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DEVELOPMENT OF MEASUREMENT AND CALIBRATION TECHNIQUES FOR DYNAMIC PRESSURES AND TEMPERATURES – RESULTS AND ACHIEVEMENTS

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Abstract:
This paper presents the main results and achievements of the EMPIR DynPT project [1]. Dynamic measurement 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 and methods and characterized sensor technologies and means of estimating measurement uncertainties in real process conditions.

Keywords: Dynamic; calibration; pressure; temperature; sensor

1. NEED FOR THE PROJECT

Improved dynamic measurements of pressure and temperature is 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 (ICE) is 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 is 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 were, 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.

2. PROJECT OBJECTIVES

The overall objective of the project was to improve the quality of dynamic measurements in demanding industrial applications. The specific objectives were as follows:

Objective 1: To provide traceability for dynamic pressure and temperature in the range up to 400 MPa and 3000 °C, respectively, through development of measurement standards and calibration procedures.

Objective 2: To quantify the effects of influencing quantities (e.g., pressure, temperature, signal frequency and measurement media) on the response of dynamic sensors.

Objective 3: To develop new measurement methods and sensors for measuring dynamic pressure and temperature in demanding industrial applications.

Objective 4: To validate the developed methods and sensors through demonstrations in real industrial settings, e.g., combustion engines.

Objective 5: Facilitate industry uptake through workshops, guidelines, and input to standards.

3. MEASUREMENT STANDARDS

New and improved measurement standards and calibration methods for dynamic pressure and temperature were developed in the measurement range 0.1 - 400 MPa and up to 3000 °C, respectively, with the aiming at uncertainties of 1% for pressure and 3% for temperature, as required by industry.

3.1. 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 and to extend the measurement range from 5 MPa up to 40 MPa, and thus cover the pressure range relevant to ICE applications and to achieve an overlap between low- and high-pressure methods.

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. In the low frequency end, 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 [3]. The operational frequency and pressure ranges of this method are 0.2 - 10 kHz and 0.5 MPa, respectively.

At RISE, the shock tube was adapted to enable assessment of the realized pressure amplitude using the Mach-number method. This adaption included making all the measured quantities traceable to SI to establish a primary method of calibration [4].

3.2. Novel high-pressure shock tubes

Conventional shock tubes are limited to the lower end of the pressure range (≤ 7 MPa) due to limitation caused by the high pressure required in the driver section. In this project, KTH and RISE successfully 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 [5]. Numerical simulations predicting the pressure profile were developed and compared with the experimental profile (Figure 1). Using this technique, pressure pulses with peak amplitudes in the range of 30 - 40 MPa, with uncertainties < 3.4% based on numerical reference profile were realized.

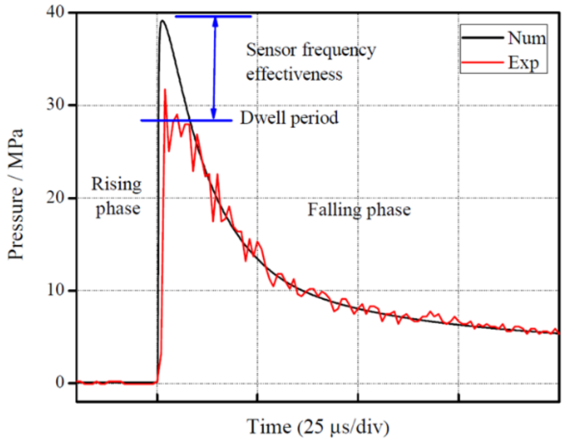

Figure 1: Experimental and numerical pressure profile of the KTH shock tube with converging section measured for Mach number (M_s) = 2.52 shock wave.

3.3. Drop-weight devices based on interferometric method

VTT MIKES developed its drop-weight dynamic pressure primary standard further to extend the pressure range down to 2 MPa and to enable calibrations at elevated temperatures, and thus enable traceable calibrations of cylinder pressure transducers at conditions relevant to engine applications [6]. Developments included improved control and measurement of the falling weight, a new lighter drop-weight for low-pressure operation and a heating option for calibrations at high temperatures. The overall uncertainty (k = 2) of calibration is estimated to be around 1.7% in the applicable pressure range. 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 2.4% [7].

TUBITAK developed a dynamic pressure standard up to 400 MPa based on drop-weight method [8]. 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).

