Publishable Summary for 17IND07 DynPT
Development of measurement and calibration techniques for dynamic pressures and temperatures

Overview

Dynamic measurements of pressure and temperature are a key requirement for process control in several demanding applications, such as automotive, marine and turbine engines, manufacturing processes, and ammunition and product safety. The quality of these measurement has been significantly improved in this project through development of dynamic measurement standards (e.g. shock tubes and drop-weight devices) and methods (e.g. blackbody and rapid shutter systems), and characterised sensor technologies (e.g. non-contact thermometers and novel pressure sensors) and means of estimating measurement uncertainties in real process conditions (e.g. inside a combustion engine), and thus support the innovation potential and competitiveness of European industry.

Need

Improved dynamic measurements of pressure and temperature were needed for developing next generation technologies and products with improved quality, energy and material efficiency, and safety. Developments within this project have a wide-ranging impact on competitiveness of European industry, mitigating climate change and improving the safety and welfare of European citizens.

The need for better accuracy and reliability of dynamic measurements is driven from a variety of industrial sectors. Better knowledge about the pressure and temperature inside an internal combustion engine was needed for improving engine performance, i.e. engine power and fuel consumption. In manufacturing processes, e.g. injection moulding, better process control through improved dynamic pressure measurements will result in higher product quality and more efficient use of materials and energy. Improved dynamic measurements was needed in many safety critical applications, such as crash testing of cars, ammunition safety testing, explosion protection, and dynamic mechanical testing of materials, to reduce the currently very wide safety margins and thus ensure user safety in a cost-effective way.

Measurement standards for dynamic pressure were developed in an earlier joint research project (EMRP IND09 Dynamic). Further development and validation was, however, necessary to enable industry to adopt these new calibration methods. In addition, dynamic temperature needed to be considered because in many processes, e.g. inside an engine, dynamic pressure and temperature changes take place simultaneously. Current practice to calibrate pressure and temperature sensors only at static conditions significantly limits the achievable measurement accuracy, errors up to 10 % might occur. To ensure the quality of measurements, new sensor technologies that can withstand harsh condition, e.g. inside an engine, was needed in addition to a better understanding of the influence of process conditions on sensor response. To implement a shift from static to dynamic, industry needs guidelines and standards for dynamic measurements and calibrations.

Objectives

The overall objective of the project was to improve the accuracy and reliability of dynamic pressure and temperature measurements that are widely performed as part of manufacturing, product and safety testing, and research and development activities. The specific objectives of the project are:

1. **To provide traceability for dynamic pressure and temperature through development of measurement standards and validated calibration procedures.** Pressure and temperature ranges up to 400 MPa and 3000 °C, respectively, will be covered with uncertainties relevant for industries and applications involved, e.g. 1% for internal combustion engine (ICE) applications.

2. **To quantify the effects of influencing quantities** - such as pressure, temperature, signal frequency, and measurement media - on the response of dynamic pressure and temperature sensors, in order to determine the appropriate calibration procedures and measurement uncertainties for industrial

measurements. Novel simulation models will be developed for analysing the effect of transient conditions on measurement results.

3. **To develop new measurement methods and sensors for measuring dynamic pressure and temperature in demanding industrial applications.** Improved accuracy and reliability obtained with the new methods and sensors will be demonstrated, including for the durability of dynamic pressure sensors. The pressure and temperature ranges up 400 MPa and 3000 °C, respectively, will be covered with uncertainty levels relevant for respective application.

4. **To validate all of the methods and sensors developed in this project (i.e. non-contact temperature measurement methods and novel pressure sensors) through demonstrations in selected industrial applications.**

5. **To ensure by close engagement with industry, that the developed calibration and measurement techniques and technology are adopted by industry**. Workshops and guidelines for the best measurement and calibration practices including uncertainty estimation of dynamic pressure and temperature will be prepared to facilitate efficient uptake by industry and serve as input to the preparation of international standards.

Progress beyond the state of the art

This project continued the work started in EMRP IND09 *Dynamic* and the scope was widened to include dynamic temperature. Most importantly, going beyond IND09 the traceability up to the end users was established and supported by a study on the influence of process conditions including documented calibration and measurement procedures.

