Publishable Summary for 16ENG09 LNGIII
Metrological support for LNG and LBG as transport fuel

Overview

The overall aim of this project was to enable the large-scale roll-out of liquefied natural gas (LNG) and liquefied biogas (LBG) as transport fuel. The custody transfer measurements of flow, density, and composition need to be underpinned with a clear and traceable metrological infrastructure, and properties which are important for fuel combustion, i.e. the density and the methane number (MN) need to be assessed cost-effectively.

To address this, the project combined expertise from industry, instrument manufacturers, universities, research institutes, and national metrology institutes, to establish the necessary test facilities and validation methods. Key project outcomes are SI-traceable calibration capabilities for LNG flow, composition, and density, and the development of three types of cost-effective MN sensors for LNG engine management. These outcomes of the project were implemented in relevant written standards, and communicated in workshops, conferences, and journal publications to stimulate the use of LNG and LBG as transport fuel.

Need

As addressed in the “Clean Transport Fuel Strategy”, the utilisation of LNG and LBG as transport fuel constitutes one of the pillars of the European clean fuel strategy. LNG implementation would enable the stringent pollutant emission limits of future EURO VI standards to be met more cost-effectively as compared to conventional fuels. In addition to this, engines running on LNG produce far less noise than diesel-operated engines and are therefore becoming the preferred choice for deliveries in urban areas. LNG is also an attractive fuel to meet the new limits for sulphur content in marine fuels and for nitrogen oxides (NOx)-emissions from ship engines.

The large-scale roll-out of LNG and LBG as transport fuel, however, requires reliable determination of the amount, density, composition and other physical properties of the cryogenic fuel; and although substantial progress had been made in the predecessor LNG metrology projects (EMRP ENG03 and ENG60), important metrological infrastructure and expertise was developed during the project addressing:

Refuelling/bunkering:

A calibration facility for LNG flow and composition measurements was constructed at the Rotterdam Port area in the Netherlands. This facility was put into operation with liquid nitrogen (LiN) in 2019 and provides an excellent platform for testing and validation of LNG flow metering technologies suitable for fuelling and bunkering applications. The facility enables systematic research into LNG flow meters under variable cryogenic conditions for which there is high demand from industry.

Composition, density and LNG particulates:

The composition of LNG, and consequently the energy content and other physical properties, varies from source to source. Furthermore, the LNG composition in carriers and storage tanks typically changes over time through a process known as “ageing”; which means that the LNG composition gets richer in heavier components. Therefore, standards to accurately define the composition of LNG/LBG mixtures are urgently needed.

LNG produced from Biogas (BG) can contain small particles which affect engine performance over time. Moreover, silicon dioxide particles can be formed through the combustion of siloxanes present in biogas. Therefore, the presence and the source and nature of the particles in LNG from BG also needs to be known to be able to decide the service intervals and the type of particle filters to be used at fuelling stations.

Engine performance:

To operate an engine in the most efficient way it should run as close as possible to its knocking point, i.e. the point where the fuel spontaneously ignites. The MN, together with the engine type and the operational conditions, determines this knocking point. Consequently, to run an engine at its most efficient setting, the MN needs to be determined using highly accurate and cost-effective methods.

Depending on the combustion process, part of the methane may not burn in the engine and thus can be released to the atmosphere (also known as methane slip (MS)). Thus, for economic and environmental reasons (i.e. methane is an important greenhouse gas), engine performance needs to be carefully monitored and managed to increase the combustion efficiency and minimise MS.

Objectives

The goal of this project was to enable the large-scale roll-out of LNG and LBG as transport fuel. The specific objectives were:

