Thermometry with embedded SI traceability for industrial applications

Jonathan Pearce [1*], *Henrik* Kjeldsen[2], *Jan* Nielsen[2], *Ingmar* Müller[3], *Christian* Krause[3], *Gavin* Sutton[1], *Alexander* Fateev[4], and *Aurik* Andreu[5]

[1]National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, United Kingdom
[2]Teknologisk Institut, Kongsvang Alle 29, 8000 Aarhus, Denmark
[3]Physikalisch Technische Bundesanstalt, Abbestr. 2-12, 10587, Berlin, Germany
[4]Danmarks Tekniske Universitet, Søltofts Plads, Bygning 229, 2800 Kongens Lyngby, Denmark
[5]Advanced Forming Research Centre, 85 Inchinnan Dr, Inchinnan, Renfrew PA4 9LJ, United Kingdom

Abstract. Most industrial processes rely on temperature measurement, which directly influences product quality, energy efficiency, process optimization and emissions. The European Partnership on Metrology project "Thermometry with embedded SI traceability for industrial applications (ThermoSI)" is a 3-year research and development project (late 2024 – late 2027) which will overcome some specific process control challenges (calibration drift, surface thermometry, dynamic gas temperature variations) by implementing embedded traceable thermometry *in situ* through driftless practical primary thermometry and self-validation, hot gas temperature measurement, and new traceable surface temperature measurement methods. Measurement traceability will be either directly to the redefined SI kelvin, or indirectly via the International Temperature Scale of 1990 (ITS-90). The activities are grouped into four categories: 1) Develop techniques for traceable, quantitative thermal imaging from -100 °C to 500 °C; 2) Improve practical primary Johnson noise thermometry by developing sensing electronics and a robust probe for use up to 1200 °C; 3) Develop thermographic phosphor thermometry up to 1250 °C; 4) Develop artificial intelligence approaches to enable *in-situ* traceable thermometry. The approaches, and how they will be developed and trialled in collaboration with industrial stakeholders, are outlined.

1 Introduction

Advanced manufacturing, improved energy efficiency and measurement traceability in process optimization are key to the industrial strategy of many regions around the world [1-3]. Most industrial processes rely on temperature measurement, which directly influences product quality, energy efficiency, and emissions. All conventional temperature sensors exhibit calibration drift leading to inefficiencies. Inaccurate surface thermometry causes process control challenges in advanced manufacturing. Poor gas temperature measurement and control leads to sub-optimal noxious emissions, greenhouse gas emissions and reduced efficiency. This project will address and overcome specific process control challenges by implementing embedded traceable thermometry *in situ* through driftless practical primary thermometry and self-validation, hot gas dynamic temperature measurement, and new traceable surface temperature measurement methods. Traceability will be either directly to the redefined SI kelvin [4], or indirectly via the International Temperature Scale of 1990 (ITS-90) [5].

Reliable, traceable surface temperature measurement with thermal imaging is notoriously difficult. It requires knowledge of the surface emissivity and any reflected thermal radiation, including knowledge of the geometry of the scene. Contact probes are subject to heat flow effects which perturb the thermometer and the temperature being measured. There is a need for a completely new approach which can provide a reliable, non-perturbative measurement of the surface temperature in the field of view.

Long-term reliable temperature measurement and control is required to make autonomous production/Industry 4.0 a reality [2,3]. However, in the harsh measurement environments encountered in industry (e.g. high temperature), sensor materials degrade, leading to calibration drift. There is a need for practical 'primary' thermometers capable of measuring thermodynamic temperature directly, that do not drift, irrespective of any damage to the sensor.

Traditional techniques for surface temperature measurement such as thermal imaging are seriously compromised due to the aforementioned difficulties with emissivity of the surface and reflected and background thermal radiation. For welding, forming, forging and additive manufacturing, surface temperature measurement is not sufficiently accurate. Phosphor (also known as luminescence) thermometry offers a solution

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[*] Corresponding author: jonathan.pearce@npl.co.uk

but robust coatings, new phosphor formulations and higher temperature operation (up to 1250 °C) are needed.

Self-validating thermometers which make use of an *in-situ* reference temperature are of growing interest for autonomous in-process recalibration but require manual intervention; automation requires recognition of characteristic features in temperature-time data which is beyond conventional software techniques, and artificial intelligence (AI) solutions are needed. Spectroscopic *in-situ* infrared gas temperature measurement for industrial hot gases (e.g. combustion and post-combustion) processes also relies on AI to retrieve the temperature, but this needs to be improved to reduce the temperature measurement uncertainty to ± 2 %.

