FINAL PUBLISHABLE REPORT

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1 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.

2 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.

3 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.

4 Results

4.1 Traceability for dynamic pressure and temperature

Accurate and reliable dynamic pressure and temperature measurements are needed for optimizing performance in modern combustion engines, manufacturing processes and aerospace applications. Typically, in these applications, fast pressure and temperature changes take place at the same time. Therefore, precise knowledge of both quantities is essential for understanding and optimizing these processes. Development of new measurement standards and calibration methods for dynamic pressure and temperature, as well as improvements to existing ones, were made to provide accurate and reliable dynamic calibrations with traceability to SI system of units. Pressure ranges from 0.1 MPa up to 400 MPa and temperatures up to 3000 °C was covered with the aim at reducing measurement uncertainties towards the industry target of 1 % for pressure and 3 % for temperature, required e.g. in ICE applications.

Development of shock tubes and fast opening devices

Further development of "low-pressure" methods based on shock tubes and fast-opening devices were made to reduce the measurement uncertainties towards the 1 % target and to extend the measurement range from 5 MPa up to 40 MPa, and thus cover the pressure range relevant to combustion engine applications and to achieve an overlap between low- and high-pressure methods.

Within this project, ENSAM improved its existing collective standard method by extending the pressure and frequency range up to 5 MPa and 30 kHz, respectively, for calibration in gas. The estimated uncertainty was < 7 % (k = 2) at 30 kHz. The so-called Mach number method was developed and validated in the frequency range from 1 kHz to 30 kHz and pressure up to 5 MPa. The estimated uncertainty is < 10 % (k = 2) at 30 kHz (Figure 1). In the low frequency range, a fast-opening device was developed having a pressure range up to 5 MPa and an uncertainty < 1 % (k = 2) at 0.1 kHz. Moreover, a secondary method was developed based on the comparison principle using a calibrated reference sensor. The operational frequency and pressure ranges of this method are 0.2 - 10 kHz and 0.5 MPa, respectively.

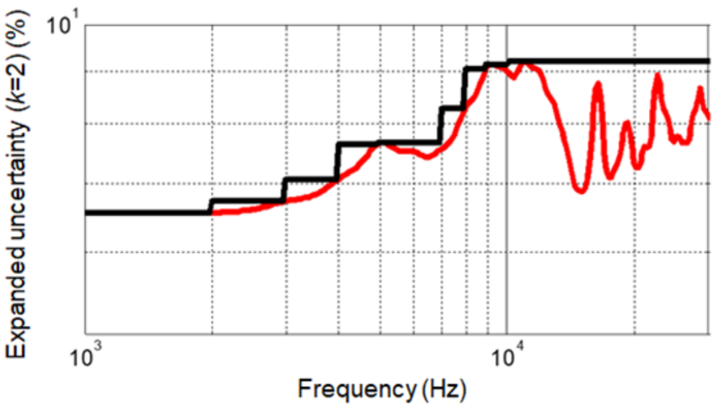

Figure 1. Graphical presentation of expanded uncertainty (k = 2) of dynamic pressure meausurement with the ENSAM shock tube (Mach number method). Raw data shown in red.

Conventional shock tubes are considered well suited for dynamic calibrations due to their inherent capability of generating pressure pulses of desired amplitude and fast rise time. However, they are currently limited to the lower end of the pressure range (≤ 7 MPa). In this project, KTH and RISE succesfully extended the operational pressure range of shock tubes up to 40 MPa and 26 MPa, respectively. This was achieved by implementing a converging test section that smoothly transforms the incident plane shock into a spherical shock wave that converges, accelerates and thereby amplifies its strength. Numerical simulations predicting the pressure profile were developed and compared with the experimental profile. Using this technique, pressure pulses with peak amplitudes in the range of 30 - 40 MPa, with uncertainties of < 3.4 % based on numerical reference profile were realized. An example of the generated pressure profile is given in Figure 2.

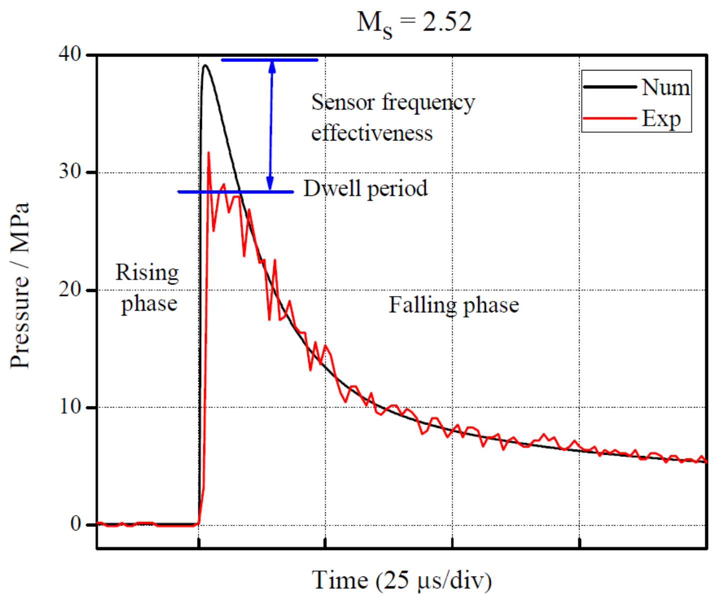

Figure 2. Comparison plot between experimental and numerical pressure profile of the KTH shock tube with converging section measured for Mach number = 2.52 shock wave.

At RISE, the shock tube was adapted to enable assessment of the realized pressure amplitude using the Mach-number method (Figure 7). This adaption included making all the measured quantities traceable to SI in order to establish a primary method of calibration. Moreover, a converging test section (similar to the KTH design described above) was implemented to extend the pressure range up to 26 MPa. Amplification by cone including uncertainties were determined by numeric simulations. Furthermore, a method was formulated and applied to describe the dynamic behaviour of pressure sensors in frequency domain.

Development of drop-weight devices

New and improved measurement standards for high-pressure dynamic calibrations based on the drop-weight method were developed in the pressure range from 2 MPa to 400 MPa with the aim to lower the uncertainties towards the 1 % requirement and extend the pressure range downwards from 20 MPa to 2 MPa. With this method, half-sine shaped pressure pulses with a few millisecond durations are generated. This corresponds well to pressure pulses inside combustion engines and those generated in ammunition safety testing, making this method well suited for calibrating dynamic pressure sensor used in such high-pressure applications.

In engine applications, besides fast pressure transients, dynamic pressure transducers are subject to elevated temperatures. Sensors are to some degree affected by temperature, the so-called temperature sensitivity. Therefore, transducers should ideally be calibrated at conditions that correspond to the operating environment. To answer these needs, VTT MIKES has developed its drop weight dynamic pressure primary standard further. Developments include improved control and measurement of the falling weight, extension of the pressure range to combustion engine pressures down to 2 MPa and a heating option for dynamic pressure transducers under calibration. These advances enable traceable calibration of cylinder pressure transducers at conditions relevant to engine applications. The overall uncertainty (k = 2) of calibration is estimated to be around 1.7 % in the applicable pressure range. The performance was demonstrated by calibrating a piezoelectric pressure transducer in the pressure range from 7 MPa to 30 MPa at temperatures 20 °C, 120 °C and 180 °C (Figure 3). As a result, traceable calibrations of dynamic pressure transducers can be performed at conditions relevant for engine applications. This improves the reliability and accuracy of in-cylinder pressure measurements. Moreover, a secondary dynamic pressure calibrator based on reference sensor principle was developed to provide a cost-effective calibration solution for calibrating dynamic pressure sensors in the range from 2 MPa up to 50 MPa at temperatures up to 200 °C with an uncertainty (k = 2) of 3 %.

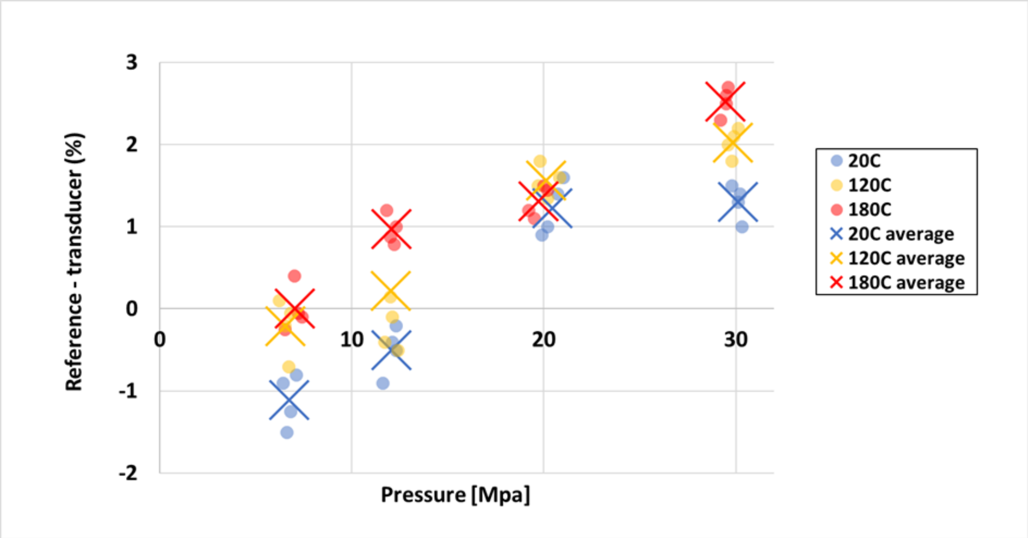

Figure 3. Calibration results with the VTT MIKES primary dynamic pressure standard for a commercial piezoelectric transducer.

PTB has developed a drop-weight device for dynamic calibration of pressure sensors based on the refractive index method (Figure 4), where the pressure is derived from the change in refractive index of the pressurized medium, as measured by a laser vibrometer. The applicable pressure range of the developed dynamic pressure measurement standard is 60 MPa up to (at least) 400 MPa. An important thing was to investigated the difference between adiabatic and isothermal compression of liquids by an impacting weight, as observed in the resulting change to the index of refraction. The liquids examined were sebacate, glycerol, and water. For practical reasons, sebacate is best suited for the use of a drop-weight device as a metrologically traceable calibration facility for dynamic pressure. It was found that its optical properties under adiabatic and isothermal compression can be converted into each other using literature values of its thermodynamic properties. Care has to be taken to avoid cavitation-like effects, an observation that might need to be taken into account for other methods of generating short pressure pulses in the hundreds-of-MPa range. PTB also investigated two different traceability routes for its drop-weight standard. Both routes require their own set of detailed material parameters which, however, are not sufficiently known. At its current state, the estimated relative measurement uncertainty is in the 1 - 2 % range, increasing for pressures below 100 MPa.