3.4. Drop-weight devices based on refractive index method

PTB developed a drop-weight device based on the refractive index method, 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 measurement standard is 60 MPa up to (at least) 400 MPa. An important thing was to investigate the difference between adiabatic and isothermal compression of liquids by an impacting weight, as observed in the resulting change to the index of refraction [9]. It was found that the optical properties under adiabatic and isothermal compression can be converted into each other using literature values of thermodynamic properties. 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.

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. 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.

3.5. Dynamic temperature calibration method based on a shock tube

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%.

3.6. Radiance based dynamic temperature calibration methods

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 combustion pyrometer (presented in section 6), with maximum dynamic temperature matching static temperature.

4. INFLUENCING QUANTITIES

The influence of process condition on dynamic pressure sensor response was studied in a wide pressure, frequency and temperature range of 0.1 - 400 MPa, 1 - 30 kHz and up to 200 °C, respectively. For the developed non-contact thermometers, research was undertaken to better understand how optical signals relate to process parameters, such as temperature and pressure of the media, to determine and reduce the uncertainty of measurements closer to the target level of 5%. Based on the results, appropriate calibration procedures and uncertainty estimation methods were developed.

4.1. Effect of process parameters on dynamic pressure sensor performance

Pressure signal frequency, measurement media and temperature, were all found to influence the response of dynamic pressure sensors. The response of dynamic pressure sensors was found to be strongly frequency dependent even at frequencies well below the nominal resonance frequency of the sensor

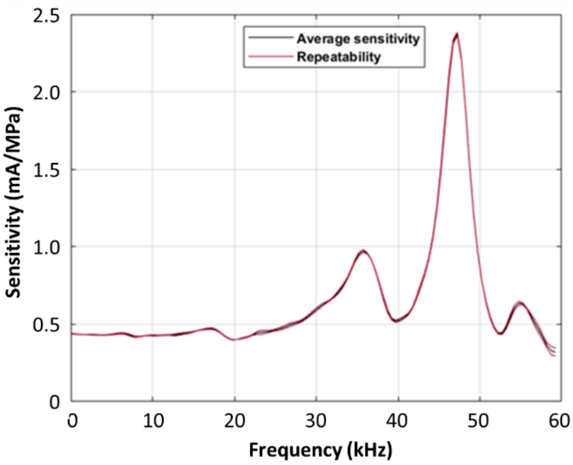

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Figure 2). Temperature was found to influence both sensor response at low frequencies, the so-called temperature sensitivity, as well as the resonance frequency of the sensor, so called Q-factor, at high frequencies. The effect can be as high as 1%/100 °C for piezoelectric sensors used in high temperature applications, such as inside an ICE. Other effects were found less significant. 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.

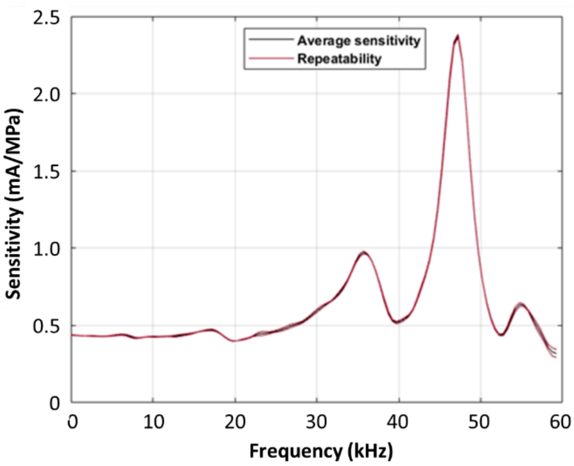

Figure 2: Frequency dependant sensitivity of a dynamic pressure sensor at 12 MPa defined with RISE shock tube.

4.2. Influence of process parameters on dynamic temperature sensor response

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% (Figure 3). 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. 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. 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 combustion pyrometer and a spectroscopic dynamic thermometer. Moreover, uncertainty models for estimating uncertainties of dynamic temperature were successfully developed and published in peer-review journals.

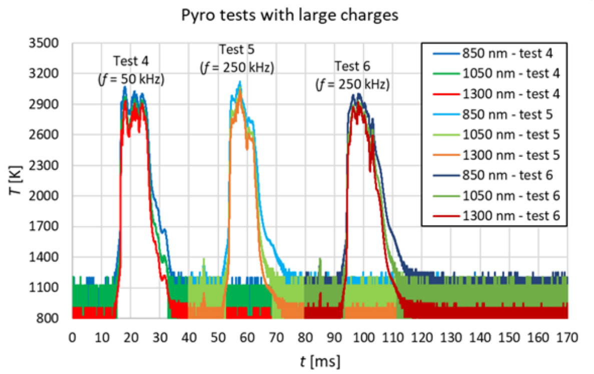

Figure 3: Time trend of temperatures measured with the fibre optic thermometer for pyrotechnic tests with large charges – temporal offset introduced for clarity.

