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Traceability of Marine LNG Bunkering Measurements

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1.0 INTRODUCTION

Industrial use of liquefied natural gas (LNG) has a surprisingly long history. The first practical refrigeration system was built in 1873; the first commercial liquefaction plant was built in 1917. Over time two applications have been developed that are relevant to the current paper. The first involves storage of LNG to handle peak demand in pipeline systems, the process is identified as "peak shaving". A second application is the transport of hydrocarbon fuel where gas pipelines are unavailable.

More recently LNG for use as a vehicle fuel has been the subject of research and investment. The interest is being driven by three factors: environmental regulations, cost and geopolitics. The abundance of domestic natural gas production has reduced the commodity cost while competition has produced innovative infrastructure improvements. More fueling options are available, portable storage options have been developed and more engine options are available. Domestic production is also highlighting the employment opportunities and political benefits of a local fuel source. Meanwhile, other nations are seeing LNG as an opportunity to obtain their energy from a more favorable political partner.

The rapid growth in marine LNG fuel mirrors other sectors of the LNG industry. The first LNG powered vessel, Glutra a Norwegian passenger ferry, began operation in 2000. As of 2016 77 LNG fueled vessels (excluding LNG cargo carriers) were in operation. Most (69%) were operating in Norway a country with an abundance of natural gas and marine transportation. In the United States, 24 Jones Act[1] compliant vessels are expected to be operating by 2022.

The custody of traditional vehicle fuels takes place based on systems and procedures that have evolved over time. The same can be said for natural gas used for heating, power generation and an industrial feedstock. In both cases the quantities transferred range from relatively small sales to individuals to very large quantities used by power plants. As the LNG based energy industry grows a similar broad range of custody transfer volumes is becoming evident.

2.0 EMISSION CONTROL AREAS

Environmental regulations is listed above as one of the three drivers behind the growth of LNG. In the marine environment Emission Control Areas (ECA[2]) are the result of a regulatory infrastructure being implemented to reduced sulfur emissions in many coastal areas. Three options are typically available to achieve ECA compliance. The first is to install a scrubbing system that removes sulfur. The second is to operate with lower sulfur fuel within an ECA and high sulfur fuel elsewhere. The third traditional option is to burn natural gas. All three options involve costly capital investment. A fourth, newer option, is to burn a mixture of natural gas and diesel fuel [3,4,5]. This option promises much less capital investment than the other three. The third and fourth options require LNG fuel and are of interest in the current paper.

3.0 LNG BUNKERING

From Reference 6: "the term bunker is generally applied to the storage of petroleum products in tanks, and the practice and business of refueling ships." The term originates from the days of ship-board coal bunkers. This section provides a discussion of LNG bunkering methods.

Three LNG traditional bunkering sources are currently in use, fixed storage, truck and barge. Bunkering from a fixed storage tank accounts for 17% of volume while barge and truck transfers each account for 33%[7].

A truck may deliver an entire load to one vessel in which case the delivered quantity be directly traceable to mass. The mass measurements are made of the truck plus cargo before and after bunkering, the difference is the LNG mass loaded into the vessel. This simple mass measurement is not applicable when LNG is delivered to multiple vessels because the individual delivered quantities are required. Flowrate measurement during bunkering is required.

Neither the mass of a barge nor a fixed tank can be determined, both methods will require measurement during bunkering.

A fourth bunkering approach involves portable LNG storage containers[8] and accounts for 17%[7] of volume. For example, standard 20 ft and 40 ft ISO size cryogenic tanks are being use to provide fuel for container ships. Smaller storage tanks a would prove attractive for smaller vessels such as river barges. Traceability of portable storage containers is achievable through direct mass measurement.

A newer development that will likely impact bunkering is sometimes called "nano scale" LNG production[9,10,11]. A small dedicated liquefier connected to a local gas supply slowly produces LNG. The bunkering process is slower to save equipment cost. The method is suited to applications where a vessel has regular periods of idle time. The logical traceability path is through measurement of the gas entering the liquefier; custody measurement of dry gas is well developed[12].

Sometimes the solution to a problem comes from others that have solved a similar problem. One current potentially relevant application of marine measurement is loading LNG for transport as cargo. For this application measurements are traceable through tank volume and liquid level. The uncertainty increases when attempting to measure smaller volumes used for bunkering.

