Summary of InK2: Overview and progress report for CCT

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Overview

In the Autumn of 2018 the International Committee for Weights and Measures (the CIPM) plans to redefine the SI units in terms of fixed values of fundamental constants. The redefinition of the temperature unit, the kelvin, is being supported by the "Implementing the new kelvin" (InK) projects part funded by the EURAMET EMRP and EMPIR programmes, though both projects include participants from around the world. The InK 1 project outcomes are summarised in *Philosophical Transactions of the Royal Society A* "Towards Implementing the new kelvin" **374**, 28 March 2016. The InK 2 project has now been running for 1 year and an overview and summary of progress is given here.

Research in InK 2 is focused on delivering primary thermometry results needed to facilitate an effective unit redefinition. In particular; robust T-T_{90} and T-T_{2000} data will be determined to provide a complete thermodynamic temperature data set for the *MeP*-K-19 annex, and, in the longer term, for the potential new international temperature scale, the so called ITS-xx[1].

Objectives

The overall aim of InK 2 is to facilitate a successful transition to the new kelvin ensuring that the necessary research is completed and necessary structures (e.g. documentation) are in place. The project has following objectives:

1. To develop the facilities and methodologies for thermodynamic temperature measurements and to determine T-T90 in the range from ~ 430 K to ~ 1358 K using two different primary methods (acoustic and radiometric) and with a target standard uncertainty of 5 mK.

2. To establish a robust uncertainty budget for Refractive-Index Gas Thermometry. To determine T-T90 in the range ~5 K to ~200 K using three different methods (acoustic, refractive-index, dielectric constant) and with a target standard uncertainty of 0.5 mK.

3. To investigate three novel thermometry methods (Doppler Broadening Thermometry, Double Wavelength thermometry and Radiation Thermometry Traceable to Synchrotron Radiation). To establish novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in T-T_{90}.

4. To improve primary thermometers (pMFFT, CSNT, CBT) for the ultralow temperature thermometry regime (0.9 mK to around 1 K). To resolve the PLTS-2000 background data discrepancy (6 % at lowest temperatures) including revised T-T_{2000} data over the range 0.9 mK to 1 K (target standard uncertainty of 1 %).

5. To contribute to new or improved international standards. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain.

The InK 1 project performed measurements in the temperature regions 1 K to 0.02 K and ~80 K to ~300 K, and established thermodynamic temperatures for a selection of high temperature fixed points. That data will be combined with that of InK 2 to make a comprehensive set of T-T_{90} and T-T_{2000} for the *MeP*-K-19 annex.

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[1] The ITS-xx, if required, is likely to be introduced in the late-2020s at the earliest where the current temperature scales (the International Temperature Scale of 1990 [ITS-90] and the Provisional Low Temperature Scale of 2000 [PLTS-2000]) could be replaced by a combination of the new scale and, at the temperature extremes with practical primary thermometry.

Progress to date

The Participants are in the process of establishing experimental capabilities for the measurement phase of the project. Progress towards developing these capabilities is described below.

Development of the facilities and methodologies for thermodynamic temperature measurements and determination of T-T_{90} in the range from ~ 430 K to ~ 1358 K using two different primary methods (acoustic and radiometric) and with a target standard uncertainty of 5 mK.

The high temperture acoustic gas thermometry of both NPL and NIM is under development. In particular an air bath furnace for the 30 °C to 700 °C temperature range, along with an associated pressure vessel have been constructed. A selection of acoustic and microwave waveguides have been designed and manufactured to allow for signal injection to and extraction from the cylindrical resonator..

Primary radiometry and blackbody reference sources, both variable temperature and fixed points at lower temperatures, are in the process of being constructed. The NPL primary radiation thermometry facility, consisting of pressure controlled heat pipe system, fixed point blackbody sources and 1600 nm primary radiation thermometer (the NIRT3) is being set up. The pressure controlled potassium heat pipe (673 K to 973 K) has a stablity of ± 5 mK. The Sn, Zn and Al fixed point blackbody cells have been constructed and filled, and testing begun. The NIRT3 is being characterised at the premises of the supplier. CEM and IO/CSIC have undertaken a preliminary characterisation of two radiation thermometers at 650 nm with initial measurements of the Cu point. LNE and CNAM have constructed/ selected a set of blackbody fixed point cells, including 3 new Zn, 3 new Al and 3 Ag cells. The temperature uniformity of the fixed point furnaces has been optimised to improve the plateaux. In addition a new measurement facility devoted to medium temperatures (300 °C to 1200 °C) along with new furnaces and a1600 nm radiation thermometer have been established. A provisional determination of the thermodynamic temperature to the Al fixed point has been carried out at LNE and CNAM, by extrapolation from the Cu fixed point at 1260 nm, 1470 nm and 1600 nm. This gave a result only a few (~2) mK away from T_{90} with an uncertainty below 50 mK.

Establishment of a robust uncertainty budget for Refractive-Index Gas Thermometry. Determination of T-T_{90} in the range ~5 K to ~200 K using three different methods (Dielectric constant gas thermometry, (DCGT), refractive index gas thermometry (RIGT) and acoustic gas thermometry (AGT)) and with a target standard uncertainty of 0.5 mK.

