Publishable Summary for 23IND09 MaritimeMET
Metrology for green maritime shipping: Emission control through traceable measurements and machine learning approaches

Overview

The maritime shipping sector is seeking to embrace alternative fuels such as green ammonia, hydrogen, synthetic fuels, and Power-to-X (PtX) solutions like methanol and biomethane to reduce their environmental impact. This transition demands the development of engine technologies to adapt to these new fuels and a growing need for accurate and traceable measurement systems to support these advancements and validate their performance. Accurate pressure, temperature, and emission concentration measurements are essential for research and development in this sector, and at the same time, benefit related sectors. This project will advance the methods and techniques to control and monitor engine emissions through traceable measurements of pressure, temperature, and emission compositions and apply them in real-world maritime applications. The project will exploit the advances in machine learning approaches and modelling to optimise the power units and exhaust after-treatment systems significantly.

Need

In July 2023, the International Maritime Organization (IMO) revised their 2018 strategy (MEPC 73) target to reduce emissions further through a commitment to ensure the uptake of alternative zero and near-zero greenhouse gas (GHG) fuels by 2030. To achieve this, metrological support is needed to accelerate the deployment of sustainable fuels like methanol, dimethylether, and ammonia in this sector.

Currently, the sector requires traceable measurements of emission components according to the International Convention for the Prevention of Pollution from Ships (IMO MARPOL), Regulations 13 and 14. There is an inherent need to ease the availability of traceable standards, check the compatibility and ability of existing and new emission monitoring techniques to accurately measure pollutants from future fuels, along with a better understanding of instrument characterisations and their uncertainties (i.e., span drift, instrument linearity, and cross interferences). Calibration of measurement systems using gas standards (required below 2 % uncertainty) can be substituted by spectroscopy-based techniques. However, these are only established for specific species (e.g. NO_2) at limited pressure, temperature, and gas matrix operating conditions and must be explored for existing and new species relevant to future fuels (Objective 1).

The transition to renewable energy carriers necessitates further engine system development and retrofitting of existing power units and after-treatment systems. These activities require traceable measurements of dynamic pressure and temperature at engine operating ranges to monitor and optimise the in-cylinder processes for efficient operation. The dynamic sensors used for this purpose are quasi-statically calibrated, which can lead to significant uncertainties and require traceable measurement methods (Objective 2).

Engine manufacturers require accurate sensors with traceable measurement methods to reduce uncertainties during the R&D phase and for ensuring optimal control of engines during commercial operation. There is a need to increase the reliability of low-cost sensor data deployed in different engine systems through machine learning approaches. However, machine learning models require large amounts of accurate and traceable data. The combined needs must be addressed through testing low-cost and high-quality sensor techniques in application test benches, and in the process, this can lead to exploring cost-effective virtual sensor concepts (Objective 3).

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Objectives

The overall objective of the project is to provide metrological references for emission parameters, dynamic pressure, and temperature through traceable measurements on a system level that benefit the maritime sector, and to develop novel, innovative solutions and technologies that serve the industry and society.

The specific objectives are:

1. **To develop new and improve existing traceable emission measurement methods for online and in-situ measurements of typical gaseous** (e.g., NO, NO_2, N_2O, NH_3, CH_3OH, CO, CH_2O) and PM, black carbon (BC) emissions generated with the use of Power-to-X (PtX) fuels (e.g. methanol, dimethylether, ammonia). The methods and selected commercial low-cost sensors will be validated and applied for dynamic measurements in industrial environments such as test engines running on selected fuels. Sources of measurement uncertainties will be identified and quantified. Measured quantities will be used in predictive model developments using machine learning tools.
2. **To establish quality-assured dynamic measurements of the in-cylinder dynamic pressure and temperature** necessary for assessing and optimising the quality and efficiency of the energy conversion processes using renewable fuels. This will be achieved by developing primary standards and robust measurement methods covering the 0.1 MPa - 30 MPa pressure range and up to 2500 °C range in temperature. The frequency ranges of 0.5 kHz - 100 kHz and up to 1 kHz in pressure and temperature, respectively, with an uncertainty of 1 % will be targeted. An inter-laboratory comparison and engine tests will validate the developed standards and methods. The results will be used in the predictive model development.
3. **To create predictive models for engine emissions and performance using chemical kinetics and machine learning**. Furthermore, **virtual sensor concepts will be developed based on data-driven and physics-based models** to estimate hard-to-measure quantities or substitute costly sensors. Emission measurements (objective 1) and in-cylinder pressure and gas temperature (objective 2) will deliver the required database for model development, a mandatory input to complete these objectives. All models will be validated, and uncertainty estimations will be done.
4. **To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain** (e.g. accredited laboratories, instrument manufacturers), standards developing organisations (e.g. ISO, CEN/CENELEC), end users (e.g. marine, power and aviation industries), and via the European Metrology Networks (such as Energy Gases, Pollution Monitoring, Climate and Ocean Observation, and Mathematics and Statistics).