Measurements standards for dynamic pressures and temperatures have been developed to provide SI traceable calibrations in a wide pressure, temperature, and frequency range 0.1 – 400 MPa, up to 3000 °C and 1 – 30 kHz, respectively. The target uncertainty of 1 % for dynamic pressure was achieved in the pressure and frequency range up to 5 MPa and 100 Hz. At higher pressure and frequencies, the uncertainties were in the order of 2 % and 5 %, respectively. The target uncertainty of 3 % was achieved for dynamic temperature calibrations up to 3000 °C.

Studies on the influence of process conditions show that the response of dynamic pressure sensors is strongly frequency dependant even at frequencies well below the nominal resonance frequency of the sensor. Other effects were found less significant. Based on experimental studies at varying combustion conditions, e.g. clean and sooty flames and high pressures, correlation models for extracting temperature data from the measured signal was successfully developed for a fibre-optic and spectroscopic dynamic thermometer.

New dynamic pressure and temperature sensors, namely a novel cylinder pressure sensor, fibre-optic combustion pyrometer and a spectroscopic band shape sensor, have been developed and tested in real operating environments, i.e. inside a maritime combustion engine. The overall target uncertainties of 2 % and 5 % for dynamic pressure and temperature measurements, respectively, in ICE applications was achieved. As a special feature of the spectroscopic band shape sensor both temperature and pressure data is retained from the combustion process.

Results

In this project, a solid framework for dynamic pressure and temperature measurements has been developed. This will enable a shift in paradigm from static to dynamic, which will significantly improve the accuracy and reliability of dynamic measurements in industry.

Traceability for dynamic pressure and temperature

New measurement standards for dynamic pressure and temperature have been developed and validated to provide traceability for dynamic measurements, and thus a solid basis for accurate and reliable measurements. Measurements standards for dynamic pressure based on shock tubes, fast opening and drop-weight devices were developed to provide SI-traceable calibrations in a wide pressure and frequency range 0.1 – 400 MPa and 1 – 30 kHz, respectively. The measurement range of “low-pressure” shock tubes was extended up to 40 MPa and the range for “high-pressure” drop-weight devices was extended down to 2 MPa. Consequently, traceability of measurements in the pressure range from 5 MPa to 30 MPa (relevant to ICE applications) was achieved for the first time. Moreover, the equivalence of shock tubes and drop-weight devices was demonstrated through an inter-comparison. The target uncertainty of 1 % was achieved in the pressure and frequency range up to 5 MPa and 100 Hz. At higher pressures — measured with drop-weight devices — the current uncertainty level is around 1.5 – 2.0 %. At higher frequencies, the uncertainties of shock tube calibrations become larger reaching a level of around 5 % at 30 kHz. However, sub-millisecond pressure step amplitudes can be generated at uncertainties around 2 %. Three calibration methods and standards for dynamic measurements of temperature was successfully developed and validated. The calibration system, based on rapid shutter systems, for calibrating radiance thermometer and high temperature black bodies was able to measure up to 2200 °C with temperature uncertainties below 5 °C and response time of 1 ms. In another approach, an existing blackbody calibration setup was modified for calibrating dynamic thermometers to provide traceability to the ITS-90. The performance was demonstrated by calibrating an ultra-high-speed combustion pyrometer over the temperature range from 1073 K to 2873 K with residuals < 1 %. A temperature bench based on shock tube method was developed for dynamic calibrations with µs step response up to temperature of 3000 °C with an uncertainty of 3 % (k = 2). New calibration services have been made available to customers in the pressure and temperature range up to 400 MPa and 3000 °C, respectively, to enable a wide-spread use of the developed measurement capabilities. The dynamic pressure calibrator technology developed in this project is offered to industrial end-users to enable traceable and cost-effective calibrations of dynamic pressure sensors. A calibrator has already been sold to a major European calibration service provider with the aim to launch the first accredited calibration service for dynamic pressure in Europe. Guidelines on designing, constructing, and validating measurement standards for dynamic pressure have been prepared and will be published as a EURAMET guide. Moreover, input to international standardisation organisations, such as ISO/TC108/WG34 and C.I.P., SC-2, GT 2-7, have been given to advise end-users on best practices for dynamic pressure measurements. These activities will support industry in a shift to dynamic calibrations. The objective was achieved.

