Publishable Summary for 22IEM07 INFOTherm
Integrated European research, calibration and testing infrastructure for fibre-optic thermometry

Overview

The measurement and control of temperature plays a key role in achieving the goals of the European Green Deal for a low-carbon energy system. Fibre-optic thermometry is an emerging technology that can improve the measurement of temperature in extreme environments for energy providers and the industry sector due to distributed sensing and immunity to electromagnetic fields. However, fibre optic thermometers exhibit cross sensitivities to other quantities (e.g. strain, vibration, humidity) and ageing effects that need to be investigated, quantified and minimised to obtain traceable and reliable measurements. Therefore, this project aims to overcome the limitations that prevent the widespread use of fibre-optic thermometry by creating a dedicated European metrological infrastructure addressing research (e.g. measurement uncertainty), testing (e.g. industrial case studies), calibration (e.g. services and guides), and training (e.g. stakeholder workshop).

Need

Transforming Europe's energy system towards a higher share of renewable energy to meet the goals of the European Green Deal for a low-carbon energy system will require some infrastructure changes. For example, energy from wind and solar resources can be stored when production is high and released when less energy is produced. This can be achieved by thermal energy storage, such as tanks of molten salt at temperatures up to 560 °C, which require the measurement of the exact temperature and its distribution to quantify the loading state and to minimise losses through mixing. There is also a need to provide geothermal energy and seasonal storage of thermal energy in underground areas through multiple boreholes. Monitoring such boreholes can greatly improve system operation and integrity, but reliable temperature measurements with high spatial resolution are required along a path, not just at a few points.

Fluctuations in renewable energy production caused by local weather conditions increase the dynamics of the electrical grid and put additional stress on its components such as power cables and transformer stations. Monitoring temperature with instruments that are not affected by electromagnetic fields, such as fibre-optic thermometers, allows better utilisation of existing infrastructure. In addition, some high-temperature processes (e.g. silicon production for solar cells or semiconductors) require precise temperature monitoring and control for efficient operation and product quality. Conventional high temperature thermometers (mostly thermocouples) have serious limitations due to ageing and drift. Stable contact thermometers for temperatures up to 1600 °C are urgently needed.

Existing commercial fibre-optic systems are not traceable to the International System of Units (SI). Therefore, more work is needed to validate fibre-based thermometry and make its use in key industrial applications more attractive. Most fibre-optic thermometers have a Technology Readiness Level (TRL) between TRL4 and TRL7. However, for applications related to critical infrastructure monitoring and control, advanced manufacturing processes or quality control, this is not sufficient and independent verification, also known as TRL9, is required. TRL9 is provided by calibration services from accredited calibration laboratories, NMIs or an approved body under the Measuring Instruments Directive (MID).

Fibre-optic thermometers allow temperatures to be measured in all the cases mentioned above, but they suffer from cross-sensitivities to other quantities (e.g., strain, vibration, humidity). In order to exploit the full potential

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of fibre-optic sensors (e.g. Fibre Bragg Gratings (FBGs) in silica or sapphire fibres) or distributed sensing techniques (using Rayleigh, Brillouin or Raman scattering), it is necessary to investigate, minimise and quantify these cross-sensitivities so that reliable results can be obtained. Standards, calibration guides and services are required to integrate fibre-based thermometry into the existing energy system and infrastructure.

Objectives

The overall objective of the project is to develop a research, calibration and testing infrastructure for fibre-optic thermometry measurements. The specific objectives of the project are:

1. To develop accurate methods for quantifying the sources of measurement uncertainty and cross-sensitivities of existing fibre-optic thermometers. This includes (i) disturbance effects such as thermal expansion, strain, vibrations, humidity of surrounding air or pressure, (ii) ageing effects and (iii) the influence of sensor mounting.
2. To develop accurate and validated distributed temperature sensing (DTS) techniques for large scale applications, based on Rayleigh, Raman and Brillouin scattering or multiplexed fibre FBGs. Measurement uncertainty and spatial resolution will be determined for the DTS methods, with an expanded target uncertainty ($k=2$) of 3 °C up to 500 °C.
3. To develop validated fibre-based thermometry (e.g., FBG sensors) for harsh environments. These will include high temperature process control with an expanded target uncertainty of 3 °C up to 1600 °C and precise temperature monitoring at elevated temperatures (expanded target uncertainty 1 °C up to 700 °C).
4. Using the techniques developed in Objectives 1 to 3 to perform 12 case studies in key application areas for fibre-optic thermometry: (i) monitoring of electrical power cables and other parts of the grid, (ii) control of energy-intensive high-temperature processes, (iii) monitoring of the loading state of heat storage tanks, (iv) monitoring of geothermal heat storage, and (v) NMI intercomparisons. To provide validated information on suitable fibre-optic thermometry techniques for specific applications, specific temperature ranges, spatial temperature resolution and achievable measurement uncertainties.
5. To establish an integrated European metrology infrastructure with certified European training centres and accredited calibration laboratories for fibre-optic thermometry. This will include the development of testing and calibration guides. In addition, to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, certification and accreditation bodies), standards developing organisations (IEC) and end users (sensor manufacturers, industry and energy sectors).

