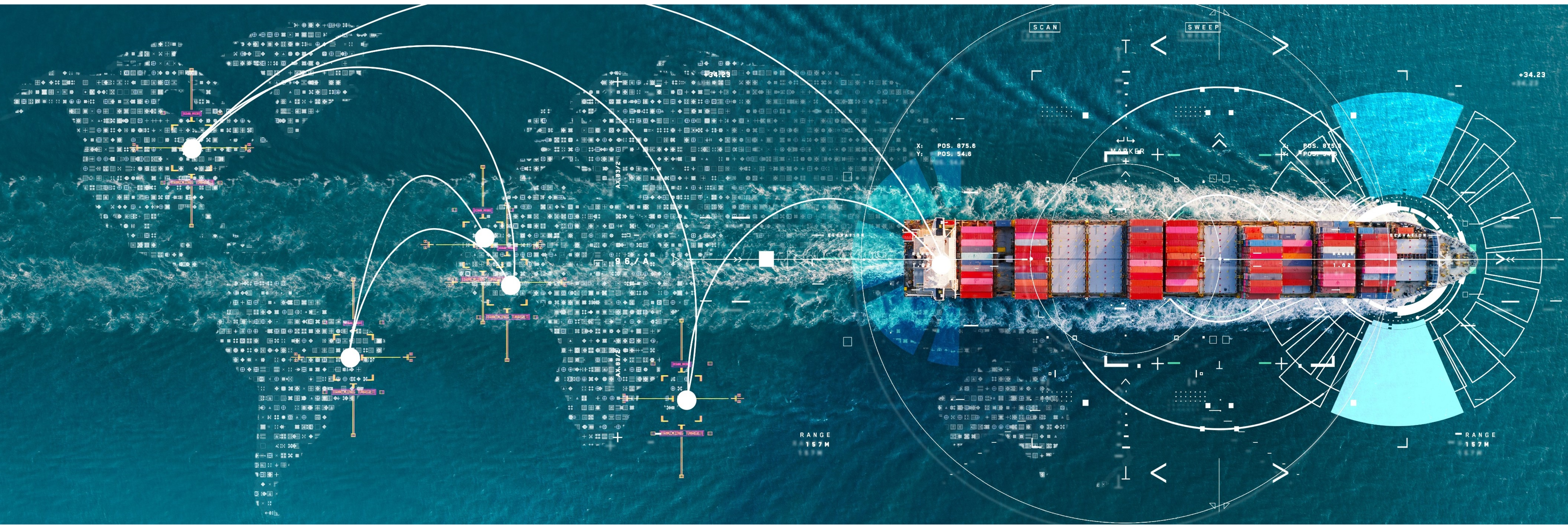
Metrology for Green Maritime Shipping

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).

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 to 30 MPa pressure range and up to 2500 °C range in temperature. The frequency ranges of 0.5 kHz to100 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).

