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JRP-Coordinator	
Name, title, organisation	Oswin Kerkhof, M.Sc., VSL
Tel:	+31 15 2691509
Email:	okerkhof@vsl.nl
JRP website address	www.lngmetrology.info

JRP-Partner 1: VSL B.V., the Netherlands	JRP-Partner 6: SP, Sweden
JRP-Partner 2: TUV NEL, United Kingdom	JRP-Partner 7: JV, Norway
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	JRP-Partner 12: ENAGAS, Spain

Researcher name, title	Markus Richter, Ph.D.	Start date: 1 November 2010
(Home organisation Short name, country)	RUB, Germany	Duration: 30 months

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1 Executive Summary

An improved infrastructure for LNG is one of the priorities of the EC integrated energy policy, motivated by the need to ensure a more diversified and secure energy supply and fair and open trade in natural gas. The growing importance of the LNG market creates an urgent need to build a metrological infrastructure to provide industry and society with accurate and reliable LNG measurements and this project has contributed to that goal.

The problem

The transfer of LNG from buyer to seller ('custody transfer') involves significant finanical risk due to a lack of accurate information on measurement uncertainties in the transferred energy. This uncertainty translates to finanical risk for both the buyer and seller. A clear view on the total measurement uncertainty for the delivered energy of LNG has been lacking with estimates ranging between 0.5 - 1.0% and even higher. In addition very few calibration standards have been available for validating LNG measurement equipment. This called for efforts to clarify and reduce measurement uncertainties by developing measurement standards, methods and procedures.

The solution

In response to the challenges described above, the project set out to develop a better understanding of the measurement uncertainties and the development of measurement standards by accomplishing the following objectives:

1 Developing traceability for LNG flow meters
2 Testing and evaluating LNG quantity metering systems
3 Improving LNG composition measurement systems
4 Reducing uncertainties in LNG density and calorific value calculations
5 Contributing to measurement guidelines, written standards and legal metrology

The overall objective of the project has been to contribute towards reducing the measurement uncertainty by a factor two assuming that the uncertainty is 1% at the start.

Results

Several studies have been made to assess measurement uncertainties and standards have been developed to promote reducing measurement uncertainties.

The studies have led to the confirmation that the overall uncertainty on LNG energy using current methods is around 1% with the disclaimer that this depends on the situation. For example an uncertainty assessment of tank level gauging revealed the complexity of the measurement process and the many potential sources of uncertainty that need to be accounted for on a case by case base.

Several (first) steps have been made towards reducing the measurement uncertainty:

1. A primary LNG mass flow standard was developed and validated. The claimed measurement uncertainty (CMC) is between 0.12 – 0.15% on mass over the range of 10 - 40 m^3/h (5 – 20 ton/h).
2. A prototype Laser Doppler Velocimeter standard was developed for measuring flow with a proven measurement uncertainty of 0.6% and a potential for reaching 0.2%.
3. Two alternative LNG density meter standards were developed and validated. However only the sinker-type densitometer could be used to produce valid data with a measurement uncertainty of 0.06 – 0.08%. Future improvements should lead to further reduction of the measurement uncertainty to 0.02%. The new reference data produced was sufficient to make a preliminary comparison with the currently used Equations of State. A thorough validation will follow when additional reference data becomes available

Early Impact

- The project outputs have been widely disseminated to relevant stakeholders. Presentations and reports have been exchanged with the key relevant standards committees: ISO TC67/WG10 and ISO TC193, WELMEC WG10 and with the GIIGNL Technical Standing Group. As a result a dynamic flow measurements section has been incorporated in the ISO10976 standard.The results are also likely to contribute to changes in the relevant legal metrology guidance provided by OIML in order that LNG can be included alongside other energy commodities.
- Industry awareness about sources of measurement uncertainties has increased.
- Small diameter mass flow meters have been calibrated using the primary LNG mass flow standard showing typical deviations of flow meters.
- A design and plan for a LNG flow and composition calibration facility has been developed and is being embraced by industry.

In the longer term as the metrology capabilities are further developed and taken up by the LNG industry, the determination of transferred energy in LNG will improve leading to reduced financial exposure and a more efficient and effective industry.

2 Project context, rationale and objectives

Project background

Liquefied Natural Gas (LNG) is a strategic and, in the case of long distances, a more economical alternative for pipeline gas. It is also used to transport natural gas from and to locations where no pipeline infrastructure exists. After regasification of the liquid form, the natural gas is transported to the main users: power plants, industry and households. Recently the use of LNG as a cleaner transport fuel has been added to the list of important applications.

In comparison with other commodities like natural gas or gasoline the total uncertainty of measured energy is high for LNG and has been estimated to be up to 1 %. One (ship) carrier load of LNG load can be as valuable as 50 million euro and even an optimistic estimate of uncertainty represents a financial risk of 400 k€. A single large production facility may thus be exposed to this on a daily basis. However the high uncertainties and lack of direct traceability to SI leads to the delayed introduction of new measurement methods in the LNG business. A sound metrological framework is an indispensable element for the development of LNG as transport fuel, which is one of the pillars of the EU clean fuel strategy.The LNG custody transfer handbook of GIIGNL is the often referenced industry standard and claims a total measurement uncertainty for the delivered energy of about 0.86 %. Before the start of the project this rather high level of uncertainty was even considered to be optimistic and not taking all possible errors into account. What was needed first was to assess the real uncertainties in the determination of LNG volume, density and calorific value by following sound metrological principles. This was followed by efforts to reduce these uncertainties by developing measurement standards, methods and procedures.

Flow metering in general is a much more accurate method for measuring transferred volume or mass of liquids than (in the case of current LNG practice) level gauging. The lack of test and calibration standards for LNG flow meters is however blocking their introduction to the market. In the first place because the Measuring Instruments Directive formally requires that custody transfer measuring instruments are type approved before they are allowed on the market. In the second place because the LNG industry is demanding a demonstration of the flow meter performances under real conditions before implementing them in custody transfer systems.