4.0 TRADITIONAL FLOW MEASUREMENT TRACEABILITY

A traditional flow measurement primary standard is traceable to mass or length and time. In some applications totalized mass or volume is required instead of rate, time measurement is then not required. A secondary standard is a meter that has been calibrated against a primary standard or another secondary standard. Finally, a meter under test (MUT) is calibrated against one or more secondary standards. This approach is very common in flowmeter calibration.

4.1 Primary Standards

Primary standards can be classified as gravimetric or volumetric. A gravimetric standard is traceable directly to mass; a volumetric standard requires density to achieve traceability to mass. The most common approach establishes steady flow through a MUT and the primary system is operated to sample the flow. A less common approach is to control the flowrate from zero to a desired steady value and then back to zero. The second method includes very low flowrates in the beginning and end of a batch which represent meter operation with higher uncertainty. A batch transfer of liquid in the field begins and ends at zero flow, operating a primary standard in a similar manner can be considered more realistic.

4.2 Gravimetric Primary Standard

Fundamentally the process involves measuring the mass of a vessel both full and empty. In this regard the process is the same as described above for some bunkering operations.

Two similar systems are in common use, the first is illustrated in Figures 1a and 1b. A collection vessel fitted with a drain valve is supported by load cells. The flow from the test section is directed into a downward flowing free jet. A diverter valve installed below the jet pivots to divert the flow into or out of the collection vessel.

The calibration process begins with the flow diverted outside of the vessel (Figure 1a). The mass of the nearly empty vessel is recorded by the load cells. The diverter valve is then actuated (Figure 1b) and liquid begins to collect in the vessel. After a predetermined mass has been collected the diverter valve is actuated again.

The flow diversion process also triggers a time measurement system; the change in mass per unit time is mass flowrate. The diverter valve is designed to minimize uncertainty and not transmit pressure pulses into the test section. Initial and final mass measurements are made with the after any fluid motion has dissipated, hence this system is commonly identified as "static".

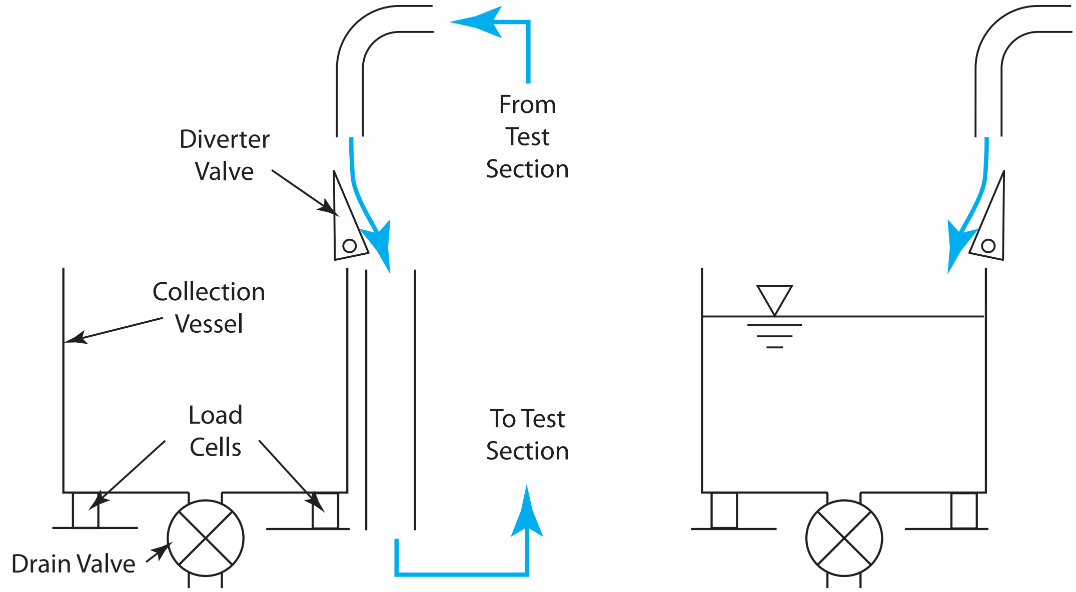

Figure 1a (left) and 1b (right): Static Gravimetric Primary Standard

The second system is illustrated in Figure 2. The vessel, drain valve and load cells are similar to the static system components. Liquid from the test section enters the vessel through a submerged standpipe, a diffuser at the outlet directs the flow to eliminate momentum in the vertical direction. The calibration process begins with continuous flow through the drain valve. The drain valve is large enough to support the highest calibration flowrate and the vessel remains empty. The drain valve is closed and liquid begins to fill the collection vessel. Initial and final mass measurements are made while the liquid is accumulating, this system is commonly identified as "dynamic".

