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

Overview

The overall aim of this project is 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 will combine expertise from industry, instrument manufacturers, research institutes, and national metrology institutes, to establish the necessary test facilities and validation methods. The outcomes of the project will also be implemented in relevant written standards 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 has been made over the past few years, several issues still need to be resolved, such as:

Refuelling/bunkering:

A calibration facility for LNG flow 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 LBG 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 methods which are yet to be developed.

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 is to enable the large-scale roll-out of LNG and LBG as transport fuel. The specific objectives are:

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 (ENG60 LNGII), a mid-scale calibration facility for LNG was developed, which has been delivered for use with LiN in 2019. This project builds on its predecessor ENG60 and has 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 through the use 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.

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 Gas Chromatography (GC) and Raman Spectroscopy. Both analytical techniques need metrologically traceable LNG reference standards for calibration, which do not currently exist. Within this project metrological institutes, a university and a commercial liquefier manufacturer 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 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.

When LNG is used as transport fuel in combustion engines, the MN must be accurately known to enable optimal engine performance. However, currently no harmonised method for the determination of the LNG MN exists. Within this project an existing MN algorithm from ENG60 was improved and is made applicable for use for reaction kinetics through to full scale truck experiments.

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 %).

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 allow for the flow disturbance tests in ambient water and cryogenic conditions. A test program for the water calibrations was agreed between partners and 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 will still enable the study of the impact of flow disturbances under cryogenic measurement conditions and contrasting them against the water flow disturbance measurement effects. Water calibration has been successfully performed and the cryogenic flow disturbance calibrations have been completed for four out of six meters. Due to strong interest from industry, project partners have included six meters from five different suppliers in these tests.

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 %.

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 (ENG60) and it has been validated in representative settings (i.e., a weigh bridge facility and at an LNG terminal) as part of this project. Development on the seeding unit for the LDV is currently ongoing.

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 %).

The initial design of the LNG research and calibration facility, which was made under predecessor project ENG60 and has been 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 has been investigated as part of a cryogenic piston prover feasibility study (see the results 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 objective 1 above) was tested and validated for flow rates up to 100 m^3/h. It is expected that it can also provide calibrations at flow rates covering the small- and mid-scale applications.

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.

From the review of small-scale liquefaction approaches it was concluded that only a design based on supercritical liquefaction would satisfy the metrological requirements. A collaboration with a liquefier manufacturer (EffecTech) has been established and joint research and test activities have been undertaken (i) to investigate the liquefiers' measurement uncertainty, (ii) to validate the liquefier, and (iii) to write a guide for the design of a "metrologically sound" reference liquefier. Thermodynamic modelling is being used to validate the liquefier, to make predictions about the best way to operate it, and to predict the magnitude of the effect on the liquid composition by operating at vapour-liquid equilibrium.

The prototype LNG density and speed-of-sound measurement device that was produced in the preceding ENG60 project has been validated for the measurement of speed-of-sound. Work is ongoing to perform cryogenic density measurements in static mode, and to measure the density at ambient conditions in a flowing liquid (water).

Objective 4: to improve methods and (in-line) sensors for cost-effective measurement of the gas composition, MN and MS.

Three sensors to measure the methane number were defined and tested: Coated Capacitive Chip (ECC), Tuneable Filter Infrared (TFIR), and Fourier Transform Infrared (FTIR). Sensor tests with reference gas mixtures comprised of hydrocarbons C1 – C6 (i.e. methane, ethane, propane, butane, pentane, and hexane) were performed by project partners in laboratory tests. Work is ongoing to perform sensor validation tests and to compare the sensor systems. In these tests 16 artificial reference gas mixtures are being used that form a common, traceable reference. Results show that the longer hydrocarbon chains can be detected up to 0.1 volume percent. Initial results indicate that the MN-sensors will be able to fulfill the in-field requirement to measure the MN within 2 MN units.

A gravimetric method for the weighing of particulate filters used in LNG and LBG refuelling stations was developed. This will allow to traceably determine the mass concentration of particulates on a filter when fuelling LNG or LBG and to assess the potential impact of these particulates. Ambient filter contamination work has been carried out at NPL (at a Hydrogen refuelling station) and found to be negligible. Work is ongoing to perform particulate measurements at elevated pressures.