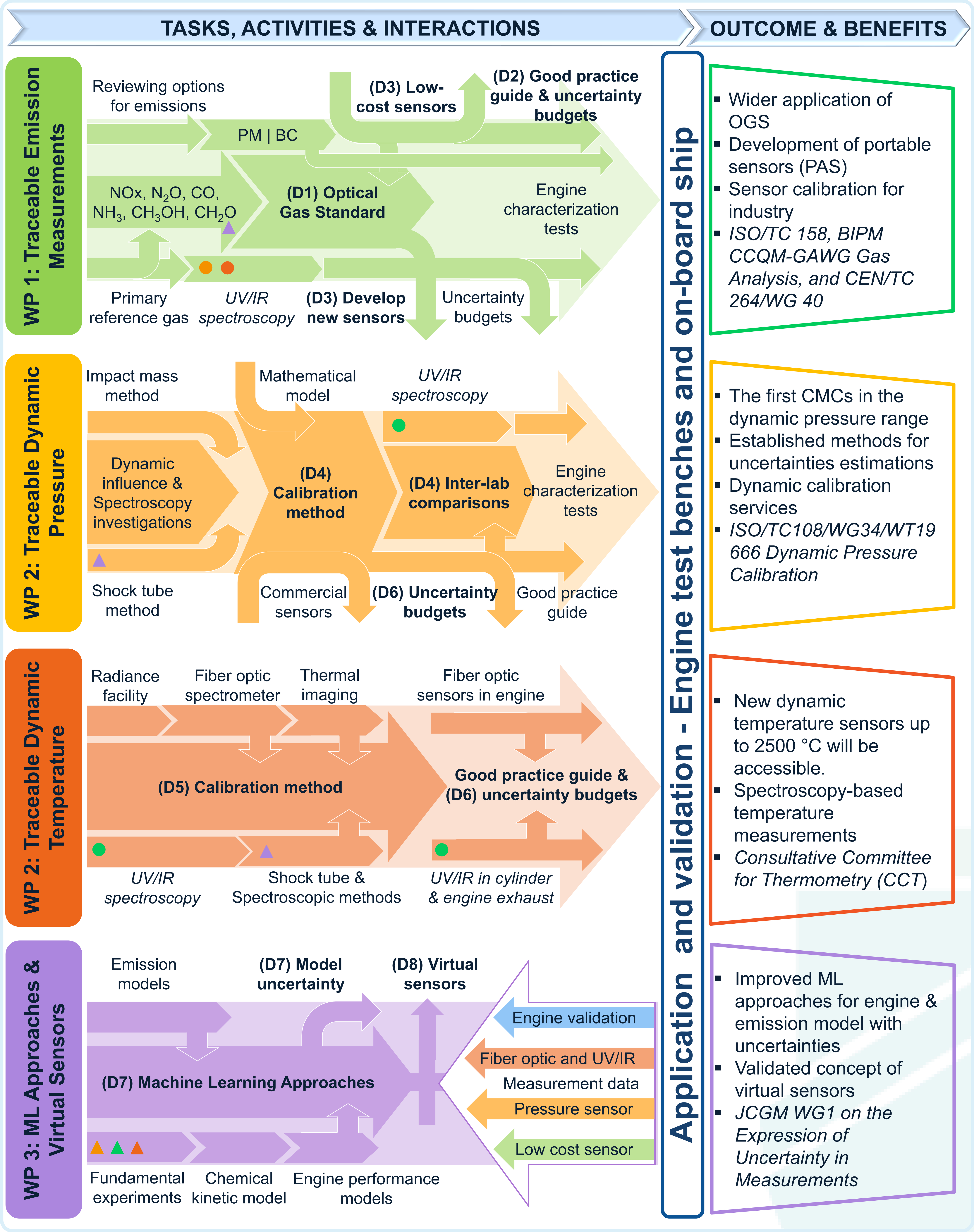
Progress beyond the state of the art and expected results

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 previous projects (16ENV05, 16ENV07, 16ENV08, 19ENV09 MetroPEMS, 16ENV02 Black Carbon, IMPRESS2), they have not been rigorously tested in dynamic environments typical for the shipping sector.

Consortium Members

Moreover, the techniques have often been validated against single molecules at limited pressures and temperatures, and the exhaust gas composition from future fuels could lead to interference effects in the pollutant measurements that have not been well quantified. Therefore, pollutant measurement techniques and their operation principles must be studied and validated for accuracy and reliability, specifically in the shipping sector. The optical gas standard (OGS) proposed in previous projects based on the spectroscopy principles will be tested against the reference gas standards for deployment in the maritime sector. OGSs can potentially complement or substitute reference gases in the field where continuous measurements and calibration are required for the long term. As methanol and ammonia are the next generation of fuels commonly suggested for this sector, the related pollutants and fuel slip are of interest, especially nitrous oxide (N_2O) and formaldehyde (CH_2O), the latter being unregulated. For methanol engines, it is observed that there is an increased formation of formaldehyde in the exhaust gases. New spectroscopic-based traceable methods will be developed and explored in engine validation tests. Additionally, a selection of low-cost commercial sensors available in the market for the marine industry will be compared and characterised against the primary standards available in the project. A report on the uncertainty analysis will be available for the industry stakeholders and the 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 operated at different frequencies (i.e., < 1 kHz for impact mass and 0.5 kHz 100 kHz for shock tube). 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%. Several steps, like extending the measurement frequencies, performing cross-comparison of the two techniques, and understanding the influence of non-linearities and dynamic effects through numerical and experimental investigations are planned to better understand the impact of the sensor and the calibration techniques.

Approach



On the dynamic temperature aspect, non-contact-based sensors were developed with 3% uncertainty in a similar temperature range, and they will be further improved in this project. Further development of these sensors and techniques is planned through a fibre-optic spectrometer with a 250 kHz sample rate and three different frequencies. It will also be characterised by a laser-based radiance facility for its spectral performance and response time. Thermal imaging techniques will be deployed for developing and implementing traceable calibrations up to 2500 ˚C. Additionally, absorption spectroscopic techniques used in chemical kinetic studies will be explored in the temperature range up to 1500 ˚C, frequency between 5-10 kHz, and target uncertainties of 1%. In-cylinder measurements are also planned in the engine 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 will be explored in this project due to the availability of engine validation tests performed as part of the first two objectives. First, predictive models for exhaust after-treatment systems will be undertaken using stand-alone models or a combination of physical and data-driven approaches. 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. 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. 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.

MaritimeMET

Contact: ajoy.ramalingam@ptb.de

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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.

EUROPEAN PARTNERSHIP
Co-funded by the European Union
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