The static and dynamic designs discussed above report data on a batch basis because only the initial and final mass values are recorded. No data are recorded during the mass collection process. A newer approach[13] begins with the same basic dynamic design modified so the output of the load cell(s) is logged on a continuous basis. For each reading the change in mass divided by the change in time, the mass flowrate, is reported. This primary standard configuration is not a batch operation; more information is provided along with the potential for lower uncertainty.

4.3 Volumetric Primary Standard

A volumetric standard is directly traceable to volume and indirectly traceable to mass. Standards are further classified as variable and fixed volume, a variable volume design is shown in Figure 3. It operates based on a displacer that moves within a cylindrical barrel. A sensing rod moves with the displacer and triggers start and stop signals that define the displaced volume.

The displacer includes an integral poppet valve connected to the displacer shaft. A limit to the displacer shaft motion to the right opens the poppet and allows the liquid to continue flowing. A motorized mechanism returns the displacer to the left and another measurement begins. A single data point usually consists of multiple displacer "passes".

Other designs are in use based on the same principle. The oldest design, dating to the 1950s, is based on a

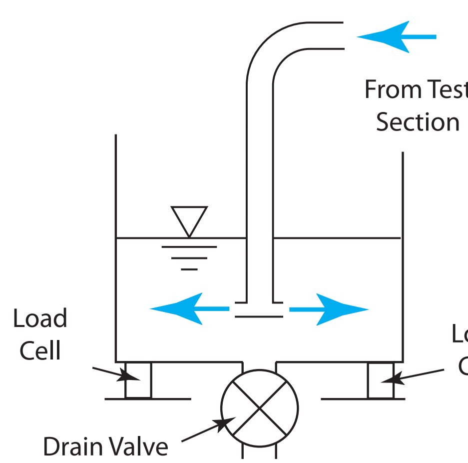

Figure 2: Dynamic Gravimetric Primary Standard

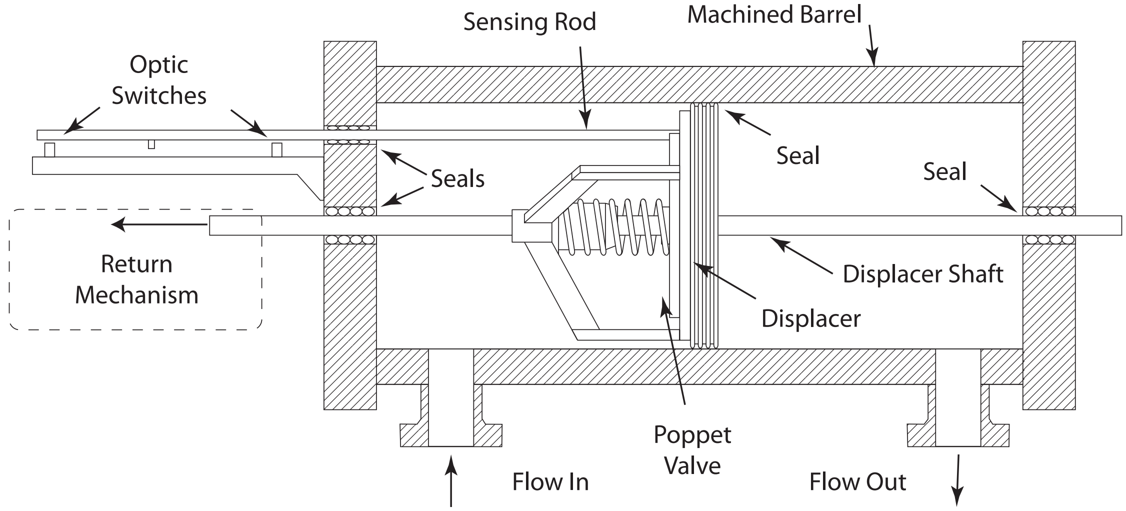

Figure 3: Variable Volume Volumetric Primary Standard

spherical displace; it is often called a "pipe" or "ball" prover. These prover designs are commonly applied to the direct calibration of liquid hydrocarbon meters in the field[14].