All of these examples reflect the need to introduce traceability to the SI in process. The overall aim of the ThermoSI project is to enhance advanced manufacturing and process control by improving temperature measurement capability. The specific objectives of the project are:

1. To develop techniques for truly traceable, quantitative thermal imaging, by using at least 4 key engineering materials and selected thermographic phosphors with known temperature in the field of view of the thermal imager in the temperature range from -100 °C to 500 °C with an uncertainty of less than 5 °C. This will include characterisation (e.g. spectral, angular, and hemispherical emissivity) of the surface and of the phosphor itself and *in-situ* correction for camera non-uniformity.
2. To improve practical Johnson noise thermometry by bringing it up to a technology readiness level (TRL) of 6, with an uncertainty of less than 3 °C, and to provide truly driftless thermometry for harsh environments (e.g. nuclear power generation/decommissioning). In particular, to develop a robust probe assembly for measuring Johnson noise and demonstrate its performance in harsh environments (e.g. high temperatures up to 1200 °C, ionising radiation such as gamma rays and neutrons, and electromagnetic fields).
3. To develop robust thermographic phosphor techniques for surface temperature measurement with an uncertainty of less than 3 °C and up to temperatures of 1250 °C in collaboration with metals processing organisations and end-users (e.g. marine manufacturing) to progress towards the goal of zero carbon production (e.g. steel processing) and more generally improved energy efficiency of heavy industry.
4. To develop artificial intelligence (e.g. machine learning) approaches to enable traceable *in-situ* temperature measurement for industrial applications with an uncertainty of less than 2 % up to 1500 °C, demonstrated through at least three cases studies: 1) machine learning for autonomous operation of self-validating thermometers, 2) spectroscopic infrared thermometry for *in-situ* gas temperature and gas temperature profile measurements and 3) a reference surface temperature calibration insert for dry-block calibrators.

Significant progress in this collaborative research was made in the two EMPIR projects EMPRESS and EMPRESS 2 [6,7], particularly in developing working prototypes of several novel thermometers including a phosphor thermometer for surface temperature measurement, self-validating thermocouples, a portable standard flame and combustion temperature diagnostic techniques, and these, as well as the newer techniques, will be further developed to extend capabilities.

The focus of this project is to address specific process control challenges by demonstrating improved in-process temperature measurement traceable to the International Temperature Scale of 1990 (ITS-90) [5] or directly to the SI kelvin [4] during the life of the project.

Several European National Metrology Institutes are project partners including project coordinator DTI (Denmark), NPL (United Kingdom, providing technical leadership), CMI (Czech Republic), PTB (Germany), SMU (Slovakia), University of Ljubljana (Slovenia), VTT (Finland) and NSC-IM (Ukraine). Other university partners include the Danish Technical University (Denmark), Otto-von-Guericke University (Germany), and the University of Manchester (United Kingdom). Engagement is built into the project with the partnership of Beamex (Finland), Advanced Forming Research Centre at the University of Strathclyde, BAE Systems, CCPI Europe and Metrosol (United Kingdom). Each partner brings a specific area of expertise which will be employed as part of the collaborative activities. There is also a stakeholder community associated with the project, consisting of organisations interested in contributing to, or hearing about, the project activities, as well as workshops and other dissemination events.

2 The project

2.1 Thermal imaging

Thermal imaging is used to monitor surface temperature in a wide range of applications, including forming and forging, welding, annealing, spacecraft thermal vacuum testing, nuclear waste monitoring, and gas turbine manufacturing and operation. The difficulty of characterising the surface emissivity when performing quantitative thermal imaging results in measurement uncertainties which are often so large that the process quality/efficiency is significantly reduced.

There is a need for a completely new approach which can provide a reliable measurement of the local surface temperature without perturbing it. Thermographic phosphor spots can be adhered directly to the surface being measured and in the thermal imager field of view, allowing the surface emissivity to be determined and hence the true surface temperature to be determined, but this approach requires a) knowledge of the emissivity of the phosphor itself and b) knowledge of the inherent camera non-uniformity. Existing phosphor thermometry techniques are well established from ambient temperatures up to 750 °C, with prototype instruments able to approach 1000 °C. However, there is a growing need to measure below 0 °C, e.g. for the space sector, where traditional thermal imaging is particularly challenging due to the low signal levels and relatively high background thermal radiation, and above 1000 °C for manufacturing processes e.g. high reliability steel structures.