Effects of influencing quantities

Comprehensive studies on the influence of process conditions — such as pressure, temperature, signal frequency and measurement media — on the sensor response were performed to obtain data on the behaviour of dynamic sensors at “real world” measurement conditions. For dynamic pressure sensors, the influence of process condition was studied in different measurement media in a wide pressure, frequency, and temperature range, i.e., 0.1 - 400 MPa, 1 – 30 kHz and up to 200 °C, respectively. Measurement media (liquid vs. gas) was found to influence the response at higher frequencies above 1 kHz. The effect was found to be several percentages of the reading. Temperature was found to influence both sensor response at low frequencies — known as temperature sensitivity — as well as the resonance frequency of the sensor, so called Q-factor, at high frequencies. To conclude, the response of dynamic pressure sensors was found to be strongly frequency dependant even at frequencies well below the nominal resonance frequency of the sensor. The effect of temperature was found similar to the temperature sensitivity stated by the sensor manufacturers. Therefore, to achieve optimum accuracy and reliable performance, dynamic pressure sensors need to be calibrated at conditions that match as close as possible the application. The influence of process conditions on the response of dynamic temperature sensors was studied at gas and body temperatures up to 3000 °C and 350 °C, respectively, with both clean and sooty flames at pressures up to 20 MPa. Studies were made for the dynamic combustion pyrometer, which is based on blackbody radiation at three wavelengths. Although the probe is unlikely to be exposed to the hot environment, tests showed a small effect on the calibration when the probe tip was exposed to temperatures of up to 350 °C, amounting to less than 1% of temperature. For the spectroscopic dynamic thermometer, based around UV and IR emissions and absorption spectra, it was demonstrated that it is possible to identify dynamic spectral features sensitive to temperature and/or pressure, i.e., pressure and temperature data can be (independently) extracted from the spectra. The response of different dynamic temperature measurements techniques showed a good agreement in different measurement media, which indicate that the developed measurement models are valid. Data from on the effects of process conditions is valuable for sensor manufacturers and end-users as it supports the interpretation of measurement results, and most importantly, enables improvements in the quality of measurements through development of better sensors and data analysis methods. To support this, models have been developed and validated to establish a robust physical basis for analysing measurement data. In addition, appropriate calibration procedures have been defined, as well as procedures for estimating measurement uncertainty in dynamic measurements. Key results and findings of these studies have been made available to public through scientific publications in peer-reviewed journals. The objective was achieved.

New measurement methods and sensors

New dynamic pressure and temperature sensors, namely a novel cylinder pressure sensor, fibre-optic combustion pyrometer and a spectroscopic band shape sensor, have been developed and characterised in partners' respective facilities in harsh environments mimicking real operating conditions inside an internal combustion engine. An IR- and UV-based spectroscopic band shape sensor was developed for ICE combustion diagnostics. It was demonstrated using NPL's standard flame that the IR-sensor provides comparable results (within 1 %) with the reference method, i.e., Rayleigh scattering technique, traceable to the International Temperature Scale (ITS-90). Extensive laboratory testing of the developed UV sensor at different pressures and temperatures up to 100 bar and 800 °C, respectively, show that both pressure and temperature can be derived from the shape of the NO absorption spectra. A novel ultra-high-speed combustion pyrometer, based on collection of thermal radiation via an optical fibre, has been successfully developed, including associated models for interpreting the acquired signal. The instrument has been traceably calibrated to the ITS-90 over the temperature range T = (1073 – 2873) K with residuals < 1 %. Dynamic tests with pyrotechnic charges have demonstrated that the instrument can measure rapid (sub-ms) events, due to its high sampling rate (up to 250 kHz): a temperature rise rate of up to ~3.25 K/µs has been estimated for explosions of large pyrotechnic charges. The accuracy of the temperature measurements can be assessed by considering the extent of agreement between readings at the three wavelengths, a self-diagnostic feature that is a critical strength of the technique. Laboratory characterisation results show that the novel dynamic pressure sensor performance is comparable to a state-of-the-art piezoelectric sensor, with respect to accuracy, repeatability, linearity and temperature sensitivity. Moreover, it was shown that a static calibration provides similar results as a dynamic calibration for the novel sensor. Therefore, a factory calibration can be performed using existing (static) pressure standards, which gives the technology a significant cost advantage compared to commercial piezoelectric sensors, which need to be calibrated by means of dynamic methods. The work on development of novel dynamic sensors have been published in peer-reviewed journals and conference proceedings. The objective was achieved.