Progress beyond the state of the art and results

Developing new and improved traceable emission measurement methods for online and in-situ measurements of typical gaseous (e.g., NO, NO_2, N_2O, NH_3, CH_3OH, CO, CH_2O) and PM, black carbon (BC) emissions generated with the use of Power-to-X (PtX) fuels (e.g. methanol, dimethylether, ammonia).

Even though many of the pollutants mentioned and their measurement techniques have been investigated in many previous projects they have not been rigorously tested in dynamic environments typical for the shipping sector. Moreover, the techniques have often been validated against single molecules at limited pressures and temperatures in dry gas, particle-free environments and low amount fractions, while the exhaust gas composition from combustion of PtX fuels can lead to interference effects in the pollutant measurements and possible sensor contamination and degradation that have not been well investigated and quantified.

Traceable optical spectroscopy-based methods and facilities for absolute concentration measurements of gaseous species have been developed by the project partners. These methods are being validated by 1) certified static reference gas mixtures which have been produced in the project for the species NO, NO_2, CH_3OH and 2) with use of dynamic portable reference NH_3 generator which generates NH_3 with H_2O.

Use of methanol and ammonia as PtX fuels cause generation of nitrous oxide (N_2O) and formaldehyde (CH_2O) as byproducts, respectively. Formaldehyde emissions are not yet regulated. New laser-based sensors for the absolute determination of CH_2O and N_2O in an engine exhaust gas have been developed and its validation is on-going.

Three commercially available low-cost sensors (NO, NO_2 and NH_3) have been acquired. Performance of the sensors is planned to be tested at the project partner test bed (an engine running on methanol- and optionally ammonia-diesel blends). Because of the differences in sensors measurement ranges and above-mentioned species amount fractions in the engine exhaust, a metrologically validated dilution probe will be used in conjunction with the engine tests. Performance of the sensors will be compared against advanced traceable measurement analysers available at the partner. The development of spectroscopic methods for calibration of the different sensors is on-going. Finally, the sensors will be compared and characterised against the primary standards which are available in the project and the results will be summarized in a report distributed to the project stakeholders and metrology community.

Establishing calibration standards and measurement methods to ensure traceability for dynamic pressure and gas temperature.

Previous projects (EMRP IND09 Dynamic and EMPIR 17IND07 DynPT) have taken the initiative to establish the metrological infrastructure that addresses pressure and temperature ranges similar to those in this project. However, the two calibration techniques developed for dynamic pressure namely impact mass devices and shock tubes operated at different pressure and frequency ranges. The reported uncertainties were around 2 % between 5 MPa - 30 MPa for the impact mass technique while, the uncertainty for the shock tube technique was even higher at about 5 %. The need from the industry is to reduce the uncertainty to 1 %. Further development of the two techniques was performed by the project partners. The lower pressure limit of the impact mass devices was extended to 2 MPa and the upper limit of the shock tube was extended to 30 MPa, hence the two methods are well overlapped. The achieved uncertainty ($k = 2$) in the reference pressure is less than 1 % for the impact mass device method and less than 2.5 % for the shock tube method. The validation of the developed calibration techniques and standards, by performing an inter-laboratory comparison, is ongoing. Furthermore, the project partners will evaluate the performance of a state-of-the-art commercial dynamic pressure sensor by characterizing it before and after testing it at Wärtsilä's engine testing facility. On the dynamic temperature aspect, non-contact-based sensors were developed with 3 % uncertainty in a similar temperature range. Further development of these sensors and techniques was performed by the project partners. A fibre-optic spectrometer with a 250 kHz sample rate and three different frequencies was developed and its characterization by a laser-based radiance facility for its spectral performance and response time is ongoing. Thermal imaging techniques is deployed for developing and implementing traceable calibrations up to 2500 ˚C. Additionally, traceable absorption spectroscopic techniques were developed and will be explored in the temperature range up to 1500 ˚C, frequency between 5-10 kHz, and target uncertainties of 1 %. The validation of the developed methods is ongoing. In-situ measurements are also planned in a rapid compression and expansion machine (RCEM) facility at Wärtsilä using the fibre-optic spectrometer and Ultraviolet / Infrared (UV/IR) spectroscopy.