Another important (and probably underestimated) source of uncertainty is the **sampling and vaporization of LNG** prior to analysing the composition. Moreover, the industry view is that the current ISO 8943 [11] on sampling of LNG still falls short of providing practical guidance with regards to the demands and uncertainties involved in sampling of cryogenic fuels. A clear assessment of the uncertainty contributions of various sampling system designs was needed that will lead to recommendations for improvements of both sampling systems and the ISO standard.

The density of LNG is calculated on the basis of the measured composition, temperature and pressure. Important sources of uncertainty are the choice of the correct equation of state as well as temperature and composition gradients. New and more accurate density reference data need to be produced in order to validate the many available density calculation methods that are based on old reference data. This will lead to reduced uncertainties and improved transparency.

Whereas LNG contracts necessarily refer to written standards and/or guidelines these also needed to be a focus of attention in the project. By assuring that the project results find their way into revisions of standards and guidelines the impact of the project will be maximised.

Objectives

The overall objective of the project has been to contribute to a significant reduction of uncertainty in the determination of transferred energy in LNG custody transfer processes. The total measurement uncertainty of transferred energy at the start of the project was estimated at about 1 % or more. The longer-term objective of the research in this area is to provide a clear estimate of the uncertainty and at the same time contribute to reducing it by at least a factor two.

The more specific objectives of this JRP can be summarized as following:

O1 Developing traceability for LNG flow meters
O2 Testing and evaluating LNG quantity metering systems
O3 Improving LNG composition measurement systems
O4 Reducing uncertainties in LNG density and calorific value calculations
O5 Contributing to measurement guidelines, written standards and legal metrology

Improving traceability and reducing uncertainties in each of these areas will contribute to a reduced measurement uncertainty for the delivered energy of LNG.

3 Scientific and technological results and foreground

The main scientific and technological results obtained during the project are:

As related to objective 1

1. Development and validation of a primary LNG mass flow standard
2. Comparison of LNG flow meter calibration results using water, liquid nitrogen and LNG
3. Pre-study and development of a prototype Laser Doppler Velocimetry system to be used as a volume flow standard

As related to objective 2

4. Uncertainty evaluation of tank gauging systems
5. Results of a comparison of a flow metering system with a weigh bridge method
6. Report about the effects of cryogenic media on flow metering systems

As related to objective 3

7. Assessment of sampling systems

As related to objective 4

8. Development and validation of a primary LNG density standard
9. Calculation of LNG calorific value at different reference conditions

These results are reported in turn in the sections that follow.

1. Development and validation of a primary LNG mass flow standard

A primary LNG mass flow standard was developed by VSL to be used in the range of 5 – 25 m^3/hr (20-100 ton/hr) and validated using liquid nitrogen with SP. Based on these results the system was improved and prepared for LNG testing in the field at Gasunie peakshaver site (see figure 1).

Figure 1 Primary LNG mass flow standard installed (temporarily) at Gasunie peakshaver

The system was fully validated with LNG together with SP and FORCE. A thorough analysis of the measurement results was completed and uncertainty budgets have been assessed. The lowest single point measurement uncertainty found was 0.08%. The CMC of the combined flow standard and flow meter under test over a flow range up to 40 m^3/hr (4 kg/s) lies between 0.12 - 0.15% (see figure 2). The conclusion has been drawn that the CMC can be decreased down to 0.10% with relatively simple measures. Although this is higher than the original target measurement uncertainty of 0.05% it is believed to be a sufficient base for calibrating flow meters using a mid-scale LNG flow facility traceable to the primary standard. A concept and preliminary design of this higher flow facility has been made.

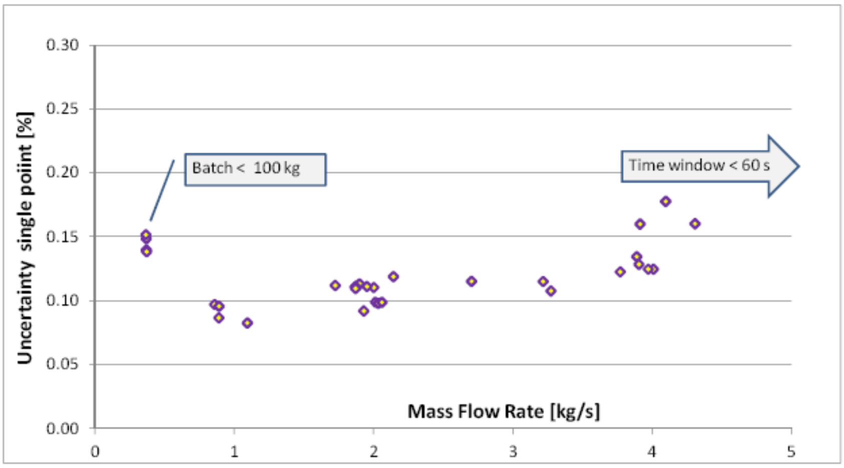


Figure 2 Typical uncertainties of reference mass flow rate

The validated primary LNG flow system has been used to test four different Coriolis type flow meters (see figure 3). One of them has also been tested with the weigh bridge test method set-up by Justervesenet (main result no. 5 referred to above and described further down). The comparison showed that the results are consistent within the combined measurement uncertainty.

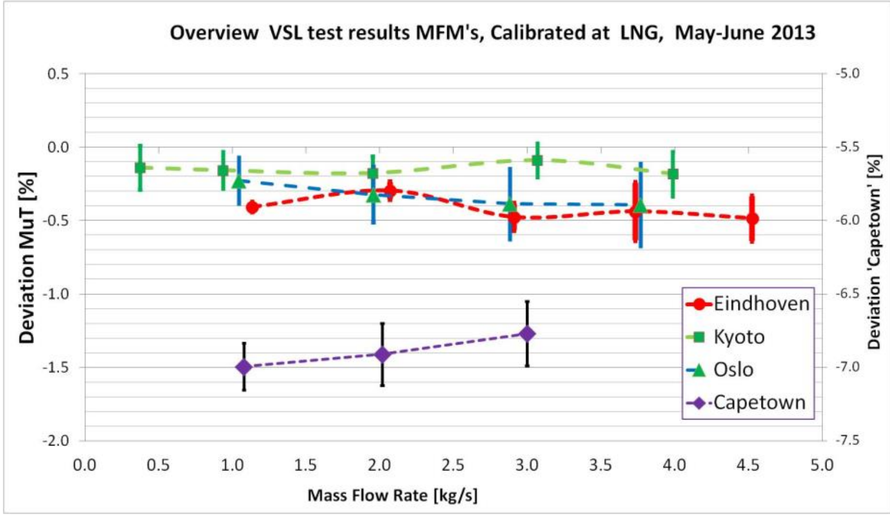


Figure 3 Overview of test results with four different LNG mass flow meters

2. *Comparison of LNG flow meter calibration results using water, liquid nitrogen and LNG*

