and Ramìrez-Bazàn [7] proposed the ITS-90 defining equations as the interpolation functions for IPRTs in the range from 0 °C to 420 °C, where the a and b parameters of the deviation function are estimated by means of a least-squares method. Weckstrom [8] and Andersen et al. [9] showed that good results with the ITS-90 defining equations can even be obtained with low-α IPRTs. Marcarino et al. [10] used a factorial equation combined with CVD and, without adding extra calibration points, achieved interpolation uncertainty at the level of 0.01 °C. Moiseeva [11] investigated the CVD A/B coefficients ratio and proposed a suitable correction to the coefficients.

The aim of this work was to further investigate the interpolation approach based on the ITS-90 deviation functions in the temperature range from −196 °C to 420 °C, in order to provide experimental support to the necessary changes to the IEC 60751 standard. In the reported investigation, 20 IPRTs with $W(100) = R_{100}/R_0$ ranging from 1.385 to 1.392 (or equivalently, α from 0.00385 °C^{-1} to 0.00392 °C^{-1}) were calibrated by comparison against a standard PRT, and different interpolation schemes, based on ITS-90 equations with different degrees of freedom, were fitted to the experimental data.

2 IPRT Characteristics and Experimental Procedure

In IPRT applications, the choice of the calibration scheme is often dictated by a trade-off between the required measurement accuracy and cost factors. A better approximation of the IPRT response can easily be obtained by increasing the number of points in the calibration range, but this makes the calibration more expensive. Bearing in mind these constraints, the rationale of the work was the following:

- the number of calibration points of any new interpolation function should be lower than, or equal to, the number of points used with the CVD equation;
- any new function should minimize the impact on industrial applications by avoiding any change in the software routines that run in field instruments or any specific training of the personnel;
- such functions should be easily applied to any industrial calibration laboratory that performs either comparison calibration or fixed-point calibration.

A set of 20 IPRTs were studied in the temperature range from 0 °C to 420 °C and, successively, a subset of 7 IPRTs were also studied from −196 °C to 0 °C. The IPRTs were selected with platinum wires of different grade (α equal to 0.00385 °C^{-1} and 0.00392 °C^{-1}) and of different stem sizes and materials (see Table 1). Partially supported sensing elements with nominal $R(0\,°\mathrm{C}) = 100\ \Omega$ were chosen.

Before starting the measurement run, the assembled IPRT probes were submitted to the following heat treatment in order to minimize the sensor hysteresis:

Table 1 Summary of the IPRTs used in this work

ID	α (°C^{-1})	Stem o. d. (mm)	Stem length (mm)	Sheath material
A1	0.00392	8	440	Stainless steel
A2	0.00392	8	440	Stainless steel
A3	0.00392	8	440	Stainless steel
A4	0.00392	8	440	Stainless steel
B1	0.00385	7	600	Stainless steel
B2	0.00385	7	600	Stainless steel
C1	0.00385	3	420	Stainless steel
C2	0.00385	6	420	Stainless steel
D1	0.00385	7	450	Silica
D2	0.00385	7	450	Silica
D3	0.00385	7	450	Silica
D4	0.00385	7	450	Silica
D5	0.00385	7	450	Silica
D6	0.00385	7	450	Silica
E1	0.00385	7	450	Silica
E2	0.00385	7	450	Silica
E3	0.00385	7	450	Silica
E4	0.00385	7	450	Silica
E5	0.00385	7	450	Silica
E6	0.00385	7	450	Silica