A fixed volume standard is designed to contain or deliver a fixed volume; one application is the periodic checking of gasoline pump meters. A set of fixed volume standards typically used to determine the base volume of the prover (BPV); the volume standards are calibrated against mass using distilled water. The BPV calibration process is called "water draw".

The need for density measurement represents the primary design challenge and a significant uncertainty source. A significant contribution to the density measurement is proper sampling required to determine composition. An additional cryogenic design consideration is the care required in material selection to maintain proper displacer clearance and sealing. These considerations are in addition to the obvious need for considerable insulation and/or operation within a "cold box".

4.4 Proving and Calibration

The terms "proving" and "calibration" are often applied to the same process. The terms "proving" and "prover" evolved over time within the petroleum industry while the term calibration is commonly applied in many industries. The present authors consider calibration to be a laboratory process undertaken over a range of well controlled process variables. In conventional applications typical variables include flowrate, temperature and viscosity. Proving is considered a field process completed with less control over process variables. The purpose of calibration is to characterize a meter; the purpose of proving is to confirm consistent meter performance over time.

5.0 CRYOGENIC PRIMARY STANDARDS

Two large cryogenic primary standards are known to be in operation. They are briefly described in this section. In addition a cryogenic volumetric standard, similar to Figure 3 has been operating for six months[15].

5.1 NIST Primary Standard

This dynamic gravimetric standard was built in 1968 flowing liquid nitrogen[16,17]. The facility traditionally served the aerospace and specialty gas industries; newer applications support LNG measurement. In 2016 the standard was moved from the Boulder (Colorado) NIST campus to the CEESI facility in Nunn, Colorado.

A 0.378 m^3 "weigh tank" is suspended within a vacuum jacketed "catch tank". An assembly containing a load cell and calibration weights is located above the catch tank. The load cell is checked "in situ" at three mass readings (113, 227, and 341 kg). The measured mass values vary between 113 and 237 kg, the collection times vary between 8 and 230 sec. The combinations of mass and time result in a flowrate range of approximately 1-10