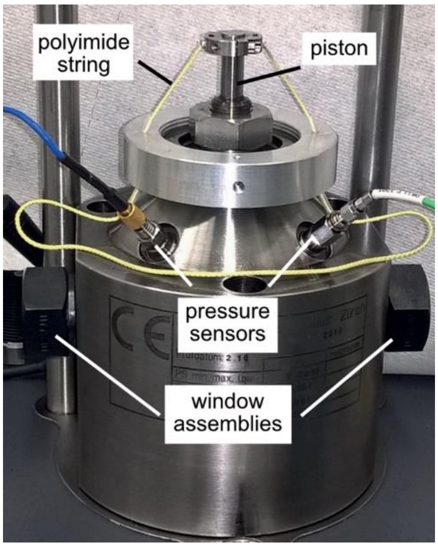

Figure 4. Detail of the pressure cell of the PTB dynamic pressure standard, showing the polyimide strings needed to prevent the formation of cavitation bubbles.

TUBITAK has developed a dynamic pressure standard up to 400 MPa based on drop-weight method. Experimental measurements were performed from 50 MPa to 400 MPa. The displacement of the dropping-mass during impact (needed for deriving impact force and further pressure) was measured using a 3-beam laser interferometer configuration. Using three laser beams, yaw and pitch errors of the vertically moving mass were minimised. Additionally, to reduce beam misalignment errors, the path of the laser beam was shortened by increasing the weight of the dropping mass to enable a smaller drop height. Experimental results show that the expanded uncertainty is around 2 % (k = 2). An example of the generated pressure pulses is given below (Figure 5).

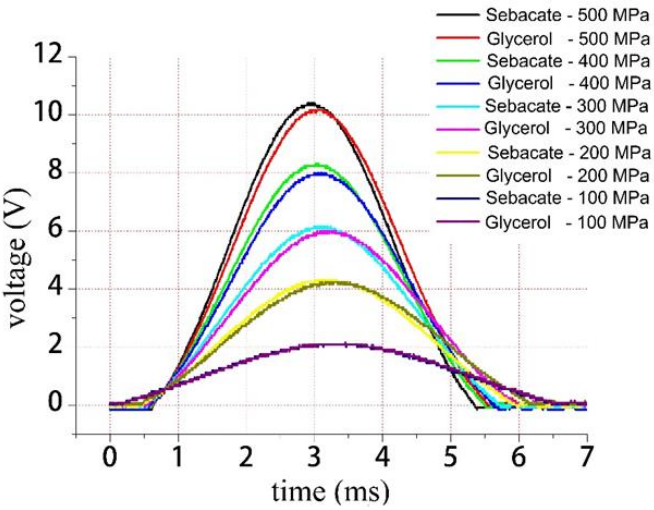

Figure 5. Pressure pulses generated with the TUBITAK dynamic pressure standard in the pressure range 100 – 500 MPa for different pressure transmitting liquids as recorderd by a commercial pressure transducer.

VSL and Minerva jointly developed a new dynamic pressure standard based on laser vibrometer measurement of the change in refractive index of pressurized fluid. Through a static calibration, the vibrometer output signal is linked to a traceable pressure. In order to apply this calibration for dynamic pressure measurements, a static-dynamic conversion factor has to be applied to account for the difference between isothermal static compression and adiabatic dynamic compression. This conversion factor has been derived successfully and confirmed in an empirical manner. Validation measurements using commercial dynamic pressure sensors indicate that the approach is viable and has potential for a cost-effective solution for dynamic calibrations in industry. Further development is needed to estimate the uncertainty and secure the performance at higher pressures above 100 MPa.

Development of dynamic temperature calibration methods

Temperature sensors are currently calibrated at steady state conditions, even if they are used in non-static conditions. This means that the validity of the calibration curve during transient temperature changes is questionable, which has direct implications on the reliability of temperature data used for, e.g. engine development. Some approaches for characterizing sensor response under dynamic conditions exists, but these methods have not been properly validated nor do they provide traceability to SI. In this project, three new approaches for calibrating high-frequency response sensors were investigated covering the temperature range up to 3000 °C, with a target uncertainty of 3 %.

A fully automated diaphragm-less shock tube for dynamic temperature measurement was developed at KTH. The facility was tested with helium-air and helium-argon compositions. Studies on the effect of boundary layer on the resulting temperature profile were made. Results indicate negligible effect of boundary layer on the resulting temperature profile at measurement stations. The newly constructed shock tube was tested using various methods (like optical, shock velocity, pressure sensor method etc.) for temperature measurement. The shock tube was able to achieve 3000 °C and the feasible estimation method was shock jump relations/shock velocity measurement technique with expanded uncertainty (k = 2) of 2 % (Figure 6). A cross-validation of the developed calibration setup was performed together with DTU and NPL.

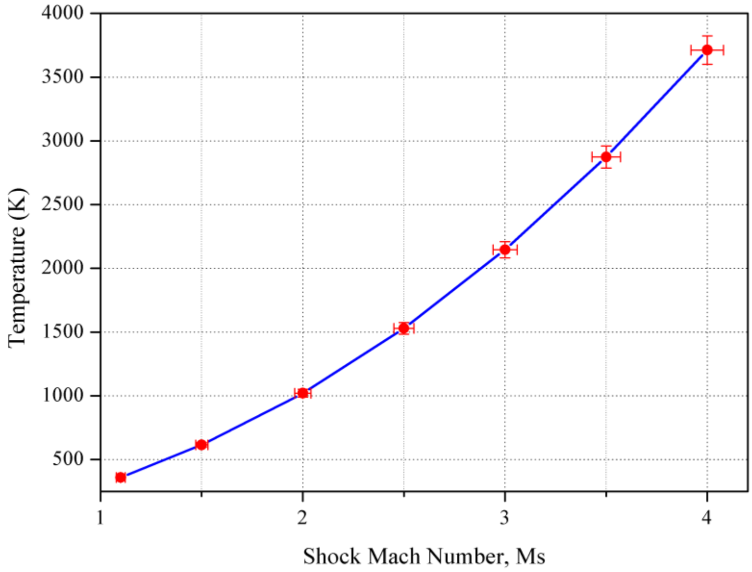

Figure 6. Temperature validation curve of the shock tube dynamic temperarature calibration bench

At NPL, a radiance-based facility for calibration of dynamic thermometers traceable to ITS-90 using high-temperature blackbody furnace up to 3000 °C has been developed for fibre-optic dynamic thermometers. 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 new dynamic calibration system and method for calibration of radiance thermometers based on rapid shutter systems and high temperature black bodies was developed at RISE. The estimated uncertainty (k = 2) of calibration at 500 °C and 2200 °C was 2.2 K and 4.5 K, respectively. Cross-validation between calibrations facilities was performed at various temperatures and chopping frequencies (up to 1 kHz, i.e. 1 ms). The test proved the speed of the NPL fibre-optics dynamic thermometer (presented in 4.3), with maximum dynamic temperature matching static temperature.

Summary of development of dynamic pressure and temperature calibration methods

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. 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 7 % 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 were 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 less than 1 ms. In another approach, an existing blackbody calibration setup was modified for calibrating dynamic thermometers to provide traceability to the ITS-90 over a temperature range from 1073 K to 2873 K with an uncertainty of less than 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). The target uncertainty of 3 % was thus achieved for the newly developed methods and, as such, these methods provide a reliable and accurate reference for calibrating dynamic thermometers.

The project achieved the objective with these results.

4.2 Effect of influencing quantities

Standard industry practice is to calibrate dynamic pressure sensors at room temperatures using the so called quasi-static method, which is based on applying a pressure balance (static reference). However, in actual applications, e.g. inside a combustion engine, fast transient pressure changes take place and temperatures can be as high as 300 °C (surface temperature), and even 3000 °C (combustion gas). The validity of the quasi-static calibration is, therefore, questionable and errors up to ten percent might occur. In this project, the influence of process conditions — such as pressure, temperature, signal frequency, and measurement media — on the response of dynamic pressure sensors was investigated and quantified. Based on the results, appropriate calibration procedures and uncertainty estimation methods were developed.

For measuring very fast dynamic temperature changes, conventional contact thermometers are not applicable due to their slow response times. Instead, high-frequency dynamic temperature sensors based on the measurement of the optical properties of the observed media are frequently applied. However, there are no appropriate means available to evaluate the uncertainty of these measurements due to insufficient understanding of factors influencing their response. In this project, research was undertaken to better understand how optical signals relate to process parameters, such as temperature and pressure of the media, in order to determine and reduce the uncertainty of measurements closer to the target level of 5 %. Models were developed and validated to establish a robust physical basis for analysing measurement data.

Effect of process parameters on dynamic pressure sensor performance

Calibrations are inherently always performed under well controlled and defined conditions to establish traceability to the quantity of interest and to achieve a good repeatability, and thus a low uncertainty. This, however, implies that assumptions and simplifications with respect to “real world” measurement conditions need to be made. To make smart compromises and achieve an optimum balance between representativeness and uncertainty of calibration, the effect of process conditions on the sensor response needs to be well known. Knowledge of the effect of process parameters on the sensor response is also needed for estimating the measurement uncertainty in real process environments. In this project, the influence of the following parameters was studied in detail: measurement media (liquid/gas), temperature (up to 200 °C) and signal frequency (1-10 kHz) in the pressure range from 0.1 MPa to 400 MPa.

TUBITAK investigated the influence of different pressure transmitting fluids (sebacate and glycerol) on the calibration results in the pressure range from 100 MPa to 500 MPa using their newly developed drop-weight dynamic pressure standard. Calibrations results (Figure 5) show a difference of 1 - 2 % in the recorded peak pressure for different pressure media. The observed differences are believed to be attributed to the measurement standard rather than to the dynamic pressure transducer under calibration. Although the differences are rather small and within the calibration uncertainties, further studies are needed to better understand the reasons for the observed deviation.