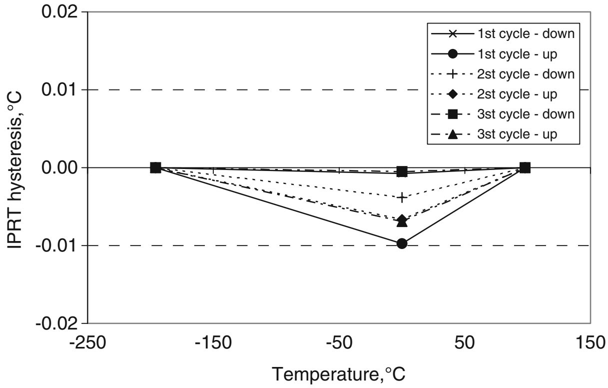

Fig. 2 Annealing treatment and hysteresis cycle for the IPRT identified as A1

Table 2 Temperature baths used in comparison calibration and their associated measurement uncertainty $U(k = 2)$ in the given temperature range

Temperature range	Bath type	$U(k = 2)$(°C)
−196 °C	LN_2 Boiling point	0.010
(−90 to 0) °C	Ethanol bath	0.010
0 °C	Ice point	0.005
(0–99) °C	Water bath	0.005
(100–250) °C	Silicon oil bath	0.010
(250–450) °C	Salt bath	0.025

– first, they were annealed for 12 h at 450 °C. Then their resistance at 0 °C (R_0) was checked before and after another 1-h exposure at 450 °C. If the R_0 reading changed more than 0.01 °C, the procedure was repeated;
– second, they were cycled between 100 °C and about −196 °C (LN_2 boiling point) thrice, each time checking that the R_0 maximum change was within 0.01 °C. A typical example of the patterns found for the hysteresis check of the IPRTs is shown in Fig. 2.

All thermometers were then calibrated in the temperature range from 0 °C to 420 °C by comparison against an SPRT calibrated at the fixed points of the ITS-90. Ten calibration temperatures, distributed over the whole range, were selected, i.e., (0, 30, 60, 100, 150, 220, 270, 320, 370, and 420) °C. Seven thermometers were also calibrated below 0 °C at the following temperatures: (−40, −80, and 196) °C. The comparison calibration always started from the highest temperature. A summary of the expanded measurement uncertainties, $U(k=2)$, and thermal bath equipment, for each calibration range, is reported in Table 2.

The following interpolation schemes were analyzed and compared in terms of interpolation errors and fitting residuals in the temperature range above 0 °C:

1. *CVD scheme*: This used Eq. 1 with five calibration points selected among the listed temperatures. The data pairs were used to estimate R_0, A, and B by means of an ordinary least-squares (OLS) fitting (degrees of freedom, $\nu = 2$). Five additional calibration temperatures were used to independently assess the goodness of the model in the intervening temperature ranges.

2. *DW5p scheme*: This used the deviation function $\Delta W(T_{90})$ of the ITS-90 as shown in Eq. 2 with five calibration temperatures. The same data pairs as used for the CVD scheme were used to estimate a and b by means of an OLS fitting ($\nu = 2$). Again, five intermediate calibration temperatures were used to assess the goodness of the model in the intervening temperature ranges.

$$\Delta W(T_{90}) = W(T_{90}) - W_r(T_{90}) = a\,[W(T_{90}) - 1] + b\,[W(T_{90}) - 1]^2\,. \quad (2)$$

3. *DW3p scheme*: This used the deviation function $\Delta W(T_{90})$ of the ITS-90 in Eq. 2 with three calibration temperatures. The data pairs were used to calculate a and b (i.e., $\nu = 0$). Seven intermediate calibration temperatures were used to assess the model in the intervening temperature ranges.
   For the subset of IPRTs also calibrated below 0 °C, the following interpolation schemes were investigated:
4. *CVD scheme*: The coefficient C of Eq. 1 was calculated at the lowest calibration temperature (−196 °C) while A, B, and R_0 came from the OLS estimation obtained from CVD scheme 1. The calibrations at −40 °C and −80 °C were used to assess the model in the intervening temperature range.
5. *DW5p scheme*: This used the deviation function $\Delta W(T_{90})$ of the ITS-90 as shown in Eq. 3 with three calibration temperatures to estimate a and b by means of an OLS fitting ($\nu = 1$).

$$\begin{aligned}\Delta W(T_{90}) &= W(T_{90}) - W_r(T_{90}) \\ &= a\,[W(T_{90}) - 1] + b\,[W(T_{90}) - 1]\ln W(T_{90}). \end{aligned} \quad (3)$$

6. *DW3p scheme*: This used the deviation function $\Delta W(T_{90})$ of the ITS-90 in Eq. 3 with two calibration temperatures (−80 °C and −196 °C) to calculate a and b($\nu = 0$). The calibration data at −40 °C were used as a check point of the model.