For the research into the knocking behaviour a test program has been defined and work to convert an engine for the knocking tests is ongoing. The knocking tests will use the 16 artificial reference gas mixtures and are scheduled to be completed by the end of 2019. The ECC sensor has been already tested in an automotive test laboratory and further tests to validate this sensor in an engine setting are currently ongoing.

Within this project an chemical kinetic model which can accurately predict the combustion and ignition behaviour of LNG with different MN ranges was developed. This chemical kinetic model was updated with shock tube experimental data. Strategies to then reduce this model for use in actual LNG engine simulation were tested and a strategy was selected. Currently this strategy is being used to optimise the chemical kinetic model reduction mechanism for LNG engine simulation.

Impact

So far two LNG metrology training meetings have taken place, one in Delft, The Netherlands alongside the project's kick-off meeting (August 2017) and one in Aberdeen, UK, alongside the project's 18 month progress meeting (October 2018). Stakeholders, a collaborator, and members of the consortium all participated (approx. 50 attendees) and more information is available on the project website. A final workshop is planned at the project's end date. The project has also disseminated it's outcomes at conferences in journals, and at metrology workshops, such as: Kuwait 3rd Flow Measurement Conference, Nov 2017, Clean Fossil Fuels Seminar, UK Sep 2017, XXIVth Encontro Luso Galego de Química, Portugal, November 2018, European Combustion Meeting, Portugal, April 2019, Flomeko 2019 18th International Flow Measurement Conference, Portugal, June 2019, and Micro Fluidic Handling Systems, The Netherlands, Oct 2019.

The project has one peer-reviewed journal publication as an outcome of the project. The project has achieved uptake by the metrological, industrial, standardization, and scientific communities comprising the establishment of cryogenic research and calibration services, release of a new standard on dynamic LNG flow measurement (ISO DIS21903), delivery of a cryogenic LDV standard, adoption of FTIR MN determination in a pre-operational plan of an LNG terminal, and a commercialization project of an ECC MN sensor.

Impact on industrial and other user communities

The advisory board has been (re)established (a continuation from that in ENG60) and a new chair has been elected. The advisory board was expanded to include nine additional stakeholders from the engine manufacturer industry. The project board has actively participated in the project's progress meetings. The project is also disseminating the project's outcomes to industry working groups such as the GIIGNL Technical 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) will be provided.

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.

Further to this, the project has developed a target 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

The LNG research and calibration facility will be made commercially available for traceable calibration of LNG flow and composition instruments with LiN. This calibration facility supports the reliable LNG measurements needed for a varierty of small and mid-scale LNG applications. The project is contributing to the calibration services know-how by studying the effects of upstream flow disturbances for water and LNG. 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. It is expected that the LDV system will be ready for customer services at the end of the project. The collaboration with a liquefier manufacturer (EffecTech) should also result in the required metrological knowledge to validate composition measurements by means of a reference liquefier.

Two cryogenic density meters are also being 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.

Impact on relevant standards

The knowledge and experience for LNG measurement and calibration is shared within various ISO-standard-working-groups, OIML technical committees and user groups such as GIIGNL. Standards include ISO/TC 28 WG20, OIML/TC8 SC3 and SC6, ISO TC 193 WG8, the Gas Processors Association and American Petroleum Institute, and the GIIGNL Technical working group.

Project partners have developed a new standard "Refrigerated Hydrocarbon Fluids —Dynamic Measurement — Guidance for the calibration, installation and use of flow meters for LNG and other refrigerated hydrocarbon fluids" within ISO/TC 28 WG20 which was converted to a draft ISO-standard (expected publication date April 2020). Project knowledge is also being disseminated to the GIIGNL Custody Transfer Handbook The cryogenic LDV standard was presented to the GIIGNL task force in September 2019 in Brussel and is expected to be included as new route to traceability in the new revision of GIIGNL in January 2020. Further to this, the novel algorithm to calculate the MN from the LNG composition the results were disseminated to ISO/TC 193 WG8.

Longer-term economic, social and environmental impacts

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 emissions of greenhouse gases, nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particles. 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).

List of publications

1. 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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2017, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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<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
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