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Approximating the ITS-90 between Zinc and Copper with an Infrared Thermometer at NIS-Egypt

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Abstract This paper presents an approximation to the International Temperature Scale of 1990 (ITS-90) between the Zn (420 °C) and Cu (1085 °C) fixed points using a 900 nm narrow-band radiation thermometer. This thermometer has a 400 mm working distance and a 150 mm objective focal length. An image of the measured target is focused by the objective lens onto a 1 mm aperture (drilled mirror). The light passing through the aperture is conveyed by a condenser lens through an interference filter with a nominal central wavelength of 900 nm and a half-bandwidth of 10 nm before reaching a silicon photodiode working in the photovoltaic mode. The thermometer was calibrated at the Zn, Al, Ag, and Cu blackbody fixed points. The results of the calibration were used to determine the constants A, B, and C of the Sakuma-Hattori interpolation equation. The results showed that the ITS-90 can be approximated within ±0.051 °C throughout the Zn-Cu interval when the thermometer is calibrated at the Zn, Al, Ag, and Cu fixed points.

Keywords Blackbody fixed point · ITS-90 · Sakuma-Hattori equation

1 Introduction

At temperatures above the freezing point of silver (961.78 °C), the International Temperature Scale of 1990 (ITS-90) is realized according to the equation:

$$\frac{L_{90}(x)}{L_\mathrm{t}} = \frac{\exp\left(c_2/\lambda T_\mathrm{t}\right) - 1}{\exp\left[c_2/\lambda T_{90}(x)\right] - 1} \tag{1}$$

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where $T_{90}(x)$ is the radiance temperature of the fixed-point blackbody source in kelvin; T_t is the radiance temperature of the test source in kelvin; $L_{90}(x)$ is the radiance intensity from the fixed-point blackbody, L_t is the radiance intensity from the test source; λ is the wavelength at which the comparison is made; c_2 is the second radiation constant 0.014388 mK; and (x) is the silver, gold, or copper fixed point.

Realization of the ITS-90 according to its definition is not always technically or economically advantageous [1]. This was acknowledged by the Consultative Committee for Thermometry (CCT) with publication of the document "Techniques for Approximating the ITS-90" by its Working Group 2 in 1990. A technique relying upon fixed-point calibrations of infrared thermometers in the temperature region between the zinc and copper fixed points is particularly advantageous.

Below the freezing point of silver, infrared thermometers are usually calibrated against platinum resistance thermometers or thermocouples using blackbody cavities as transfer sources. The difficulty with this approach is that, unless a very sophisticated blackbody and furnace apparatus is used, significant errors can arise from such factors as temperature gradients between the contact sensor and the radiating surface of the blackbody, the less than ideal emissivity of the blackbody, and the temperature non-uniformity along the cavity walls. To avoid these errors, a reference radiation thermometer can be used that has been calibrated using fixed-point blackbody sources, i.e., without comparing it to a contact thermometer [2].

The procedure for calibrating a radiation thermometer according to the ITS-90 above the silver point requires measurement of the signal level at a fixed-point temperature and the determination of both the spectral responsivity of the thermometer and the non-linearity of the detector. This procedure is complicated since very accurate measurements of responsivity and non-linearity must be made to avoid large extrapolation errors.

When using radiation thermometers at temperatures below the freezing point of silver, the above procedure is not practical since larger spectral bands are needed to compensate for the lower radiant fluxes, and this entails greater difficulty in measuring the spectral responsivity of the thermometer. An alternative and simpler approach was first devised by Sakuma and Hattori [3], and further analyzed in [4,5]. It requires a calibration at three or more fixed-point temperatures to derive the coefficients of an empirical relationship between the thermometer output and temperature. With this method, spectral responsivity and non-linearity measurements are not needed.

In the experiments described in [3,4], a set of fixed points (Al, Ag, and Cu) were used to calibrate silicon-detector thermometers. The uncertainty of the calibration of the radiation thermometer at the fixed points was $\pm 0.1\,^{\circ}\mathrm{C}$, leading to an uncertainty of $\pm 0.5\,^{\circ}\mathrm{C}$ in realizing a temperature scale with the thermometer from 600 °C to 1100 °C. Larger uncertainties were found for temperatures below 600 °C and above 1100 °C.