Progress beyond the state of the art and results

This project will go beyond the state of the art by developing new and validating existing methods to identify and quantify sources of measurement uncertainty of various point-like fibre-optic sensors (e.g. silica/sapphire FBG, Fabry-Pérot interferometer) and for distributed temperature sensing techniques (using Rayleigh, Brillouin or Raman scattering) used in the metrology community and industry sector. Based on these findings, calibration routines will be developed and validated for different temperature ranges and applications. The measurement uncertainty of at least three different fibre-optic temperature measurement techniques will be metrologically determined (partly for the first time) and improved. The aim is to achieve low extended target uncertainties (k=2) in expanded temperature ranges beyond the state of the art: 3 °C at up to 500 °C for distributed temperature sensing (DTS), 1 °C at up to 700 °C for FBG and 3 °C at up to 1600 °C for sapphire FBG. Finally, the sensors will be tested in industrial case studies relevant to the European energy system.

Objective 1: Quantifying the sources of measurement uncertainty.

Several institutes around the world have carried out studies on the reliability of temperature measurements using fibre-optic sensors, but no validated SI traceable calibration of these sensors has been carried out in Europe. This project will establish methods to investigate the specific effects for the different fibre-optic sensing methods and their influence on the temperature uncertainty. This will include the effects caused by thermal expansion, strain, vibration, ambient humidity and pressure, ageing effects and the influence of sensor mounting position. The aim is to fill existing knowledge gaps regarding the causes of measurement uncertainties and to increase the reliability of fibre-optic sensors, in order to establish calibration routines for fibre-optic sensors.

Objective 2: Development and validation of DTS techniques.

Existing calibration infrastructure and methods are designed for the needs of point-like temperature sensors. In order to fully exploit the advantages of fully distributed sensing, novel validation and calibration approaches with respect to measurement uncertainty and spatial resolution will be developed. This will be used to determine the measurement uncertainty for a DTS method with an expanded target uncertainty (k=2) of 3 °C at up to 500 °C. An interlaboratory comparison will be performed to ensure the robustness of the validation. Furthermore, quasi-distributed point sensors (FBG) and distributed sensors (DTS) will be compared to determine performance differences.

Objective 3: Development of fibre-based thermometry for harsh environments.

This project will develop, validate and calibrate silica and sapphire FBG-based temperature sensing techniques for industrial conditions at high temperatures. FBG sensors in silica fibres will be developed and characterised to achieve an expanded target uncertainty (k=2) of 1 °C at up to 700 °C with traceable calibration. The promising results of EMPIR 17IND04 EMPRESS2 with sapphire-based FBG sensors will be improved to achieve an expanded target uncertainty of 3 °C at up to 1600 °C (compared to 10 °C at 1500 °C) and to meet industrial requirements. In addition, alternative approaches using modified sapphire FBGs with wavelengths around 800 nm, high-resolution Fabry-Pérot interferometers, and fluorescence-based fibre thermometers will be investigated to overcome the lack of metrological validation.

Objective 4: Case studies in key application areas.

The project will carry out 12 case studies in 5 key application areas for fibre optic thermometry to demonstrate the practical use of traceable fibre-optic sensors in a wide range of applications, each with its own specific requirements, including (i) power cables and other parts of the electrical grid, (ii) energy-intensive high-temperature processes, (iii) heat storage tanks, (iv) geothermal heat storage, and (v) NMI intercomparisons.

For the first time, the operational status of high-voltage components will be demonstrated using a calibrated fibre-optic sensor at operating voltages of up to 100 kV. Monitoring of high-voltage cables over many kilometres to improve electrical load management will also be carried out, and the defect analysis of transition joints will be investigated with unprecedented high spatial and temperature resolution (target 0.5 m and 0.1 °C).

Monitoring of energy-intensive high-temperature processes for glass and silicon production using sapphire FBG-based sensors at temperatures up to 1600 °C will be performed with improved accuracy, allowing advanced process optimisation.

The existing local electrical temperature sensors will be replaced by distributed and quasi-distributed temperature sensing solutions to monitor thermal storage systems, such as molten salt tanks. The fibre-optic sensors will cover a temperature range up to 500 °C and are expected to provide high-resolution temperature profiles needed to optimise storage efficiency.