Creating predictive models for engine emissions and performance using chemical kinetics and machine learning, with developing virtual sensor concepts based on data-driven and physics-based models.

Different approaches to model engine emissions and key parameters are explored in this project. The availability of engine validation tests performed as part of the first two objectives are key for model development; engine tests are currently in progress and provide data. This means that an initial measurement database is already available, allowing to begin with the modeling tasks. With regard to the data-driven models, initial exploratory data analyses have been conducted to evaluate if the data quality is sufficient and which models might be suitable. Initial spot checks look promising but require much more detailed examination. A much more extensive database will be collected for thorough evaluation and modeling. Predictive models for exhaust after-treatment systems will be undertaken using stand-alone models or a combination of physical and data-driven approaches. Here further dedicated measurements of emissions before and after the after-treatment system are required, which is planned to be measured within the next months. A second approach will utilise data from chemical kinetic mechanisms along with GT-Power engine simulation software while validating the engine parameters and emissions obtained from the engine tests. The GT-Power model is currently under development based on the initial measurement database and will soon deliver first results. Additionally, a detailed uncertainty evaluation of both approaches will be performed to better understand their capabilities and boundaries. In addition, machine learning methods will be extended to virtual sensors. Measurement data from the other work packages with low-cost sensors and laboratory sensors is planned and will serve as input. Unlike conventional physical sensors, which record physical phenomena directly, virtual sensors leverage existing physically measured data to infer the values of desired parameters. The validation measurements on the engine and calibration information from low-cost sensors will be utilised to model parameters of interest. As a first step, studies have already been conducted to determine which algorithm design would be most suitable for these kinds of models.

Outcomes and impact

Key Dissemination and Communication Activities:

During the first 18 months of the project, MaritimeMET has actively engaged with industrial stakeholders, metrology organisations, standardisation bodies, and the wider scientific community to ensure that project developments address real-world needs and support uptake of the results by maritime, but also other industries.

A dedicated stakeholder meeting was organized, primarily targeting then members that provided the letter of interest and potential members for the stakeholder committee, that included maritime industry and authorities, instrument and sensor manufacturers, research organisations, universities, and industry associations. Beside to the Stakeholder Committee members, project outputs, results, events and news were communicated to a broad audience via social media channels and project website. Two collaborations were established, one with Siemens AG, focusing on uncertainty evaluation in machine-learning-based emission prediction models, and second with PCB Piezotronics, supporting the validation of dynamic pressure calibration standards through participation in an international inter-laboratory comparison.

Webinar series were organised in collaboration with ZERO44 and SBH4, addressing challenges related to emissions monitoring and maritime decarbonisation. Project developments were further disseminated through articles in Envirotech Online and Gasworld, as well as through project newsletters and contributions to the European Metrology Network for Energy Gases.

The consortium delivered 14 project-related presentations (9 oral presentations and 5 posters) at 12 international events, including IMEKO World Congress, International Conference on Measurements of Energy (ICME), TEMPMEKO-ISHM, Gas Analysis Symposium, EMN Energy Gases Joint Workshop, VUP-Calibration excellence Days 2025, and the LEC Sustainable Shipping Technology Forum.

The project organised its M18 stakeholder workshop at Wärtsilä in Finland, combining technical presentations, stakeholder discussions, facility visits, and networking activities to strengthen interaction between project partners and end users.

<u>Outcomes for industrial and other user communities</u>

For emission measurements, new SI-traceable laser spectroscopic methods have been developed for key species relevant to future maritime fuels, including N_2O, NO, CH_2O, NH_3, CH_3OH and NO_2. These developments provide the basis for improved calibration and validation of emission monitoring systems operating under conditions representative of maritime applications. New reference gas mixtures and portable calibration systems have also been established to support sensor validation activities. The outcomes of this project will help in future research, development, and implementation phases by ensuring accurate measurement techniques are reflected in products and sectors. Developing compact online sensors to monitor possible fuel slip (e.g., methanol, ammonia) will help in closed-loop engine control and potentially lead to new spin-off developments such as new sensors and instruments.

