An Ultrasonic Flowmeter for Custody Transfer Measurement of LNG: A Challenge for Design and Calibration

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1. INTRODUCTION

For the transport of natural gas, liquefying gas is becoming popular compared to for example transporting gas over large distance pipelines. Transport of gas is receiving much attention worldwide as for example gas is increasingly being found in remote areas and importing countries are looking for ways to diversify the resources of their gas supplies. Another trend is the increasing number of parties involved in the LNG market place. In addition, the costs of the liquefaction and re-gasification of gas and the transport of LNG are decreasing. An increase in the trade of LNG also means an increase in the custody transfer and fiscal metering points for gas in cryogenic conditions. Tank gauging has been a popular measurement method for LNG, but it has its limitations and increased demand for very accurate flow measurements can be observed.

For more than 20 years ultrasonic flowmeters have been used for the fiscal measurement of gas and for more than 10 years for the fiscal metering of liquid hydrocarbons [1],[2],[8],[9],[10]. Over the past years, much experience has been gained with hundreds of custody transfer ultrasonic flowmeters operating in the field. The application of highly accurate ultrasonic flowmeters have been very successful and can be considered as a proven technology in this field [3].
Next to successful applications at ‘normal’ operating conditions, the ultrasonic measurement principle in itself is also very suitable for high accuracy flow measurement at cryogenic conditions. The development, construction and calibration of an ultrasonic flowmeter for custody transfer of LNG is, however, not simple taking into account the very low temperatures and the limitations regarding the calibration under reference conditions.

This paper describes the development of an ultrasonic flowmeter for the fiscal measurement of LNG. The following items are discussed:

- Transducer design
- Flowmeter body design
- Calibration concept
- Tests results on liquefied nitrogen

This paper finishes with some conclusions and a discussion the steps to be taken in the next future.

2. TRANSDUCER DESIGN

2.1. Tests with piezo crystals at low temperatures

The behaviour of acoustic piezo crystals is one of the areas that have to be investigated for use of ultrasonic flowmeters at cryogenic conditions. The acoustic piezos form the basis of any ultrasonic flowmeter measurement. They generate the acoustic waves, which are sent up and down the flow. The difference in transit times is directly proportional to the flow. When the piezos do not perform well, the ultrasonic flow measurement will suffer from it.

The investigation has been focussed on researching the electric, acoustic and mechanic properties of piezo ceramic material at cryogenic conditions [4].
As a first step we were interested in the performance of just the piezo i.e. in a situation whereby the piezo forms no part of the transducer construction. The behaviour of the piezo might be affected, when it is part of the transducer construction.
The construction that has been build for this test consists of a frame with two free positioned piezos in the middle (see Figure 1).

Figure 1 Set up for piezo tests at liquefied nitrogen (-196 [ºC]).
Left hand figure: Frame with piezo crystals hanging above the container with liquefied nitrogen.
Right hand figure: frame with piezo crystals submerged in the container with nitrogen.

In order to create a reference situation with respect to electric and acoustic properties, the construction first has been submerged in water at ambient conditions, and afterwards the same construction in liquefied Nitrogen at a temperature of -196 [ºC]. The electric and acoustic properties have been measured again.

It turns out that the electric impedance reduces with approximately 8 [dB] when compared to water at a temperature of 20 [ºC]. In addition, the acoustic bandwidth slightly decreases. This can be observed from **Fout! Verwijzingsbron niet gevonden.**. The effect is, however, not significant.