RISE studied the influence of different non-corrosive gases (Ar, air, N_2 and a mix of CO_2 and N_2) on the dynamic sensor sensitivity in the pressure range up to 1.4 MPa using their shock tube facility (Figure 7). It was found that the pressurized media did not affect the dynamic response of the piezoelectric dynamic pressure sensor used in the study. RISE also performed studies on the influence of media and sensor body temperature on the sensitivity of a commercial piezoelectric sensor at temperature up to 150 °C. Evaluation of results, including numerical simulations on the Influence of temperature on pressure measurements, were conducted in collaboration with KTH. Results show that the sensor under test becomes less damped with increased sensor temperature. A change in media temperature should not affect the sensor characteristics directly although it may have indirect effects through temperature correlation.

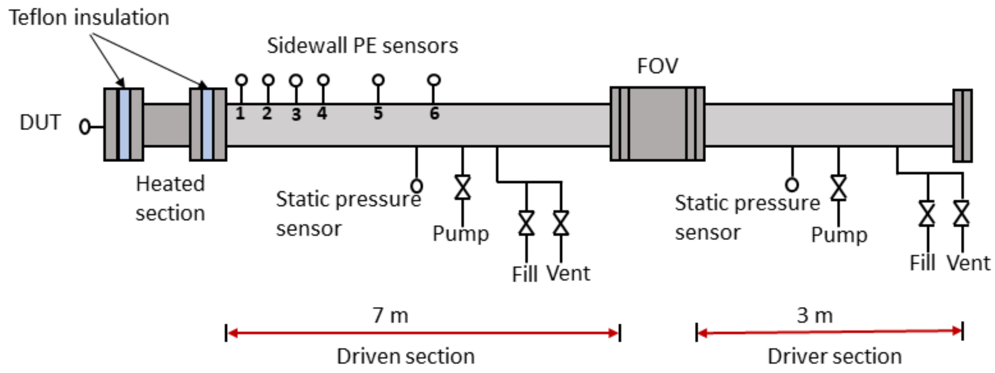

Figure 7. Extension of RISE shock tube allowing independent heating of driven gas and sensor.

The influence of signal frequency and measurement media (nitrogen vs. silicon oil) on dynamic pressure sensor response was studied at ENSAM. Measurements with the shock tube show that the dynamic sensor response depend on the signal frequency and that the calibration uncertainty increases with frequency (Figure 8). These results imply that the current industry method of quasi-static calibration provides equivalent results with the shock tube only at low frequencies (below one kilohertz for this particular piezoelectric sensor), which underlines the importance of calibrating dynamic sensors in the frequency range corresponding their actual use. Also, the sensor response is different in nitrogen (gas) and silicon oil (liquid) at higher frequencies above 1 kHz where damping of the sensor response is observed.

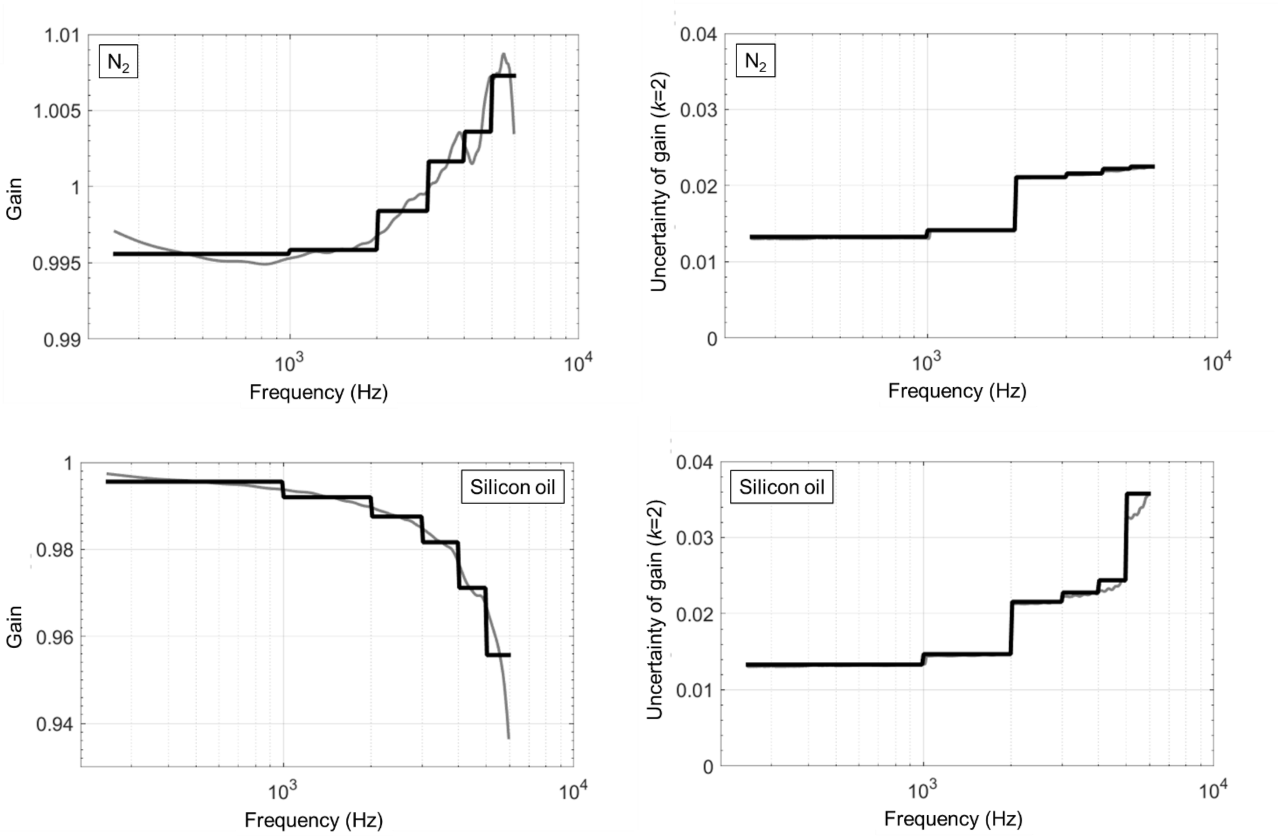

Figure 8. Calibration results for a commercial piezoelectric sensor calibrated in nitrogen and silicon oil media. Graphical representation of the sensor gain (left) and expanded uncertainty (k = 2) (right). Raw data in gray for information.

At KTH, the influence of media (air and water) on the response of a piezoelectric sensor was investigated using a vertical shock tube (up to 15 MPa) and an exploding wire setup (0.5 – 0.6 MPa), both capable of generating shock waves with very short rise time. For the vertical shock tube an oscillating profile with larger offshoots during initial impact were observed due to the reflection of the shock wave across the water column.

To avoid the oscillating nature of the profile, experiments were performed in the exploding wire setup. A 15 % overshoot of the sensor response was observed for measurements in water media relative to measurements in air. This result appears to be contradictory to the results of ENSAM, were damping of sensor response was observed in liquid. The observed discrepancies might be caused by the different sensors used in the studies, as well as the experimental condition, e.g. different liquids (water vs. silicon oil) and frequency content of generated shock wave. Consequently, it was not possible to draw general conclusions on the behaviour of sensors in different media. Further studies are needed to understand the phenomena causing changes in the sensor response. The main conclusion is that sensors should preferably be calibrated in a pressure media corresponding the actual application. This is especially important when measuring high-frequencies above 1 kHz.

VTT studied the influence of temperature on the dynamic response of a commercial piezoelectric sensor. To realise a reliable, i.e. SI traceable, method for calibrating dynamic pressure sensors at high temperatures, the VTT MIKES primary dynamic pressure standard was applied with modification to the measurement head to enable heating of the sensor (Figure 9). Silicon oil was used as the pressure media to enable heating up to 200 °C. Calibration measurements were performed at peak pressures of 7 MPa, 12 MPa, 20 MPa and 30 MPa for temperatures of 20 °C, 120 °C and 180 °C. Pressure pulses generated with the VTT MIKES primary standard have a half-sine shape and a duration of around 4 ms and thus corresponds well to pressure pulses inside an internal combustion engine. Calibration results indicate that there is a temperature sensitivity of about 1 % / 100 °C (Figure 3), which is within the manufacturer specification of ±0.02 % / °C. The results indicate that it is necessary to calibrate dynamic pressure sensors at temperatures that correspond to the actual operating temperature to achieve optimum accuracy and ensure traceability of measurement. For instance, the 1 % accuracy requirement in combustion engines applications can only be achieved by calibrating the sensor at operating temperature, typically around 150 - 200 °C, depending on the engine type. This is an important finding, which will influence the recommendations for calibration procedures and uncertainty estimations at process conditions.

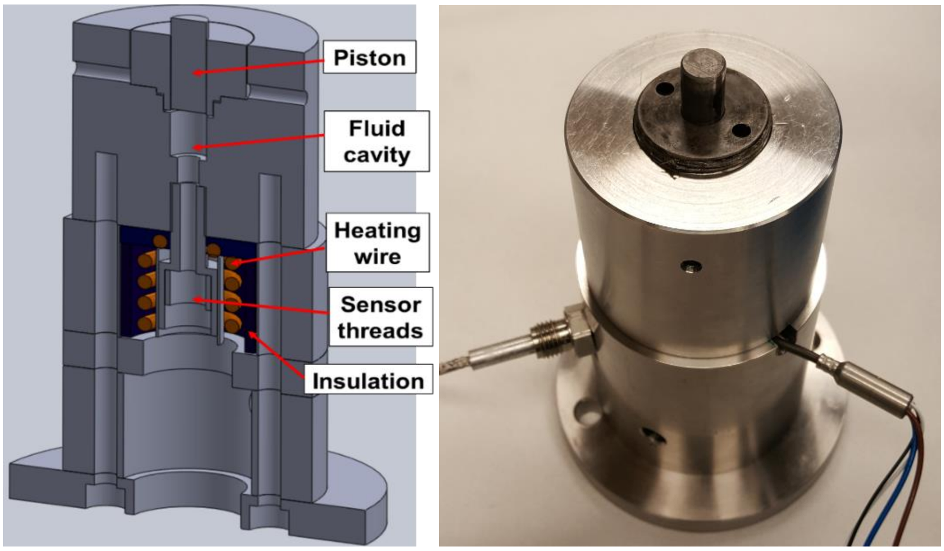

Figure 9. Modified measurement head with heating option. The sensor is connected from below using sensor threads of the measurement head. The fluid inside the cavity is in contact with the sensor membrane, thus transferring pressure generated by piston compression to the sensor.

