

TOWARDS DIGITALIZATION OF TEMPERATURE MEASUREMENTS

Jonathan Pearce^{a,*}, *Radka Veltcheva*^a, *Declan Tucker*^a, *Graham Machin*^a

^a National Physical Laboratory, Teddington, United Kingdom

* Corresponding author. E-mail address: jonathan.pearce@npl.co.uk

Abstract – Autonomous control systems rely on input from sensors, so it is crucial that the sensor input is validated to ensure that it is ‘right’ and that the measurements are traceable to the International System of Units. The measurement and control of temperature is widespread, and its reliable measurement is key to maximising product quality, optimising efficiency, reducing waste and minimizing emissions such as CO₂ and other harmful pollutants. Degradation of temperature sensors in harsh environments such as high temperature, contamination, vibration and ionising radiation causes a progressive loss of accuracy that is not apparent. Here we describe some new developments to overcome the problem of ‘calibration drift’, including self-validating thermocouples and embedded phase-change cells which self-calibrate *in situ* by means of a built-in temperature reference and practical primary thermometers such as the Johnson noise thermometer which measure temperature directly and do not suffer from calibration drift. All these developments will provide measurement assurance which is an essential part of digitalisation to ensure that sensor output is always ‘right’, as well as providing essential ‘points of truth’ in a sensor network. Some progress in digitalisation of calibrations to make them available to end-users via a website and/or an Application Programming Interface is also described.

Keywords: temperature, thermometry, traceability, primary thermometry, process control

1. INTRODUCTION

The control and monitoring of temperature is a key part of almost every technological process. The thermodynamic temperature of a system is related to the average kinetic energy of the constituent particles of the system. However, this cannot be measured directly, so another parameter, such as the speed of sound in a gas, must be measured and then related to the temperature through well understood physics. In general, such an approach to temperature measurement is very complicated and expensive, and is not well suited to practical thermometry.

Most thermometry therefore makes use of practical sensors such as thermocouples and resistance thermometers. These yield a temperature dependent property such as voltage or resistance, which must then be related to temperature by comparison with a set of known temperatures, i.e. a calibration. The global framework for approximating the SI unit of temperature, the kelvin, is the International

Temperature Scale of 1990 (ITS-90) [1]. The measurement infrastructure that makes this possible is maintained by National Metrology Institutes (NMIs), who perform periodic global comparisons of their own standards to ensure the equivalence of thermometry worldwide.

A key drawback of this empirical approach to thermometry is that when the sensing region of the thermometer is degraded in use, for example by exposure to high temperatures, contamination, vibration, ionising radiation and other factors. The relationship between the thermometer output and its temperature changes in an unknown way. This is referred to as ‘calibration drift’, and it is insidious because there is no indication in process that it is occurring. This is a big problem for applications where temperature monitoring and control is critical, such as in long-term monitoring (e.g. nuclear waste storage), or where processes need to operate within a narrow temperature window (e.g. aerospace heat treatment). The result is often reduced safety margins, sub-optimal processing, lower efficiency, increased emissions, and higher product waste or rejection.

In this article some new developments at the UK’s National Physical Laboratory (NPL) are described to overcome the problem of calibration drift and to provide assurance that temperature sensor output is valid – a key part of increasingly widespread digitalisation to ensure sensor output is ‘right’ by providing *in-situ* validation. These include self-validation and *in-situ* calibration which provide traceability to the SI kelvin at the point of measurement, and practical primary thermometry which measures temperature directly, has no need for calibration, and does not suffer from calibration drift.

Finally, some developments in the digitalisation of calibrations are described, which will substantially reduce the amount of paperwork and opportunities for operator error and will facilitate digital transfer of calibrations and traceability for paperless audit trails.