1. To reduce the onsite flow measurement uncertainty for small- and mid-scale cryogenic applications to the level comparable to meet the current OIML recommendations (1.5 %). To include a systematic assessment of the impact of flow disturbances and the impact of meter insulation.
2. To undertake a technical feasibility study to develop an LNG flow calibration facility for flow rates typically encountered in small- and mid-scale applications (400 m^3/h ~ 1000 m^3/h). The Calibration and Measurement Capability (CMC) of this facility should be low enough to at least meet the current International Legal Metrology Organisation (OIML) recommendations (1.5 %), but ultimately the uncertainty should be comparable to the one for conventional fluids i.e. (0.5 %). Furthermore, to assess whether the (on-site) measurement uncertainty can be reduced using a cryogenic piston prover.
3. To develop and validate a reference liquefaction technique (small scale liquefier) for the validation of LBG and LNG sampling and composition measurement systems.
4. To improve methods and (in-line) sensors for cost-effective measurement of the gas composition, methane number (MN) and methane slip (MS). In particular to: i) develop an SI-traceable density calibration method; ii) validate cost effective (in-line) density sensors; iii) validate sensors for composition and MN to enable real-time engine management, engine performance and the measurement of MS; iv) validate the existing MN algorithm from JRP ENG60 and reaction kinetics through full scale truck experiments; v) assess the source, content and potential impact of particles, particularly in LBG fuels.
5. To facilitate the take-up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (ISO, CEN) and end-users (transport and energy sectors). In particular to: i) input to an ISO standard for cryogenic flow metering, including recommendations on water calibration transferability; ii) input to an ISO standard for the calculation of the MN and iii) implement relevant results from the three LNG projects (EMRP ENG03 and ENG60, and this project) in the International Group of Liquefied Natural Gas Importers (GIIGNL) handbook for LNG custody transfer.

Progress beyond the state of the art

For billing purposes, the amount and energy content of LNG has to be determined. As part of the predecessor project (EMRP ENG60), a mid-scale calibration facility for LNG was developed, which has been delivered for use with LiN in 2019. This project built on its predecessor EMRP ENG60 and used the facility for a systematic research into flow meter performance under cryogenic conditions to assess onsite flow measurement uncertainty for small- and mid-scale cryogenic applications. Furthermore, this project investigated how traceability up to higher flow rates can be achieved by using of a cryogenic piston prover, and an alternative calibration principle based on a cryogenic Laser Doppler Velocimetry (LDV) sensor was validated as part of the project. A standard for dynamic LNG flow measurement (ISO 21903:2020) was developed and released during the project.

The composition of LNG depends on the origin of the LNG. Furthermore, the LNG composition in carriers and storage tanks changes over time through a process known as “ageing”; whereby the LNG gets richer in heavier components. The composition of LNG is usually analysed by LNG sampling, vaporisation and gas analysis equipment, and Raman Spectroscopy. For the metrological validation of the LNG composition measurement systems, a reference liquefier is needed which can provide accurate validation results and provide traceability on the composition measurement and suitability for use. Both analytical techniques need metrologically traceable LNG reference standards for calibration. Within this project a metrological institute (VSL), a university (RUB), and a liquefier manufacturer EffecTech have collaborated to metrologically validate an LNG liquefier.

The density of LNG is usually calculated based on its composition and an equation of state. Density meters for cryogenic liquids were developed under EMRP ENG60. Project partners have developed a prototype LNG density and speed-of-sound measurement device.

The composition of LNG changes during storage or transport, therefore "smart low-cost" sensors need to be developed to monitor the MN at the point of use, so that engines equipped with intelligent motor management systems can then be tuned to the actual MN to maximise their performance. Project partners have developed three different sensors for composition and MN to enable real-time engine management, engine performance and the measurement of MS. Actual MN's as determined in engine tests were determined, and further experiments were performed to determine the Ignition Delay Times (IDT) of the project's reference gases for the purpose of improving existing MN algorithms for LNG engine management. Chemical kinetic modeling that can accurately predict the combustion and ignition behaviour of LNG with different MN's was performed and validated with the IDT-determination measurements. This was combined with the service MN measurements to develop an improved MN algorithm, in terms of increased accuracy, that reflects real LNG engine behaviour.

Results

Objective 1: to reduce the onsite flow measurement uncertainty for small- and mid-scale LNG applications to the level comparable to meet the current OIML recommendations (1.5 %). To include a systematic assessment of the impact of flow disturbances and the impact of meter insulation.