Influence of process parameters on dynamic temperature sensor response

Studies on the influence of process parameters, such as media (clean/sooty flames), pressure and sensor body temperature, was performed for different types of dynamic temperature sensors developed within this project, namely a fibre optic thermometer and a spectroscopic band shape sensor. Measurements were performed at gas and body temperatures up to 3000 °C and 350 °C, respectively, with both clean and sooty flames and at pressures up to 10 MPa in the operational frequency range of the respective measurement facilities of partners.

NPL performed studies on the influence of the probe temperature (up to 350 °C) on the performance of a fibre optic thermometer (presented in 4.3). The test setting was designed to simulate conditions that could be expected during field trials on an internal combustion engine. It was shown that heating the probe to 623 K (350 °C) resulted only in a small temporary change in the measured temperature (less than 2 K). If a typical process has a temperature of 2000 K, this amounts to a 0.1 % error, which is negligible considering the overall uncertainty of 5 % for this method. Moreover, the dynamic response and accuracy of the fibre optic thermometer in measuring temperature of rapidly changing sooty flames was studied at NPL's pyrotechnics facility. For small charges, agreement at the three measurement wavelengths was poor (up to 600 K difference). For larger charges, the agreement was better than 137 K (4.5 %), due to the fact than the emission from the fireball is similar to that of a blackbody (Figure 10). The system was also demonstrated to be able to detect extremely fast changes in temperature of at least 3.25 K/µs. The dynamic performance of the fibre-optic sensor was further characterised at RISE high-speed shutter calibration facility, where a response speed of at least 1 kHz (limited by the speed of the shutter system) was demonstrated. The absolute differences in measured radiance temperature between that measured by RISE (using traceable methods) and the NPL thermometer were found to be less than 2.5 % — this is believed to be due to the size of source effect of the fibre-optic probe and can be mitigated with improved sensor head design.

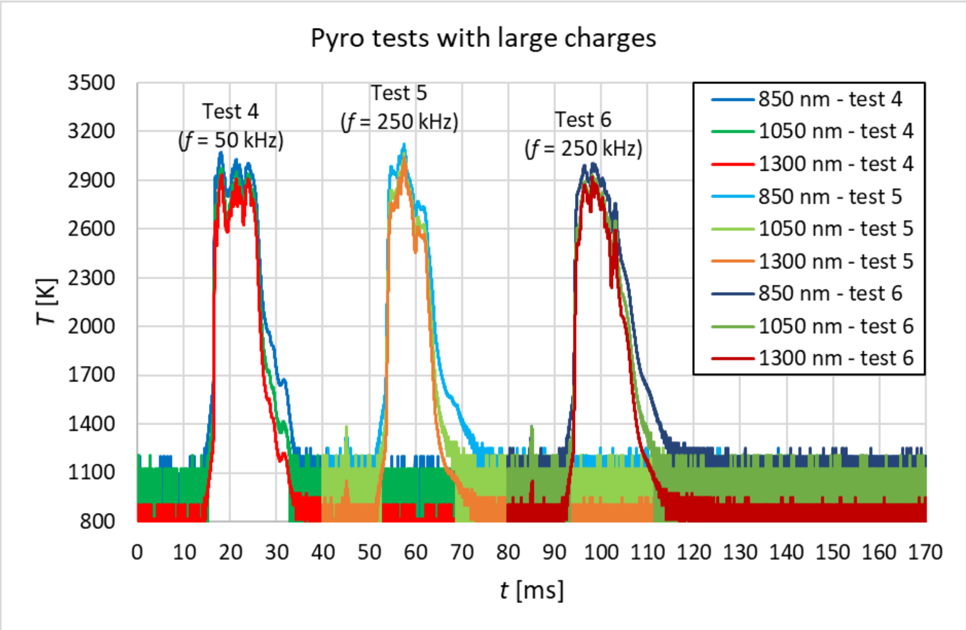

Figure 10. Time trend of temperatures measured with the fibre optic thermometer for pyrotechnic tests with large charges – temporal offset introduced for clarity.

The performance of the DTU UV- and IR-based spectroscopic sensors (presented in 4.3) in sooty flame environments was investigated at NPL's pyrotechnics facility. Several types of explosions in terms of their duration and power were utilized. It was demonstrated that the spectroscopic sensors can be used for dynamic temperature measurements in sooty environments and both sensor's (UV and IR) performances were not affected by the measurement media. To investigate joint effects of pressure and temperature on the response of the spectroscopic sensors, measurements in DTU's high-temperature/high-pressure gas cell were performed. Results indicate that both temperature and pressure can be extracted by analysis of spectral features of the measured signal (Figure 11). The sensor dynamic response in the micro- to millisecond range was demonstrated at the dynamic temperature calibration facility (shock tube) at KTH and using the high-speed shutter calibration setup of RISE. Moreover, it was concluded that the probe temperature does not affect the performance of the spectroscopic sensors, because the receiver part of the sensor, which holds the collimating optics and a fibre, is placed outside of the high-temperature environment, i.e. it is held in an ambient environment, below 50 °C, to which most electronic components are rated. Such low temperatures have only a minor effect on the performance of the spectroscopic sensors. Any variations in ambient temperature is accounted for just prior the measurements in hot medium by the so-called dark or background measurements.

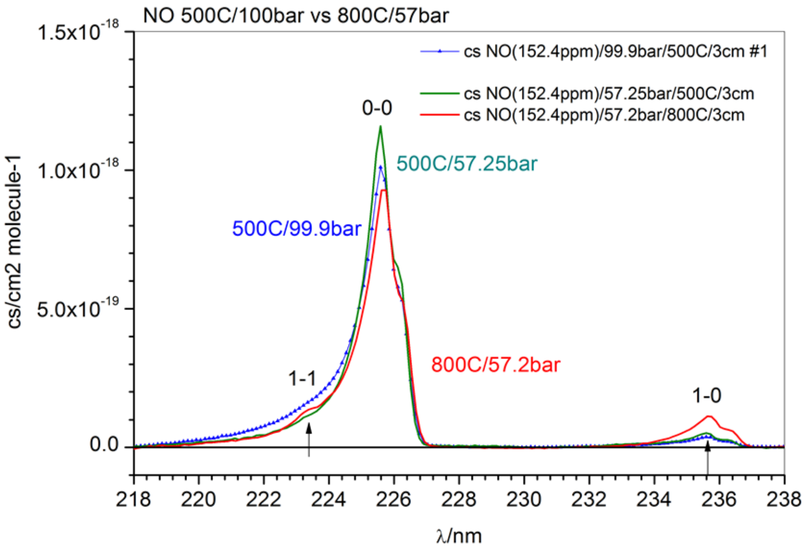

Figure 11. Band shape of UV-/IR-sensor depend on both pressure and temperature as shown for NO absorption cross-sections. Different colours correspond to different pressures/temperatures.

Summary of effect of influencing quantities

The influence of process condition was studied in a wide pressure, frequency and temperature range of 0.1 - 400 MPa, 1 – 30 kHz and up to 200 °C, respectively. Pressure signal frequency, measurement media and temperature, were all found to influence the response of dynamic pressure sensors. Measurement media (liquid vs. gas) was found to influence the response at higher frequencies above 1 kHz. The effect can be several percentages of the reading. In some experiments damping of the sensor response was observed for measurements in liquid (as opposed to measurements in gas) at frequencies above 1 kHz, while other results indicate an overshoot of the pressure signal. The observed discrepancies might be caused by the different sensors used in the studies, as well as the experimental condition, e.g. different liquids (water vs. silicon oil) and frequency content of generated shock wave. Consequently, it is not possible to draw general conclusions on the behaviour of sensors in different media. Further studies are needed to understand the phenomena causing changes in the sensor response. Temperature was found to influence both sensor response at low frequencies (as shown in experiments made in liquid), the so-called temperature sensitivity, as well as the resonance frequency of the sensor, so called Q-factor, at high frequencies. Temperature sensitivity is known to be sensor dependent, and therefore results presented in this study cannot be generalized for other sensors. It can be concluded that sensors need to be calibrated at conditions that match as closely as possible to actual measurement conditions in terms of temperature, frequency and measurement media. Based on data on influencing factors and experience on development of dynamic pressure measurement standards, guidelines and recommendation for dynamic pressure calibrations, including means of estimating uncertainties, were made and published as a EURAMET guide.

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 10 MPa. Studies were made for the NPL dynamic combustion pyrometer, which is based on blackbody radiation at three wavelengths. Measurements at NPL's pyrotechnics facility demonstrate that the agreement between the three wavelengths (a measure of the sensor accuracy) was better than 4.5 %. Moreover, an agreement of 2.5 % was achieved when compared to the RISE high-speed shutter facility. Therefore, it was concluded that the target accuracy of 5 % for dynamic temperature measurements was achieved. Dynamic tests show that the sensor is extremely fast and able to detect dynamic temperature changed of at least 3.25 K/µs. Probe temperature (up to 350 °C) was found to influence the sensor response only slightly (effect on calibration was less than 1 %). Additionally, spectroscopic modelling demonstrated that the system is suitable for sooty flames only. For DTU's spectroscopic dynamic thermometers, 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. Moreover, uncertainty models for estimating uncertainties of dynamic temperature were successfully developed and published in peer-review journals.

The project achieved the objective with these results.

4.3 New dynamic pressure and temperature sensors

One of the key objectives of this project was to develop new measurement methods and sensors that are suitable for measuring dynamic pressure and temperature in harsh conditions, with particular emphasis on their application in internal combustion engines. Currently dynamic pressure sensors that are used in harsh conditions, such as inside a combustion engine, tend to degrade and break down, which compromises the validity of results with implications on product quality and cost effectiveness. In this project, novel pressure sensors based on bending membrane (patented) design with improved reliability was developed and characterised in the laboratory. Moreover, a commercial prototype sensor designed for combustion engine applications was fully characterised by means of static and dynamic pressure measurement. Non-contact dynamic temperature sensors provide superior response times compared to contact thermometers, but the interpretation of the acquired data is complex, which may result in significant uncertainties. In this project, novel high-speed sensors based on optical methods were developed and metrologically validated in the laboratory to improve the performance through a better understanding of uncertainty sources. In addition, tests in real engines were performed to demonstrate their performance in real operating environments (presented in 4.4).