Due to the uncertain (often unknown) emissivity and reflected background thermal radiation, thermography can suffer from uncertainties in excess of ± 100 °C even at relatively modest surface temperatures. This project is overcoming these difficulties by employing thermographic phosphors in the form of a coated area in the field of view of the thermal imager. By using the phosphor (which is immune to the above confounding influences) to measure the surface temperature, the temperature indicated by the thermal imager can be calibrated by adjusting the emissivity setting, thus determining both the true surface temperature and emissivity simultaneously, dramatically reducing the measurement uncertainty to a target of around 5 K. To facilitate this, capabilities for measuring the emissivity of both the surface under investigation and the emissivity of the phosphor itself – which are both needed for the thermal imager correction – are being established, as well as the effect of perturbing environmental influences such as surrounding gas and humidity; these factors can limit the achievable uncertainty in the temperature measurement. These challenges are being addressed by several tasks:

- NPL is developing ITS-90 traceable calibration targets [8]. Emissivity measurements of the phosphors at PTB will enable a thermal model of the calibration targets to be developed, facilitating the connection between contact and non-contact thermometry.
- The emissivity of commonly used materials in industry under controlled environmental conditions such as pressure, relative humidity, and temperature are being measured by PTB. The reference emissivity data set will be made available to the public. This information will help industry to reduce the uncertainties and to extent the scope of application to non-contact thermometry.
- Large-area flat-plate reference blackbodies are being developed by VTT and Beamex. In conjunction with a digital twin of these devices, the temperature and heat flux distribution on the surface can be calculated. The blackbody sources will provide a compensated, high-resolution surface with a known, traceable thermal radiation temperature. This will be validated by comparison measurements by NPL and PTB.

2.2 Practical Johnson noise thermometry

Conventional thermometers are all prone to calibration drift which results in progressive loss of information about the process temperature and necessitates regular thermometer recalibration or replacement. Recent work by participants Metrosol and NPL [9], PTB [10], UL and CMI together with established routes to market will, for the first time, result in the world's first practical Johnson noise thermometers (JNTs) for industry with varying degrees of performance (and hence cost). All the JNTs exist as prototypes but the formidable technical challenges around electronics and probes fit for industry, as well as the unexplored traceability mechanisms, are common to all types of JNT. This is of great importance for applications where long-term monitoring and control is needed; examples include ionising radiation environments including nuclear waste storage and aerospace heat treatment. JNT is also needed for calibration laboratories.

JNT is very challenging because a) the noise voltage is minuscule [11] and needs to be extracted from other, much larger electrical noise and b) the requirement for sensing elements and probes are more demanding than for conventional thermometers. The route for traceability of the Johnson noise voltage measurement and resistance measurement to electrical standards, and a robust sensing element and probe assembly useable to 1200 °C need to be developed. Graphene is a promising candidate for the sensing element [12] but destructively oxidises at modest temperatures so the development and characterisation of a practical ceramic-encapsulated graphene sensing element is needed. JNT is one of the practical primary thermometry types recommended for further development by the BIPM Consultative Committee on Thermometry (CCT). It is in the CCT strategy (2021-2030+) as it implements the redefined kelvin by offering the possibility of thermometry free from calibration and drift. Joint development of the distinct JNT approaches is needed to provide a) diversity of design, metrological performance and cost, which translates into more options for customers; b) downward price pressure, and c) increased propagation to end users.

The redefinition of the kelvin in 2019 in terms of the Boltzmann constant opened the way for practical benefits through stimulating the development of practical primary thermometers which measure temperature directly, independent of any temperature scale. Primary thermometry therefore offers the possibility of a method that is free from calibration and is free from calibration *drift* in harsh environments. The type closest to commercialisation is the JNT. The temperature-dependent voltage arising from thermal motion of electrons can be measured, and thermodynamic temperature determined from first principles. Because all parameters associated with the thermometer which are degraded by harsh environments can be measured, a drift-free thermometer with continuous reference to the SI units based on fundamental constants can be implemented. Several JNTs exist in NMI laboratories, but they are essentially large physics experiments and are far from practical for industry. Four practical JNTs are currently being actively developed which are portable and practical to operate [9]. The key outstanding tasks are:

- The basic principle of the PTB dual-mode auto-calibrating resistance thermometer (DART) (which is called dual-mode because it is a joint JNT and resistance thermometer with the JNT used to calibrate the resistance thermometer *in situ*) and its electrical calibration have already been discussed in several publications [10]. However, the experiments presented were carried out with simplified prototypes which did not have the complete functionality of a practical noise thermometer. In this project a complete noise thermometer which makes traceable temperature measurements will be demonstrated.