For dynamic pressure measurements, novel primary standards have been developed by project partners covering pressure ranges relevant to marine engine operation. Validation studies have demonstrated uncertainties below 1 % for impact-mass-based systems and below 2 % for shock-tube-based systems, representing a substantial improvement over previous capability. An international inter-laboratory comparison involving four consortium laboratories and PCB Piezotronics Inc. is scheduled and represents the first comparison of its kind for dynamic pressure calibration. Such conditions benefit the chemical engineering, aviation, energy, and space industries, where the thermo-chemical conversion process is much more dynamic and critical. Additionally, it will establish capabilities for national and accredited laboratories in Europe and support consistency in measurement methods.

The project has progressed the characterisation of commercially available low-cost emission sensors for NO, NO_2 and NH_3 and has established facilities for their traceability evaluation. These activities will support sensor manufacturers and engine developers in understanding sensor performance, limitations, and uncertainty sources under realistic operating conditions. Furthermore, this project will provide the perfect mix of industry, metrology, and data sciences, to establish approaches that could benefit them all. The concept of virtual sensors depends mainly on inferring desired parameters through the measurement data of existing physical sensors. However, the accuracy of the transfer functions would largely depend on the accuracy of the physical sensor and with insights into low-cost sensor characterisation study, the reliability of the virtual sensor concept can be enhanced and used in the sector and other industries.

The project has also upgraded and adapted a maritime engine test facility for methanol and alternative fuel operation, enabling the generation of large-scale, high-quality measurement datasets for future model development, sensor validation, and engine optimisation studies. The updated outcomes from the project are being disseminated to industry stakeholders like maritime engine manufacturers, dynamic pressure and temperature sensor manufacturers, and calibration laboratories.

Outcomes for the metrology and scientific communities

Through the outcomes from this project, regarding the development of primary calibration standards, national metrology institutes (NMIs) can benefit through knowledge transfer. This will also impact the secondary calibration laboratories and the subsequent calibration chain, up to the end user. The detailed investigations performed on the calibration techniques and sensors will provide a sound basis for good practice guides that are the foundations of standardisation (e.g., OGS against primary reference gas standards; calibrations using impact mass and shock tube methods). Using numerical approaches to understand the influence of dynamic effects during calibration and the investigations on the influence of non-linearities from sensor mountings will provide new insights and guidelines for the metrology and scientific community. The outcomes from modelling approaches to emission predictions and their uncertainty comparison would provide a holistic understanding of the methods and help improve them in subsequent steps.

During the first 18 month, MaritimeMET has established new measurement capabilities and scientific knowledge that advance the state of the art in traceable emission monitoring, dynamic pressure measurement, dynamic temperature measurement, and uncertainty evaluation. Significant progress has been achieved in optical spectroscopy-based measurement techniques. New SI-traceable instrumentation for nitrous oxide measurements in maritime applications has been developed, while additional studies have established high-temperature spectroscopic parameters for nitric oxide and demonstrated simultaneous high-speed measurements of NO, H2O and temperature with MHz time resolution.

In dynamic pressure metrology, several new primary calibration standards have been developed and validated. The project has demonstrated uncertainty levels significantly below the current state of the art and has initiated the first international inter-laboratory comparison covering both shock-tube and impact-mass-based calibration methods. These activities provide an important foundation for future calibration and measurement capabilities in dynamic pressure. The project has also advanced dynamic temperature measurement techniques, including laser absorption spectroscopy, fibre-optic sensing approaches, and high-temperature reference facilities. These developments will support future traceable measurements under demanding combustion and energy-conversion conditions.

Outcomes for relevant standards

The outcomes from emission monitoring methods, guides, reports and review of articles along with project progress will be communicated to ISO/TC 158 Analysis of Gases, CEN/TC 264/WG 40, EURAMET TC-MC SCGA – Gas Analysis, and will be harmonised with ISO 8178-1 standard which covers NOx, PM, N_2O, Particle Number (PN), CO, CH_2O, CH_3OH emission measurements from engines. Guidelines for good practices on pressure calibration and measurement, including the results from inter-laboratory comparison and uncertainty estimation models, will be communicated to the BIPM Consultative Committee for Mass and Related Quantities (CCM) working group on pressure and vacuum (WGPV) and to ISO/TC 108/WG 34/WT 19666, Dynamic Pressure Calibration, to support standardisation work. The consortium participants will also provide regular updates to the EURAMET Technical Committee – Mass and Related Quantities (TC-M) pressure sub-committee. Similarly, the outcomes from the dynamic temperature measurements, guidelines and reports on project progress will be communicated to the Consultive Committee for Thermometry (CCT), CCT Working Group on Contact Thermometry (WG-CTh), and the EURAMET Technical Committee on Thermometry (TC-T). Additionally, the modelling approaches and their uncertainties, the developed mathematical models for uncertainty calculations in dynamic quantities measurements and the numerical approaches to understand different dynamic effects during calibrations will be communicated to EURAMET TC-IM WG M4D. The consortium maintain will open communication with the European Metrology Network (EMN) for Pollution Monitoring (POLMO), EMN for Climate and Ocean Observation (COO), and EMN for Mathematics and Statistics (Mathmet) to provide updates on the project and to receive feedback.