Development and characterisation of novel dynamic pressure sensors

Current dynamic pressure sensors tend to degrade and break down when used in harsh environments, e.g. inside combustion engines. At the moment, in these applications dynamic pressure sensors are used basically on a throwaway-basis, causing substantial cost (a single sensor might cost up to 4 k€). Improved durability of sensors will also open up totally new opportunities, as it will enable engine manufacturers to install in-cylinder pressure sensors and thus achieve better engine control and improved engine performance (more power and reduced fuel consumption). There is an apparent need for a new generation of sensors, which can handle short-term overloading by pressure and temperature without breaking, and additionally, withstand unprecedented numbers of pressure pulses during their lifetime. Within this project, novel sensors (bending membrane capacitive sensor and a commercial prototype sensor) were characterized for use in ICE applications. The performance was demonstrated and compared to state-of-the-art sensors currently in use.

VTT has developed a new sensing technology for dynamic pressure measurements at harsh conditions (Figure 12), such as inside a maritime combustion engine, where cylinder pressures can reach up to 30 MPa. Moreover, sensors mounted into the cylinder head need to withstand temperatures up to 200 °C. To demonstrate the performance of the developed technology, validation measurements were performed using the primary dynamic pressure standard of VTT MIKES equipped with a heating option (Figure 9). The pressure pulses generated with the VTT dynamic pressure standard have a half-sine shape and a duration of a few milliseconds, which corresponds well to pressure pulses inside an engine cylinder. Results of calibration measurements at pressures and temperatures up to 30 MPa and 180 °C (Figure 13), respectively, show that the performance of the VTT sensor is comparable to a state-of-the-art piezoelectric sensor with respect to accuracy, linearity, repeatability and temperature sensitivity (calibration results for a piezo-electric sensor shown in Figure 3). 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.

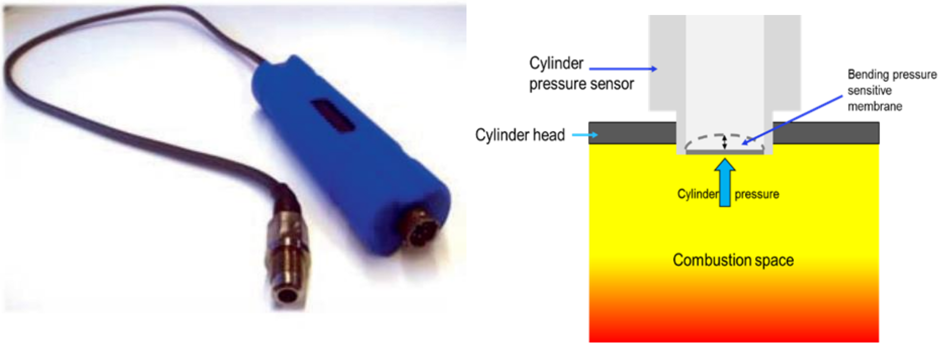

Figure 12. VTT dynamic pressure sensor (left figure) is based on sensing the change in capacitance between the bending membrane and the static electrode (principle shown in figure to the right).

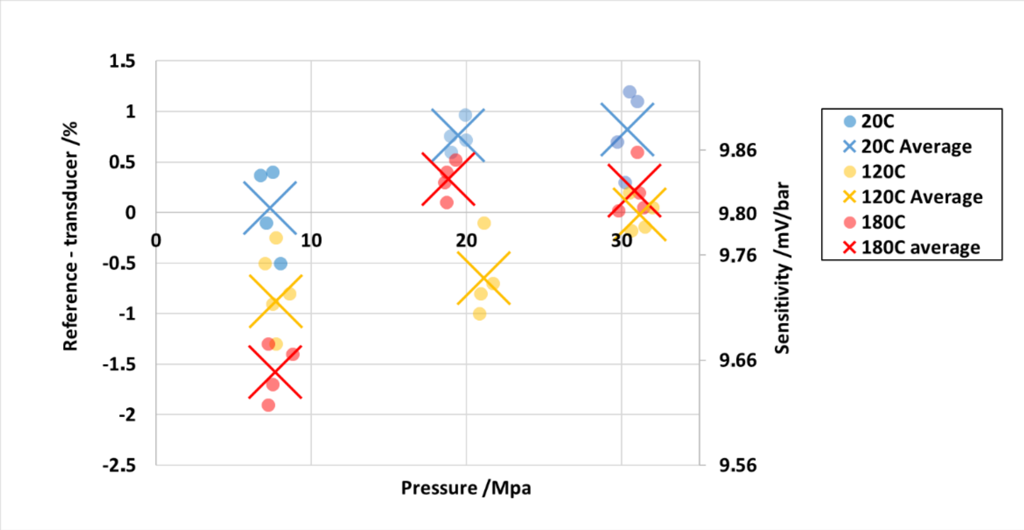

Figure 13. Calibration results of the VTT dynamic pressure sensor.

The dynamic behaviour of a commercial prototype pressure sensor was determined at RISE shock tube facility in the pressure range up to 26 MPa and results were compared to a static calibration. A good agreement (within experimental uncertainties) was found between the sensitivity in the vicinity of 0 Hz from the dynamic calibration and that calculated from the static calibration (Figure 14). Moreover, the dynamic response was found to be fairly flat up to frequencies of about 25 kHz, indicating that the sensor dynamics is sufficient for engine applications.

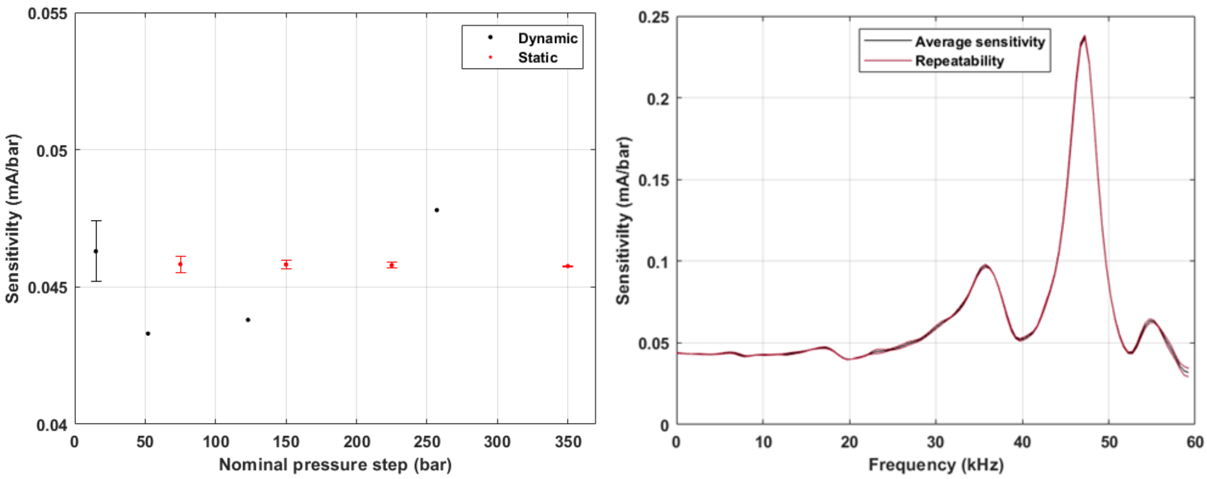

Figure 14. Left figure: A comparison of the sensitivity in the vicinity of 0 Hz calculated from dynamic and static calibrations. The error bars represent the expanded uncertainty. Right figure: Dynamic sensitivity at a shock amplitude of 12.3 MPa.

VSL and Minerva undertook collaborative work on testing dynamic pressure sensors from two different manufacturers using their newly developed refractive index based drop-weight dynamic pressure standard. Performance tests were made up to 250 MPa. In order apply the measurement standard for dynamic pressure measurements, a static-dynamic conversion factor was used to account for the difference between isothermal static compression and adiabatic dynamic compression. Results show similarity between the measured sensitivity by the measurement standard and the manufacturer specified sensitivity, which indicates that the method has potential to become a primary method for dynamic pressure.

Development and characterisation of novel dynamic temperature sensors

Dynamic temperature sensors can be divided into two categories: contact and non-contact. Contact sensors, such as the fine wire mineral-insulated thermocouple (diameter about 250 μm), have moderate response times on the order of 10 ms and measure their intrinsic temperature. This leads to complexity in inferring the temperature of the dynamic media that the probe is immersed in (flames, gases and other fluids) and can easily result in large errors. More recently, state-of-the-art non-contact temperature sensors based on the measurement of the optical properties of the media itself (e.g. emission/absorption spectrum) have advanced and found more widespread use. These sensors have response times that are only limited by the detector response and required signal integration time. For internal combustion engines, sample rates of 100 kHz or higher are now possible. However, due to the complexity in interpreting the acquired signal and the subsequent data reduction, the measurement uncertainty can often be significant. Within this project, novel high-speed sensors based upon thermal radiance and spectroscopic absorption/emission bands were developed. Traceability is provided by calibration against the International Temperature Scale of 1990 (ITS-90) and validation was performed in both shock-tubes and internal combustion engines (presented in 4.4).

Measuring reliably the correct temperature of a sooty flame in an internal combustion engine is important to optimise its efficiency. However, conventional contact thermometers, such as thermocouples, are not adequate in this context, due to drift, temperature limitation (≤2100 K) and slow response time (~10 ms). To overcome these issues, NPL developed a novel ultra-high-speed combustion pyrometer (Figure 15), based on collection of thermal radiation via an optical fibre, and performed extensive calibration, testing and validation experiments to verify its performance. The instrument was traceably calibrated to the ITS-90 over the temperature range T = (1073 – 2873) K with residuals <1 % and a combined relative uncertainty (k = 2) of less than 2.5 % (Figure 16). Dynamic tests with pyrotechnic charges demonstrated that the instrument can measure rapid (sub-ms) events (Figure 10), due to its high sampling rate (up to 250 kHz): a temperature rise of up to ~3.25 K/µs was 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. Based on developed measurement models and laboratory experiments, the dynamic thermometer was found suitable for measuring sooty flames, representative to combustion conditions inside diesel engines.