Three Coriolis flow meters from different manufacturers have been tested for three fluids; water at ambient conditions, liquid nitrogen (LIN) at about -193 °C and LNG at about -161 °C. Depending on prevailing circumstances during the project, not all flow meters were tested with the three fluids, however, each meter was tested with water and one or both cryogenic fluids. The main objective of the test programme was to assess the cryogenic correction models that are used to transfer a standard factory calibration with water at ambient conditions, to cryogenic conditions. Typically, these correction models are based on the Young's Modulus.

The water testing results show that all flow meters performed well within their specified accuracy. The measurements have also shown good measurement repeatability and reproducibility. The results for the LIN and LNG calibrations have shown that the cryogenic correction factors do significantly improve the flow meter accuracy for cryogenic fluids. However, even with this correction, for LNG, the flow meter deviation remains in the order of 0.2 to 0.5%, which is considerably more than for other high-value commodities (order 0.1%). For LIN the flow meter deviation is somewhat better, better than 0.3%. This is no surprise because the cryogenic correction models have typically been tuned for calibrations with LIN. The larger deviation found for LNG implies that there is room for improvement regarding the correction factors. Calibrations with LNG are probably necessary when the lowest possible uncertainties are required. These results are based on testing 2" flow meters and in this stage it cannot be assumed that these results apply to larger flowmeters until larger units are tested in the same way.

3. *Pre-study and development of a prototype Laser Doppler Velocimetry system to be used as a volume flow standard*

A novel cryogenic flow metering technology, Laser Doppler Velocimetry (LDV), has been explored as an alternative to ultrasonic and Coriolis flow metering. A feasibility study of LDV technology applied to LNG flow metering was carried out. The study focused on the technological challenges and solutions for extending the LDV method to cryogenic temperatures, and on the estimation of the uncertainty that can be realistically achieved with such a system.

A first report [8] was delivered describing the needs for LNG flow rate measurements and a literature survey concerning the technical feasibility of a cryogenic LDV measurement package. Flow rate measurement based on LDV is a mature technology for gaseous natural gas [5, 6]. The German National Laboratory "pigsar™" achieved with a LDV technology the primary flow rate standard for natural gas under high pressure up to 50 bar and flow rates up to 6500 m3/h, with a relative flow rate uncertainty of 0.1 %.

A second report [11] presented the technical feasibility study for a cryogenic LDV metering system for LNG. Numerical flow simulations have been performed to optimise the internal shape (convergent, throat, divergent) of the measurement package. A measurement package has been designed whereby the optical access points for the LDV measurements have been studied and sized to allow velocity measurements with high accuracy. The design of the internal geometry (convergent, throat, divergent) has been validated by computer simulations. Two seeding systems have been studied, designed and integrated into the model (gas injection or formation of micro-bubbles).

A prototype Cryogenic LDV measurement package (see figure 4) has been constructed and validated with pressurized air at CESAME EXADEBIT where similarity of Reynolds numbers was used to simulate the LNG flow conditions.

Figure 4 Prototype cryogenic Laser Doppler Velocimetry system

The feasibility study has shown, by preliminary tests realized with pressurized air (1-10 bar) on a simplified prototype of cryogenic LDV measurement system, that was possible to measure flowrate with an accuracy of 0.4% - 0.6%. With a number of identified improvements in the design it is believed that a relative accuracy of 0,2% under cryogenic conditions can be achieved.

4. Uncertainty evaluation of tank gauging systems

Transferred LNG volumes nowadays are measured using ship based tank gauging systems. An evaluation of the uncertainty model adopted in the GIIGNL Custody Transfer Handbook (3rd edition) and a validation of the uncertainty figure of the (un)loaded LNG volume has been carried out and reported. In order to achieve this goal various experts in the field of LNG shipping have been interviewed. In addition, a significant data set of LNG (un)loadings has been collected and analyzed.

No final conclusions about the level of uncertainty regarding LNG (un)loadings have been drawn although there are strong indications that the uncertainty figures commonly used by the industry for transferred volume are somewhat underestimated. The scope of the study has been to evaluate the existing model and to recommend further detailed study of specific (and sometimes new) elements. The models and uncertainty budgets developed in the report can be generally applied to Moss and Membrane type tanks. However, the magnitude of the uncertainty sources should be determined specifically for each ship. Figure 5 gives an illustration of the complexity of the measurement process and the many different elements to be considered.