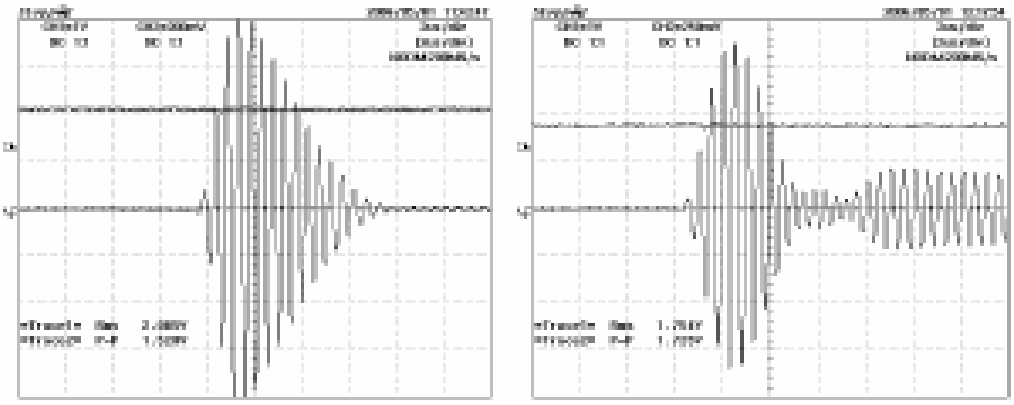

Figure 2 Acoustic signals of the piezo ceramic material.
Left figure: water at 20 [ºC],Right hand figure: liquefied nitrogen at -196 [ºC].

The same holds for the efficiency of the output signal. It turns out that thermo shocks can be handled without any problem. No damage to the construction, nor a reduced performance has been observed, when submerging the construction into the liquefied nitrogen several times.

With respect to the use of piezo ceramic material the conclusion can be drawn that it is suitable for cryogenic application down to temperatures of -196 [ºC].

2.2 Transducer performance at cryogenic conditions

The next step in our investigation concerned measurements whereby the piezo element forms part of a transducer construction. Several items have to be taken into consideration, of which the acoustical coupling between the piezo and the acoustic window is the most critical one (see Figure 3).

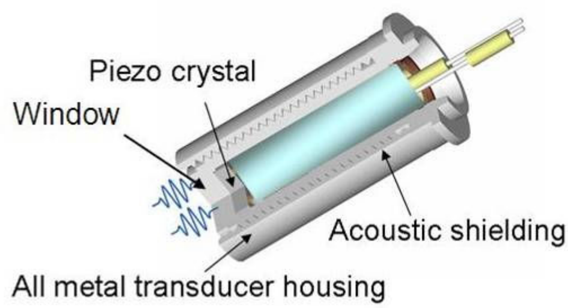

Figure 3 Basic design of an acoustic transducer

As soon as the acoustical contact between the piezo crystal and the acoustic window is lost, the transducer no longer functions. Therefore, it is important to have a reliable acoustical contact between piezo and window, even if considerable geometrical changes occur due to thermal expansion as a result of large temperature spans.

For most applications a standard coupling grease can be used to establish an efficient acoustical coupling between piezo and (sensor housing) window. However, for temperatures below e.g. -70 [ºC] normal coupling grease cannot be used. The grease becomes solid and its volume decreases as a result of shrinkage due to solidification. Consequently, the mechanical contact is lost and the acoustic signal disappears. For this reason a special cryogenic grease has been tested. According to its specifications it can be used for temperatures down to -200 [ºC]. This grease should have less shrinkage due to solidification.

A special test object has been built, consisting of two transducers with a wave guide in between to test the effect of low temperatures on the flowmeter (see Figure 4). The wave guide has been very useful for purposes of simulating the liquid in these tests and was not intended for precise flow measurements. It was also decided not to use the wave guide construction for the final design of the flow meter body. Reason for this is that the wave guide construction introduces an additional uncertainty in the transit time measurement. The transit time of the acoustic wave is affected by the speed of sound in the wave guide. The speed of sound varies with temperature changes. The temperature of the wave guide is not known accurately. This leads to an additional error in the transit time measurement and thus in the flow measurement. For this reason the wave guide has been left out and the wetted transducer design has been applied for the final design.