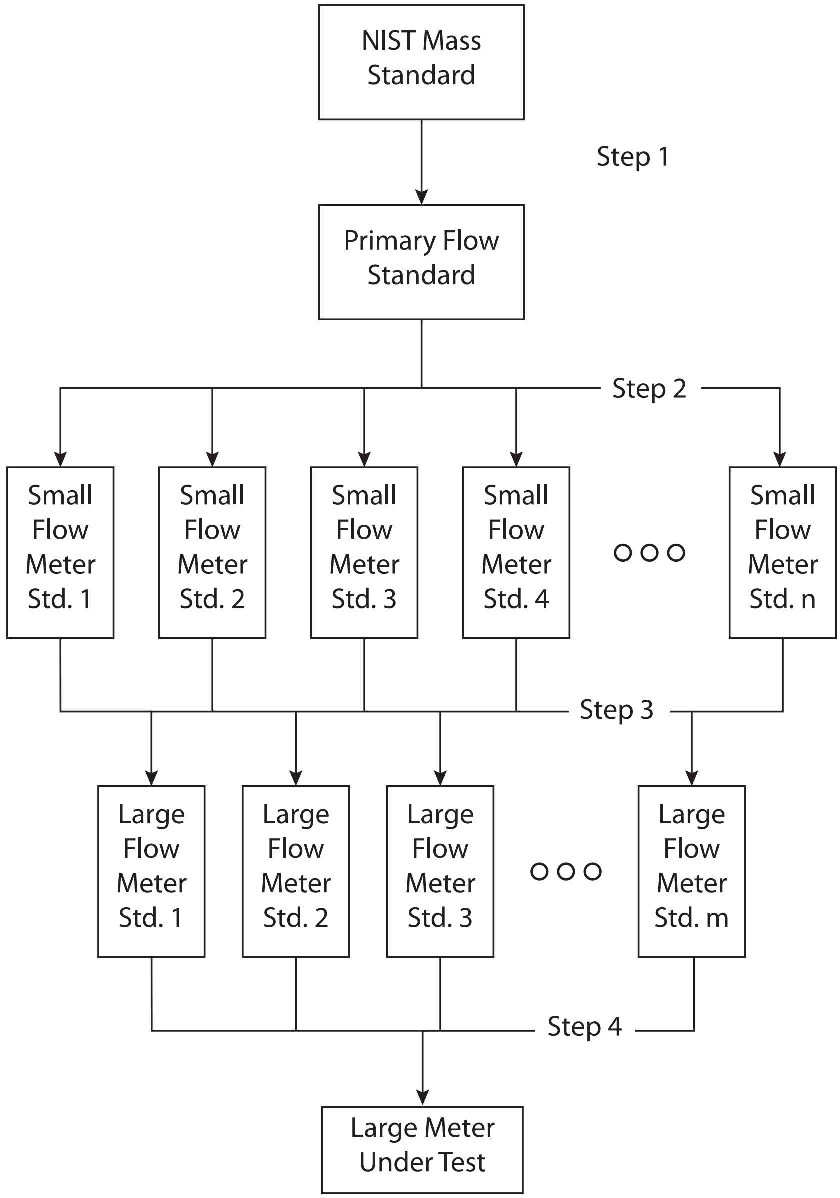

Figure 4: One Approach to Flow Measurement Traceability

kg/s. Operation with liquid nitrogen instead of LNG results in a less expensive, safer system. It is well suited for work towards the development of LNG meters.

5.2 VSL Primary Standard

VSL is the national measurement institute of the Netherlands. They have built[18] a static gravimetric standard flowing LNG over the 10 - 35 m^3/hr (1.3 - 4.5 kg/s). The operating principle is the same as Figure 1 except that a closed diverter valve is used instead of the open jet design. The 0.5 m^3 weighing system contains 240 kg of LNG. Flowing LNG provides calibrations using the actual flowing liquid. The complexity of operation will likely result in more expensive. In contrast to the NIST facility the VSL standard is very new and only a few data points have ben obtained.

6.0 ONE APPROACH TO FLOW MEASUREMENT TRACEABILITY

A common approach to flow measurement traceability is contained in Figure 4. It is used for gas flow calibration[19] and proposed by VSL for LNG. Referring to Figure 4, the traceability begins with a NIST mass standard. Step 1 uses a weight set to calibrate a gravimetric primary standard. Typically a mass vendor or state weights and measures group is involved; direct traceability to NIST is not commercially available. In Step 2 the primary standard is used to calibrate several (n) smaller secondary standards. In Step 3 the smaller standards are installed in parallel to calibrate one of several (m) larger secondary standards. In Step 4 multiple large standards are installed in parallel to calibrate a meter under test (MUT).

6.1 Cryogenic Flowmeter Design

Traditional cryogenic measurements used turbine meters. While turbines are still in use, two newer technologies are more commonly applied, particularly when measuring LNG. The design and operation of the newer technologies, Coriolis[20] and ultrasonic[21], are briefly discussed in this section. In the present discussion these flowmeters are used as either secondary calibration standards or "fiscal" meters. Other terms are "transfer standard" and "master meter".

6.2 Coriolis Meter

The liquid flows through a pair of bent tubes. A coil/magnet pair is energized to vibrate the tube/liquid system at resonance. An additional pair of coils and magnets sense the tube motion. The cross product of the tube and liquid velocity vectors results in a third vector that represents Coriolis acceleration. The magnitude of the Coriolis acceleration is proportional to the liquid mass flowrate.

Young's modulus of elasticity of the tube material relates the tube deformation to the mass flowrate. One application concern is the non-linear dependence of Young's Modulus on temperature under cryogenic conditions. A second concern is pressure drop that can result in vapor bubbles. System design incorporating adequate subcooling helps to maintain single phase conditions. Another application consideration is the cost of a typical meter which increases with size leaving Coriolis meters better suited for lower flowrates. The correct Coriolis meter size is typically selected based on the vendor flowrate range specifications.

6.3 Ultrasonic Meter

A pair of transducers form an acoustic signal path oriented 30 - 60 degrees from the flow velocity. Ultrasonic signals travel with slightly different velocities in the "upstream" and "downstream" directions. The difference is proportional to the average liquid velocity along the acoustic path. For custody transfer applications multiple transducer pairs provide more effective sampling of the flow area. The volumetric flowrate is the product of average velocity and flow area.

The primary concern with LNG ultrasonic measurement is the need to add a measurement of density. Very low blockage means negligible pressure drop and less likelihood of multiphase flow. The uncertainty increases as transit time decreases; larger meters have lower uncertainty.

The correct ultrasonic meter size is typically selected based on velocity. A typical minimum is 0.15 m/s; a typical maximum is 8 m/s, sometimes as high as 10 m/s. The uncertainty varies with the inverse of the velocity, in some applications the minimum velocity depends on desired uncertainty.

