Title: Next generation process thermometry for advanced manufacturing

Abstract

The European economy is now very dependent on advanced manufacturing and its supply chain, but it has many unsolved temperature measurement challenges which reduce the efficiency and effectiveness of production. The EU also has a vibrant sensor manufacturing base; the global market for temperature sensing alone is estimated to be worth $4.5 billion; sensors for monitoring process variables account for the majority of this. These sensors are known to exhibit calibration drift, which leads to inefficient energy use, reduced yield, increased rejection rates, and sub-optimal processing. Poor surface temperature measurement causes process control problems in welding, coating, forming and additive manufacturing processes. Processes in harsh environments and at high temperature suffer from serious inefficiencies due to sensor degradation. Proposals addressing this SRT should aim to overcome specific process control challenges with improved temperature traceability and validation of new techniques *in situ*.

Keywords

Temperature, phosphor thermometry, surface temperature, thermocouples, aerospace, optical fibre, practical primary thermometry, process control, advanced manufacturing, additive manufacturing

Background to the Metrological Challenges

Accurate and traceable surface temperature measurement can be difficult but is often the only option during high temperature dynamic processes. Poor temperature measurement can lead to control problems in processes (e.g. welding, coating, forming and additive manufacturing) that are used in advanced manufacturing industries. The current state of the art for contact thermometry measurements up to 1300 °C are metal sheathed (MI) Type K and N thermocouples, or for higher accuracies Pt-Rh alloy thermocouples. The most common temperature sensors used in industry are the base metal mineral insulated, MI cable thermocouples as they are inexpensive, practical, and ubiquitous. When these MI thermocouples are used at high temperatures, there is evidence of spurious effects, including instabilities and insulation resistance breakdown, causing errors, which are difficult to assess during measurement, resulting in unreliable thermometry. The quality of the insulation material can play a role, as impurities can cause a reduction in the insulation resistance and can contaminate the thermocouple wires, both effects causing calibration drift to an unknown extent. Similarly, the use of conventional Pt-Rh alloy thermocouples in particular temperature ranges (e.g. between about 550 °C and 900 °C) cause reversible changes of the Seebeck coefficient and therefore a degradation of accuracy. A means of identifying the problem before the thermocouples enter service is urgently needed. Phosphor thermometry offers a solution to these challenges but is currently limited to 750 °C for both single spot measurements and imaging. Although progress has been made with the development of practical traceable phosphor thermometry, further research is needed to ensure successful applicability to industrial situations that are characterised by harsh and dynamic environments through the development of robust coatings, new phosphor formulations and higher temperature operation, for both imaging and single spot technologies.

When semi-conductor-based sensors are placed in harsh environments, consequent damage to the probe causes a corresponding change in the calibration, which is unfeasible to determine, and it is often difficult or time consuming to remove the probe for recalibration. Furthermore, conventional contact probes such as thermocouples and resistance thermometers must be calibrated to yield traceable measurements. Current primary thermometry techniques require large, complicated apparatus, which do not meet industry requirements and cannot easily be integrated into chips that perform other functions (e.g. microprocessors). There is a need for a practical primary thermometer, which can directly measure properties related to the temperature without the need for calibration. This would be advantageous for applications where long-term monitoring and control is needed (e.g. casting and heat treatment of gas turbine components, ionising radiation environments including nuclear waste storage). Johnson noise-based thermometry can be used to reduce the disruption associated with sensor recalibration or replacement, since it enables measurement of all variables that have changed due to exposure to the harsh environment, providing the true thermodynamic temperature irrespective of such changes.

In harsh environments, (e.g. silicon and steel processing, high temperature, nuclear fuel/waste processing and decommissioning) thermocouples cannot be used reliably. However, fibre-optic thermometry could be used as it can be immune to the effects of the environment. Although new speciality fibre-based approaches are less susceptible to ionising radiation effects, further improvements and technical developments are needed in this area for better application in industry. Supplementary research into remote thermal imaging via infrared fibre bundles is also needed. At present, fibre-optic temperature sensors are readily available but rarely offer the possibility of traceable measurements and have a limited maximum operating temperature. Their calibration drift and performance are poorly characterised. In addition, the sensors are fragile and not always straightforward to implement in a robust manner, especially in harsh environments. Distributed temperature sensing (DTS) techniques utilising Raman, Brillouin or Rayleigh scattering offer the prospect of high spatial resolution temperature mapping for thermal monitoring at large scale facilities in harsh environments and can replace large numbers of conventional sensors, but calibration capabilities above 100 °C do not yet exist. Furthermore, the contact surface probes that are currently used in a various industries (such as aerospace, automotive and additive manufacturing), are prone to large uncertainties and traditional non-contact techniques such as thermal imaging are compromised due to the unknown emissivity of the surface being studied, background radiation, and rapidly changing temperatures. Therefore, in terms of thermal imaging, better knowledge of the surface emissivity and any reflected thermal radiation is needed to ensure reliable and traceable temperature measurements.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of temperature and *in situ* validation of new techniques, to support next generation process thermometry for advanced manufacturing

The specific objectives are

1. To develop at least one primary thermometer based on Johnson noise, either as a stand-alone device or to be integrated with other devices on the same chip. In addition, to investigate the effect of local noise sources and produce suitable probes which can retain effective electromagnetic noise suppression needed to measure the Johnson noise signal with an uncertainty ±2 °C, at temperatures up to 1100 °C (macroscopic industrial probes), and between cryogenic temperatures and 70 °C (microscopic miniature sensors on e.g. silicon wafers).
2. To establish traceable and robust fibre-optic thermometry approaches by developing i) thermal imaging via fibre bundles (up to 1900 °C, with an uncertainty ±20 °C) for remote measurements, ii) specialised photonic fibre-optic thermometry (up to 130 °C, with an uncertainty ±1 °C), iii) practical sapphire fibre-based sensors for high temperatures (up to 1600 °C ,with an uncertainty ±3 °C), and iv) distributed temperature sensing (DTS) by Raman/Brillouin/Rayleigh scattering in optical fibres (up to 400 °C, with an uncertainty ±3 °C). Each approach to be tested in at least one harsh environment to demonstrate viability.
3. To investigate the correlation between the composition of the ceramic insulation material, composition of the wires, and the thermoelectric properties of mineral insulated metal sheathed thermocouples at high temperatures. In addition, to investigate and overcome the limitations of current technology that lead to Pt-20%Rh/Pt thermocouples instabilities and unexpected behaviour in the temperature range between 0 °C and 1300 °C.
4. To develop surface phosphor thermometry methods (up to 1000 °C), with an uncertainty ±5 °C to the point of being process-ready, and in combination with thermal imaging to overcome emissivity, background radiation, and dynamic measurement challenges. A demonstration should be performed in at least one advanced manufacturing setting.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, advanced manufacturing industries such as aerospace, nuclear power, petrochemical), standards developing organisations (ISO, CEN) and end users

(thermometry instrumentation manufacturers, iron and steel manufacturers). In addition, a viable prototype for remote thermal imaging via fibre bundles and speciality fibre optic thermometry (Objective 2) will be made available to end-users.

Proposers shall give priority to work that meets documented industrial needs and include measures to support transfer into industry by cooperation and by standardisation. An active involvement of industrial stakeholders is expected in order to align the project with their needs – both through project steering boards and participation in the research activities.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€ and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 30 % of the total EU Contribution across all selected projects in this TP.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Transfer knowledge to the advanced manufacturing sector.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.