- The JNT being developed by Metrosol and NPL (IJNT) is aimed at practical industrial use [11,13]. Currently it is a pure JNT, not dual mode. This thermometer has already had some testing at EMC facilities. Several factors limiting accuracy, calibration of the electronics, and improved stability for this thermometer need to be developed. Use in harsh environments such as high temperature, ionising radiation (gamma and neutron) and challenging electromagnetic environments (e.g. induction furnace) needs to be demonstrated.
- The JNT being developed at UL (ULNT) is also aimed at practical industrial use, using low-cost components such as a PC sound card. It operates over the temperature range from -196 °C to 300 °C. The uncertainty is approximately 0.5 °C. The device uses a relatively small 46 kHz bandwidth (i.e. audio frequency range); a key aim is to integrate this low-cost device with a practical probe suitable for industrial use and validate it.

This project is building on the existing JNTs by extending their temperature range (which is currently 0 °C to approximately 150 °C) up to 1200 °C, greatly increasing the range of applications in which they can be applied. A common theme for all four JNTs is the development of a robust sensor element and probe assembly. Conventional wire-wound resistive sensors and a completely novel sensor using graphene [14] will be developed. Boron nitride encapsulated graphene devices are robust against oxidation and can sustain high lattice temperatures up to about 1300 °C without degradation [15] and their resistance can be tuned to match the requirements of the measurement setup. This is being incorporated in a practical, robust probe assembly and tested in harsh environments.

Equally importantly, traceability of the Johnson noise voltage measurement and resistance measurement to electrical standards will be developed jointly by the project participants to ensure the accuracy and traceability of the JNT measurements. As the small signal in JNTs can easily be distorted by electromagnetic interference, testing in very high power electrical and induction furnaces will allow for unprecedented realistic testing of the suitability of the practical JNT in a very harsh environment. The participants will also assess the effect of high temperatures and ionising radiation environments. These three types of tests reflect the most likely stakeholder interest.

2.3 Phosphor thermometry to 1250 °C

Accurate and traceable non-contact temperature measurement of surfaces is challenging but is often the only option during high temperature dynamic processes. Traditional non-contact techniques such as thermal imaging are seriously compromised due to the unknown and changing emissivity of the surface being measured, background thermal radiation, and often rapidly changing temperatures. In industry such as marine, aerospace and space manufacturing, surface temperature measurement is not sufficiently accurate, and imaging capability is needed to obtain instantaneous temperature gradients. Phosphor thermometry offers a solution to these challenges and has been progressed substantially in EMPIR projects EMPRESS [6] and EMPRESS 2 [7]. However, although it can work at temperatures approaching 1000 °C, for consistent use it is currently limited to 750 °C for both single spot measurements and imaging. Robust coatings, new phosphor formulations and higher temperature operation for both imaging and single spot technologies are needed to extend the upper temperature to 1250 °C bringing many relevant applications in its purview e.g. steel processing and marine manufacturing.

Thermographic phosphor thermometry is being developed for operation at higher temperatures than previously attempted to validate surface temperature spot measurements to provide *in-situ* reference temperature ‘spots’ to facilitate qualitative thermal imaging. The maximum continuous temperature is currently 750 °C with intermittent use to 1000 °C; this project is elevating the maximum continuous temperature to a target of 1250 °C. This will be through development of enhanced instrumentation, robust coating formulations and application methods, and phosphor formulations that exhibit sufficient fluorescence at elevated temperatures. These will be demonstrated through in-process implementation in a range of manufacturing field trials. The techniques developed will be applied to practical devices for calibrating end-user thermometers, including contact surface temperature probes, ultimately for implementation as ISO 17025 [16] compliant services.