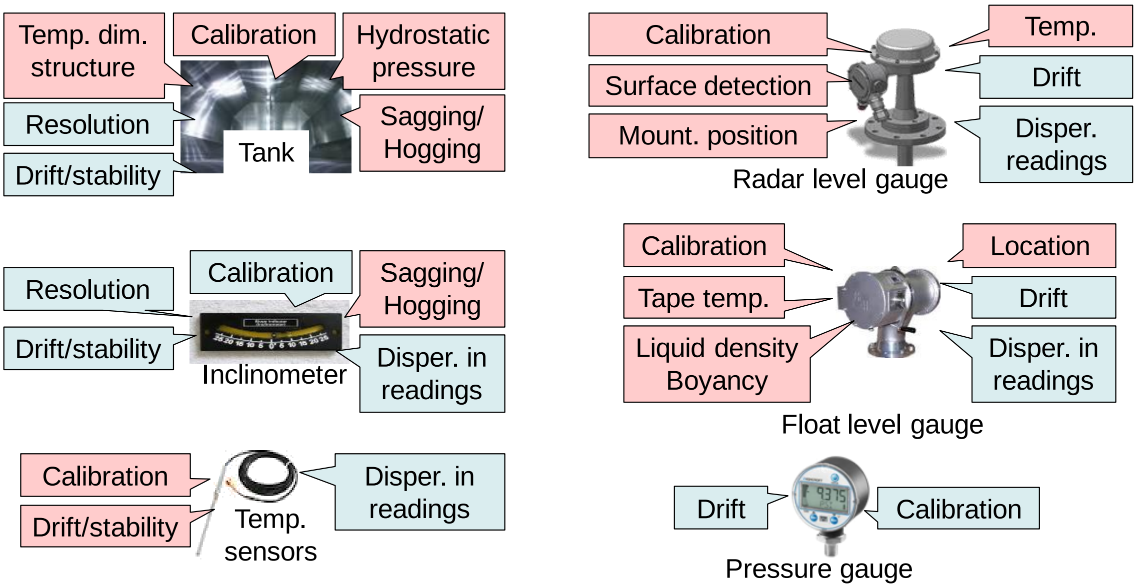


Figure 5 Relevant input quantities for tank based measurements

The main conclusions of the study report are: 1) the uncertainty in LNG (un)loaded as stated in ISO8310 (Refrigerated light hydrocarbon fluids- Measurement of temperature in tanks containing liquefied gases- Resistance thermometers and thermocouples) is not evaluated/propagated for a (un)loading situation in a metrological sound manner and 2) the uncertainty in LNG (un)loaded as stated in the GIIGNL Custody Transfer Handbook (3rd edition) is optimistic This is in contrast with what is commonly believed, i.e. that the uncertainty achieved in LNG volumes is typically in line with the GIIGNL. The people involved in writing the GIIGNL custody transfer handbook are aware of the report and the conclusions and appear inclined to take account of them in the next revision.

5. Results of a comparison of a flow metering system with a weigh bridge method

A series of measuring comparisons for LNG static and dynamic mass measurements have been performed onsite. The comparison consists of observing the difference in indicated and measured LNG mass from several measurement systems. The measurement systems belonged in one of the two categories:

1) Static mass measuring system by the use of a scale (truck weighbridge) and

2) Dynamic mass measuring system (coriolis mass flow (CMF) meter).

A LNG road tanker was used to transfer the mass of LNG between the two categories of measurement systems. The dynamic measurement from simultaneously unloading of a road tanker semi-trailer filled with LNG through three coriolis flow meters connected in series were compared to the measuring results of a static non-automatic weighbridge used before and after the unloading of the road tanker.

Figure 6 LNG road tanker (tractor plus semi-trailer) on weighbridge at Stena Recycling, Laksevågneset

The possibility to make uncertainty validations was limited but nevertheless a list of possible significant influences for the measurements of transferred mass could be drawn. An estimate for the uncertainty for the dynamic metering (coriolis flow meters) indicated that the expanded uncertainty at k=2 should be within 0.2%. In this model calculation the weighbridge calibration, stability and the road tanker road debris are assumed to contribute significantly to the uncertainty in the measurements in addition to the linearity and repeatability of the coriolis meter.

The results of the comparisons indicate good consistency of data between the dynamic metering method of meter 1 (-0.16% error, 0.2% uncertainty) and meter 2 (-0.11% error, 0.2% uncertainty) with the static metering method of weighing. Meter 3 (0.67% error, 1,5% uncertainty) installed on the road tanker seems to have a more significant variation related to the other meters and the weighbridge mass. This could be related to both the type specification and its challenging mounting position.

The relatively high reproducibility (0.06%) of meter 1 and meter 2 indicate that the influences from random errors are low. This shows that the method of using road tanker on a weighbridge as reference for LNG mass can be performed by careful measurements and that the method gives good results in field.

6. Study of the effects of cryogenic media on flow metering systems

Physical measurements

A cryogenic test rig was constructed and successfully commissioned at TUV NEL. The successful commissioning tests were followed by a complete test programme to look at the effects of cryogenic media on instruments. Data sets were taken from the rig at various flow rates. At each flow rate stability data was gathered from temperature and pressure instruments as well as the Coriolis flow meter. The flowmeter was also tested with and without its insulation jacket to check the influence of ambient heat gain on its performance. A full report, describing the system, commissioning programme and test results, has been completed [11].

The PRTs (Platinum Resistance Thermometers) in the test rig were stable and showed deviations from mean value within 0.4% across the working range of the facility. The upstream, downstream and flowmeter PRT's gave consistent readings. The upstream PRT generally measured higher LIN temperature than the downstream PRT by about 0.5°C due to the heat gain in the pipe work between them. The flowmeter temperature measurement was around 5°C higher than the downstream PRT. This was considered reasonable as the flowmeter measures its wall temperature.

The pressure transmitters within the rig were stable to within 3% across the working range of the facility. These were considered to be genuine pressure fluctuations caused by the bottom pressure control system in the liquid nitrogen storage tank. Pressure fluctuations will affect calibrations due to lack of flow stability and it is therefore recommended that within a traceable facility more effort is put into pressure control. In a closed loop system where a circulation pump is carefully designed with a sub-cooling system, better stability can be achieved. The pressure drop between the upstream and downstream transmitters was measured at around 0.13 to 0.15 bar depending on the flowrate. It was noted that both pressure transmitters showed the same trend which indicates that they are operating well at cryogenic conditions.

Another important aspect of the test programme was to investigate the effect of insulation on flowmeter performance. It was found that the stability of the flowmeter was largely unaffected by the removal of insulation. This was due to the fact that the flowmeter wall temperature was below the fluid saturation temperature by about 9°C resulting in no boiling at the wall. However, in practice, it is unlikely to have any significant subcooling, in particular in LNG custody transfer applications, and therefore the flowmeter must be operated with insulation jacket. It was shown that the effect of the insulation in these series of tests was to reduce heat gain to the flowmeter by around 2°C. This illustrates the importance of insulation for cryogenic flowmeters because a lack of insulation could lead to boiling within the flowmeter. Boiling within the flowmeter should be avoided as it will increase errors in the flowmeter measurements.

