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SELECTED PRESENTATION

Temperature measurements according to the International Temperature Scale of 1990 and its associated uncertainties

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Abstract The measurement of temperatures accompanies almost every determination of physical quantities or material properties. This paper gives an outline of the concept of the traceability of temperature measurements according to the International Temperature Scale of 1990 (ITS-90) and the determination of measurement uncertainties. Furthermore, differences between ITS-90 and thermodynamic temperatures are discussed.

Keywords Uncertainty · Temperature measurements · ITS-90

Introduction

Temperature measurements with low uncertainties are increasingly important for many areas of metrology. Numerous materials properties, such as density or salinity, are functions of temperature and, for a large number of properties, the temperature measurement is the largest contribution to the uncertainty budget. One of the earliest examples in metrology was the 1872 decision of the International Commission on the Metre that each prototype of the metre would be accompanied by a calibrated thermometer in order to allow the specification of the length and temperature coefficient of the prototype metre bars [1]. Some years later, thermometers accompanying prototype metres were considered as a carrier of the temperature scale for general use. Since then, the unique definition and dissemination of temperature scales is an ongoing task for metrologists.

The current definition of the unit of temperature is based on an idea of William Thomson (Lord Kelvin) published in 1848 [2]. It used absolute zero as the null point and the Celsius scale for defining the division of the scale. The modern version of the definition of the unit kelvin was established by resolutions of the General Conference of Weights and Measures (10th CGPM in 1954 and 13th CGPM in 1967/1968) according to "The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water."

But the accurate realisation of other thermodynamic temperatures requires a considerable metrological effort. In order to ensure world-wide uniformity and long-term stability of temperature measurements, so-called International Temperature Scales were developed by the Consultative Committee of Thermometry (CCT) and adopted by the CGPM. The actual is the International Temperature Scale of 1990 (ITS-90). There are two advantages of using the ITS-90 compared with thermodynamic temperatures. The first is that high-precision temperature measurements according to the ITS-90 are easier to realise compared with thermodynamic temperature measurements. Furthermore, for a considerable part of the range covered by the ITS-90, the reproducibility of temperature measurements is almost one order of magnitude better compared with thermodynamic temperature measurements.

The value of an ITS-90 temperature (T_{90}) is an approximation of the thermodynamic temperature T with a well-defined reproducibility. By CCT, a regularly updated set of T–T_{90} values and associated uncertainties will be published (Fig. 1).

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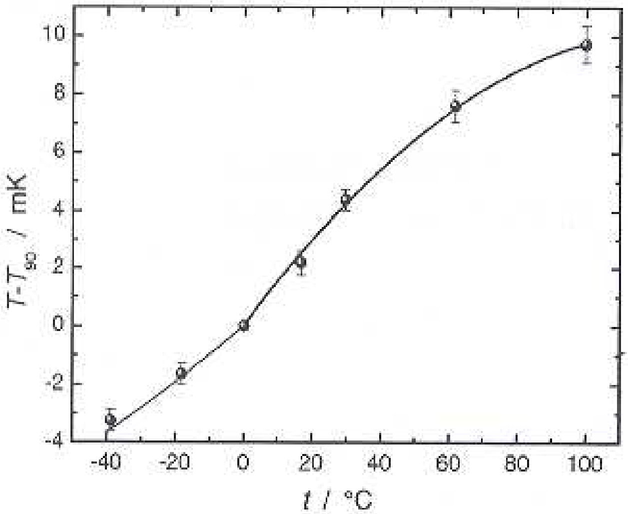

Fig. 1 Differences between thermodynamic temperatures and ITS-90 temperatures presently under consideration of the CCT. T thermodynamic temperature, T_{90} ITS-90 temperature, t Celsius temperature according to: $t/°C = T/K - 273.15$

Methods

ITS-90 is based on the thermodynamic equilibrium states of 15 pure substances, i.e. the defining fixed points of the ITS-90. Most of them are melting/freezing or triple points. At very low temperatures, T_{90} is defined in terms of the vapour–pressure/temperature relation of ^{3}He and ^{4}He. Depending on the temperature range, different instruments for the interpolation between the fixed points and for the extrapolation at temperatures above the freezing point of copper (1,084.62 °C) are defined. These include not only the method used for the interpolation but also the functional form of the interpolation. In the temperature range between the triple point of hydrogen (−259.3467 °C) and the freezing point of silver (961.78 °C), the standard platinum resistance thermometer (SPRT) is used for the interpolation. Although the SPRT is the very best interpolation instrument for this temperature range, its stability is still influenced by oxidation, impurities and thermally or mechanically induced defects in the platinum wire. As a consequence, changes of the SPRT resistance at the triple point of water between regular calibrations corresponding up to 10 mK are possible. Therefore, high-accuracy temperature measurements with SPRTs are always associated with resistance ratios W, i.e. the resistance of the SPRT at a specific temperature divided by the resistance at the triple point of water: $W = R(T)/R_0$. This procedure ensures a repeatability of SPRT measurements typically better than 0.25 mK.

For the measurements resistance, ratio bridges are used. AC-resistance ratio bridges are based on inductive voltage dividers and allow measurement uncertainties down to two parts in 10^8. The principle of DC-resistance ratio bridges is the current comparator. With DC-bridges, uncertainties of about five parts in 10^8 can be realised.

Measurement uncertainties

According to general understanding among thermometrists, temperature measurement uncertainties are related to ITS-90 and do not include contributions from deviations between ITS-90 and thermodynamic temperatures. Recently, the Working Group 3 of the Consultative Committee of Thermometry agreed on models and procedures for a more advanced determination of uncertainties in the

Table 1 Typical uncertainties of the triple point of water and the gallium (Ga) point calibrations by means of standard platinum resistance thermometers (SPRTs)

Uncertainty contribution	Triple point of water $u(x)$/μK	Ga fixed point $u(x)$/μK
Contributions related to the comparison of a pair of cells		
Repeatability for a single realisation	5	25
Reproducibility for different realisations	10	50
Reproducibility for different SPRTs	10	10
Hydrostatic head (from both cells)	6	6
SPRT self-heating (from both cells)	10	10
Thermal effects	5	10
Resistance measurement	5	5
Contributions related to the properties of the national reference		
Reproducibility	10	20
Chemical impurities	10	100
Isotopic composition	10	3
Gas pressure	5	5
Drift	10	10
Combined standard ($k = 1$) uncertainty	29	118

realisation of the SPRT subranges of the ITS-90 [3]. Currently, this method is not yet fully implemented at National Metrology Institutes because of a lack of knowledge on some of the sensitivity coefficients. Several research activities were initiated in order to achieve lower measurement uncertainties, e.g. by a better understanding of the influence of impurities on the phase-transition temperatures of ITS-90 fixed-point materials.

Table 1 shows typical state-of-the-art ITS-90 uncertainty budgets for calibrations of the triple point of water and gallium fixed-point cells by means of SPRTs. When, in the next step, the SPRT is used for the interpolation between the fixed points, i.e. as a carrier of the scale, further contributions from interpolation errors and non-uniqueness must be considered. The resulting expanded ($k = 2$) measurement uncertainty in the temperature range between the triple point of mercury (−38.8344 °C) and the melting point of gallium (29.7646 °C) amounts to about 0.5 mK.

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