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Progress in Realising the Redefined Kelvin

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Summary:
The redefinition of the SI unit the kelvin in May 2019 opened new possibilities for the realization, dissemination and measurement of temperature. Besides the two practical temperature 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. Initial progress towards realizing the redefined kelvin will be discussed, with emphasis on temperatures >1235 K and <25 K.

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

Introduction

The redefinition of the kelvin resulted from coordinated global activity by the thermometry community [1-4]. The redefinition, in terms of a defined value of the Boltzmann constant [1], 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]. Initial results will be described, especially at high (>1235 K) and low (<25 K) temperatures. 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 link to the redefined kelvin, via high temperature fixed points (HTFPs) [2, 10]. HTFP blackbodies have been constructed for Fe-C (1426 K), Pd-C (1765 K), Ru-C (2226 K) and WC-C (3020 K) and performance assessed. In the next year low uncertainty thermodynamic temperatures will be determined, then dissemination of thermodynamic temperatures (>1235 K) with uncertainties comparable to ITS-90 (U<0.05%) will be demonstrated.

At temperatures <25 K the ITS-90 is complex to establish and disseminate. Primary thermometry techniques are being established for the realisation and dissemination of thermodynamic temperature from 1 K to 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). Progress will be by sensors (e.g., primary Johnson Noise and Coulomb Blockade thermometers) and gas-based thermometry.

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, SF_6) including its integration within ITS-90.

To facilitate primary thermometry uptake in the intermediate temperature region (>25 K) thermophysical properties of noble gases (e.g., He,

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Ne, Ar) are required over a wide range of conditions. 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 generally currently uncompetitive with the ITS-90.

These are only the first steps towards realising the redefined kelvin. Progress will be reported to the CIPM Consultative Committee of Thermometry to ensure on-going fitness of realisation and dissemination of the temperature unit.

Impact of the kelvin redefinition

The potential impact of the kelvin redefinition, in the short to the long term, on the practice of thermometry is discussed below.

In the *short term* the current temperature scales will continue to 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 will only do this when similar uncertainties to the current defined scales can be attained.

The developments described here 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 <4 K, Coulomb blockade, acoustic gas or polarising gas thermometry <25 K) may provide sufficiently reliable low uncertainty thermodynamic temperatures so that the PLTS-2000 and the ITS-90 (<25 K) are superseded.

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 possibly be the last defined temperature scale, though a future 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.

In the longer term the kelvin redefinition, may lead to the advent of *practical* primary thermometry. Advances in practical Johnson Noise thermometry [12] are an early example. As *in-situ* practical primary thermometry becomes 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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