5. DYNAMIC SENSORS

New dynamic pressure and temperature measurement methods and sensors, namely VTT cylinder pressure sensor (CPS), NPL combustion pyrometer and DTU spectroscopic 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.

5.1. VTT cylinder pressure sensor

VTT has developed a new technology for dynamic pressure measurements at harsh conditions, such as inside a maritime combustion engine, where cylinder pressures can reach up to 30 MPa and cylinder head temperatures as high as 200 °C. To demonstrate the performance of the developed technology, calibrations were performed using the primary dynamic pressure standard of VTT MIKES equipped with a heating option. Results of calibration measurements at pressures and temperatures up to 30 MPa and 180 °C, 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 [10].

5.2. NPL combustion pyrometer

NPL developed a novel ultra-high-speed combustion pyrometer, based on collection of thermal radiation via an optical fibre, and performed extensive calibration, testing and validation experiments to verify its performance [11]. 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 4). Dynamic tests with pyrotechnic charges demonstrated that the instrument can measure rapid (sub ms) events (Figure 3), 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.

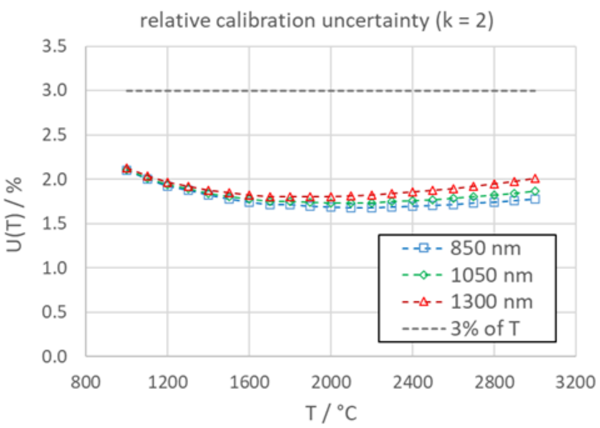

Figure 4: Relative calibration uncertainty (k = 2) of NPL combustion pyrometer.

5.3. DTU spectroscopic sensor

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 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. 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.

6. VALIDATION OF SENSORS IN INDUSTRIAL APPLICATIONS

To demonstrate and validate the performance of the newly developed methods and sensors in real industrial applications, testing was performed inside a combustion engine and at special testing facilities simulating corresponding conditions.

6.1. Engine tests of cylinder pressure sensor

The performance of the VTT CPS was tested inside a 4-stroke marine diesel engine (type Wärtsilä 4R32 LN DF, brake power 1640 kW) with engine loads from 17% to 90% [10]. The sensor was shown to provide comparable results with a state-of-the-art piezoelectric sensor (Figure 5). 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.

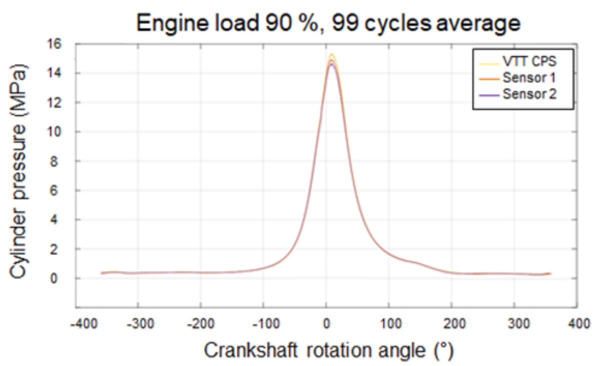

Figure 5: Cylinder pressure at 90% load for the VTT VTT CPS and piezoelectric sensors (Sensor 1 and 2) as a function of crankshaft rotation angle.

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 8 MPa 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 at 3 kHz and higher frequencies. 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.

6.2. Tests of novel dynamic temperature sensors

Tests in Wärtsilä's spray chamber with NPL's high-speed combustion 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 (Figure 6).