At PTB new equipment for stabilisation of the cryostat above 140 K has been purchased and stability tests underway. The system is ready for a first measurement campaign in the temperature range between 40 K and 80 K. INRIM is leading mass-spectrometric and hygrometric analysis of the composition and water content of the samples of He and Ne used in RIGT experiments by different partners. INRiM has completed the realization of a pulse-tube cryostat which is currently undergoing leak-tests before assessment of its cooling power. A copper microwave cavity is currently being manufactured and will be supplied in Spring 2017. TIPC-CAS is cooperating with LNE-Cnam to build its RIGT. A spherical resonator has been ordered and manufacturing is in progress. The design of the cryostat is in progress. At LNE-CNAM the low-temperature AGT has been equipped with capsule standard platinum resistance thermometers (CSPRTs) calibrated in the full temperature range from 13 K to 273 K, in order to run a combined AGT+RIGT experiment. Measurements to cover the range 13 K – 24 K are planned to start in Apr 17. The five partners involved in this activity, with the collaborator NRC (Canada), have drafted a preliminary version of a robust uncertainty budget for RIGT.This will be submitted to CCT in May for incorporation into the *MeP*-K-19.

Investigation of three novel thermometry methods (Doppler Broadening Thermometry, Double Wavelength thermometry and Radiation Thermometry Traceable to Synchrotron Radiation).

Establishment of novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in T-T_{90}.

Doppler broadening thermometry: At SUN the DBT has undergone significant technical upgrade, in particular, inprovement of the stability of the reference laser, reduced thermal drift of the reference oscillator and absolute stabilization of the reference laser LNE-CNAM and UP13 have selected a resistive-wire method for constructing a variable temperature thermostat. Improvement in the design of the heating and vacuum leakage of the spectroscopic gas cell in the operating temperature range is underway.

Novel radiometric approaches for primary thermometry: TUBITAK is working on the requirements for the optimal design of the double wavelength thermometer (DWT): identification of suitable wavelength ranges for lowest uncertainties; availability of optics covering wide range of infrared spectrum. InGaAs and InSb detectors were selected. LNE-CNAM is working with an acousto-optical based tuneable pyrometer, which allows the application of the double wavelength method (with narrow band and broadband detection). The theoretical study and the writing of the computational algorithm for the double wavelength methods have begun. PTB has undertaken measurements at the synchrotron storage ring (MLS) in order to identify uncertainty contributions arising from beam profile, beam-line window, polarization and parameter of the ring current. Based on this an ideal window design (tilted quartz window with wide opening) was identified and a four wavelength filter radiometer was designed and built at PTB. This instrument will be used at the synchrotron storage ring and at a High Temperature Blackbody using the same aperture for all 4 wavelengths, thus minimizing the uncertainty due to absolute aperture area. This instrument is currently calibrated in the VIS and NIR and is expected to be installed at the MLS in summer 2017. VNIIOFI has is developing Re-C fixed-point cells with a 14 mm wide aperture.

Improvement of primary thermometers (pMFFT, CSNT, CBT) for the ultralow temperature thermometry regime (0.9 mK to around 1 K). Resolving the PLTS 2000 background data discrepancy (6 % at lowest temperatures) including revised T-T_{2000} data over the range 0.9 mK to 1 K (target standard uncertainty of 1 %).

Intensive research is underway on all three thermometry approaches Magnetic Field Fluctuation Thermometry (pMFFT), Coulomb Blockade Thermometry (CBT) and Current Sensing Noise Thermometry (CSNT). This work is to optimise sensor design for low temperature operation, understand and quantify sources of uncertainty and prepare for the measurements below 20 mK. Abstracts have been written on thermodynamic temperature measurements by low-temperature Johnson Noise Thermometry (pMFFT and CSNT) and by CBT to be included in the updated *MeP*-K-19. The abstracts are currently under review by the CCT-TG-K.

Future meetings

The next meeting of the research partners will be at CNAM, St Denis, 7 Dec 2017.

It is planned that in Spring 2019 a workshop will be held at PTB, and comprehensive low uncertainty T-T_{90} and T-T_{2000} data sets for the annex of the *MeP*-K-19 will be developed, based on InK 1, InK 2 and other thermodynamic temperature data.

Invited talks on these developments will be given at the Spanish Metrology Congress 17 (June 2017), Metrologie 17 (September 2017) as well as at conferences in 2018.

List of publications

O. Hahtela, E. Mykkänen, A. Kemppinen, M. Meschke, M. Prunnila, D. Gunnarsson, L. Roschier, J. Penttilä & J. Pekola "Traceable Coulomb Blockade Thermometry", *Metrologia* (2017) 10.1088/1681-7575/aa4f84

B. Gao, L. Pitre, E.C. Luo, M.D. Plimmer, P. Lin, J.T. Zhang, X.J. Feng, Y.Y. Chen, F. Sparasci "Feasibility of primary thermometry using refractive index measurements at a single pressure", *Measurement*, http://dx.doi.org/10.1016/j.measurement.2017.02.039

D. I. Bradley, A. M. Guénault, D. Gunnarsson, R. P. Haley, S. Holt, A. T. Jones, Yu. A. Pashkin, J. Penttilä, J. R. Prance, M. Prunnila, L. Roschier " On-chip magnetic cooling of a nanoelectronic device", *Scientific reports (Approved, awaiting publication)*

G. Machin, "Towards the new kelvin", Low temperature news Dec 2016

G. Machin, "Towards the new kelvin", Gas world supplement Mar 2017

List of participants in, and collaborators with, the InK 2 project

Participants
NPL, United Kingdom
CEM, Spain
CNAM, France
INRIM, Italy
IO/CSIC, Spain
LNE, France
PTB, Germany
TUBITAK, Turkey
VTT, Finland
Aalto, Finland
RHUL, United Kingdom
SUN, Italy
UP13, France
NIM, China
TIPC-CAS, China
VNIIOFI, Russian Federation
NSC IM, Ukraine

Collaborators
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