3 Experimental Results

3.1 Temperature Range from 0 °C to 420 °C

A comparison among the interpolation schemes 1–3 above 0 °C is shown in Fig. 3 for a single IPRT. The fitting residuals are defined as the difference between the ITS-90 reference temperature and the corresponding temperature calculated by the interpolation function given by either Eq. 1 or 2. The fitting residuals from each function are connected by a solid line for clarity. The symbols that are not connected by a line represent the deviation error obtained at the intermediate calibration temperatures from each interpolation scheme. From Fig. 3, the impact of each interpolation scheme on the fitting error is clearly shown.

A quantitative assessment of the performance of the interpolation schemes can also be carried out by comparing for each function, e.g., the maximum deviation error and the standard error of the estimate (SEE), as defined in Eq. 4:

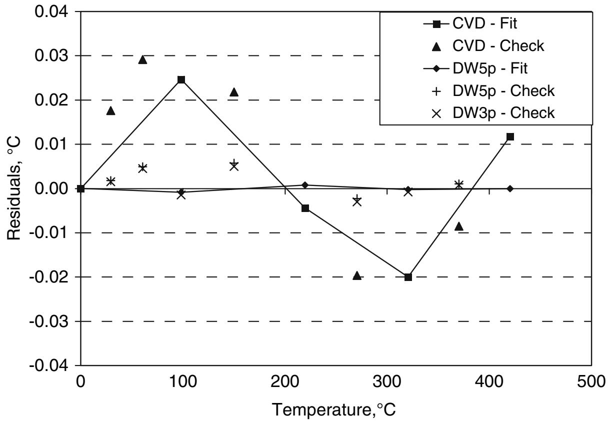

Fig. 3 Fitting residuals for a single IPRT as obtained by the CVD, the DW5p, and DW3p interpolation schemes in the temperature range from 0 °C to 420 °C (see text)

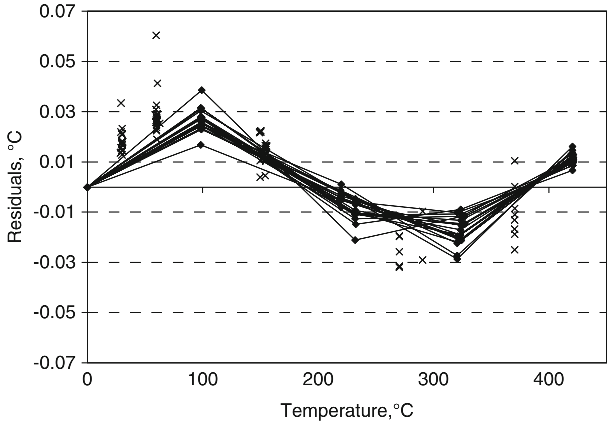

Fig. 4 Residuals of the CVD scheme (ν = 2) given by Eq. 1. Solid lines connect the data points used by the OLS adjustment; cross symbols represent the deviation error at the intermediate check temperatures (♦ = fit points, × = check points)

$$\sigma = \sqrt{\frac{1}{\nu}\sum_{j=1}^{m}\left(r_j\right)^2}, \qquad (4)$$

where r_j is the fitting residual at the jth point and ν is the number of degrees of freedom.

The results of the investigation are presented in Figs. 4–6. Each graph collects the residuals obtained from a single interpolation scheme for all IPRTs.

1. *CVD scheme*: Figure 4 shows the residuals for the CVD fitting; they range from −0.029 °C to 0.039 °C. At intermediate temperatures (check points), the residuals were between −0.015 °C and 0.020 °C.