The optimisation of seasonal geothermal heat storage with borehole depths up to 200 m using distributed temperature sensing will be investigated by studying the long-term stability of the sensors under operating conditions. In addition, methods will be developed to determine the effects of fibre ageing in existing borehole installations.

Finally, NMI intercomparisons between participants will be carried out to characterise the behaviour of sensors and readout units of different origins and to analyse systematic effects of the calibration infrastructure. This will provide the basis for future calibration services.

Outcomes and impact

This project will remove barriers to the widespread use of fibre-optic thermometry in various sectors by providing novel, traceable temperature measurement solutions where temperature measurement and control play a key role but are inaccessible to conventional electrical methods. This will make the energy infrastructure more resilient and reliable in the face of future challenges. In addition, this project will strengthen fibre-optic temperature measurement manufacturers and service providers in Europe.

Outcomes for industrial and other user communities

Energy transmission networks are expected to benefit from the project. Better temperature measurements of power cables, transformer stations and other key components will lead to advanced load management of the European electrical grid. Fibre-optic sensor technology will enable the energy industry to manage the increasing demands on electrical infrastructure.

The project will develop and implement monitoring and control solutions for energy storage systems that have the potential to significantly minimise the downtime of solar and wind power. These solutions will improve the measurement of the thermal energy available in energy reservoirs based on molten salts or other materials by determining a distributed temperature profile rather than a single point temperature measurement. This will increase the efficiency of thermal energy storage and ensure operational safety by detecting local hot or cold spots and efficiency losses due to unwanted mixing.

The results of the project can also be used by the nuclear energy sector to improve measurements in areas that are difficult to access or have high electromagnetic fields that can interfere with measurements made with conventional temperature sensors such as thermocouples and platinum resistance thermometers.

To promote the uptake of the project, extensive engagement with a wide range of stakeholders will take place throughout the project. The training on novel methodologies planned within the project aims to promote early adoption of the technology by stakeholders (e.g. sensor and instrument manufacturers) to enable future competitive products and services.

A reliable European calibration infrastructure will enable a valuable market comparison between conventional (electrical) and optical temperature sensors. As a result, the use of calibrated fibre-optic sensors will increase.

Outcomes for the metrology and scientific communities

The development of guidelines and best practices will have a high impact on the metrology community, as it will create a higher degree of reproducibility between laboratories. NMIs will be able to work towards meeting the needs of project stakeholders as a natural part of the project. Improved and calibrated fibre-optic thermometry instruments will make them suitable for a variety of research fields, ranging from electrical engineering of power converters to optimisation of chemical production, where this type of temperature sensors is much less susceptible to errors caused by the harsh environment.

In order to promote the uptake of the results of this project by these communities, the consortium will invite them to participate in the project workshops and will further disseminate the results through the strong link between the project participants and the CCT and TC-T, as well as through conferences and open access publications.

Outcomes for relevant standards

The results of the project will be promoted to the standardisation community with the aim of incorporating the project results into standards. In order to achieve this, the participants will disseminate the results of the project to the working groups in which they are involved, such as IEC TC 86/SC, IEC TC 86C/WG2, SEAFOM, a forum promoting the growth of fibre-optic monitoring system installations in the oil and gas industry, the European Metrology Networks (EMNs) on climate and ocean observation, clean energy, and advanced manufacturing, and the CIGRE Council on Large Electric Systems. This will initiate the preparatory process for the development of new standards.

Longer-term economic, social and environmental impacts

The project will remove barriers to the widespread use of fibre-optic thermometry in various sectors where temperature measurement and control is critical but inaccessible by other methods. This will increase the efficiency of energy-intensive processes and power generation, and improve the resilience of increasingly stressed electrical grids.

A resilient and efficient energy supply is a key factor for the location of many industries. The necessary optimisation and monitoring of energy infrastructure is therefore essential to keep energy-intensive industries in the EU in the long term. This will enable the EU to achieve the desired increased economic independence. It will also help to improve the quality of industrial processes and reduce downtime, thereby reducing indirect costs and strengthening the EU economy in the global market.

Europe plays a key role worldwide in the field of fibre-optic sensors. The creation of new standards, the capability for traceable calibration of fibre-optic sensors and the penetration of these technologies into the wider society will enable an innovative industry to be maintained and expanded. This will create high quality jobs in sensor and instrumentation manufacturing and measurement application services.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 September 2023, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Stephan Krenek, PTB Tel: +49 30 3481 7745 E-mail: infotherm@ptb.de
Project website address: www.infotherm.ptb.de</td></tr>
<tr><td>Internal Beneficiaries:
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