2. SELF-VALIDATION

Thermocouples are widely used in industry but are particularly susceptible to drift of the calibration in harsh environments, whereby the relationship between emf and temperature changes in an unpredictable manner. This can be monitored *in situ* by using a miniature phase-change cell (fixed-point) in close proximity to the measurement junction (tip) of the thermocouple [2]. The fixed point is a crucible

containing an ingot of metal (or metal-carbon alloy [3] or organic material [4]) with a known temperature. The latest devices developed by NPL are able to accommodate the entire thermocouple and fixed-point assembly within a protective sheath of outer diameter 7 mm. Importantly, this means that the self-validating thermocouple presents the same external form factor and appearance as a regular process control thermocouple. It is also of course compatible with existing connections and electronics. A self-validating thermocouple is shown in Figure 2.1.

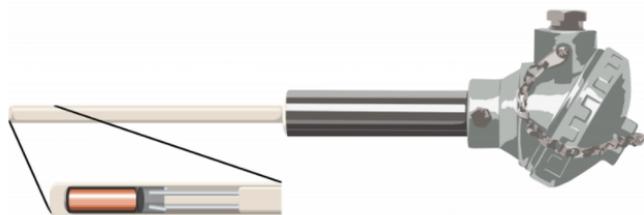


Fig. 2.1. Self-validating thermocouple with protective sheath. Image courtesy of CCPI Europe.

In use, when the process temperature being monitored passes through the melting temperature of the ingot, the thermocouple output exhibits a ‘plateau’ during melting, due to the heat of fusion of the ingot restraining further temperature rise. Once the ingot is completely melted the indicated temperature resumes its upward trend. As the melting temperature of the ingot is known, the thermocouple can be recalibrated *in situ*. A typical output of a self-validating thermocouple during the recalibration process is shown in Figure 2.2. This device has been extensively characterised [5], and has been licensed by NPL to UK thermocouple manufacturer CCPI Europe, under the tradename INSEVA [6], who are executing a series of trials in high value manufacturing industries.

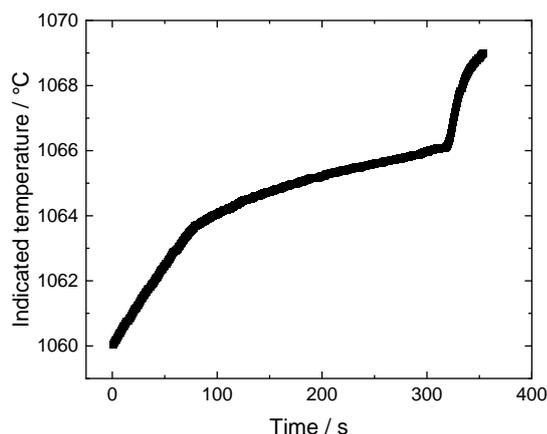


Fig. 2.2. Melting curve observed during the recalibration of the INSEVA self-validating thermocouple, here using a gold ingot (melting temperature 1064.18 °C).

A similar concept has been employed for an application in space-borne instrumentation, where the phase-change cell is part of the system whose temperature is to be measured. Such an embedded fixed-point has been demonstrated by NPL in collaboration with RAL Space on a prototype blackbody calibrator designed for operation as part of a spacecraft-borne

earth observation instrument suite [7]. The phase-change cell, containing approximately 2 g of gallium (melting point 29.7646 °C), is embedded in the aluminium blackbody calibrator base, close to an embedded platinum resistance thermometer (PRT). This enables the *in-situ* recalibration of the PRT in orbit.

In this application, some key developments included a mechanism to promote reliable freezing of the gallium without necessitating a large supercool (gallium is prone to cooling several degrees below its freezing temperature before nucleation is triggered), and a mechanism for preventing mechanical contact between the gallium ingot and the stainless steel cell wall, thereby avoiding the possibility of long-term contamination of the ingot and hence a change of its melting temperature. The ingot is shown in Figure 2.3.