The flow meters required for the systematic research into the flow meter performance were provided by the instrument manufacturer stakeholders. These flow meters were installed into two testing skids. These skids allowed for the flow disturbance tests in ambient water and cryogenic conditions. A test program for the water calibrations was agreed between partners and instrument manufacturer stakeholders. Due to the delay in commissioning of the mid-scale calibration facility for LNG, it was decided to carry out the cryogenic flow disturbance tests with LiN instead of LNG. The pertinent flow properties of LiN are similar to LNG and therefore this still enabled the study of the meter deviation and impact of flow disturbances under cryogenic measurement conditions and contrasting the meter deviations and flow disturbances against the water flow calibrations. The influence of removing the meter insulation on mass flow rate measurement accuracy can be more significant (meter error > ±0.50%) than the influence of many typical upstream disturbances when the meter is preceded by a straight piping length equal to twenty pipe diameters (20D) [i]. Due to strong interest from industry, project partners included six meters from five different suppliers in these tests. After succesfull completion of the ambient and cryogenic measurement campaigns, results were made public prior to full disssemination in peer reviewed journal papers. Given the estimated SI-traceable calibration uncertainty at 0.30% (k = 2) of reference mass flow rate, the objective can be considered achieved with LiN [ii].This project investigated how traceability up to higher flow rates can be achieved through the use of a cryogenic piston prover with a feasibility study. The study revealed that a cryogenic piston prover can be used as a primary system in the mid-scale LNG facility to achieve a calibration facility uncertainty well below 0.5 % in volumetric flow.

The mid-scale calibration facility reference standards are based on a gravimetric standard and Coriolis mass flow meters. An alternative reference principle is based on cryogenic Laser Doppler Velocimetry (LDV). A prototype cryogenic LDV sensor was developed under the predecessor project (EMRP ENG60) and it was validated in two test campaigns. This resulted in validation of the LDV seeding unit, and a cross comparison with a weigh bridge was in agreement to within 0.59% (k = 2) of LNG mass transferred.

Objective 2: to undertake a technical feasibility study to develop a LNG flow calibration facility for flow rates typically encountered in small- and mid-scale applications (400 m^3/h ~ 1000 m^3/h). The CMC of this facility should be low enough to at least meet the current OIML recommendations (1.5 %), but ultimately the uncertainty should be comparable to the one for conventional fluids i.e. (0.5 %). Furthermore, to assess whether the (on-site) measurement uncertainty can be reduced using a cryogenic piston prover.

The initial design of the LNG research and calibration facility, which was made under predecessor project EMRP ENG60 and was validated for a flow rate for LiN of 100 m^3/h in this project, included a third line to expand the targeted flow rate to 400 m^3/h. The uncertainty in flow calibrations when expanding to higher flow rates was investigated as part of a cryogenic piston prover feasibility study (see the results of objective 1 above). The study considered a flow rate of 600 m^3/h. It was found that when combining dominant uncertainty sources of the prover and its integration into the facility, the expected lower limit on the expanded uncertainty is about 0.2 % in volumetric flow rate. The cryogenic piston prover primary standard is in terms of volume, while that of the current facility is in terms of mass. Thus, the facility provides the potential means to compare various cryogenic flow metering principles.

The cryogenic LDV standard (see results of objective 1 above) was tested and validated with LiN and LNG for flow rates up to about 100 m^3/h. It is expected that it can also provide calibrations at flow rates covering the larger small- and mid-scale applications.

At the start of the project, another feasibility study for expanding the flow rates of the calibration facility was planned, which was not completed because more resources were devoted to the objective 1 activities. From the cryogenic piston prover feasibility study, the validation of the cryogenic LDV, and the establishment of the calibration facility for LNG it can be concluded that extending these techniques to the small- and mid-scale applications, given the stated uncertainties, is possible (400 m^3/h ~ 1000 m^3/h), with which the objective was achieved.

Objective 3: to develop and validate a reference liquefaction technique (small scale liquefier) for the validation of LBG and LNG sampling and composition measurement systems.