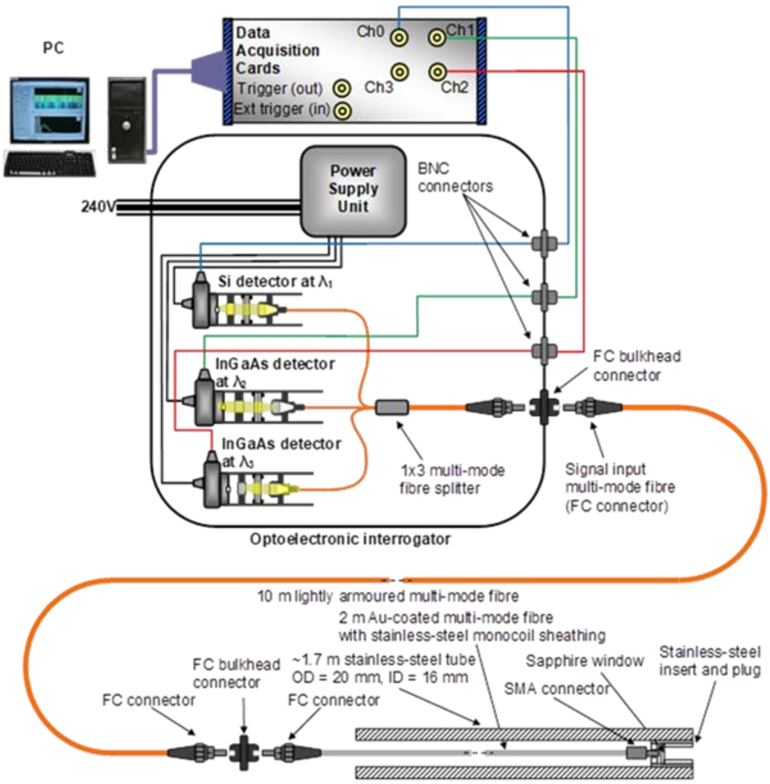

Figure 15. The NPL dynamic combustion pyrometer.

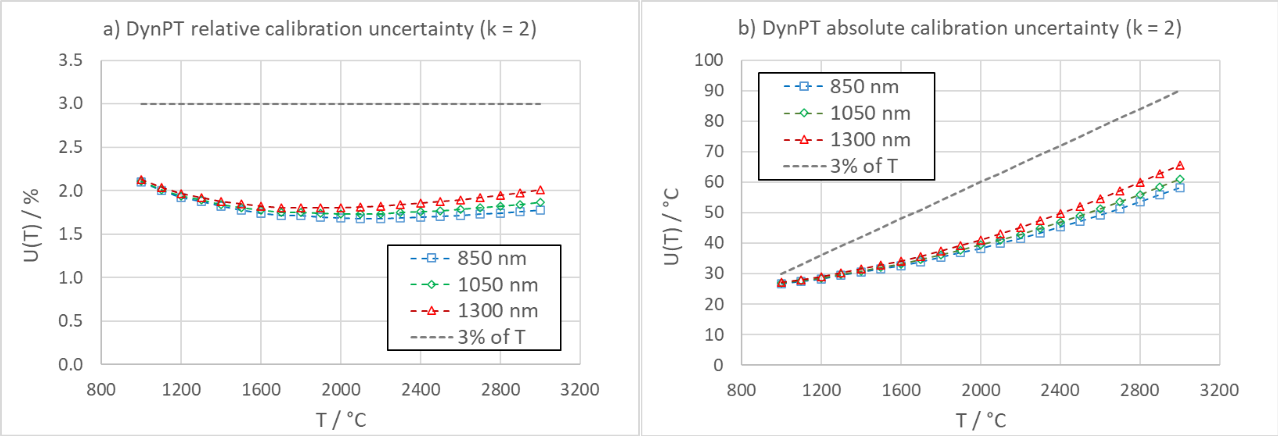

Figure 16. NPL DynPT combustion pyrometer calibration uncertainty (k = 2): a) relative, b) absolute.

At DTU, an IR- and UV-based spectroscopic band shape sensor was successfully developed and tested. It was demonstrated using NPL's standard flame that the IR-sensor (Figure 17) 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 (Figure 18) at different pressures and temperatures up to 100 bar and 800 °C, respectively, show that both pressure (Figure 11) and temperature (Figure 19) can be derived from the shape of the NO absorption spectra. Models for extracting both temperature and pressure data from the spectral features were developed to provide a robust physical basis for interpreting the measured signal.

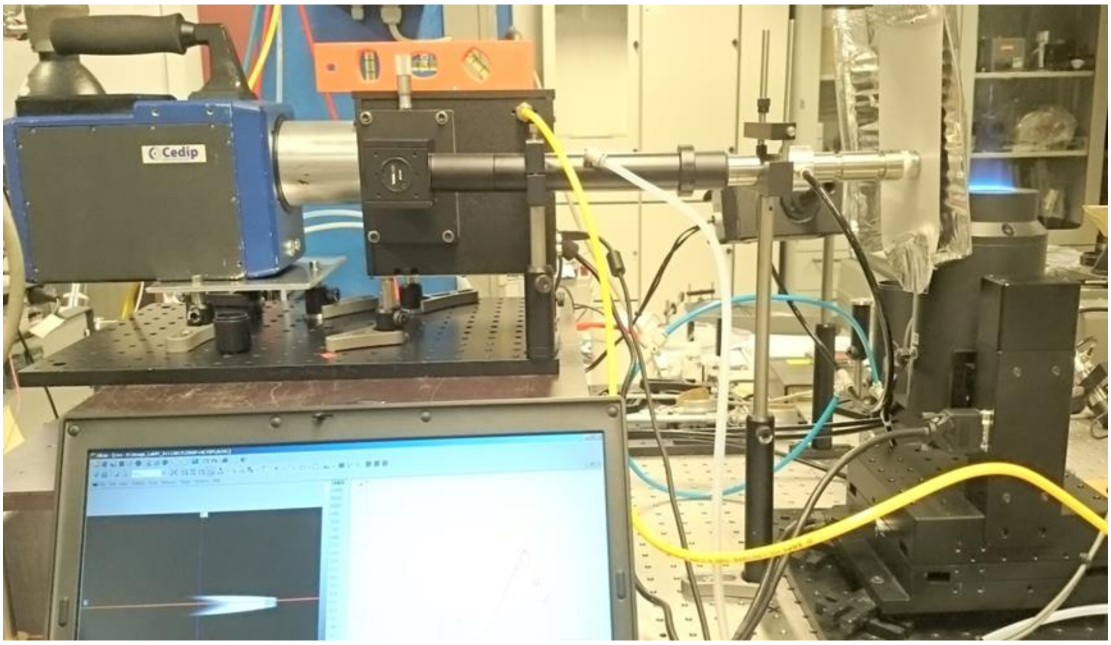

Figure 17. IR-based sensor at NPL's STD flame. Flame thermal image is shown on the computer display as a narrow white-coloured strip.

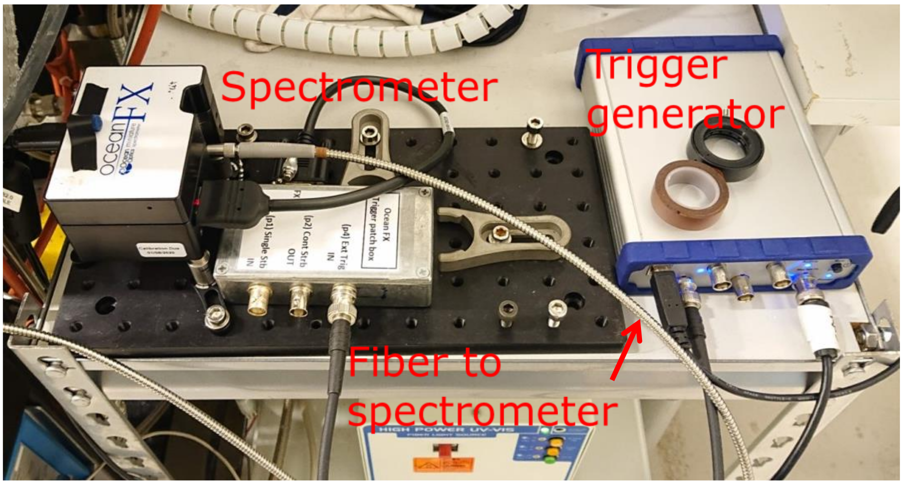

Figure 18. DTU's fast compact UV spectrometer with own trigger generator.

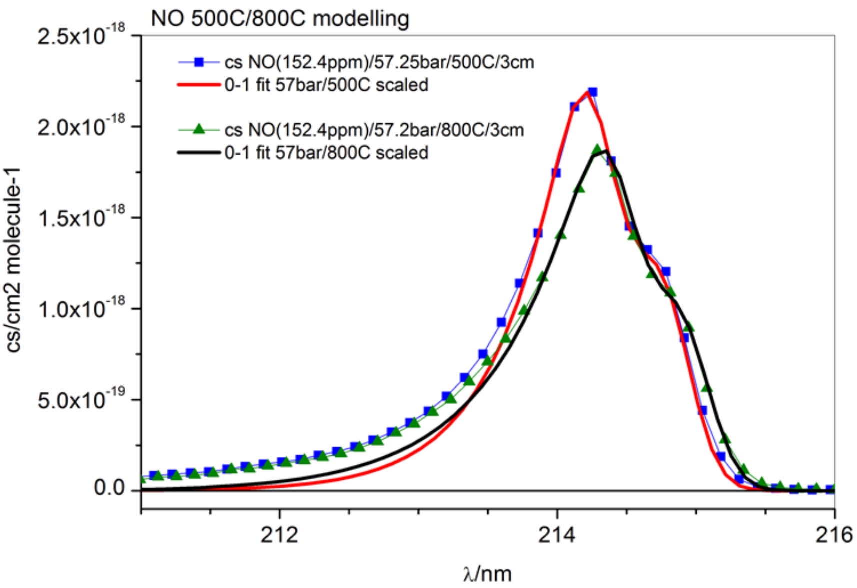

Figure 19. Measured NO absorption cross sections at 500 °C (blue) and 800 °C (olive) at about 57 bar and their modelling (red and black, respectively).