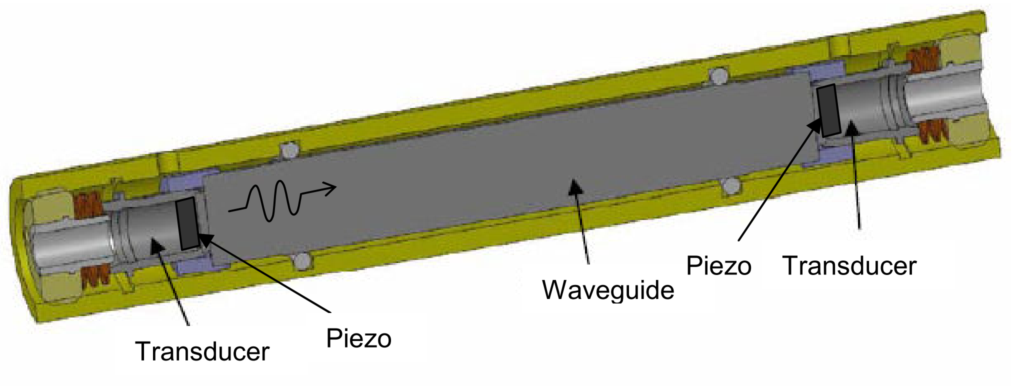

Figure 4 Test set up with two transducers at both ends and a waveguide in between simulating the liquid.

To test the acoustic contact, measurements have been carried out whereby the performance of the transducer construction has been studied over the entire temperature span. This test object has been installed in a refrigerator, which can be slowly cooled down to a temperature of -196 [ºC] (see left hand figure in Figure 5).

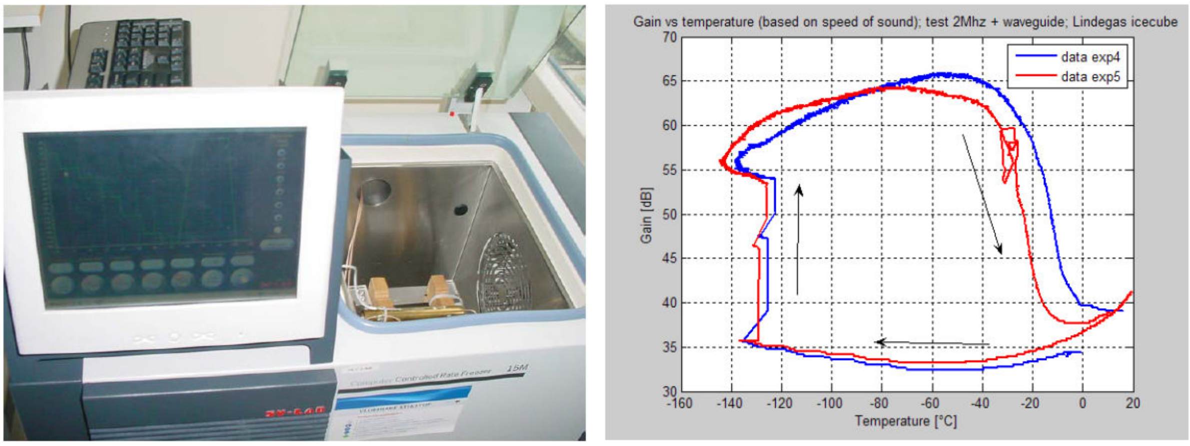

Figure 5 Left hand figure: Test set-up with test object in the refrigerator.
Right hand figure: Amplification factor (Gain) as function of temperature .

During the test, the electronic amplification factor (gain) of the signal has been monitored on-line. The gain is the amplification factor required to obtain a signal with a fixed amplitude. The test results are shown in the right hand figure (Figure 5).

The experiments started at the lower right hand corner of the graph with a temperature of about 0 [ºC] and a gain of ~35 [dB] (see the blue curve). The temperature in the refrigerator has been slowly decreased. Figure 5 shows that down to temperatures of approximately -130 [ºC] the gain stays more or less constant.
From this point a sudden increase in the gain up to a value of about 55 [dB] has been observed. It means that the signal is attenuated roughly with a factor 10. Increasing the temperature does not help. The gain has even increased up to a value of about 65 [dB] at temperatures of approximately -50 [ºC]. From that point the gain strongly dropped again until it reached more or less its original value of about 35-40 [dB] at temperatures between 0 and 20 [ºC]. Repeating the same test (see the red curve), resulted in a curve which reproduced fairly well.

The most likely explanation for the strong increase in attenuation at -130 [ºC] are small cavities that occur in the coupling grease as a result of the solidification of the grease. Solidification causes a decrease in volume of the grease, while at the same time the volume in between the piezo crystal and the window, which is filled up by the grease, stays more or less constant. This leads to very small cavities in the grease. Which in its turn result in a strong additional acoustical attenuation. Consequently, the transducer gives a significantly weaker output signal.