6.4 Meter Diagnostics

A diagnostic is a parameter recorded by a meter that might indicate the presence of a measurement problem. Both meter designs include multiple diagnostic parameters.

6.5 Meter Transient Response

The bunkering process begins and ends with zero flow. A meter must capture the initial and final transients with acceptable uncertainty. Both meter designs are capable of responding to rapid changes in flowrate.

6.6 Density Measurement

Density measurement is required when ultrasonic meters are calibrated based on mass measurement. In the present discussion, the density is required in Step 3 of Figure 4. This section briefly discusses LNG density.

The density of a cryogen varies with pressure, temperature and composition. The density changes by 0.3% per Kelvin and 10 ppm per psi[22]. Density values from five “typical” LNG mixtures[23] were found to vary by ±3.4%. The methane content of the five mixtures varied between 87.7 and 96.9 mol%.

Field conditions can also result in variation in density. One condition is the stratification that can result from multiple sources delivered to a storage facility. Another field condition is relatively rich boil off gas leaving behind LNG with a slightly different composition.

6.7 Sampling

A system is required that obtains a representative sample of the LNG to determine the composition[24,25]. The traditional hydrocarbon sampling processes have been developed to maintain the sample in single phase condition. Understanding the thermodynamic behavior of the sampled material is always critical. Volatile liquids are kept under pressure, gasses are heated and LNG temperature is maintained with a vacuum jacket. Ideally the sample point temperature is well above (gas) or below (LNG) the phase boundary.

An LNG system must first obtain and maintain the sample in the liquid phase and then completely vaporize the sample for laboratory analysis. Systems may include gas compression and an on-line chromatograph. Operation may be continuous or intermittent.

The current design and operational guidelines were developed for sampling LNG cargo loading and unloading. The cost associated with uncertainty is high because the cargo volume is large. The sampling system is complex as a result. Bunkering involves transferring much smaller volumes with a lower uncertainty cost. Simpler and less expensive sampling systems may better serve this market over time.

7.0 TYPICAL FLOWRATES

This section is divided into two parts. The first discusses the constraints that limit the flowrate calibration capability. The second section presents some information regarding current and anticipated LNG bunkering flowrate ranges. Flowrate is obviously an important parameter in the design of calibration processes.

The first topic consists of numerical example based on the traceability path in Figure 4 with LN_2 as the calibration fluid. The NIST primary system operates over the 1-10 kg/s range. The example begins with the selection of 6 kg/s as a conservative maximum flowrate value. This flowrate is adequate to calibrate a one inch Coriolis meter at approximately 65% of maximum flow. Selecting four meters in parallel (n = 4 in Figure 4) results in a maximum flowrate of 24 kg/s. This flowrate corresponds to 6.1 m/s through a three inch ultrasonic meter. Once again selecting four meters in parallel (m = 4 in Figure 4) results in a maximum flowrate of 96 kg/s. This corresponds to a six inch ultrasonic MUT with a velocity of 6.1 m/s.

A flowmeter is typically calibrated over a flowrate range. The primary system minimum flowrate is 1 kg/s which corresponds to 0.06 m/s in a six inch ultrasonic MUT. The rangeability is the ratio of minimum to maximum flowrates; for a six inch MUT the rangeability is 96:1.

As noted earlier, the VSL primary standard is the first of three stages. The second step is a system based on secondary standards with maximum flowrate of 400 m^3/hr (26 kg/s). A third stage is planned with maximum flowrate of 4000 m^3/hr (260 kg/s).

In general the user community wants to reduce bunkering time which results in the highest practical flowrate. The constraints on maximum flowrate limits typically include pump size, flow area, and pressure drop. With LNG bunkering being very new the expected range of flowrate has not been well established. Listed below are some published values of LNG flowrates, the mass flowrates are calculated based on an assumed density of 480 kg/m^3.

- An LNG delivery truck is fitted with a pump that operates over the 37 - 230 l/min range which corresponds to 0.3 - 1.8 kg/s.
- A freight truck is refuelled at rate of 100 l/min, which corresponds to 0.8 kg/s.
- A bunkering barge believed to be under construction will have the capability of delivering “570,000 gallons within 4.5 hours” which corresponds to 136 l/min and 1.1 kg/s.
- Railroad locomotives for industry evaluation are refuelled at rate of 1820 l/min, which corresponds to 14.6 kg/s.

