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$T - T_{90}$ for Radiation Thermometry Realization Above the Copper Point

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Abstract

The differences, $T - T_{90}$, between thermodynamic temperature, T, and temperature, T_{90}, on the International Temperature Scale of 1990 (ITS-90) above the Cu fixed-point temperature, 1357.77 K, were investigated using relative primary radiometric thermometry. The Ag and Cu fixed points were used as reference points for temperature realization by the ITS-90 ($n = 1$) scheme. The values of $T - T_{90}$ for the Ag and Cu fixed points have been previously determined as 46.2 mK and 52.1 mK, respectively. Extrapolating these differences based on the sensitivity coefficient used to propagate the uncertainty in the fixed-point temperature to other temperatures results in values of $T - T_{90}$ of 325 mK or 303 mK at 3000 °C when using the Ag or Cu point $T - T_{90}$ difference, respectively. These values were confirmed by realizing $n = 1$ temperature scales using either the thermodynamic values or the ITS-90 values of these fixed points as the reference temperatures and comparing the differences on the two scales. Measurements at the Co–C eutectic point indicated the consistency of thermodynamic temperature realization using the $n = 1$ scheme, and also demonstrated the equivalence of absolute and relative radiometric thermometry.

Keywords International Temperature Scale of 1990 (ITS-90) · Radiometric thermometry · Thermodynamic temperature

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1 Introduction

On 20 May 2019, the International System of Units, the SI, was redefined. The four units of the kilogram, ampere, kelvin, and mole are now based on exact values of four fundamental constants. The kelvin is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit $J{\cdot}K^{-1}$, which is equal to $kg{\cdot}m^2{\cdot}s^{-2}{\cdot}K^{-1}$, where the kilogram, meter, and second are defined in terms of the Planck constant, h, the speed of light in vacuum, c, and the unperturbed ground state hyperfine transition frequency of the caesium 133 atom, $\Delta\nu_{Cs}$, respectively [1]. The SI Brochure was revised to the 9th edition [2], and contains in Appendix 2 the *mise en pratique* for the definition of the kelvin [3], prepared by the Consultative Committee for Thermometry (CCT). For realization of the kelvin, primary thermometry methods based on a well-understood physical system, for which an equation of state describing the relationship between thermodynamic temperature, T, and other independent quantities, shall be used. At high temperature, one such method can be implemented using either absolute primary radiation thermometry, where there is no requirement to measure any reference point ($n=0$, where n is the number of fixed points, FPs), or relative primary radiation thermometry, where at least one FP ($n \geq 1$) must be utilized.

To overcome difficulties associated with thermodynamic temperature measurement, a practical temperature scale was established and is used worldwide, the latest version of which is called the International Temperature Scale of 1990 (ITS-90). While ITS-90 satisfies the needs of most users, the differences between thermodynamic temperature and ITS-90 are of concern at high temperature, especially for users who are interested in the measurement of thermal properties of materials. The temperature differences, $T - T_{90}$, have been previously determined by the CCT [4] for a range of temperatures and fixed points up to the Cu point (1357.77 K). The values of $T - T_{90}$ above the Ag FP (1234.93 K), for example, are (46.2 ± 14) mK, (39.9 ± 20) mK, and (52.1 ± 20) mK with a coverage factor of $k=1$ for the Ag, Au, and Cu FPs, respectively [4], and for temperatures from the triple point of water (273.16 K) to the Cu FP, the CCT recommends the following relationship for estimating $T - T_{90}$:

$$\left(T - T_{90}\right)/\mathrm{mK} = \left(T_{90}/\mathrm{K}\right) \sum_{i=0}^{4} c_i \times \left(273.16\mathrm{K}/T_{90}\right)^{2i}, \tag{1}$$

where $c_0 = 0.0497$, $c_1 = -0.3032$, $c_2 = 1.0254$, $c_3 = -1.2895$, and $c_4 = 0.5176$.

While Eq. 1 is only valid up to the Cu FP, the sensitivity coefficient used with radiation thermometry to propagate the uncertainty on ITS-90 in the fixed-point temperature of either Ag, Au, or Cu to higher temperature can be used to give an estimate of the $T - T_{90}$ differences at higher temperature based on the known differences at the fixed points [5]. This is investigated in this work. The $n=1$ method of relative primary radiometric thermometry was used to confirm these higher temperature differences. The values of $T - T_{90}$ were determined by comparison between the thermodynamic and ITS-90 scales when temperatures were realized using the same FP, but with either thermodynamic or ITS-90 temperatures assigned to the FPs. The predicted $T - T_{90}$ difference at the Co–C eutectic point (~1597 K) was also compared with direct measurements of this FP.