This experiment has clearly demonstrated that the special cryogenic grease is not the right answer for applications with very low temperatures. Other methods are is required to guarantee a reliable acoustical coupling.

A solution has been found in the choice of another coupling technique. A thorough investigation has lead to a special design consisting of a combination of an acoustic coupling and a reliable transducer construction. To this extend the Finite Element Method has been used to simulate the mechanical properties into details. The patent for this solution is pending.

For the final design of the transducer construction we have been successful in maintaining an almost identical construction for cryogenic applications as for the standard construction. The advantage of using a standard construction is that it is well proven and reliable. The standard construction has already been used in thousands and thousands of applications with other ultrasonic flowmeters.

The final transducer construction has been tested according to the very similar test procedures as described above. In addition, tests have been carried out whereby the entire transducer construction was submerged instantaneously in liquefied nitrogen in order to realize a thermo shock (see Figure 6).

Figure 6 Test object with final transducer construction, submerged in liquefied Nitrogen at -196 [ºC].

During the submersion the acoustic signal has been monitored continuously. It turned out that even during the thermo shock the transducer kept on working. An example of the acoustic signals can be found in Figure 7.

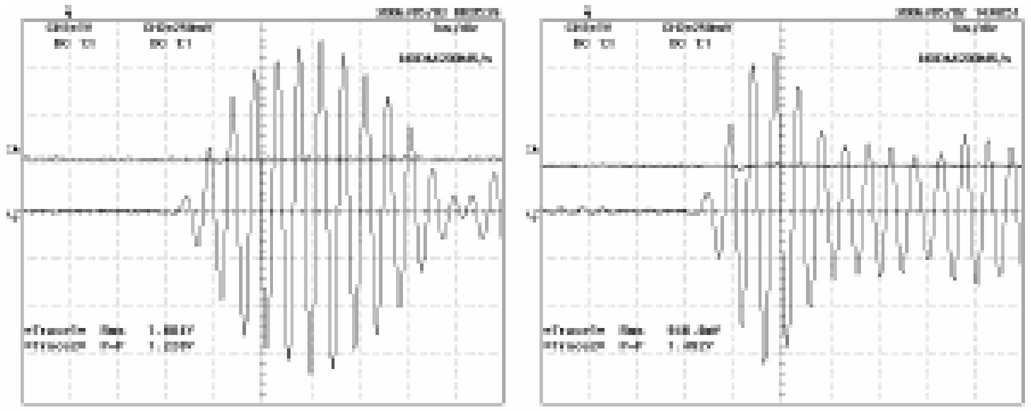

Figure 7 Acoustical signals with final transducer construction.
Left hand figure: signal in water at 20 [ºC].
Right hand figure: signal in liquefied Nitrogen at -196 [ºC].

The final additional attenuation obtained in liquefied nitrogen is about 6 [dB]. This is caused by the reduced electric capacitance of the acoustic piezo at -196 [ºC]. The signal shape is very well suited for a reliable signal detection required for a reliable flow measurement.

3. FLOWMETER DESIGN AND STATIC TESTS

The underlying concept for the development of the LNG flowmeter body design, was to keep it as close as possible to the standard design of a five beam ultrasonic flowmeter. The proven meter body design hardly needed any construction changes for the special cryogenic transducers as described in the previous chapter (see Figure 8).

Next to the special cryogenic transducers, another change in construction is the placement of an additional cap at the back side of the transducer, required to prevent the formation of ice on the inside of the transducer. Ice formation occurs due to water vapour in the air which freezes onto cold surfaces. In a worse case scenario, it might lead to malfunctioning of the transducers. A cap, closing off transducers completely, prevent ice formation inside the transducer.

