Plenary Talk
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Realising the Redefined Kelvin

Graham Machin[1], M. Sadli[2], A. Peruzzi[3], J. Pearce[1], J. Engert[4], R. Gavioso[5]
[1]National Physical Laboratory (NPL), Teddington, TW11 0LW, UK
[2]LNE-CNAM, Laboratoire commun de métrologie, 93210 Saint-Denis, France
[3]VSL, Thijsseweg 11, 2629 JA Delft, Netherlands
[4]Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, DE
[5]Instituto Nazionale di Ricerca Metrologica (INRIM), 91 Strada delle Cacce, 10135, Torino, Italy
Corresponding Author's e-mail address: graham.machin@npl.co.uk

Summary:
The redefinition of the SI unit the kelvin in May 2019 has opened new possibilities for the realization, dissemination and measurement of temperature. Besides the two practical scales that were in place before the redefinition, now, through the mechanism of the *mise en pratique* for the definition of the kelvin, temperature can be realized and disseminated through primary thermometry approaches with direct traceability to the redefined kelvin. In the medium to long term practical primary thermometry approaches could be developed allowing for in-process driftless thermometry.

Keywords: kelvin redefinition, primary thermometry, temperature scales, ITS-90, PLTS-2000

Introduction

The redefinition of the kelvin resulted from co-ordinated global activity by the thermometry community [1-4]. The redefinition, in terms of a defined value of the Boltzmann constant [1], has opened new possibilities for realizing and disseminating temperature. Instead of the two defined scales, the International Temperature Scale of 1990 (ITS-90, [5]) and the Provisional Low Temperature Scale of 2000 (PLTS-2000, [6]), being the accepted means of attaining traceability, now a more flexible approach, by the *mise en pratique* for the definition of the kelvin (*MeP*-K-19) [7, 8] is possible. The *MeP*-K-19 details how to attain temperature traceability by means of primary thermometry without recourse to any defined scale.

In this paper the possibilities for temperature realization and dissemination, linked to the redefined kelvin, are discussed, mainly in the context of the European Metrology Programme for Innovation and Research (EMPIR) project "realising the redefined kelvin" (Real-K) [9].

An outlook of the impact of the kelvin redefinition on the practice of thermometry in the short, medium and longer term, including on the practice of practical thermometry, is given.

Required progress and challenges

To turn the *MeP*-K-19 into a reality requires substantial research effort. The aim of the EMPIR Real-K project is to begin this process through the following research activities:

At high temperatures >1235 K indirect primary radiometry will be used to directly link to the redefined kelvin, via known temperature high temperature fixed points (HTFPs) [2, 10]. Low uncertainty thermodynamic temperatures of Fe-C (1426 K), Pd-C (1765 K), Ru-C (2226 K) and WC-C (3020 K); will be determined. Both realisation *and* dissemination of thermodynamic temperatures >1300 K with uncertainties like the ITS-90 (U<0.05%) will be demonstrated.

At temperatures <25 K the ITS-90 is complex to establish and disseminate and hardly ever realised in practice. Primary thermometry techniques will be established for the realisation and dissemination of thermodynamic temperature from 1 K and 25 K to provide a direct link to the redefined kelvin, as well as ensuring a smooth transition to the PLTS-2000 range (i.e. <1 K).

To give time for primary thermometry techniques to become established in the intermediate temperature region (25 K - 1235 K) life extension research addressing two of the ITS-90's most pressing problems will be performed; namely reducing non-uniqueness uncertainty by 30% in calibration of platinum resistance thermometers and preparing a suitable fixed-point replacement for the mercury triple point (e.g. CO_2 or SF_6) including addressing integration of a replacement fixed point within ITS-90.

To facilitate the uptake of primary thermometry in the intermediate temperature region (>25 K) thermophysical properties of gases (e.g. He, Ne, Ar) are required over a wide range of condi-

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tions. These will be determined by *ab initio* calculations and experiment. These values will be used to reduce the attainable uncertainties by primary thermometry, which are, with a few exceptions, currently uncompetitive with the ITS-90.

These are only the first steps towards realising the redefined kelvin. Progress will be monitored closely by the CIPM Consultative Committee of Thermometry, especially its Strategy Group, to ensure on-going fitness of realisation and dissemination of the temperature unit.

Impact of the kelvin redefinition

Here the impact of the kelvin redefinition both the short to long term implications and the potential impact on the practice of thermometry in the wider user community will be discussed.

In the *short term* the current temperature scales will be used to provide temperature traceability. For those requiring thermodynamic temperature, the $T - T_{90}$ and $T - T_{2000}$ data available in the *MeP*-K-19 annexes will allow users to access thermodynamic values.

In the *medium to long* term primary thermometry, directly linked to the redefined kelvin, could supplant the defined scales for realisation and dissemination of the unit. Primary thermometry may do this when similar uncertainties can be attained to the current defined scales. These developments may by the mid-2020s, lead to the ITS-90 (>1235 K) being superseded by relative primary radiometry. On a similar timescale, for temperatures <25 K, different approaches to primary thermometry (variants of Johnson Noise <1 K, or acoustic gas or polarising gas thermometry <25 K) may provide sufficiently reliable low uncertainty thermodynamic temperatures so that the PLTS-2000 the ITS-90 (<25 K) could be superseded by low temperature primary thermometry.

For a time primary thermometry, the ITS-90, and the PLTS-2000 will co-exist. But in the long-term (2030s+) progressive elimination of the defined scales may be possible as primary thermometry for temperature realisation and dissemination becomes increasingly adopted. The ITS-90 may become the last defined temperature scale, though a restricted-range scale may be needed at intermediate temperatures (the so-called ITS-20XX [11]). Nevertheless, the redefinition of the kelvin has opened the way for improvements in thermometry that can be introduced through the *MeP*-K-19 with no disruption to the user community.

<u>*Implications for science and industry*</u>

The redefinition of the kelvin, may lead to *practical* primary thermometry. Thermometers where there is a direct link to the redefined kelvin will become available. Advances in practical Johnson Noise thermometry [12] is an early version of this. In fact if *in-situ* practical primary thermometry were to become a reality then the need to calibrate temperature sensors would ultimately be un-necessary. These new sensing methods are essential if autonomous production is to be a reality.

Summary

The kelvin redefinition has ushered in a paradigm change in the field of thermometry. Temperature realization and dissemination will increasingly be based on direct linkage to primary thermometry and in the long-term users will turn to self-calibrating practical primary thermometry to address their thermometry needs.

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