During the first 18 months, project results have already been presented to several metrology and standardisation bodies, including EURAMET TC-M, EURAMET TC-MC, APMP TCQM Gas Analysis, APMP EEFG and CEN/TC 264. These interactions ensure that emerging project results are visible to the relevant standardisation and metrology communities and provide a pathway for future contributions to international standards and guidance documents.

Longer-term economic, social, and environmental impacts

Maritime shipping contributes to transporting approximately 80 % of the trade volume worldwide, and nearly 70 % of the market share on low-to-medium speed engines is from European Union (EU) manufacturers. This is only the engine manufacturing market; the EU is also home to many manufacturers of engine sub-systems. Moreover, according to the European Community Shipowners' Association report, the EU shipping industry directly contributed 54 billion € to the Gross Domestic Product (GDP) in 2018. According to the report, for every 1 € the EU shipping industry contributes to the GDP, a further 1.8 € is supported elsewhere in the EU economy. Similarly, 1.9 jobs are supported elsewhere in the EU economy for every job employed directly by the shipping industry. As the need to reduce emissions grows, and policies worldwide change to support the use of future fuels, the maritime industry should be able to increase its foothold in the global market. With the help of supporting infrastructures and measurement capabilities, the market will refrain from shifting to other geographies, leading to increased revenue and job growth in the EU. For example, an increase in market share of 5 % in the low to medium engine segment will equal sales by 100 M€, where the market is 2 B€ per year.

The reduction of emissions from the maritime sector is the goal to fulfil societal needs. The development of accurate tools and the proper infrastructure to support new products will increase the system's efficiency and allow the industry to quickly adapt to sustainable choices, lowering the carbon footprint in the sector and dependent industries. This will lead to a cleaner environment with lower emissions, reducing the health risks associated with pollution and decreasing the strain on the medical infrastructure and society. A better standard of living and a healthier society would participate more actively in the economy and, in so doing, add more benefits to the entire cycle.

The technical developments achieved during the first 18 months provide early evidence that the project is establishing the measurement infrastructure required to support the transition towards low-carbon maritime fuels. Improved traceability of emission, pressure and temperature measurements will support engine optimisation, regulatory compliance, and the deployment of cleaner propulsion technologies, contributing to long-term reductions in greenhouse-gas and pollutant emissions from shipping

List of publications

Zhu, D. et al (2025) 'Progressing TDLAS instrumentation for SI-traceable measurements of nitrous oxide in maritime applications', *tm - Technisches Messen*, 92(9-10) p. 361-368. Available at https://oar.ptb.de/resources/show/10.7795/120.20260602A

Zhu, D. et al (2025) 'Simultaneous dynamic NO, H2O and temperature measurement using an intrapulse laser with MHz time resolution', *Sensors and Actuators B: Chemical*, 445 p. 138596. Available at https://oar.ptb.de/resources/show/10.7795/120.20260602B

Zhu, D. et al (2026) 'Spectroscopic investigation of NO transitions near 1915 cm−1: high-temperature line parameters and uncertainty quantification', *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 347 p. 126990. Available at https://oar.ptb.de/resources/show/10.7795/120.20260602C

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

Project start date and duration:		1 September 2024, 36 months
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Internal Beneficiaries: 1. PTB, Germany 2. CMI, Czechia 3. DFM, Denmark 4. ENSAM, France 5. RISE, Sweden 6. TUBITAK, Türkiye 7. VSL, Netherlands 8. VTT, Finland	External Beneficiaries: 9. DTI, Denmark 10. DTU, Denmark 11. FORCE, Denmark 12. GERG, Belgium 13. Instrumatic, Denmark 14. LEC, Austria 15. TUBS, Germany 16. Wärtsilä, Finland	Unfunded Beneficiaries: -