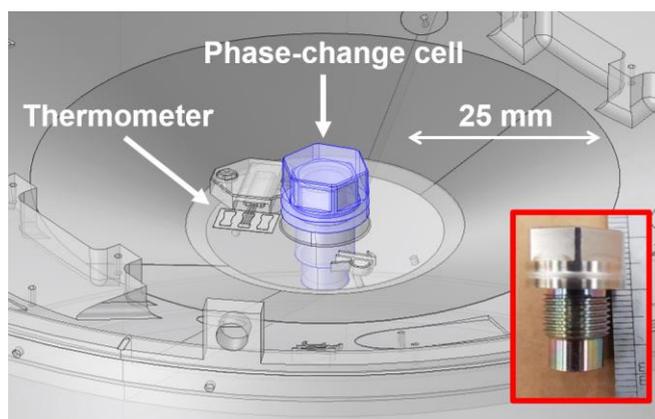


Fig. 2.3. Phase-change cell embedded in the blackbody calibrator base; the adjacent PRT is to the left. Inset: photograph of the phase-change cell.

It can be seen in Figure 2.4 that the remotely located PRT is able to indicate clearly defined melting curves with a useful duration of several hours, and a melting temperature range of less than 0.01 °C. By calibrating the phase-change cell against NPL’s reference standard gallium cell, it is possible to perform *in-situ* traceable calibrations of the PRT on board the spacecraft with an uncertainty of less than 0.01 °C.

For both the self-validating thermocouples and the embedded phase-change cell techniques, vigorous efforts are ongoing to automate the detection of the melting plateau, and, once detected, to characterise the ‘fixed point’ representing the invariant part of the melting curve. This is challenging to implement algorithmically in a manner sufficiently robust against noise and spurious artefacts in the data, but it is essential for autonomous *in-situ* recalibration.

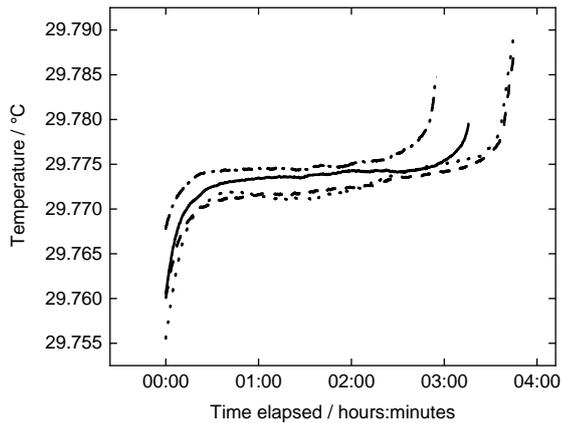


Fig. 2.4. Melting and freezing curves observed during the *in-situ* calibration of the PRT using the miniature embedded phase-change cell, showing the narrow melting range and excellent reproducibility.

3. PRACTICAL PRIMARY THERMOMETRY

The limitations of conventional temperature sensors which rely on calibration prior to use, and hence are prone to calibration drift, has led to renewed interest in practical primary thermometry. Primary thermometers measure some property that can be related to temperature directly through well-understood physics, and do not require a temperature scale or calibration. In addition, if all parameters needed to infer the temperature are measured simultaneously, the sensor is not subjected to calibration drift, since any change in the sensor material is accounted for in the measurement. Examples include acoustic thermometry (measuring the speed of sound) and Johnson noise thermometry (measuring the temperature-dependent voltage arising from the thermal motion of charge carriers in a resistor).

To turn one of these into a practical, commercially available reality, NPL has been collaborating with Metrosol Limited to develop a practical Johnson noise thermometer [8-10]. The Johnson noise voltage is related to temperature by Nyquist's relation $\langle V_T^2 \rangle = 4kTR\Delta f$, where $\langle V_T^2 \rangle$ is the mean squared Johnson noise voltage, k is the Boltzmann constant, R is the sensor resistance and Δf is the frequency bandwidth which is a function of the sensing electronics and cables. Importantly, if R is measured at the same time as the Johnson noise voltage, then all relevant properties of the sensing resistor are measured and so even if the sensor is degraded the thermodynamic temperature is always known.