Simulations / modeling of calibration facility characteristics

A flow calibration facility at higher flow rates is planned. In order to test design concepts a numerical analysis of LNG flow in a planned mid-scale calibration facility of VSL was conducted by CMI. LNG flow through a bootstrap part of the calibration facility was investigated by means of CFD programme OpenFOAM. Three types of junctions of a supplying pipe to parallel pipes where master-meters are installed were investigated in order to find an optimal design with lowest flow disturbances in front of the Coriolis standards. Namely 45° inclined junctions, 90° junctions with sharp edges and 90° junctions with rounded edges were considered. The results of CFD modeling showed that the lowest asymmetry in the flow is achieved for the 45° inclined junctions and the lowest local pressure drops are achieved for the geometry with rounded edges. From this point of view a geometry with 45° inclined junctions and rounded edges would be optimal in order to avoid cavitation and error shifts of the Coriolis standards due to the flow disturbances.

A shift in “temperature distance” from a bubble point due to local pressure drops was estimated for the original test rig design as well as for a new design which was suggested in the meantime. The shifts towards the bubble point temperature are larger than 5.9 K for all the geometries for the new design at the maximal flowrate.

A temperature increase due to a heat gain through the pipe wall was investigated too. The temperature increase was found not to be significant if an ordinary plastic foam insulation is applied. E.g. a temperature increase in one of the blind parts of the pipe system was around 1 K for a flowrate of 50 m^3/h and wall heat flux of 100 W/m^2.

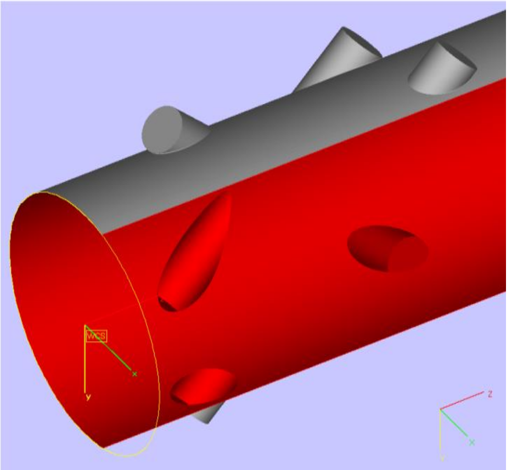
Simulations / modeling of ultrasonic flow meters

Another potential issue was investigated by means of CFD modelling: cavitation inside ultrasonic flowmeters for LNG. OpenFoam software was used again to predict pressure drops in LNG flow through the flowmeters in a neighbourhood of cavities which are between ultrasound transducer windows and the main pipe of the meter. Knowledge of these pressure drops is important for determining conditions when cavitation can occur and can help to avoid the cavitation in order to keep the measurement uncertainty in a reasonable range.

The pressure drops were simulated for a geometry corresponding to a five channel ultrasonic flowmeter of a specific brand and type. However, the results provide estimates for any similar geometry.

The largest pressure drop predicted by the simulation for a fluid velocity of 7.5 m/s was around 27 kPa. The pressure drops decrease with a decreasing fluid velocity so if we don’t go above 7.5 m/s with the flow velocity (which is usually the case for LNG) the pressure drop of 27 kPa should not be exceeded.

Minimal sub-cooling (sub-cooling = difference between actual temperature and bubble point temperature at given pressure) for which a cavitation is avoided was also determined for several fluid velocities and bulk pressures in the LNG. For example for 7.5 m/s and atmospheric pressure in the main LNG stream the minimal sub-cooling is 3.5 K. The larger is the pressure in the main stream of LNG the smaller sub-cooling is needed to avoid the cavitation (e.g. for 5 bars and 7.5 m/s it is only 1 K).



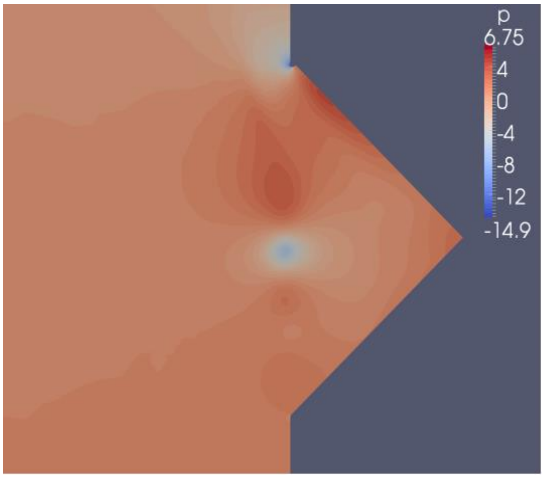


Figure 7 Geometry of ultrasonic flowmeter and pressure profile in one of the cavities obtained by numerical simulation in OpenFoam.

7. Assessment of sampling systems

An assessment of LNG sampling systems has been completed with focus on a) current practices on continuous and intermittent sampling systems, b) LNG vaporisation; practices in Middle East (LNG production plants) and European countries (LNG receiving terminals). C) Information on retention of samples during LNG loading or LNG unloading and d) Information on uncertainty associated with measured composition.

During the study, it was found that the information available on the uncertainty associated with the LNG sampling and vaporisation is limited to a NBS study which was reported in 1985. In the NBS study it is stated that “the total uncertainty of a single measurement in sampling and analysing LNG mixtures can be less than ±0.3 percent in the computed calorific value”. It appears that this value is currently accepted by the LNG industry as it is indicated in the GIIGNL Custody Transfer Handbook.

From the review and assessment of LNG sampling systems, it has been concluded that a practical guidance document on sampling system design and operation is required. The ISO 8943 provides general guidelines and requirements that must be met to achieve representative sampling of LNG but lacks detailed information and examples on operating conditions and limits of the main parameters.