Summary of development of dynamic pressure and temperature sensors

New dynamic pressure and temperature measurement methods and sensors, namely a spectroscopic band shape sensor, fibre optic-based thermometer, novel dynamic pressure sensor, and a prototype commercial pressure sensor have been successfully developed and tested. The newly developed methods and sensors were validated in partners' respective facilities and tested in harsh environments mimicking operating conditions inside an internal combustion engine. 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. Dynamic testing of the non-contact temperature sensors demonstrated that sub-ms events can be measured, which by far exceeds the response times (around 10 ms) of conventional contact thermometers. The dynamic performance of the novel and prototype dynamic pressure sensor was found suitable for cylinder pressure measurements. The reliability and accuracy of the newly developed dynamic pressure sensors have been compared to commercial sensors. In the next phase of the project, the performance of these sensors was demonstrated in real engine applications (presented in 4.4).

The project achieved the objective with these results.

4.4 Validation of developed measurement methods and sensors in industrial applications

The need for better accuracy and reliability of dynamic measurements of pressure and temperature is driven from a variety of industrial sectors. For example, there is an urgent need related to measurements performed inside an internal combustion engine. Increasingly stringent EU regulations on greenhouse gas emissions and fierce competition on the ICE (Internal Combustion Engine) market push manufacturers to develop engines with ever better fuel efficiency. Precise knowledge about in-cylinder pressure and temperature is important for better understanding the combustion process, which in turn enables optimisation of engine power and fuel consumption. Reliable measurement of in-cylinder temperature and pressure is important in the development of internal combustion engines, because it improves the understanding of the combustion event and thus allows for optimising engine power and fuel consumption. These measurements are performed under highly dynamic conditions, where temperature changes up to 200 °C (cylinder wall), or even 3000 °C (combustion gas), and pressure changes up to 30 MPa, take place simultaneously at a millisecond timescale. To demonstrate and validate the performance of the newly developed methods and sensors (presented in 4.3) in real industrial applications, testing was performed inside a marine engine and at special testing facilities simulating corresponding conditions. Dynamic measurements are also performed in many safety critical applications, such as ammunition and explosion testing where better measurement accuracy and reliability have a direct impact on human safety. A better confidence in the measurement results will also enable a reduction of the currently very wide safety margins (safety factors of 2 or even more are currently applied) leading to more efficient and cost-effective manufacture.

Engine tests of dynamic pressure sensors

Cylinder pressure sensors are exposed to extremely harsh conditions, where cyclic pressure and temperature changes take place, as well as strong vibrations from the engine. Currently, the lifetime of dynamic pressure sensors is limiting their use. Continuous monitoring of in-cylinder pressure would allow real-time optimisation of engine performance, and thus reduction of fuel consumption and an increase in engine power. There is an apparent need for novel sensor technologies with improved durability and reliability. In this project, new sensor technologies were developed for in-cylinder pressure measurements (presented in 4.3). To validate sensor performance and reliability in real operating environments engine tests were performed.

VTT has developed a novel dynamic pressure sensor based on capacitive sensing and remote reading of the bending membrane (Figure 12). In this patented design, the sensing element is not in direct contact with the bending membrane, which makes the sensor very durable. The sensor performance was tested inside a 4-stroke marine diesel engine (type Wärtsilä Vasa 4R32, rated brake power 1640 kW) with engine loads ranging from 17 % to 90 %. The sensor was shown to provide comparable results with a state-of-the-art piezoelectric sensor (Figure 20). An agreement of ±2 % in cylinder peak pressure (comparable to the cylinder-to-cylinder variation of this engine) was found for all loading conditions, demonstrating that the developed technology has great potential of providing reliable and accurate on-line monitoring of engine performance.

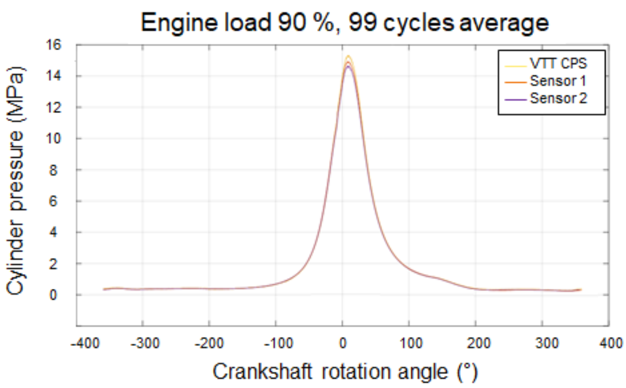

Figure 20. Cylinder pressure at 90 % load averaged over 99 cycles for the VTT sensor (VTT CPS) and the piezoelectric sensors (Sensor 1 and 2) as a function of crankshaft rotation angle (CA).

RISE performed engine tests on the commercial prototype sensor together with Wärtsilä. Field trials were performed in a maritime test engine at Wärtsilä engine test laboratory. The sensor was found to track the engine pressure, but a relative difference was observed between the prototype and the Wärtsilä reference sensor (Figure 21). The relative difference varied between different combustion processes stressing the importance to characterize sensors at operating conditions. A re-calibration showed that the prototype sensor had experienced a large zero-drift after being subjected to harsh conditions.

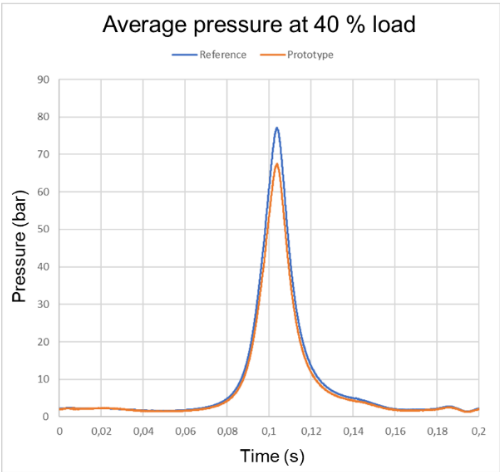

Figure 21. Pressure averaged over 25 four stroke cycles combusting gas at 40 % load. Pressures from Wärstilä reference sensor and prototype sensor are presented.

ENSAM studied the dynamic performance of a state-of-the-art commercial piezoelectric sensor after use in harsh conditions inside an engine (1.9 liter, 120 hp diesel engine, 1500 - 2000 rpm) where the sensor was exposed to peak pressures up to 80 bar and sensor temperatures of 90 °C (water cooled sensor). Results show a considerable change of up to 5 % in the sensor response and a deterioration of the sensor repeatability (shown as increased uncertainty) at 3 kHz and higher frequencies (Figure 22). These results clearly show that a static calibration is insufficient for characterizing the dynamic behaviour of a sensor, and thus underlines the importance of having a dynamic calibration to ensure reliability of measurements at dynamic conditions.

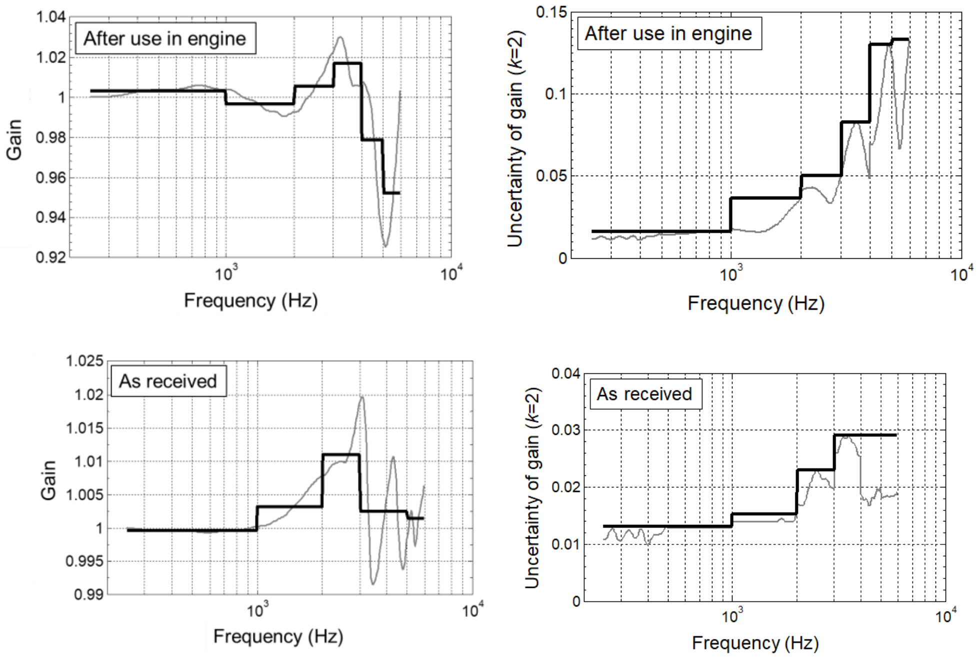

Figure 22. Dynamic response of same type of commercial pressure sensor after use in engine compared to nominal response (as received). Sensor gain shown to the left and corresponding uncertainty to the right. Raw data in gray for information.

Engine tests of new dynamic temperature sensors

Conventional temperature measurement techniques (contact thermometry) are, in many cases, inadequate for measuring in-cylinder temperature due to their slow response time (on the order of 10 ms). There is an evident need for the development and evaluation of methods and devices, which enable measurements of quick dynamic temperature changes with rise times less than a millisecond. To meet these needs, novel non-contact methods were developed and characterised in partners laboratory facilities (presented in 4.3). To demonstrate the sensor performance in real applications further testing was performed at Wärtsilä engine test laboratory.

At DTU, an IR- and UV-based spectroscopic band shape sensor was successfully developed and tested, and the operation was demonstrated at special testing facilities at the Wärtsilä engine laboratory. Testing of the UV-sensor in a Rapid Compression Expansion Machine (RCEM) at Wärtsilä's fuel laboratory facilities show that the sensor can be used for in-situ time-resolved gas temperature measurements inside an internal combustion engine (Figure 23).