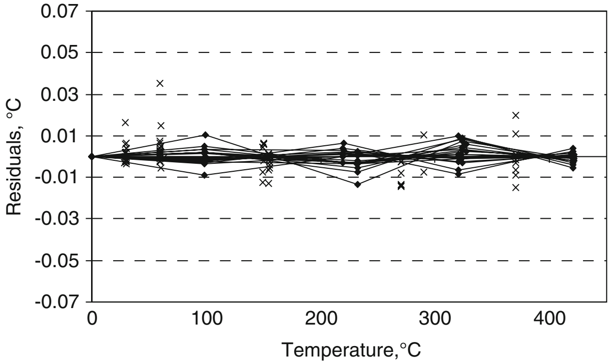

Fig. 5 Residuals of the DW5p scheme (ν = 2); the deviation function given by Eq. 2 was fitted to the experimental points (♦ = fit points, × = check points)

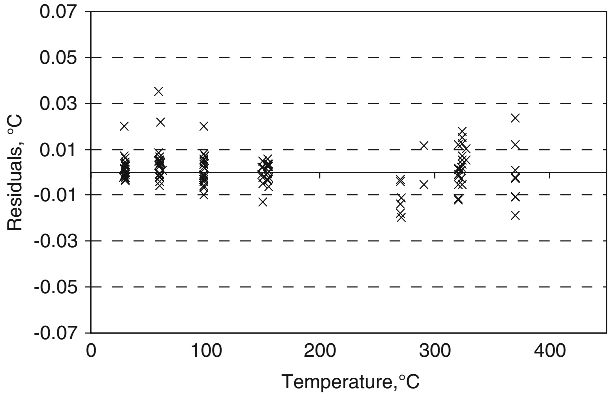

Fig. 6 Interpolation errors of the DW3p scheme (ν = 0) given by Eq. 2; the coefficients of the deviation function given by Eq. 2 were calculated at three temperatures (near the TPW, the FPSn, and the FPZn) (× = check points)

2. *DW5p scheme*: Figure 5 shows the residuals as found by a deviation function $\Delta W(T_{90})$ fitted to five calibration points. They range from −0.013 °C to 0.011 °C. At the intermediate check temperatures, the deviation error was between −0.015 °C and 0.020 °C. In order to get a relative performance index, the ratio of the SEE in Eq. 4 of CVD to DW5p was calculated for every thermometer; it was always found to be greater than 1, and ranged from about 2–29. Also, the ratio between the maximum deviation error of CVD and DW5p was always greater than 1 (about 1.5–27). Use of the deviation function given by Eq. 2 gave a better approximation of the ITS-90 than the CVD Eq. 1 for all investigated IPRTs.
3. *DW3p scheme*: Figure 6 shows the results when the coefficients a and b were calculated at three calibration temperatures chosen near, but not exactly at, the triple point of water and the freezing points of tin and zinc. At the intermediate check temperatures, the deviation error was between −0.020 °C and 0.035 °C.

The relative performance indices, defined above, were in the range from 1.2 to 2. Thus, the DW3p scheme was slightly better than the CVD scheme.

3.2 Temperature Range from −196 °C to 0 °C

For the IPRT subset calibrated below 0 °C, Figs. 7–10 present the results of the investigation. All these figures show the results for the whole temperature range from −196 °C to 420 °C. Figure 7 compares interpolation schemes 4–6 for a single IPRT; the impact of each interpolation scheme on the fitting error is clearly shown. The graphs in Figs. 8–10 collect the residuals obtained from a single interpolation scheme for all IPRTs.