The following improvements are proposed to enhance ISO8943:

- More examples of continuous and intermittent sampling systems are required. Current LNG sampling systems in operation deviate from those in the standard and cause confusion whether the system can be described as continuous or intermittent. The standard defines both continuous and intermittent systems but during the survey conducted in this work it was observed that a system which has direct feed to a chromatograph is being regarded as intermittent by one visited site although the sampling, vaporisation and analysis are continuous. This is simply due to the indication of direct feed to the analyser in the example of the intermittent sampling system only (Figure 3 of ISO8943).
- Recommendation on inner diameter of probe and sampling line to vaporiser.
- The selection of insulation type for probe and sampling line to vaporiser is left to the user. Despite cost implications, it is highly recommended to indicate that vacuum insulation should be considered first, in particular when subcooling degree is low, as it provides best insulation efficiency and withstands weather conditions when compared to traditional insulation materials.
- More information on type of vaporisers used and advantages and disadvantages of each is needed. Typical recent examples would be helpful.
- More guidance on sampling procedure is required, with the following questions in mind: minimum degree of subcooling, minimum/maximum sample pressure, minimum/maximum sample flowrate, purging process.

8. Development and validation of a primary LNG density standard

For the accurate measurement of LNG densities a special densimeter has been developed, set up and commissioned (see figure 8) in the laboratory of Ruhr University Bochum.

Figure 8 The new primary LNG densimeter with its peripheral devices

This new densimeter is covering the range from 10 kg/m^3 to 1000 kg/m^3, thus enabling density measurements in the homogeneous liquid region, along the saturated liquid line, in the supercritical region as well as in the homogenous gas region. Measurements can be carried out in a temperature range from 90 K to 290 K at pressures up to 8 MPa. The Archimedes (buoyancy) principle is applied by utilizing a single-sinker system incorporating a magnetic suspension coupling. A special Vapor-Liquid-Equilibrium (VLE) cell makes part of the system to avoid demixing in the measurement cell.

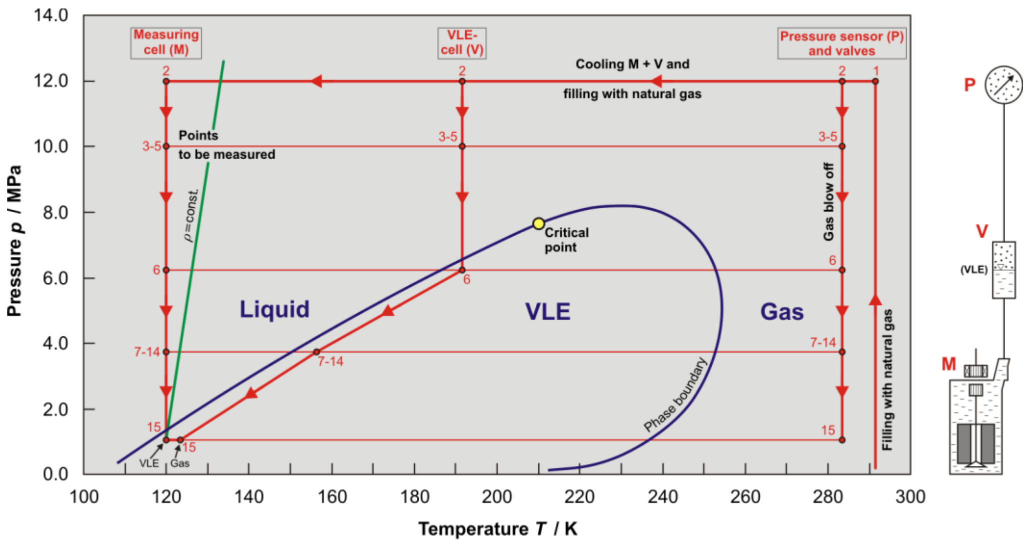


Figure 9 Phase diagram showing experimental procedure with supercritical filling and VLE cell to avoid demixing in the measurement cell.

The goal was to obtain density directly (without the need for calibration fluids) with an expanded uncertainty (k=2) of 0.02% for density measurements in the homogeneous liquid (plus an additional uncertainty of approx. few 0.01% resulting from the sample gas analysis). First density measurements of nitrogen and methane in the entire temperature range of the new apparatus did not result in data with the desired quality.

Further improvement activities on the new densimeter did not fully lead to the envisaged quality of the density measurements. However, a systematic error has been identified. This error has been corrected so that the measured density data of two LNG-like mixtures, that were measured, can be considered reliable. The expanded uncertainty of these data has been estimated to be between 0.06% and 0.08% (k=2, including influence of uncertainty of mixture composition). Data for nitrogen, methane and two LNG-like mixtures as well as comparisons to the GERG-2008 equation of state and the Revised Klosek and McKinley (RKM) Method were presented at the final project conference in Delft in October 2013. Due to the availability of less new data than expected the Equations of State validation has been less thorough than planned. The measured data agreed better with the RKM (within max. 0.08 %) than with the GERG-2008 EOS (see figure 10). However, this is not a final conclusion and no adjustment of the equations could be made or proposed. Further improvement of the primary densitometer will lead to additional and more accurate results.

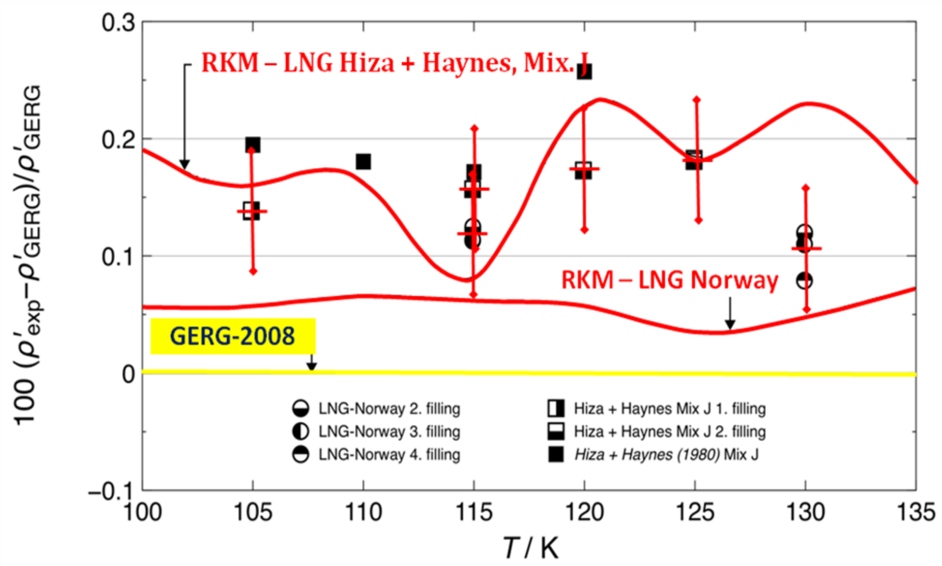


Figure 10 New reference data (LNG-Norway 2, 3 & 4) showing relatively good agreement with Revised Klosek and McKinley calculation method.