- A bunkering terminal is designed to refuel a ferry in two hours. The required flowrate is 400 m^3/hr which corresponds to 53 kg/s.

- LNG carriers are loaded at rates between 5000 and 15,000 m^3/hr which corresponds to 670 - 2000 kg/s.

8.0 UNCERTAINTY

The uncertainty of various methods and components is discussed in this section. Numerical uncertainty values are intended as rough estimates only. In this section the standard uncertainty (Reference ISO GUM) is symbolized by. The combined uncertainty at 95% confidence is symbolized by 2u.

8.1 Direct Mass

Several bunkering processes are well suited for direct mass measurement. The mass of a 40 ft ISO container tank, for example, is 13,270 kg. It can contain 15,000 kg of LNG. The "heel" is the LNG that remains in the tank to maintain low temperature; assuming a heel of 15 kg the mass discharged will be 14,985 kg.

Assume the uncertainty is a mass of u = 40 kg. It is measured twice (full and empty), the value is combined in quadrature u = 56.6 kg. A rough estimate of the uncertainty is:

$$2u = (56.6/14{,}985)*2*0.58*100\% = 0.44\%$$

The "2" term states the uncertainty at a 95% confidence level. The "0.58" term is assigned to Type B uncertainty estimates (Reference ISO GUM). Filling a 20 ft ISO containers with u = 56.5 kg results in 2u = 1.97%. The uncertainties are quite large because the measurements are made outside.

The next example assumes a truck fuel tank is adapted for portable use. The empty 282 kg tank contains 202 kg of LNG. Assuming an uncertainty of u = 1 kg, 2u = 0.81%.

8.2 LNG Cargo Volume

The major components include:

- Gauge tables that define the cargo volume, these tables are made based on measurements made during construction
- Level measurement of the LNG within the tanks
- Liquid and vapor temperature
- List and trim of the vessel
- Thermal expansion of the tanks

Typical uncertainties are 0.20% < 2u < 0.54%[26]

8.3 LNG Traceability Chain

This section identifies the uncertainty components of Figure 4. The smaller meters are assumed to be Coriolis while the larger meters are assumed to be ultrasonic.

Step 1:

- Traceability through mass
- Uncertainty in mass standards
- Load cell calibration process which is made up of small random effects

Step 2:

- Traceability through mass and time
- Coriolis meter calibration process which is made up of random effects from the load cell and the meter
- Measurement of time

Step 3:

- Traceability through mass, time and density
- Ultrasonic meter calibration process which is made up of random effects from the both Coriolis and ultrasonic meters
- Equation of state to calculate density
- Composition and sampling
- Pressure and temperature

Step 4:

- Traceability through volume
- MUT calibration process which is made up of random effects from the both MUT and ultrasonic meters
- Small corrections for density change between MUT and ultrasonic meters

8.4 Existing Primary Systems

The NIST primary standard entered service with an uncertainty of 2u = 0.18%. A provisional uncertainty of 2u = 0.5% has been estimated while the system is being upgraded. A return to 2u = 0.18% is anticipated upon completion of the work.

The uncertainty of the VSL system 0.12 < 2u < 0.15% with 2u = 0.1% as a target. The target uncertainty for the second step is 2u = 0.15%.

8.5 LNG Density

The major components include:

- Equation of state, how well it fits experimental data
- Composition, typically measured with a chromatograph
- Molecular weight
- Temperature

One generally accepted value is 2u = 0.46%[23]

8.6 Gas Phase Flowrate

As noted above, some LNG bunkering systems are traceable to gas measurement made prior to liquefaction. The uncertainty of a typical gas phase ultrasonic meter is 0.5 < 2u < 0.8%[27].

9.0 SUMMARY

Liquefying natural gas enables transport to locations where pipeline access is unavailable. In addition liquefaction represents a portable storage option that is competitive with compressed natural gas. These characteristics coupled with inexpensive resource availability make LNG an attractive marine fuel.

The development of a bunkering infrastructure is beginning with development activities at each step of the value chain. Notably absent from the extensive literature is the consideration of methods, standards and hardware for LNG measurement.

This paper has presented a review of the current state of LNG measurement for marine bunkering. While direct mass measurements will suffice for some processes, flowrate measurement will also be required. The paper topics included primary and secondary standards, traceability, density determination and uncertainty. The authors believe that LNG flow measurement will become more important in the years ahead.

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