Validation *of the methods and sensors developed in this project*

To validate and demonstrate the performance of the newly developed dynamic sensors in real operating environments, engine tests were performed in an engine testing laboratory, including tests in a real maritime test engine. The combustion pyrometer was tested in a newly developed combustion spray chamber at elevated pressure and temperature, simulating real engine operational conditions. Measurements were made for a number of different fuel/position configurations, yielding an agreement between the three measurement wavelengths of less than 50 K at over 2000 K, corresponding to 2.5 % in relative numbers. Since the level of agreement between the three separate temperature measurements gives an indication to the validity of the model, and hence uncertainty of the temperature determination, the results clearly validate the new instrument under real ICE operational conditions. The operation of the IR- and UV-based spectroscopic band shape sensor was successfully demonstrated in a Rapid Compression Expansion Machine (RCEM) at Wartsila's fuel laboratory facilities, showing that the sensor can be used for in-situ time-resolved gas temperature measurements inside an internal combustion engine. The performance of the novel dynamic pressure sensor was successfully demonstrated inside a real maritime engine. An agreement in peak pressure values of ±2 % was achieved when compared to the drop-weight dynamic pressure standard, and also when comparing against a piezoelectric sensor, which is considered an industry standard. Therefore, the novel pressure sensor is considered a viable option for cylinder pressure monitoring in large maritime engines. The overall target uncertainties of 2 % for dynamic pressure measurements up to 30 MPa and 5 % for dynamic temperature measurements up to 3000 °C were achieved. The work on developing and testing the novel dynamic sensors will be published in a special issue of the industry-oriented PTB-Mitteilungen highlighting the achievements of the DynPT project. The objective was achieved.

Impact

The project has generated 10 high-level publications in peer reviewed scientific journals. The publications are available at the end of the document or project website. In addition, the technical presentations from the stakeholder update webinars summarizing recent progress have been made available for download. Presentations include latest developments of dynamic pressure and temperature sensors and calibration techniques. A final workshop and training event was arranged in October 2021. Presentation given by project partners and invited speaker from industry are available for download at the project website. Project partners have given 12 presentations at conferences, such as the International Metrology Congress (CIM2019, CIM2021) and 9th EVI-GTI International Gas Turbine Instrumentation Conference 2019.

Impact on industrial and other user communities

Early uptake will be among accredited laboratories, companies manufacturing dynamic pressure and temperature sensors and also industry end-users exploiting the new calibration capabilities developed in this project. New calibration services for dynamic pressure and temperature have been developed and made available to customer in a wide pressure, temperature and frequency range 0.1 – 400 MPa, up to 3000 °C and

30 kHz, respectively. To further facilitate uptake, a cost-effective dynamic pressure calibrator has been developed and is now offered to calibration laboratories and industrial end-users to enable SI traceable, i.e. accurate and reliable, calibrations of dynamic pressure sensors. One calibrator has already been sold to a major calibration service provide in Europe with the aim to launch the first accredited calibration service for dynamic pressure in Europe. Moreover, a EURAMET guide on "Calibration and uncertainty for dynamic pressure" have been prepared to advise end-users on best practices on calibrating dynamic pressure sensors. In engine development, dynamically characterised pressure and temperature sensors will enhance the accuracy and reliability of measurements inside the engine and thus support development of engines with improved performance. As an example, Wärtsilä received improved capabilities to measure and analyse dynamic combustion temperature in a spray chamber and rapid compression machine engine test rigs. Recommendations for pressure and temperature measurements under harsh conditions have been given to advise end-users on suitable methods and sensors for use in combustion engines. Moreover, the novel dynamic pressure sensor technology developed in this project has received much commercial interest and negotiations on commercializing the technology is ongoing with a European sensor manufacturer. Improved dynamic pressure measurements will also benefit industries applying injection moulding, which is the principal method for plastic manufacturing, as it will contribute to improving the quality of the end products and enhance efficiency of the process through reduced scrap. Uptake and dissemination of project outcomes was ensured by close interaction with industry during the course of the project through Stakeholder Committees, workshops, training courses, (web) seminars and conferences. Almost ten conference presentations, three presentations at external events, a training course and two workshops on improved measurement of dynamic pressures and temperatures have been given. The size of audience reached so far is approximately three hundred people.

Impact on the metrology and scientific communities

New calibration services for dynamic pressure and temperature will be readily available to customers at several National Metrology Institutes (NMI) covering a wide pressure range 0.1 – 400 MPa and temperatures up to 3000 °C. This will be an important step in the transition from static to dynamic calibrations within the measurement community. The EURAMET guide on dynamic pressure includes detailed guidelines for NMIs and other high-end calibration laboratories and companies on developing and validating dynamic pressure measurement standards. This guide is the first of its kind, and as such, an important reference for calibration laboratories developing calibration capabilities for dynamic pressure. Moreover, the dynamic pressure calibrator technology developed in this project is offered to other NMI's to facilitate development of new calibration services beyond the project consortia. Negotiations with a renown European NMI on developing a primary standard for dynamic pressure standard is ongoing with the aim to launch a calibration service in 2023.