9. *Calculation of LNG calorific value at different reference conditions*

The enthalpies of five chosen LNG examples were calculated at temperatures from -80°C down to the actual liquid state using the GERG2004 equations of state which are available in the GasCalc (version 2.3.2) software. The reference state for the enthalpies was chosen at a temperature and pressure of 25°C and 1.01325 bar respectively. The enthalpies given by the NIST data base at this reference state were used.

The calorific value of the five LNG examples at the liquid state were calculated. Another way to define a calorific value for LNG would be to use the calorific value at reference conditions and apply an additional correction. The correction is determined by the difference of enthalpies between reference conditions and the real liquid condition (i.e. thermodynamic conditions on the LNG tanker). This correction would directly give the gain or loss of energy for the transfer of LNG from one thermodynamic state (e.g. liquid on the LNG tanker) into another (e.g. standard temperature and pressure conditions of the gas at the terminal, pipeline or customer). Results have shown that the enthalpy at liquid state differs by approximately 21% from that at standard conditions. Consequently, the gross calorific value at liquid state is 3.8% higher than that at standard conditions. This is equivalent to an economical value of 340 k€ (for a cargo of 150.000 m^3 and LNG price of 2 ct/kWh) when LNG vaporised to standard conditions. This is considered significant as it represents about 1.6% of cargo value.

Summary of scientific and technological outputs

At the start of the project there existed no flow calibration facility working at -163 °C anywhere in the world. The only existing system for calibrating cryogenic flow meters was based at NIST and could be used only with liquid nitrogen, up to 45 m^3/h and with a best measurement uncertainty of 0.2 %. The approach for achieving **the first objective** has been to complete the development of a primary calibration standard (to provide a direct link to SI units) with top-class accuracy (0.05 %) up to 25 m^3/h and operational with real LNG at a temperature of -163 °C.

A primary LNG mass flow standard was successfully developed and validated at a level of 0.12 - 0.15% up to 25 m^3/h. This makes it possible to calibrate small diameter (2 inch) mass flow meters. The primary standard was used to validate the performance of LNG flow meters whose flow indications are based on extrapolations from water and sometimes liquid nitrogen calibration results. The conclusion has been drawn that the flow meter error was in some cases larger than the manufacturers' stated accuracy. This means that a LNG flow calibration is always necessary to reach the lowest uncertainties and/or that further research into extrapolation curves is required.

A prototype cryogenic Laser Doppler Velocimetry system was developed. A system like this could be used as an alternative volume flow meter or reference standard. Air-based simulations and experiments have led to an estimated measurement uncertainty of 0.6% for this system with a potential for improvement by a factor of three in the future.

Simulation tools have been developed for complex LNG flow simulations using a freeware software package OpenFoam. Results were obtained in calculation pressure drops and temperature distribution in a multipipe flow skid and in a flow meter. The tool will be available for other simulations in the future.

The second objective included the establishment of the real uncertainty for (state of the art) ship-based tank-gauging methods by performing a comprehensive metrological study (desktop based and using real data and experience from industry) based on GUM (Guide to the Expression of Uncertainty in Measurement) principles. The measurement performance of tank gauging and flow metering systems has been compared by designing and performing in-field testing and reviewing test results from other pilot studies. Two newly developed cryogenic testing systems have been made available to study cryogenic and installation effects on LNG sensors and flow meter performance. This was to provide important information to assess the real uncertainty of LNG flow meters.

In order to achieve **the third objective** the performance of different sampling systems has been assessed by reviewing design principles and by analyzing real data provided by industry. This has led to recommendations for sampling system improvements. The alternative optical method for determining the LNG composition directly in the LNG pipeline has been compared with sampling based methods.

The fourth objective concerned the development of laboratory based systems to measure the density of LNG with improved accuracy. An advanced primary LNG densitometer system has been designed and realized to produce new reference data with a target uncertainty of 0.02%. This system has been validated at an uncertainty level of better than 0.08% and can be used for the production of reference density data to validate and further improve density equations of state. This will contribute to the overall reduction of the energy measurement uncertainty. The new reference data had to be confirmed by comparing the LNG densitometer results with results obtained by a pycnometer based density metering system redesigned to operate at cryogenic conditions with a target uncertainty between 0.01 % – 0.1 %. The pycnometer system however failed to produce useful results.

The fifth objective was to contribute to improvements and extensions of measurement guidelines and international standards. In existing documents the uncertainties are sometimes not well characterized, some technologies (LNG flow metering) are not yet described and in some cases insufficient guidance is provided to industry. Input to the legal metrology framework has also been provided.

The assessment of uncertainties in the project has not led to a fixed value of what should be the 'real' uncertainty while this needs to be determined on a case by case basis. However, it has strengthened the belief that a total measurement uncertainty of 0.5% is certainly not realistic and even 0.86% (according to estimates in the latest Custody Transfer Handbook) is not realistic in all cases and could be 1% or higher.

Dissemination activities

The project has resulted in 11 publications, 9 poster presentations and 35 oral presentations. Project reports and presentations are published and available for download at the project website www.lngmetrology.info.

Two project workshops have been organized in 2010 (SP, Sweden) and 2011 (NEL, UK) with approximately 80 visitors and speakers from the metrological community as well as the industry. In 2013 a two-day conference was organized by VSL in the Netherlands. Approximately 150 delegates from 22 different countries visited this event (see Figure 11).

The knowledge gained in the project has been integrated in existing gas metrology training courses by VSL and NEL. These courses have been given to professionals in the natural gas industry.