A review of small-scale liquefaction approaches was performed. An existing liquefier from EffecTech UK is accredited to ISO 17025 by UKAS. From the review it was found that the supercritical densimeter built by RUB in predecessor LNG metrology projects (EMRP ENG03 and ENG60) could be modified into a liquefier based on supercritical liquefaction and a corresponding design was made. Due to the high anticipated cost to build such a designed liquefier, a collaboration with EffecTech UK was established to perform metrological tests with the condensing cryostat built by the company. Performance tests on the condensing cryostat using certified LNG based gas mixtures were carried out. The test results were compared with the thermodynamic characterisation of the liquefier using state-of-the-art equations of state (EOS) for LNG, as implemented in the Trend 4.0 software developed by RUB as part of the project. This work showed that the liquefier can be successfully employed for metrological purposes, such as the calibration and performance evaluation of optical sensors for LNG-composition measurement. The uncertainty of the liquid composition is comparable to state-of-the-art calibration capabilities for natural gas. Consequently, validation of a reference liquefaction technique was achieved.
Supercritical liquefaction was developed at laboratory scale in the RUB supercritical densimeter and was successfully applied to obtain (1) reference data relevant to natural gas liquefaction and liquefied natural gas (LNG) thermodynamical properties and (2) improved models for the description of natural gas and LNG under cryogenic conditions. Consequently, supercritical liquefaction development for the generation of reference data relevant to LNG was achieved.

Objective 4: to improve methods and (in-line) sensors for LNG density and cost-effective measurement of the gas composition, MN and MS. In particular to: i) develop an SI-traceable density calibration method; ii) validate cost effective (in-line) density sensors; iii) validate sensors for composition and MN to enable real-time engine management, engine performance and the measurement of MS; iv) validate the existing MN algorithm from JRP ENG60 and reaction kinetics through full scale truck experiments; v) assess the source, content and potential impact of particles, particularly in LBG fuels.

The prototype LNG density and speed-of-sound measurement device that was produced in the preceding EMRP ENG60 project has been validated for the measurement of speed-of-sound and the results were publicised. Measurements to measure both speed-of-sound and density of cryogenic liquids in static mode were initiated. SI-traceable water density measurements by Coriolis flow meters were performed under different test conditions, and it was found that absolute errors were within 0.2% established with 0.03% ($k = 2$) combined measurement uncertainty.

Three sensors to measure the composition and methane number were identified: Coated Capacitive Chip (ECC), Tuneable Filter Infrared (TFIR), and Fourier Transform Infrared (FTIR). At the beginning of the project, the requirements for the methane number detection were defined, including the type of detectable components, operating temperature and pressure, response time, and methane number accuracy. The three gas detection analyzers were bench-marked in laboratory tests against the requirements using reference gas mixtures comprised of hydrocarbons C1 – C6 (i.e. methane, ethane, propane, butane, pentane, and hexane) that formed a common, traceable reference in the project. It was found that each of the sensing solutions has its own merits, but all of them are able to measure the methane number with a 1.5 methane number unit accuracy with respect to the experimentally determined values using the same set of reference gas mixtures. TFIR is a faster technique. The ECC sensor can be deployed in a larger (temperature and) pressure range.

The ECC sensor was assessed for its applicability for in-line fuel qualification and was assessed for the detection of methane slip using artificial exhaust gases. The results indicate that application of a gas quality sensor for conventional dual fuel engines enables new optimisation strategies.

The common, traceable set of reference gases was used in the following applications: 1) A chemical kinetic model was developed that can accurately predict the combustion and ignition behavior of LNGs with different MNs, 2) an array of sensors and detectors with different operation principles were tested at the intake of a spark ignition engine and a dual-fuel compression ignition engine and used to explore their potential for real time assessment of the fuel composition, i.e., MN determination, 3) a service Methane Number (SMN) was determined for each LNG gas based on the measurements in a spark ignition engine and the SMNs were compared to the MNs computed from different MN algorithms using their known composition, and 4) the relation between MN and engine knock in a dual-fuel engine was investigated for heavy-duty applications such as marine transportation. From these results an improved MN determination algorithm, in terms of increased accuracy, that reflects real LNG engine behavior was developed.

A gravimetric method for the weighing of particulate filters used in LNG and LBG refuelling stations was developed and a good practice guide highlighting many of the issues and pitfalls associated with setting up traceable measurement, from onsite sampling to the final mass value for particulates in LNG/LBG, was published on the project website. The guide describes a method for the accurate measurement of the collected particulate mass on filters building on the expertise gained from the area of ambient air monitoring. Further to this it has offered guidance on the determination of particulate losses within sampling systems used at LNG refuelling stations. The project has clearly improved methods and developed (in-line) sensors for LNG density and cost-effective measurement of the gas composition, MN and MS.