2.4 Artificial intelligence approaches for thermometry

New AI techniques are needed to address specific thermometry challenges:

- Self-validating thermometers which make use of an *in-situ* invariant temperature reference (which is based on the change of phase of materials) to overcome calibration drift [17] have been developed to the point where they are viable in industrial applications [18], and recent industry trials in aerospace heat treatment have proven their robustness and operational effectiveness. However, the feature which enables *in-situ* calibration, i.e. the ‘change point’, currently can only be identified manually by a human operator. Self-validating techniques based on change point detection (of the

in-situ phase change materials) need to be automated before they can enter widespread use. Attempts to develop conventional algorithms for automating this process have failed. AI methods such as machine learning are needed to determine the change point and its uncertainty.
- The efficiency and effectiveness of noxious emission reduction of combustion processes (e.g. waste incineration for heat and electricity production) are strongly dependent on temperature. Gas temperature retrievals are mostly limited to atmosphere and planetary research, and industrial applications. In industrial applications local and effective gas temperature measurements are frequently made with the use of thermocouples (suction pyrometers) and hand-held pyrometers. The former is time consuming and prone to possible sensor contamination and blocking, while the latter can only give an overall picture of maximum gas and effective particle temperatures in distributed industrial systems such as boilers (power plants and waste incinerators) and large-scale high-temperature (glass, steel, gas-reforming) production. Non-uniform temperature profiles can reduce NO_x removal process efficiency (so-called SNCR or SCR processes) and lead to increased reagent (ammonia, urea) consumption and unnecessarily high NO_x/NH3 emissions. Infrared spectroscopic techniques are promising but the iterative algorithms needed to extract the temperature are far too slow to be used in real time.
- Reference surfaces for calibration of thermal imagers and phosphors are extremely difficult to implement in practice due to heat flow effects, which make it difficult to determine the areal surface temperature distribution, and the effect of placing items in physical contact with them.

AI is increasingly being used throughout society, and techniques are now available that can be adapted to solve some specific thermometry challenges in this project:

- Self-validating thermocouples are now mature. To enable their automation, an algorithm was recently developed, using training data from aerospace heat treatment trials [19], which uses machine learning to locate a single instance of a melting plateau and automate the corresponding *in-situ* recalibration. This algorithm showed promising results for data drawn from a single industrial furnace environment. However, the algorithm needs to locate multiple melting plateaus and perform well across a range of industrial scenarios. This will be achieved by enhancing the algorithm and performing testing under a wide range of operating conditions to make it robust to a wide range of industrial furnace environments.
- EMPIR project EMPRESS 2 pioneered the traceable measurement of temperature profiles along a path in combustion environments with a proof-of-concept demonstration in waste incineration [20]. Improved AI techniques to retrieve the temperature profile from the spectroscopic infrared measurements in these highly dynamic environments are being developed, to enable development of simplified equipment and compact, low-cost instrumentation. The temperature of the boiler/combustor walls is also needed in temperature profile retrievals, and the phosphor thermometry and emissivity measurements will be employed. These measurements cannot currently be performed in real-time; machine learning will enable faster processing to enable real-time thermometry.
- Reference surfaces which can be inserted in conventional dry-block calibrators are being developed. These make use of AI (a neural network) to interpolate between the temperatures indicated by a network of embedded sensors, in order to establish the areal temperature distribution at the surface. This will complement the thermal imaging and phosphor thermometry developments to enable the manufacture of a practical, low-cost surface thermometer calibration device.

3 Conclusion

A suite of current pan-European research activities aimed at improving SI traceable thermometry (and hence reliable process monitoring and control) suitable for harsh industrial environments has been described. These include:

1. Truly traceable, quantitative thermal imaging, by using at least 4 key engineering materials and selected thermographic phosphors with known temperature in the field of view of the thermal imager in the temperature range from -100 °C to 500 °C with an uncertainty of less than 5 °C.
2. To improve practical Johnson noise thermometry with a technology readiness level (TRL) of 6, and an uncertainty of less than 3 °C, and to provide truly driftless thermometry for harsh environments (e.g. nuclear power generation and decommissioning).
3. To develop robust thermographic phosphor techniques for surface temperature measurement with an uncertainty of less than 3 °C and up to temperatures of 1250 °C in collaboration with metals processing organisations and end-users.
4. To develop artificial intelligence (e.g. machine learning) approaches to enable traceable *in-situ* temperature measurement for industrial applications with an uncertainty of less than 2 % up to 1500 °C, demonstrated through at least three cases studies: 1) machine learning for autonomous operation of self-validating thermometers, 2) spectroscopic infrared thermometry for *in-situ* gas temperature and gas temperature profile measurements and 3) a reference surface temperature calibration insert for dry-block calibrators.

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