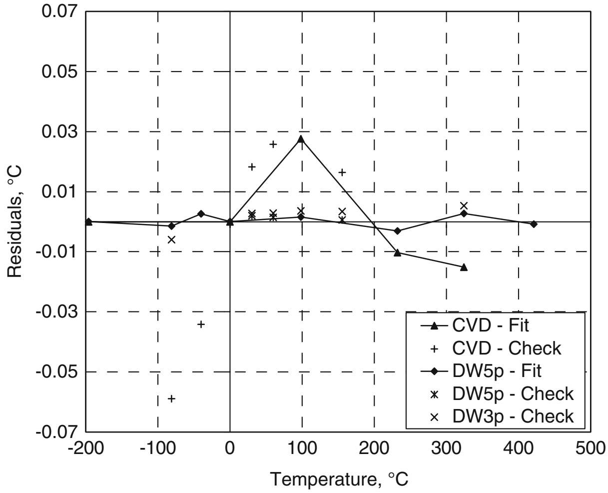

Fig. 7 Fitting residuals for a single IPRT as obtained by the CVD, the DW5p, and DW3p interpolation schemes in the whole temperature range from −196 °C to 420 °C (see text)

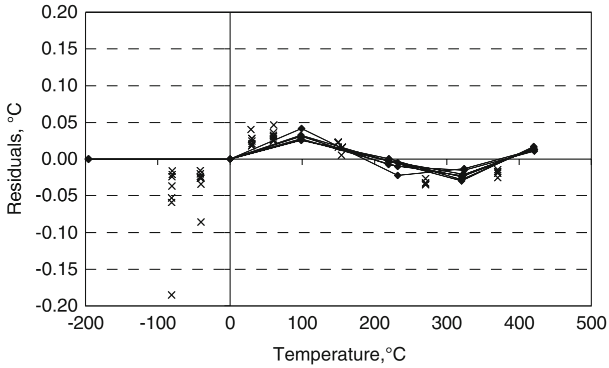

Fig. 8 Residuals of the CVD scheme given by Eq. 1. Below 0 °C, the cross symbols show the deviation error at the check temperatures when the parameter C was calculated at −196 °C (♦ = fit points, × = check points)

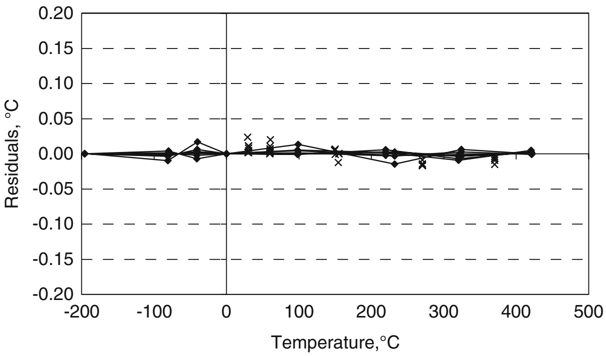

Fig. 9 Residuals of the DW5p scheme in the whole temperature range (ν = 1 below 0 °C and ν = 2 above 0 °C) (♦ = fit points, × = check points)

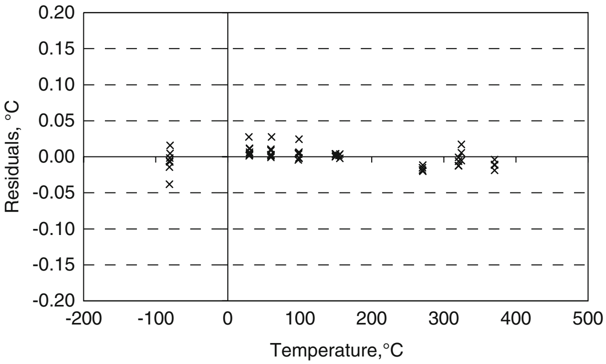

Fig. 10 Interpolation errors of the DW3p scheme (ν = 0) given by Eq. 3. The cross symbols show the deviation error at the intermediate check temperatures (× = check points)