Impact on relevant standards

Guidelines for best measurement and calibration practices developed within this project will serve as input for ongoing work towards standardisation, e.g., in ISO/TC108/WG34/WT19666: Dynamic pressure calibration and EN 60079-1 on explosion protection. Consortium members are participating actively on these working groups. A close interaction and involvement in relevant EURAMET and BIPM consultative committees in the related fields has provided a channel for regional and international dissemination of the best practices developed within the project. Regarding the safety testing of ammunition, the WG GT 2-7 ("Qualité des traveaux") of the C.I.P. has been informed about the progress of this project. A presentation of consortium activities has been given in the WG GT 1-1.

Longer-term economic, social and environmental impacts

Economic impact – Internal combustion engine and injection moulding are both multi-billion-dollar industries, where even a slight improvement in engine and process performance will give European companies in this line of business a competitive edge through better quality and reduced material and energy costs.

Environmental impact – The transportation and manufacturing industry together accounts for roughly 50 % of the global CO_2 emissions and thus an even slight improvement in energy and material efficiency will have a significant impact on the environment.

Social impact – European companies adopting new calibration and measurement techniques developed within this project will gain a competitive edge in the highly competitive global market of internal combustion engines and manufacturing. This, in turn, will generate economic growth, jobs and welfare for European citizens.

List of publications

1. Yasin, Durgut *et al* 2019. Improvement of dynamic pressure standard for calibration of dynamic pressure transducers. Proceedings of 19th International Congress of Metrology 27009. https://doi.org/10.1051/metrology/201927009

2. Saxholm, Sari *et al* 2018. Development of measurement and calibration techniques for dynamic pressures and temperatures (DynPT): background and objectives of the 17IND07 DynPT project in the European Metrology Programme for Innovation and Research (EMPIR). J. Phys.: Conf. Ser. 1065 162015. doi:10.1088/1742-6596/1065/16/162015

3. Yasin, Durgut *et al* 2018. Development of Dynamic Calibration Machine for Pressure Transducers. J. Phys.: Conf. Ser. 1065 162013. doi:10.1088/1742-6596/1065/16/162013

4. O. Slanina, S. Quabis, S. Derksen, J. Herbst, R. Wynands 2020. Comparing the adiabatic and isothermal pressure dependence of the index of refraction in a drop-weight apparatus. Appl. Phys. B 126:175 (2020). https://doi.org/10.1007/s00340-020-07519-z

5. Sarraf, Christophe 2020. A method for assessing the uncertainty of a secondary dynamic pressure standard using shock tube. Measurement Science and Technology 32.1 (2020): 015013. https://doi.org/10.1088/1361-6501/aba56a

6. Yasin, Durgut *et al* 2020. Traceable dynamic pressure measurements from 50 MPa to 400 MPa. Academic Perspective, volume 3, issue 1, pages 658-664. https://doi.org/10.33793/acperpro.03.01.120

7. Sposito, Alberto, Dave Lowe, and Gavin Sutton. Towards an Ultra-High-Speed Combustion Pyrometer. International Journal of Turbomachinery, Propulsion and Power 5.4 (2020): 31. https://doi.org/10.3390/ijtpp5040031

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10. Amer, E., Wozniak, M., Jönsson, G., and Arrhén, F. (2021). Evaluation of shock tube retrofitted with fast-opening valve for dynamic pressure calibration. Sensors, 21(13), 4470. https://doi.org/10.3390/s21134470

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

Project start date and duration:	1 May 2018, 42 months	
Coordinator: Richard Högström, VTT	Tel: +358 50 303 9341	E-mail: richard.hogstrom@vtt.fi
Project website address: https://dynamic-prestemp.com/		
Internal Funded Partners: 1 VTT, Finland 2 ENSAM, France 3 NPL, United Kingdom 4 PTB, Germany 5 RISE, Sweden 6 TUBITAK, Turkey 7 VSL, Netherlands	External Funded Partners: 8 DTU, Denmark 9 KTH, Sweden 10 Minerva, Netherlands 11 Wärtsilä, Finland	
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