Recently, a precision silicon-detector thermometer was designed at NIS-Egypt, and Zn, Al, Ag, and Cu blackbody fixed points were prepared for its calibration between 420 °C and 1085 °C.

2 Description of the Instruments

2.1 Thermometer

The radiation thermometer used in the measurements is shown in Fig. 1. It has a working distance of 400 mm using an objective lens of 150 mm focal length. The objective lens focuses an image of the target onto a drilled mirror of 1 mm aperture diameter. The light passed by the aperture is conveyed by a condenser lens through an interference filter with a central wavelength of 900 nm and half-bandwidth of 10 nm before reaching a silicon photodiode. The silicon photodiode used as the detector of the thermometer is a Hamamatsu Model S2386-44 K [6], having an active area of $3.6 \times 3.6\,\text{mm}^2$. This photodiode is used in the photovoltaic mode to convert the detected radiation into an electrical current. An external current-to-voltage converter was used to convert the electrical current of the photodiode into a voltage. The temperature of the interference filter and the photodiode is controlled to better than 0.1 °C by means of a temperature controller. The analog output from the current-to-voltage converter is measured by a digital voltmeter [7].

2.2 Fixed-Point Blackbodies and Furnaces

A three-zone tube furnace was used to contain the high-purity graphite crucible filled with the fixed-point metals, as shown in Fig. 2. The temperature gradient along the length of the central furnace tube was 0.1 °C as measured with an empty crucible by means of two thermocouples, to ensure adequate temperature uniformity along the fixed-point crucible to provide a long plateau. Argon gas at a flow rate of $0.2\,\text{L}\cdot\text{min}^{-1}$ was allowed to flow during the measurements to prevent oxidation of the graphite components. Also, the front of the furnace is covered by a water-cooled copper plate, except when making radiance measurements, to limit the entry of oxygen into the system.

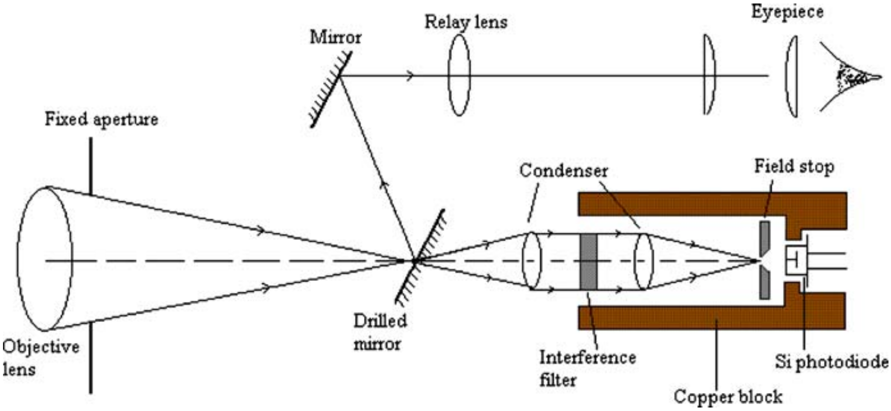

Fig. 1 Optical layout of the infrared thermometer

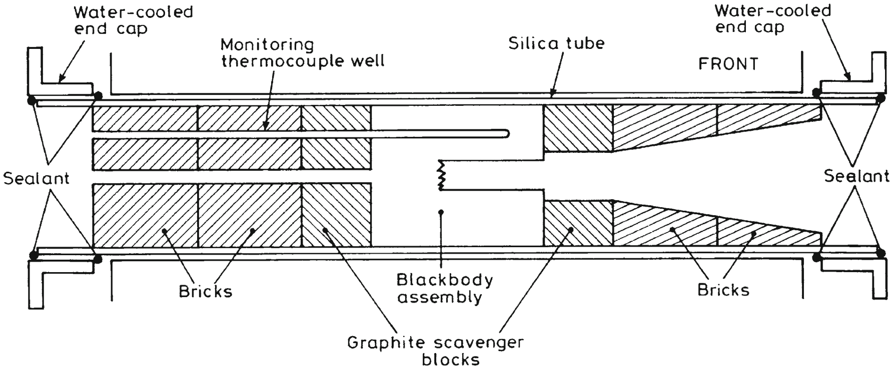

Fig. 2 Arrangement of the blackbody fixed-point furnace

The blackbodies consist of a cavity 97 mm in length with an 8 mm radius and an aperture of 1.5 mm radius [8]. The emissivity of the cavity is estimated to be 0.9999681 (assuming 0.885 as the intrinsic emissivity of the graphite).