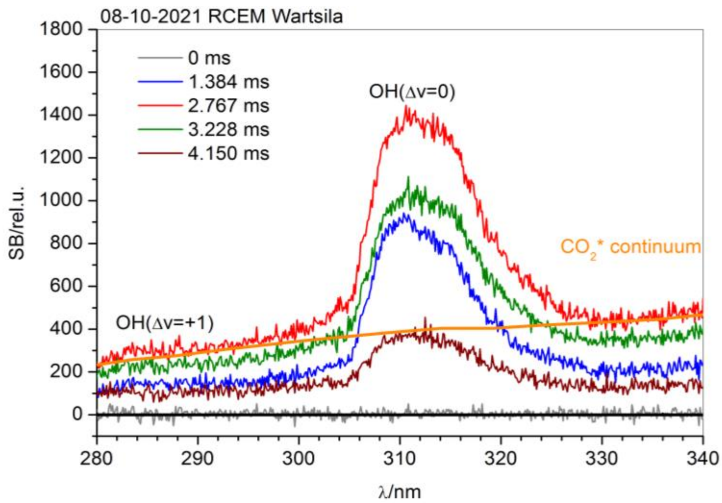

Figure 23. Measured OH emission spectra in 280 - 340 nm range. Broadness of spectra reflects the gas temperature. The measurements were triggered (started) 2.1 ms before the combustion event (labelled as "0 ms", grey line).*

NPL performed field trials at the Wärtsilä combustion spray chamber to validate the performance of the newly developed fibre-optic based dynamic thermometer. The trials involved the measurement of the dynamic temperature evolution of an ignited spray on to a solid surface 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 2100 K, corresponding to 2.4 % in relative numbers (Figure 24). 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.

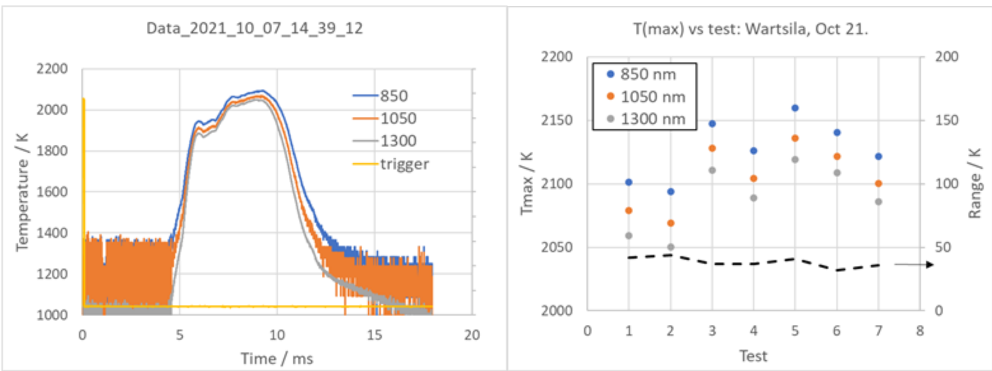

Figure 24. Example of temperature profile inside the combustion test chamber measured with the NPL dynamic thermometer (left figure). Peak temperatures at three wavelengths for seven test runs (right figure).

Validation of calibration methods for dynamic pressure sensors used in ammunition safety testing

Another application where accurate and reliable measurements of dynamic pressure is important, is safety testing of machinery and ammunition. For instance, powder-operated tools (such as nail guns used by carpenters) and ammunition for civilian weapons (alarm weapons, hunting guns etc.) are safety tested for compliance with regulations before placed onto the market. To make sure that a gun or a powder-actuated tool is not damaged by ammunition that is too strong, an international infrastructure exists to measure the maximum pressure occurring during firing of the ammunition. Typically, the pressure follows a bell-shaped curve with a width of a few milliseconds and a maximum between 150 MPa and 600 MPa (depending on the caliber), which corresponds well to pulses generated with the drop-weight method.

Within this project, PTB investigated the validity of the current (quasi-static) calibration method applied for calibrating dynamic pressure sensors used in safety testing. A comparison between a quasi-static calibration and a dynamic calibration shows good agreement in the results. Figure 25 shows the result of a dynamic calibration of the DUT. The red line is the pressure applied to the sensor, as determined with the PTB dynamic pressure standards, using a simplified evaluation procedure. The blue line is the response of the DUT, using a calibration constant that was determined previously by quasi-static calibration. Both curves overlap almost completely, indicating that in this parameter range and in this application where a specific sensor type is used (as defined by *“Permanent International Commission for the Proof of Small Arms"* – commonly abbreviated as C.I.P.), there is no difference between a static and a dynamic calibration of the DUT. Moreover, and more importantly for ammunition safety tests, the maximum of the measured pressure is the same for both calibration methods.

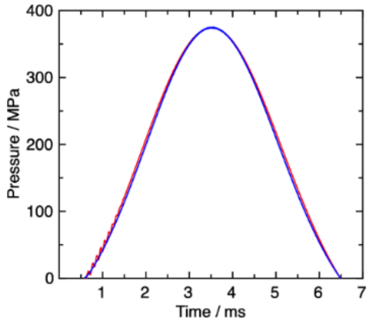

Figure 25. Pressure reading of PTB dynamic pressure standard (blue line) compared to the DUT (red line) calibrated using the quasi-static method.

Recommendations to end-users for suitable dynamic pressure and temperature sensor

Based on the experience and expertise of the project partners and latest research findings within DynPT project, recommendations to sensor manufacturers and end-users on suitable dynamic pressure and temperature measurement methods for use in harsh conditions, such as inside a combustion engine, have been prepared.

A three-step approach for selecting a suitable sensor or measurement method was advised, as follows:

1. Define the operating conditions and requirements of the application.
2. Calibrate the sensor at conditions that match as closely as possible to the operating conditions (advise on modelling of dynamic temperature signals have been given in the report).
3. Validation of the sensor performance in real operating environments, e.g. engine testing in ICE applications.

The **first step** in choosing a suitable dynamic pressure and temperature measurement method or sensor is to carefully outline the operating conditions and requirements of the specific application in mind. This is important as the measurement method and sensor performance is optimised for certain conditions, e.g., pressure, temperature, rate of change (frequency) and measurement media. The **second step** is to calibrate the sensor at conditions that resemble, as closely as possible, the operating conditions. In case of a dynamic pressure sensor, the calibration should cover the pressure and frequency ranges corresponding to the pressure variations of the application. Especially at higher frequencies errors up to hundreds of percent might occur due to sensors’ resonances. Also, temperature is found to influence the sensor response (so called temperature sensitivity), and therefore sensors need to be calibrated at operating temperatures (around 120 °C for ICE’s) to achieve optimum measurement accuracy. For optical temperature measurement methods, it is critically important to understand how the temperature relates to the optical signal measured in the process. In most situations the optical signal is either the emitted thermal radiance or the light transmitted through the process. For clean flames, a detailed spectroscopic model (using the HITEMP spectral database), that assumes a defined path length and an estimate of composition can be successful, or for sooty flames, the blackbody assumption is often valid and can be tested by the level of agreement of measurements made at different wavelengths. To establish the relationship between measured signal and temperature, calibrations need to be performed at conditions relevant to the measurement application, i.e., combustion species, clean/sooty flame, temperature etc. The **third** and last **step** is to validate the measurement methods and sensors in real operating conditions, e.g., inside an engine in case of ICE applications. This is important because there are many influencing factors that are not covered by calibrations, which are inherently done at well-controlled conditions. For example, in ICE applications dynamic pressure sensors are subject to cyclic temperature variations inside the engine, which are not accounted for in the calibration procedures. Dynamic temperature measurements inside the engine are very challenging due to the turbulent and evolving nature of the combustion process that can lead to strong temperature and pressure variations within the measurement volume on very short length and time scales.

In this project, two types of novel optical thermometers were developed to provide dynamic temperature measurements in the combustion environments. At NPL, a fibre coupled high-speed (three wavelength, 250 kHz) pyrometer system was developed, suitable for temperature measurement on luminous (sooty) flames. At DTU, two fibre coupled high-speed spectroscopic systems were developed, suitable for temperature measurement on both clean and sooty flames – measuring in the UV-VIS region of the spectrum in either emission or absorption. Engine tests at Wärtsilä with NPL's high-speed pyrometer show a very good agreement between measurements at different wavelengths indicating that the blackbody assumption is valid. The level of agreement of measurements at 2100 K combustion temperatures suggests that the temperature error is less than 50 K or 2.4 % of temperature. The test results for the novel spectroscopic method by DTU was found promising and the capability of extracting both temperature and pressure data of the combustion process was successfully demonstrated. Although piezo-electric sensors are widely used and considered an industry standard for dynamic measurements in engine applications, durability is an issue especially in marine applications where measurement condition are extremely harsh and a lifetime of 20 000 hour is required. To address this issue, VTT has developed a novel (patented) sensing technology based on capacitive measurement principle, where the sensing element is not in direct contact with the bending membrane, making the sensor very durable. Extensive calibration and testing, including real engine tests performed within this project, demonstrate that the VTT sensor performance is comparable to state-of-the-art piezoelectric sensors with respect to accuracy, linearity, repeatability, and temperature sensitivity. An agreement of ±2 % was achieved when compared to VTT MIKES primary standard and when comparing against a piezoelectric sensor. Test results for the VTT cylinder pressure sensor are very encouraging and indicate that the developed technology is well suited for dynamic measurements at extreme conditions. Further long-term engine testing is needed to verify that the lifetime requirement of the sensor is fulfilled. The recommendations were summarised in report D6 of the project, which is freely available at the project website.

Summary of validation of developed sensors in industrial applications

Dynamic pressure and temperature sensors developed in this project and a commercial prototype dynamic pressure sensor were successfully tested in real engine environments. 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. Calibration and characterisation of the sensor performance before and after engine tests, show that the developed sensors are robust, and therefore well suited for measurements at extreme conditions, such as inside a maritime combustion engine. For the tested commercial prototype sensor, a discrepancy in the sensor response compared to Wärtsilä's reference sensor was observed in engine tests. A zero-offset was also observed in the post-calibration after engine test. This is a valuable finding and strong motivation for having reliable (i.e. SI-traceable) calibrations. Moreover, it was shown for a state-of-the-art piezo-electric sensor that exposure to harsh conditions (as realised inside an engine) can alter the dynamic response at higher frequencies, which underlines the importance of having a dynamic calibration to ensure reliable measurements at dynamic conditions. Testing of a specific sensor used for ammunition safety testing in the pressure range up to 400 MPa show that the currently used (quasi-static) method of calibration provide comparable results with a dynamic calibration. Although this is true for this specific sensor type, it does not necessarily apply to other sensors from different manufacturers, as was shown for the piezoelectric sensor used in engine tests, where the high frequency "dynamic" response was different from the low frequency "static" response. Based on the research findings of this project, recommendations on suitable dynamic pressure and temperature measurement methods and sensors for use in harsh conditions were presented.

The project achieved the objective with these results.

5 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.

6 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
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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/

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