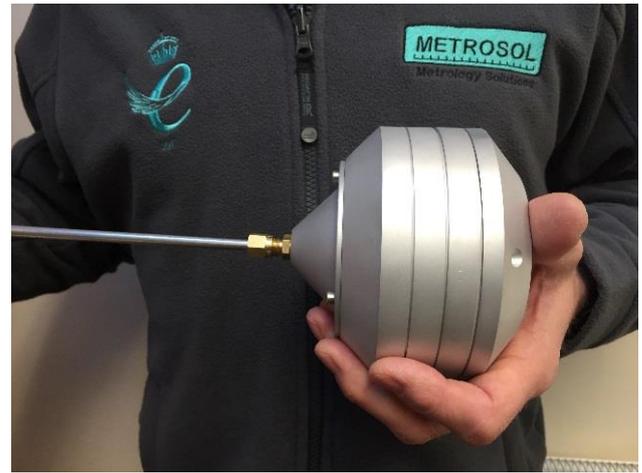


Fig. 3.1. Prototype practical Johnson noise thermometer developed by Metrosol in collaboration with NPL. The sensing electronics are housed in the container to the right; the probe extends to the left.

Johnson noise thermometry has until recently been the preserve of large national laboratories due to the extreme difficulty of isolating the minuscule Johnson noise voltage from the far larger external noise sources and the internal noise generated by the electronic components [11]. The development of a practical thermometer has been elusive and so far none have reached market, but the current NPL/Metrosol collaboration has now developed a working thermometer with unprecedented immunity to external electrical interference. The current prototype is shown in Figure 3.1. It has now passed the most stringent electrical immunity standard test, IEC 61000-4-3 [12]. The accuracy depends on the measurement duration; for an averaging period of about 5 s the measurement uncertainty is ± 0.5 °C. The most obvious application is as a replacement for thermocouples where appreciable long-term drift is unacceptable.

Further developments in the pipeline include demonstration of the feasibility of photonic-based 'lab on a chip' thermometry approaches for *in-situ* traceability to the kelvin. The approaches most likely to facilitate direct *in-situ* traceability are Doppler Broadening, Ring-Resonator, and Whispering Gallery thermometry [13]. Acoustic gas thermometry is also a candidate for practical primary thermometry; such a device was used to determine the Boltzmann constant with unmatched accuracy as part of the global endeavour to redefine the kelvin in terms of fundamental constants [14].

4. DIGITALISATION OF CALIBRATIONS

For many years the result of thermometer calibrations have been printed on paper and issued to the customer. Recently, however, there is a trend towards digitalisation of the calibrations so that the results are available online or in electronic files. This is very important functionality for many users; for example, in aerospace organisations where measurements are subject to significant regulatory compliance and demonstration thereof under frameworks such as AMS2750 which regulates heat treatment of metallic materials [15], it is very difficult to work with paper

certificates. One successful approach has been that of CCPI Europe, who have fully automated certification with their PyroTag™ system [16].

Digitalisation of calibrations has numerous benefits including the reduction in operator errors (e.g. through manual data entry), removed need for paper-based processes and transactions, and easier management for asset managers, calibration managers, and technical staff. It will result in reduction of time and cost arising from a paperless system, offers secure storage and retrieval of information, and is audit ready to demonstrate traceability compliance.

This presents some infrastructural challenges, including the way the data is presented, the internal mechanisms in the calibration laboratory for enabling digitalisation, and security of the information required to ensure that only the intended recipients have access.

NPL has embarked on a programme to automate, as far as possible, its thermometer calibrations and the generation of calibration certificates, and to make them, and the associated data and metadata available online via a secure website. The certificates will be machine readable (XML). The results will also be available through an Application Programming Interface (API), allowing integration with customers' own software. A key capability is that this can ultimately be integrated with the international Digital Calibration Certificate, whose format is currently undergoing development [17]. Importantly, the calibration history will also be available to the user.