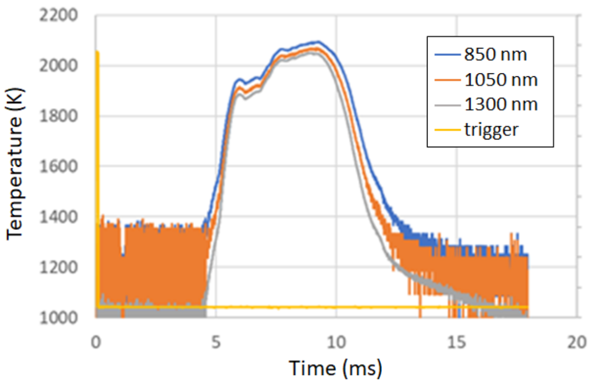

Figure 6: Temperature profile inside combustion test chamber measured with NPL's fibre-optic pyrometer.

Test results from a rapid compression expansion machine (RCEM) for DTU novel spectroscopic sensor was found promising and the capability of extracting both temperature and pressure data of the combustion process was successfully demonstrated.

7. INDUSTRY UPTAKE

The following activities were carried out to facilitate dissemination and uptake of project results:

Guidelines on dynamic pressure calibrations (draft EURAMET guide) and recommendations for selecting suitable dynamic sensors for use in combustion engines have been prepared [2].

Publications: 10 high-level publications in peer-reviewed scientific journals and 12 presentations at conferences [1, 2].

Services: New calibration services for dynamic pressure and temperature have been established in the range 0.1 - 400 MPa and up to 3000°C.

Standards: Input advising on dynamic pressure measurements have been given to ISO/TC 108/WG 34/WT19666, EN 60079-1 and C.I.P. WG GT 2-7.

Commercialization: The dynamic pressure calibration technology is now offered to industrial end-users to enable traceable and cost-effective calibrations of dynamic pressure sensors.

8. SUMMARY

In this project, a solid metrological basis for dynamic measurements of pressure and temperature was established for the first time through development of dynamic measurement standards, calibration procedures and sensors, including methods of estimating uncertainties. Calibration services, guidelines and new measurement technologies have been made available to industry to facilitate a shift from static to dynamic methods. Future developments will focus on lowering uncertainties down to 1% and to adapt dynamic temperature measurement techniques for low-carbon and non-fossil fuels to support the reduction of carbon intensity in industrial processes.

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9. REFERENCES

[1] DynPT EURAMET webpages: Development of measurement and calibration techniques for dynamic pressures and temperatures - EURAMET. Accessed 23.9.2022.

[2] Project website: https://dynamic-prestemp.com/. Accessed 23.9.2022.

[3] C. Sarraf, "A method for assessing the uncertainty of a secondary dynamic pressure standard using shock tube", Measurement Science and Technology, 32(1), 015013, 2020. DOI: 10.1088/1361-6501/aba56a

[4] E. Amer, *et al*, "Evaluation of shock tube retrofitted with fast-opening valve for dynamic pressure calibration", Sensors, 21(13), 4470, 2021. DOI: 10.3390/s21134470

[5] S. Sembian, M. Liverts, "On using converging shock waves for pressure amplification in shock tubes", Metrologia, 57(3), 035008, 2020. DOI: 10.1088/1681-7575/ab7f99

[6] J. Salminen, *et al*, "Advances in traceable calibration of cylinder pressure transducers", Metrologia, 57(4), 045006, 2020. DOI: 10.1088/1681-7575/ab8fb9

[7] C. Sander, M. Aspiala, R. Högström, "Novel secondary standard for calibration of dynamic pressure sensors", tm-Technisches Messen, 2022. DOI: 10.1515/teme-2022-0011

[8] D. Yasin, *et al*," Improvement of dynamic pressure standard for calibration of dynamic pressure transducers", Proceedings of 19th International Congress of Metrology 27009, 2019. DOI: 10.1051/metrology/201927009

[9] O. Slanina, *et al*, "Comparing the adiabatic and isothermal pressure dependence of the index of refraction in a drop-weight apparatus", Appl. Phys. B 126(11), 1-10, 2020. DOI: 10.1007/s00340-020-07519-z

[10] R. Högström, *et al*, ”Recent developments of dynamic pressure measurements in combustion engines”, Submitted for IMEKO TC3, TC5, TC16 and TC22 international Conference, Dubrovnik, Croatia, 2022.

[11] A. Sposito, D. Lowe, G. Sutton, G, “Towards an Ultra-High-Speed Combustion Pyrometer”, International Journal of Turbomachinery, Propulsion and Power, 5(4), 31, 2020. DOI: 10.3390/ijtpp5040031

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