Impact

The project outcomes were disseminated through various channels. Project members have contributed to standard development, published journal papers, and presented at scientific and industrial conferences using the project's results (for further details see below).

Impact on industrial and other user communities

The LNG research and calibration facility is commercially available for traceable calibration of LNG flow and composition instruments. This calibration facility supports the reliable LNG measurements needed for a variety of small and mid-scale LNG applications.

The advisory board was (re)established (a continuation from that in EMRP ENG60) and a new chair was elected. The advisory board was expanded to 35 members to include nine additional stakeholders from the engine manufacturer industry. The project board actively participated in the project's progress meetings, LNG metrology workshops and trainings. The project also disseminated the project's outcomes to industry working groups such as the GIIGNL custody transfer handbook working group and through the dissemination of technical reports on the project website.

The development of improved and traceable LNG flow, density, and composition measurements will support LNG custody transfer measurement traceability and stimulate the uptake of LNG as a transport fuel as the metrological infrastructure for quantity (flow and density) and quality (composition) is provided.

State-of-the-art equations of state (EOS) for LNG such as the GERG-2008 EOS were implemented in the Trend 4.0 software developed by RUB, and the .dll is made freely available for software development by interested parties involved in the computation of reliable thermodynamic properties from composition measurements.

The ECC sensor tested by the project was tested in the gas distribution network, where it successfully measured the composition of natural gas and biogas. This has led to interest from the company Bronkhorst High-Tech to further commercialise this sensor.

The TFIR sensor is further developed in a commercialisation project in conjunction with an engine company and a company specialised in optical measurement systems for online monitoring and control of a gas engine. Further to this, the project has developed and improved a chemical-kinetic model which in reduced form can be used for LNG engine design and control. This model can be taken up by manufacturers of LNG ships and trucks.

Impact on the metrology and scientific communities

In total, five journal papers stemming from the research were published, and another five are expected to be published once the peer review process is finalised. The project has achieved uptake by the metrological, industrial, standardisation, and scientific communities comprising the establishment of a calibration facility for LNG flow and composition, release of a new standard on dynamic LNG flow measurement (ISO 21903:2020), delivery of a cryogenic LDV standard, adoption of FTIR MN determination in a pre-operational plan of an LNG terminal, release of TREND software for thermodynamic modelling of LNG, and commercialisation projects of the ECC MN and TFIR MN sensors.

Three LNG metrology training meetings took place during the course of the project, one in Delft, The Netherlands alongside the project's kick-off meeting (August 2017), one in Aberdeen, UK, alongside the project's 18 month progress meeting (October 2018), and one as a teleconference alongside the project's 36 month progress meeting (May 2020). Stakeholders, members of the consortium, and a collaborator participated (maximum attendance was at approximately 50 attendees). Most presentations were disseminated on the project website. The project has also disseminated its outcomes in numerous conferences, in scientific journals, and at LNG metrology workshops. Examples are: Oil and Gas Focus Group Meeting, 2018, United Kingdom, Kuwait 3rd Flow Measurement Conference, 2017, Kuwait, Eurosensors, 2018, Austria, GasTec, 2018, Spain, German Thermodinamic colloquim, 2018, Germany, Twentieth Symposium on Thermophysical Properties, 2018, United States, Clean Fossil Fuels Seminar, 2017, United Kingdom, Emerson Global Users Exchange, 2018, Netherlands, 10th International Symposium on Fluid Flow Measurement, 2018, Mexico, Global conference & exhibition – Innovative solutions in flow measurement and control, 2017, India, 7th International Metrology Conference – CAFMET 2018, 2018, India, XXIVth Encontro Luso Galego de Química, 2018,Portugal, 3. Tagung der Fuels Joint Resesearch Group, 2018, Germany, 37th International Symposium on Combustion, 2018, Ireland, 117th General Assembly of the German Bunsen Society for Physical Chemistry, 2018, Germany, 6th International TMFB Conference, 2018, Germany, SAE World Congress, 2018, United States, Flomeko 2019, 2019, Portugal, Micro Fluidic Handling Systems, 2019, Netherlands, European Combustion Meeting, 2019, Portugal, 29. Deutscher Flammentag, 2019, Germany,
38th North Sea Flow Measurement Workshop, 2020, United Kingdom, Public Seminar at Technical University Dortmund, 2018, Germany.