The primary mass flow standard can (is expected to) be used for calibrating and validating small diameter LNG mass flow meters in combination with a newly built mid-scale LNG calibration facility (follow up project).

Recommendations and input have been provided to the ISO10976 standard were accepted as a new standard. Similarly recommendations have been provided to the work group that is responsible for the GIIGNL Custody Transfer Handbook.

The contact persons for the following ISO and CEN committees have been informed about the project and have access to the reports and presentations: ISO8943, ISO/TC67/WG10, ISO/TC193 and CEN/TC282.

The WELMEC WG10 has been provided input and presentations describing the JRPs work related to regulation in Europe

Figure 11 Participants to the Metrology for LNG conference in October 2013

4 Actual and potential impact

Early impacts

The project has already made important contribution to relevant standards:

- A section on dynamic flow measurements has been incorporated in the ISO10976 standard. This standard is used by the LNG industry as reference for designing terminals and measurement systems for billing purposes. Similarly recommendations regarding flow measurement have been provided to the work group that is responsible for the GIIGNL Custody Transfer Handbook
- The availability of LNG calibration standards has already provided a stimulus for the industry to reconsider the so called Maximum Permissible Error (MPE) levels described in the OIML recommendation documents. These high levels are currently not at par with the measurement classes for traditional fuel dispensing systems, partly due to the newness of LNG as transport fuel and partly due to the lack of calibration standards.
- The project has provided a trigger for the OIML (International Legal Metrology Organization) Recommendation R117 (Dynamic measuring systems for liquids other than water) to be revised in the near future and in coordination with the planned efforts to draft a new ISO standard for LNG flow metering systems.
- The preliminary results obtained with the primary density meter have not yet led to a decreased measurement uncertainty in the field but do provide the first independent review of the correctness of the applied equations.

Socio-economic/policy impact

The project has resulted in a foundation for the future metrological LNG infrastructure. Further work in a follow up EMRP project (LNG II) will build on these efforts to complete what should be considered as the physical backbone for the trade of LNG. A new joint industry project is expected to start after the summer of 2014 setting out to build a medium sized flow and composition calibration standard. This facility will provide the possibility to test and validate mass and volume flow meters up to 200 m^3/h (1650 kg/min) and composition measurement systems.

The long term outcome of the project is the reduction of the total measurement uncertainty of transferred energy which is currently estimated at 1% or more. The equivalent economic value of an uncertainty reduction of 0.5 % in the year 2017 is 150M€/year on the total amount of imported LNG in Europe and 500M€/year for global LNG trade. This is based on a conservatively assumed average price level of LNG of \$10/MMBTU. For a typical terminal (12 bcm throughput capacity) the current measurement uncertainty equates to 30M€/year and for one shipload (140.000 m3 LNG) the uncertainty has a value of 200 k€. Since the LNG business is expected to grow further it becomes ever more important to reduce measurement uncertainties in order to reduce financial exposures and create a better functioning market.

The project results contribute to smaller and better understood overall uncertainty which will lead to smaller balancing errors with respect to received LNG and sent out liquid and gas, increased transparency for buyers on the market and thus contribute to fair trade.

The development of a metrological infrastructure for LNG flow meters provides an alternative measurement method to challenge ship-based custody transfer measurements. Moreover, the use of flow meter systems as an alternative to ship based tank measurement is considered essential for partial shipments. This will promote open and fair trade and a better functioning internal market resulting in better and more stable prices for industries and EU citizens.

Traceable flow metering will also increase the operational range of LNG measurements in off-shore LNG applications where ship tank based level-gauging will fail due to the constant movement of ship-based tanks on open sea. Off shore LNG production will contribute to the need to “tap the full potential of its oceans and seas for energy generation” and thus also lead to increased security of energy supply. “Options to diversify supplies determine the costs of supply security interruptions” which is especially important for new EU member states in Central and Eastern Europe.

Natural gas is the cleanest of all fossil fuels. By improving and strengthening the basis for LNG and bio-LNG (LBG) trade the project has a positive effect on the popularity of this fuel and contributes to the policy of reduced CO2 emissions.

At the level of the current legal metrological requirments the results of this project have already demonstrated that flow meters can be used for the application of LNG as transport fuel. The project is therefor an enabler for the use of LNG and bio-LNG as transport fuel. Extended use of LNG as a fuel has been calculated in the Netherlands alone to potentially lead to a CO_2 reduction of 1 million ton/year and a particle reduction of 400-600 ton/year. The use of LNG for trucks leads to significantly reduced noise levels which can be considered as an environmental and social benefit. Reduced noise emissions allows for scheduling of trucks to stock shops and supermarkets during low traffic hours in the night or early morning. This leads to economical benefits.

5 Website address and contact details

www.lngmetrology.info

Project coordinator

Oswin Kerkhof, VSL, the Netherlands

+31 (0)152691509

OKerkhof@vsl.nl

6 List of publications

Papers

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Reports (available on www.lngmetrology.info upon free subscription)

[7] Evaluation uncertainty in transferred LNG volume - Henning Kolbjørnsen (Justervesenet), Peter Lucas (VSL), Tore Mortensen (Justervesenet), Lars Poder (FORCE Technology)

[8] Technical feasibility study Laser Doppler Velocimetry for LNG flow measurments - A. Strzelecki, A. Ouerdani, Y. Lehot, C. Windenberger (CESAME-EXADEBIT S.A.).

[9] Calibration facility for liquefied natural gas flow-meters – CFD modeling - J. Geršl (CMI), P. Lucas (VSL), O. Kerkhof (VSL).

[10] Performance Results from the Cryogenic Flow Facility at NEL - A. Kenbar, C. Hardie (TUV NEL).

[11] Pre-studying of Laser Doppler Velocimetry (LDV) for LNG Flow Measurements - A. Strzelecki, A. Ouerdani , Y. Lehot, C. Windenberger, J.P. Vallet (CESAME-EXADEBIT S.A.).

[10] Coriolis flow meters – calibration approach for cryogenic applications - Asaad Kenbar (TUV NEL), Peter Lucas (VSL), Tore Mortensen (Justervesenet).