3 Measurements and Discussion

The approximate expression adopted by Sakuma and Hattori [2] to relate the output signal of the radiation thermometer $S(T)$ to T is

$$S(T) = C \exp[-c_2/(AT + B)] \tag{2}$$

where $S(T)$ is the thermometer output signal; A, B, and C are constants; and c_2 is the second radiation constant. The factors A, B, and C are determined from measurements of $S(T)$ at three or more fixed-point temperatures.

$$\ln S(T) = \ln C - \frac{c_2}{(AT + B)}$$

or

$$T = \frac{c_2}{A\,(\ln C - \ln S(T))} - \frac{B}{A} \tag{3}$$

Taking

$$A = \frac{(ac_2)}{[(b/a) + c]}, \quad B = (bA)/a, \quad C = \exp\left(\frac{1}{a}\right)$$

Equation 3 will be

$$T = aT\ln(S) + b\ln(S) + c \tag{4}$$

Table 1 List of temperatures, thermometer signals, constants, and calculated temperatures

T (K)	Measured signal (mV)	Coefficients A, B, C	$T_{\text{calculated}}$ (K)	$\Delta T = T - T_{\text{calculated}}$ (K)
(Zn) 692.677	202.514	8.945174×10^{-7}	692.6793	−0.0023
(Al) 933.473	74083.99	5.258665×10^{-6}	933.4611	0.01190
(Ag) 1234.93	4749763.36	2.024431×10^{12}	1234.9618	−0.0318
(Cu) 1357.77	15261050.01		1357.7477	0.02230

where the constants a, b, and c can be determined by solving Eq. 4 using the measured fixed points listed in Table 1. This yields

$$a = 0.035289951, b = 0.207044034, \text{ and } c = 561.76022603$$

and A, B, and C will have the following values:

$$A = 8.94517255 \times 10^{-7}, B = 5.25866588 \times 10^{-6}, \text{ and } C = 2.02443155 \times 10^{+12}$$

Differences between the reference temperature and the calculated value are shown in Fig. 3. Figs. 4 and 5 show examples of the freezing curves of the fixed-point blackbodies measured by the radiation thermometer. The expanded uncertainties of each fixed point at a 95 % confidence level are shown in Table 2. The Zn-, Al-, Ag-, and