The project is contributing to the calibration services know-how by studying the effects of upstream flow disturbances under ambient and cryogenic settings. Further to this, the cryogenic LDV flow sensor was validated in pertinent LNG custody transfer settings, providing a potential alternative to Coriolis and ultrasonic flow sensors for measuring flow. The collaboration with a liquefier manufacturer (EffecTech) contributed to the required metrological knowledge to validate composition measurements by means of a reference liquefier.

The cryogenic density meter was tested and validated with the aim to improve the measurement accuracy of LNG density measurements. Development is ongoing in terms of making one of the sensors suitable for use in an industrial setting.

The ECC and TFIR are currently being commercialised with applications of gas composition measurement in the gas grid and gas engine management by MN determination. Last, improved MN determination algorithms were developed as part of the project.

Impact on relevant standards

The knowledge and experience for LNG measurement and calibration were shared within various ISO-standard working groups, OIML technical committees and user groups such as the GIIGNL including: ISO/TC 28 WG20, ISO/TC28 SC4 and SC5, OIML/TC8 SC3 and SC6, ISO TC 193 WG8, the Gas Processors Association and American Petroleum Institute, and the GIIGNL Custody Transfer Handbook (CTH) working group.

Project partners NEL and VSL have developed, together with stakeholders representing instrument manufacturers and LNG end-users, a new standard "Refrigerated hydrocarbon fluids — Dynamic measurement — Requirements and guidelines for the calibration and installation of flowmeters used for liquefied natural gas (LNG) and other refrigerated hydrocarbon fluids" within the ISO/TC 28 WG20, chaired by VSL. The standard was published in February 2020. The release of the standard addresses key issues in the proper installation and calibration of flow meters used for dynamic measurement of LNG, which can help to prove this methodology in custody transfer applications supporting the use of LNG as a transitional fuel toward clean energy.

Project knowledge was also disseminated to the GIIGNL CTH working group. Cesame's cryogenic LDV standard was presented to the GIIGNL task force in September 2019 and is expected to be included as new route to traceability in the new revision of the GIIGNL CTH. NEL created a report on the outcomes of all LNG metrology projects which will be communicated with the CTH working group after project completion. Naturgy and Reganosa have communicated their advances on the FTIR sensor method for direct MN determination. Full adoption of LNG custody transfer measurements into the GIIGNL CTH will require methods to be fully supported by published datasets.
PTB, TUBS, NPL and VSL, disseminated the the novel algorithm to calculate the MN from the LNG composition into the ISO/TC 193 WG8.
In collaboration with NIST, RUB provided input to the Gas Processors Association and American Petroleum Institute on the Enhanced Revised Klosek McKinley method for density calculations of liquefied natural gas (LNG).
VSL and NEL communicated the project outcomes within the NC 310 327 (Dutch mirror committee of CEN/TC282), the OIML/TC8 SC3 and SC8, ISO/TC28/SC4, and the ISO/TC28 SC5.

Longer-term economic, social and environmental impacts
LNG fuelled truck engines produce around 25 % less carbon dioxide (CO_2) compared to diesel engines and 85 % less NO_x. Furthermore, they produce less noise and thus are the preferred option for deliveries in urban areas and city centres, especially in the early morning or late at night (when avoiding peak traffic). The developed metrological infrastructure directly supports the European Union's strategy for liquefied natural gas and gas storage.
The uptake of LNG and LBG as transport fuel will be underpinned by robust calibration services and more efficiently running engines. This in turn enables the uptake of the relatively clean LNG and even cleaner (bio-)LNG/LBG with concomitant economic and environmental benefits. Thereby making a significant contribution to the European "Clean Transport Fuel Strategy" which aims to reduce the emission of greenhouse gases, nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particles.