2 Temperature Scale Realization by Relative Primary Radiometric Thermometry

A common method used to calibrate radiation thermometers is relative radiometric thermometry, in which a radiation thermometer's signal is measured at one or more FPs. This method is considerably less complex and less time consuming than the more fundamental absolute radiometric thermometry [6]. For ITS-90 realization, T_{90} above the Ag FP is determined from the relationship

$$\frac{L_b\left(\lambda, T_{90}\right)}{L_b\left(\lambda, T_{90}(X)\right)} = \frac{e^{\frac{c_2}{\lambda T_{90}(X)}} - 1}{e^{\frac{c_2}{\lambda T_{90}}} - 1}, \quad (2)$$

where T_{90}(X) is the temperature of either the Ag (1234.93 K), the Au (1337.33 K), or the Cu (1357.77 K) FP, $L_b\left(\lambda, T_{90}(X)\right)$ and $L_b\left(\lambda, T_{90}\right)$ are the spectral radiances of a blackbody at wavelength (in vacuo) λ at temperatures T_{90}(X) and T_{90}, respectively, and c_2 is the second radiation constant (0.014 388 m·K) [7]. This technique is the so-called $n = 1$ scheme, since it relies on the measurement of just one fixed point.

For the $n = 1$ scheme, the ratio on the left-hand side of Eq. 2 is inferred from the ratio of the signals, $S(T)$, of a radiation thermometer; e.g.:

$$S(T) = a \int L_b(\lambda, T)R(\lambda)d\lambda, \quad (3)$$

where a is a constant, $R(\lambda)$ is the thermometer's relative spectral responsivity, and $L_b(\lambda, T)$ is Planck's law for the spectral radiance of a blackbody at temperature T and wavelength λ. First, the measurement of the relative spectral responsivity of a radiation thermometer is carried out. Then, the thermometer signal is measured at the fixed-point temperature of either Ag, Au, or Cu. The relationship between signal and temperature of the FP and the details of the relative spectral responsivity are used to determine the constant a in Eq. 3. Finally, the thermometer signal at the unknown temperature is measured and Eq. 3 is solved to determine the temperature.

3 Measurements

The temperature differences between thermodynamic temperature and temperature T_{90} were investigated by comparing temperature scales realized by either the Ag or Cu FPs, with thermodynamic temperatures assigned to the FPs as determined by the $T - T_{90}$ relationship provided by the CCT [4], with those using FP temperatures as assigned by ITS-90. For these measurements, a Chino radiation thermometer, model IR-RST-65H, with a 650 nm center wavelength and FWHM of 12 nm was used. The relative spectral responsivity of the thermometer was measured using a double-grating monochromator. Measurements were made in the range 400 nm to 1200 nm with wavelength steps of

10 nm, 1 nm, and 0.1 nm depending on the value of the relative spectral responsivity (i.e., the steps were shorter in regions where the spectral responsivity is higher). The thermometer was then calibrated at the Ag and Cu FPs. The measurement data at each FP, in conjunction with measurements of the relative spectral responsivity, were used to determine the constant a in Eq. 3, where either T or T_{90} was used for the FP temperatures. In other words, there were four values of the constant a, allowing T to be realized from either the Ag or Cu FPs and T_{90} to be realized from either the Ag or Cu FPs. The measurements were carried out at National Institute of Metrology (Thailand). More details of the measurement and uncertainty analysis can be found in Ref. [8].

4 Results and Discussion

Figure 1 illustrates the results of $T-T_{90}$ in the range from the Ag FP temperature to 3000 °C realized using either the Ag or Cu FP. The dashed lines give the relationship derived from the sensitivity coefficient [5]:

$$\frac{\partial T_{90}}{\partial T_{\mathrm{ref}}} = -\frac{\frac{\partial S}{\partial T_{\mathrm{ref}}}}{\frac{\partial S}{\partial T_{90}}} \approx \frac{T_{90}^2}{T_{\mathrm{ref}}^2}, \tag{4}$$

where T_{ref} is the temperature of the reference FP used for the realization, and the solid symbols give the values derived from the calibration of the radiation thermometer at the corresponding FP. The uncertainties, $u_{\mathrm{ref}}\left(T-T_{90}\right)$, in $T-T_{90}$ at the FP temperatures were propagated, also using the sensitivity coefficient of Eq. 4, to the uncertainties, $u_T\left(T-T_{90}\right)$, in $T-T_{90}$, as indicated by the error bars:

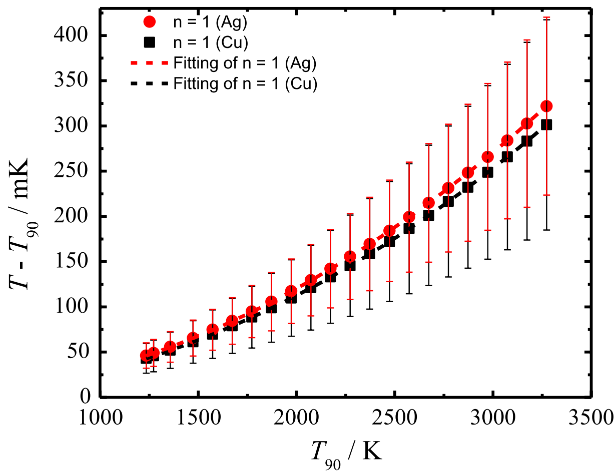

Fig. 1 $T-T_{90}$ realized using the $n=1$ scheme based on the Ag and Cu FPs. The uncertainties indicated are only due to the contribution of the $T-T_{90}$ uncertainty at the reference fixed point. The dashed lines show the results obtained using the simple sensitivity coefficient of Eq. 4

$$u_T(T - T_{90}) \approx \frac{T_{90}^2}{T_{ref}^2} u_{ref}(T - T_{90}), \tag{5}$$

where $u_{ref}(T - T_{90})$ is 14 mK or 20 mK (k=1) for the Ag and Cu FPs, respectively, as given by the CCT [4].

The results indicate that $T-T_{90}$ rises up to 322 mK and 301 mK at 3000 °C when T_{90} is realized using the Ag and Cu FPs, respectively. The values of $T-T_{90}$ at 3000 °C given directly by multiplying Eq. 4 by $T-T_{90}$ are 325 mK and 303 mK for the Ag and Cu FPs, respectively, in excellent agreement with the experimental results.

The experimental results were fitted with a second-order polynomial function of the same form as the sensitivity coefficient of Eq. 4, as shown by the dash lines in Fig. 1. The fitting results are indicated by Eqs. 6 and 7 for realization using the Ag and Cu FPs, respectively:

$$(T - T_{90})/\text{mK} = 3.01 \times 10^{-5} \cdot T_{90}^2, \tag{6}$$

$$(T - T_{90})/\text{mK} = 2.81 \times 10^{-5} \cdot T_{90}^2. \tag{7}$$

The residuals of the fit are lower than 0.4 mK. The results clearly indicate that $T-T_{90}$ realized using the Ag or Cu FPs as the reference are not the same. Therefore, users who wish to convert calibration results from T_{90} to T would need to know which FP was used for the realization of T_{90}. Then the functions for $T-T_{90}$ provided by Eqs. 6 and 7 would be suitable for the conversion.

The Co–C FP maintained by the National Institute of Metrology (NIM), China, was used to compare T_{90} with the thermodynamic temperature assigned to the point of inflection of the melting curve by absolute radiometric thermometry, i.e., T=1597.39 K ± 0.13 K (k=2) [9]. For this measurement, a KE-Technologie 650 nm radiation thermometer, model LP 4, with FWHM of 13 nm was used. The value of T_{90} for the Co–C FP was determined by the n=1 scheme with the Ag FP used as the reference point prior to this study by NIM as T_{90}=1597.18 K. Equation 6 was used to convert this temperature to T, resulting in a value of $T-T_{90}$=77 mK. Therefore, the thermodynamic temperature of the Co–C FP determined by the n=1 scheme, extrapolated from the thermodynamic temperature of the Ag FP, is 1597.26 K. This is consistent with the thermodynamic temperature determined by absolute radiometric thermometry within the uncertainty of the absolute radiometric thermometry assignment.

5 Conclusion

Values of $T-T_{90}$ for temperatures above the Cu FP were determined using relative radiometric thermometry based on published $T-T_{90}$ differences at the Ag and Cu FPs. The values of $T-T_{90}$ at 3000 °C were 322 mK and 301 mK for realization using the Ag and Cu FPs, respectively. These values are consistent with the result obtained by extrapolating the differences at the FPs using the simple sensitivity coefficient of Eq. 4. Functions for determining $T-T_{90}$ are provided by fitting the measurement results with a second-order polynomial function. The results of $T-T_{90}$ determined by relative radiometric thermometry were compared to the thermodynamic temperature of the Co–C FP realized by absolute radiometric thermometry. The results indicate the equivalence of thermodynamic temperature determined by both methods. It should be noted that even if $T-T_{90}$ at the reference FPs changes with future improvements in their thermodynamic measurement, the concept of the $T-T_{90}$ determination is still the same and the techniques used in this work can be applied.

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