5. CONCLUSIONS

Some new developments in temperature measurement have been presented which support digitalisation in various respects. Self-validation techniques to provide *in-situ* traceability at the point of measurement will provide assurance that temperature sensor output is 'always right'. Practical primary thermometry measures temperature directly, rather than requiring calibration and the risk of consequent calibration drift in harsh environments, so ensures long-term reliable measurements. For conventional sensors, digitalisation of calibrations at NPL is becoming a practical reality with a web-based interface and associated API to enable end-users to access calibration data programmatically. These developments all support digitalisation of metrology and will increase the reliability of measurements, improving process efficiency and product yield, with a consequent reduction in harmful emissions. Future work will focus on elevating the technical readiness and bringing the innovations to market.

ACKNOWLEDGMENTS

We would like to thank Trevor Ford, Peter Cowley and Phill Williams of CCPI Europe Ltd for contributions on the

self-validating thermocouples, Dan Peters and Dave Smith of RAL Space for contributions on the embedded phase-change cell, Paul Bramley and David Cruickshank of Metrosol Ltd for contributions on the Johnson noise thermometry, and Deepthi Sundaram and Stuart Chalmers of NPL for contributions on the digitalisation of calibration certificates.

REFERENCES

- [1] H. Preston-Thomas, The International Temperature Scale of 1990 (ITS-90), *Metrologia*, vol. 27, pp. 3-10, 1990
- [2] J.V. Pearce, O. Ongrai, G. Machin, S.J. Sweeney, Self-validating thermocouples based on high temperature fixed points, *Metrologia*, vol. 47, pp. L1-L3, 2010
- [3] G. Machin, Twelve years of high temperature fixed point research: a review, *AIP Conf. Proc.*, vol. 1552, p. 305, 2013
- [4] E. Webster, D. Clarke, R. Mason, P. Saunders, D.R. White, *In situ* temperature calibration for critical applications near ambient, *Meas. Sci. Technol.*, vol. 31(4), p. 044006, 2020
- [5] D. Tucker, A. Andreu, C.J. Elliott, T. Ford, Marius Neagu, G. Machin, J.V. Pearce, Integrated self-validating thermocouples with a reference temperature up to 1329 °C, *Meas. Sci. Technol.*, vol. 29, p. 105002, 2018
- [6] <https://ccpi-europe.com/2018/05/22/inseva-thermocouple-license-signing/>
- [7] J.V. Pearce, R.I. Veltcheva, D.M. Peters, D. Smith, T. Nightingale, Miniature gallium phase-change cells for *in situ* thermometry calibrations in space, *Meas. Sci. Technol.*, vol. 30, p. 124003, 2019
- [8] P. Bramley, D. Cruickshank, J.V. Pearce, The Development of a Practical, Drift-Free, Johnson-Noise Thermometer for Industrial Applications, *Int. J. Thermophys.*, vol. 38, p. 25, 2017
- [9] P. Bramley, D. Cruickshank, J. Aubrey, Developments towards an industrial Johnson noise thermometer, *Meas. Sci. Technol.*, vol. 31, p. 054003, 2020
- [10] <http://www.johnson-noise-thermometer.com>
- [11] J.F. Qu, S.P. Benz, H. Rogalla, W.L. Tew, D.R. White, K.L. Zhou, Johnson noise thermometry, *Meas. Sci. Technol.*, vol. 30, p. 112001, 2019
- [12] IEC 61000-4-3:2006 Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test
- [13] S. Dedyulin, Z. Ahmed, G. Machin, Emerging technologies in the field of thermometry, *Meas. Sci. & Technol.*, to appear, 2022
- [14] J. Fischer, et. al., The Boltzmann Project, *Metrologia*, vol. 55, pp. R1-R20, 2018
- [15] AMS2750F is an aerospace manufacturing standard covering temperature sensors, instrumentation, thermal processing equipment, correction factors and instrument offsets, system accuracy tests, and temperature uniformity surveys. These are necessary to ensure that parts or raw materials are heat treated in accordance with the applicable specification(s).
- [16] <https://ccpi-europe.com/resources/pyro-tag/>
- [17] S. Hackel, F. Härtig, J. Hornig, T. Wiedenhöfer, The Digital Calibration Certificate, PTB-Mitteilungen 127 (2017) <https://tinyurl.com/m853mpdd>. See also the DCC website <https://tinyurl.com/ycksrc2t>