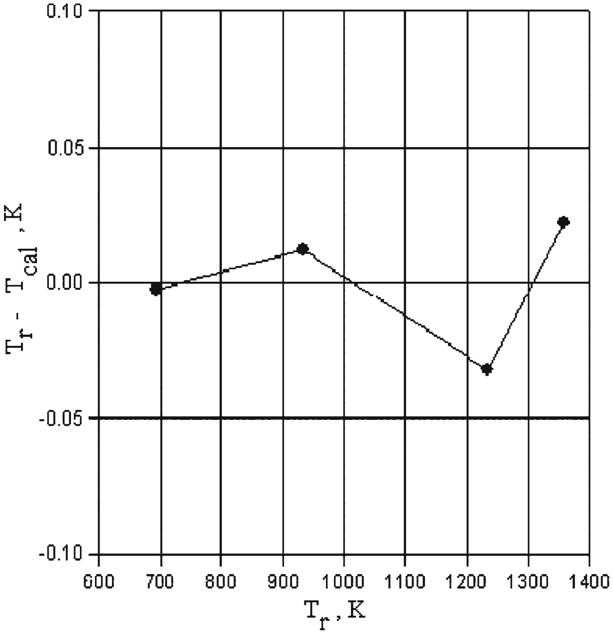

Fig. 3 Difference between the reference temperature and calculated scale

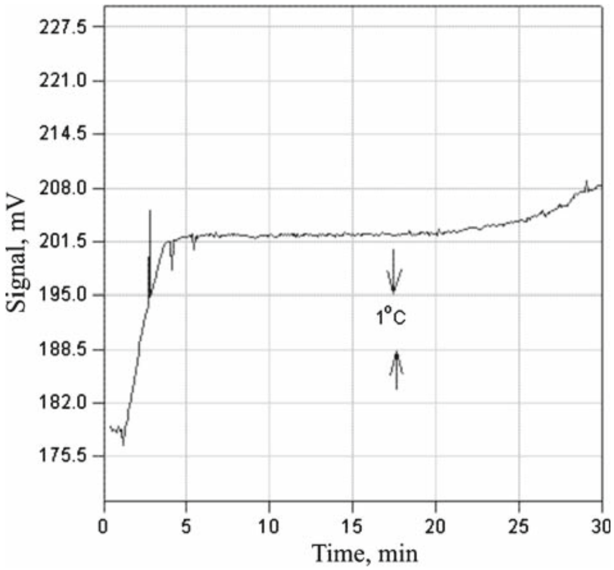

Fig. 4 Zinc freezing plateau

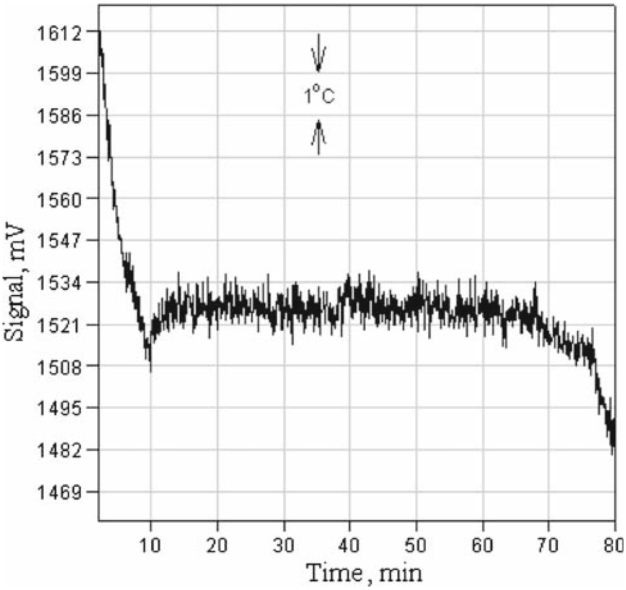

Fig. 5 Copper freezing plateau

Cu-based scale approximates the ITS-90 within an expanded uncertainty of 0.051 K at these fixed points , with a maximum temperature difference of −32 mK between the reference temperature and the calculated value at the silver point.

This approximation of the scale was selected from the different solutions of the Sakuma-Hattori equation that can be obtained from different combinations of three

Table 2 Uncertainties in the fixed-point calibration

Source of uncertainty	Uncertainty (mK)			
	Zn	Al	Ag	Cu
Impurities in the sample (Type B)	1.0	5.0	5.0	5.0
Emissivity of cavity (Type B)	0.4	0.7	1.2	1.5
Temperature drop across cavity bottom (Type B)	0.1	0.4	1.3	1.9
Size of source effect (Type B)	6.0	6.0	6.0	6.0
Random uncertainty (Type A)	6.5	8.0	11.0	13.0
Residual of the fit (Type A)	2.5	2.5	2.5	2.5
Standard combined uncertainties	9.26	11.48	13.83	15.56
Expanded uncertainty ($k = 2$)	$2\sqrt{(9.26)^2 + (11.48)^2 + (13.83)^2 + (15.56)^2} = 0.051$ K			

fixed points from the four measured fixed points, i.e., (Zn, Al, Ag), (Zn, Al, Cu), (Zn, Ag, Cu), and (Al, Ag, Cu).

4 Conclusion

An investigation has been made of a method to approximate the ITS-90 from 420 °C to 1084 °C using a narrow-band radiation thermometer with a silicon detector operating at a wavelength of 900 nm and calibrated using practical fixed-point blackbodies (Zn, Al, Ag, and Cu). This method does not require special skill for the realization and is effective in obtaining calibrated radiation thermometers. An important application of this method is the calibration of transfer standard radiation thermometers that are used as a means for accredited calibration laboratories to verify the quality of their calibrations by proficiency tests based on inter-laboratory comparisons [9].

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