4. *CVD scheme*: Figure 8 shows the deviation error at the intermediate check temperatures when the parameter C is calculated at the lowest temperature (ca. −196 °C). The deviation error is of the same order of magnitude as the theoretical fitting residuals showed in Fig. 1, i.e., up to 0.2 °C.
5. *DW5p scheme*: Figure 9 shows the residuals as found using a deviation function $\Delta W(T_{90})$ fitted to four calibration points in the range from −196 °C to 0 °C. The residuals are lower than 0.03 °C throughout the range.
6. *DW3p scheme*: Figure 10 shows the results when the coefficients a and b were calculated at three calibration temperatures chosen near, but not exactly at, the triple points of water, mercury, and argon. The calibration temperature at −80 °C was chosen as a check point. The results show a deviation from the interpolation curve lower than 0.04 °C for all IPRTs.

4 Discussion

A systematic deviation between the ITS-90 and the CVD interpolation curve is clearly evident. For precision temperature measurements, several studies have shown that this limitation can be overcome with suitable polynomial functions. Along this line, an investigation was carried out in the temperature range from −196 °C to about 420 °C by using the deviation function defined by the ITS-90 in the sub-ranges from the triple point of water to the zinc freezing point and from the triple point of water to the triple point of argon.

In the perspective of industrial applications, where a trade-off between performance and cost is often of great importance, two different approaches were followed and then assessed against 20 IPRT calibrations. First, the ITS-90 deviation functions (DW5p scheme) were fitted to the same data set used in the CVD scheme. A comparison between the fitting residuals showed that the DW5p scheme performs better than the CVD scheme by a factor of about 2–29. Second, the deviation functions were used to analytically calculate the function coefficients (DW3p scheme). In this way, only three calibration temperatures were necessary. A comparison between this approach and the CVD equation showed similar performance. However, the advantage of the DW3p interpolation scheme is that industrial users can get the same accuracy as obtained by CVD interpolation at reduced calibration costs.

The experimental results support changes to the IEC 60751 standard and suggest that any interpolation approach based on the ITS-90 equations can improve the measurement accuracy, at least in the temperature range from −196 °C to 420 °C.

References

1. H. Preston-Thomas, Metrologia **27**, 3 (1990)
2. International Electrotechnical Commission, IEC 60751-am.2 (ed. 1.0) - Industrial platinum resistance thermometer sensors (1995)
3. J.F. Dubbeldam, M.J. de Groot, Interpolation equations and uncertainties of industrial PRTs. EUROMET TC-T Workshop (Paris, France, 1998)
4. H.M. Hasheiman, K.M. Petersen, in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6, ed. by J.F. Schooley (AIP, New York, 1992), pp. 427–432
5. J. Zhang, K. Fan, S. Wu, Q. Yao, in *Temperature: Its Measurement and Control in Science and Industry*, vol. 6, ed. by J.F. Schooley (AIP, New York, 1992), pp. 433–438
6. N.E. Kaiser, in *Proceedings of TEMPMEKO '99, 7th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by J. F. Dubbeldam, M.J. de Groot (Edauw Johannissen bv, Delft, 1999), pp. 365–370
7. E. Mèndez-Lango, R. Ramìrez-Bazàn, in *Proceedings of TEMPMEKO 2001, 8th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by B. Fellmuth, J. Seidel, G. Scholz (VDE Verlag, Berlin, 2002), pp. 647–651
8. T. Weckstrom, in *Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by D. Zvizdić (FSB/LPM, Zagreb, Croatia, 2004), pp. 813–816
9. F. Andersen, T. Hansen, H. Harslund, in *Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by D. Zvizdić (FSB/LPM, Zagreb, Croatia, 2004), pp. 1211–1216
10. P. Marcarino, P.P.M. Steur, G. Bongiovanni, B. Cavigioli, in *Proceedings of TEMPMEKO 2001, 8th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by B. Fellmuth, J. Seidel, G. Scholz (VDE Verlag, Berlin, 2002), pp. 85–90
11. N.P. Moiseeva, in *Temperature: Its Measurement and Control in Science and Industry*, vol. 7, Part 1, ed. by D.C. Ripple (AIP, New York, 2003), pp. 377–382