The project has lasting impact by establishing metrological infrastructure for LNG flow, composition, and density, and the development of three types of cost-effective MN sensors for LNG engine management. Notable application examples are: i) the LNG research and calibration facility for flow and composition instruments, ii) improved calibration services know-how on cryogenic upstream flow disturbances and installation guidelines included into the ISO/DIS 21903:2018(E), iii) cryogenic LDV standard for flow measurement, iv) TREND 4.0 software for thermodynamic modelling of LNG, v) required metrological knowledge to validate composition measurements by means of a reference natural gas liquefier, v) The ECC and TFIR sensors are currently being applied for gas composition measurement in the gas grid and gas engine management by MN determination, vi) adoption of FTIR MN determination in a pre-operational plan of an LNG terminal, and vii) an improved MN algorithm. These project outcomes will support further developments for even more efficient LNG engine management, and for establishing LNG calibration traceability for the for small- and mid-scale applications and beyond.

List of publications

1. Cavuoto, G., Lago, S., Giuliano Albo, P.A., Serazio, D., 2019, Speed of sound measurements in liquid methane (CH4) at cryogenic temperatures between (130 and 162) K and at pressures up to 10 MPa, J. Chem. Thermodynamics, 142, 106007. https://doi.org/10.1016/j.jct.2019.106007

2. Shu, B., Vallabhuni, S.K., Zheng, J., Agarwal, S., Fernandes, R.X., 2020, Experimental and Modeling Studies on the Correlation Between Auto-Ignition Delays and the Methane Number of Liquefied Natural Gas (LNG) and Liquefied Biogas (LBG), *Frontiers in Mechanical Engineering,* 6, Article 47. https://doi.org/10.3389/fmech.2020.00047

3. Sweelssen, J., Blokland, H., Rajamäki, T., Sarjonen, R., Boersma, A., 2020, A Versatile Capacitive Sensing Platform for the Assessment of the Composition in Gas Mixtures, Micromachines, *11*, 116. https://doi:10.3390/mi11020116

4. Sweelssen, J., Blokland, H., Rajamäki, T., Boersma, A., 2020, Capacitive and Infrared Gas Sensors for the Assessment of the Methane Number of LNG Fuels, Sensors, 20, 3345. https://doi:10.3390/s20123345

5. Vallabhuni, S.K., Lele, A.D., Patel, V., Lucassen, A., Moshammer, K., AlAbbad, M., Farooq, A., Fernandes, R.X., 2018, Autoignition studies of Liquefied Natural Gas (LNG) in a shock tube and a rapid compression machine, Fuel, 232, 423-430. https://doi.org/10.1016/j.fuel.2018.04.168

References

i. Kenbar, A., Schakel, M., "Calibration of Industry-Standard LNG Flow Meters Under Ambient and Cryogenic Test Conditions," *submitted,* Submitted version available here: https://www.tuvsud.com/en-gb/industries/chemical-and-process/national-measurement-system/publications, 2020.

ii. Schakel, M., "Liquid nitrogen calibrations of industry-standard LNG flow meters used in LNG custody," VSL, https://www.vsl.nl/sites/default/files/rtf/Liquid%20nitrogen%20calibrations%20of%20industrystandard%, 2019.

iii. ISO/TC28/WG20, "ISO DIS21903:2020 Refrigerated Hydrocarbon Fluids —Dynamic Measurement — Requirements and guidelines for the calibration and installation of flowmeters used for liquefied natural gas (LNG) and other refrigerated hydrocarbon fluids," *ISO,* 2020.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2017, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Menne Schakel, VSL Tel: +31(0)15 269 1681 E-mail: mschakel@vsl.nl
Project website address: www.lngmetrology.info</td></tr>
<tr><td>Internal Funded Partners:
1 VSL, Netherlands
2 Cesame, France
3 CMI, Czech Republic
4 INRIM, Italy
5 JV, Norway
6 NEL, United Kingdom
7 NPL, United Kingdom
8 PTB, Germany
9 VTT, Finland</td><td>External Funded Partners:
10 Mestrelab, Spain
11 Reganosa, Spain
12 RUB, Germany
13 TNO, Netherlands
14 TUBS, Germany
15 UCov, United Kingdom</td><td>Unfunded Partners:
16 Gas Natural, Spain</td></tr>
<tr><td colspan="3">RMG -</td></tr>
</table>