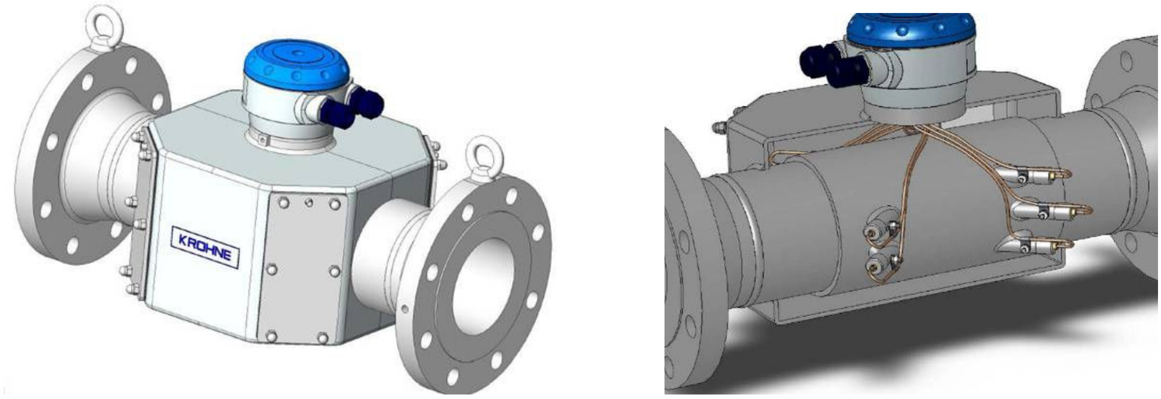

Figure 8 Five beam Ultrasonic flowmeter design for cryogenic applications (e.g. liquefied N_2 or LNG). Left hand figure: Exterior of the ALTOSONIC V. Right hand figure: housing partly removed.

The LNG flowmeter design has been used to carry out the next series of tests. These comprised of static tests whereby the flowmeter has been filled with liquefied nitrogen (see Figure 9). The results were very satisfying, as the flow meter design met all the pre-established requirements formulated by the development team. A strong acoustic signal has been obtained, as well as a large acoustic bandwidth and a good signal-to-noise ratio. During cooling-down the flowmeter kept on working. Thermal cycles turned out to have no affect on the flowmeter at all.

Figure 9 Static flowmeter tests on liquefied Nitrogen. Left hand figure: set up. Right hand figure: Flowmeter filled with Nitrogen.

All tests demonstrated that the design of transducers and flowmeter body have been working according expectations regarding accuracy, stability and reliability.
The next phase in the development project concerned a full scale test after calibrating the flowmeter prototype on water.

4. CALIBRATION CONCEPT

There are two challenges regarding the calibration of any type of flowmeter for use in cryogenic applications. So far, there are no (laboratory) test facilities in the world where flowmeters, with a diameter larger than 4 inch, can be tested on LNG or on liquefied nitrogen against a reliable reference. And, secondly, in most applications it is not possible to calibrate flowmeters on site against a reliable reference.

This asked for the development of an alternative calibration method. In close cooperation with NMi, the Dutch Board of Weight and Measurement, a special calibration procedure has been developed for calibrating ultrasonic flowmeters for use of custody transfer of LNG.

A solution has been found in calibrating ultrasonic flowmeters with water at reference conditions and to use the water calibration as a basis for the application of the flowmeter at cryogenic conditions. Basically it is based on the concept of transferring a calibration at ambient conditions to an application at cryogenic conditions. The transfer or extrapolation of the flowmeter reading with a water calibration at ambient conditions to a reading at cryogenic conditions is, however, fairly complicated.

For a correct extrapolation the following phenomena have to be taken into account:

- Demonstrate that the flowmeter linearity is a function of Reynolds only
- Linearity curve gets horizontal at high Reynolds numbers
- Thermal expansion of the meter body
- Delay times

4.1 Linearity curve based on Reynolds calibration

Over a period of more than 10 years KROHNE has gained much experience and test data in the field of calibrating (five beam) ultrasonic flowmeters for fiscal metering and transferring the calibration results to other application areas.
A key advantage KROHNE has, is the large amount of experience gained in the field of calibration with the in house availability of certified and accredited facilities for the calibration of flowmeters on water. The calibration facilities operate by direct comparison and are traceable to

National Standards. Flowmeters of any size up to a diameter of 3.2 [m] can be calibrated at a large calibration tower. The best measurement capability (BMC), as certified by RvA, the Dutch Council for Accreditation, is 0,02% (k=1) over a flow range of 18 to 18.000 m3/hr.

Even at low flow rates the calibration rig allows for stable, accurate and reliable measurements. Developments in stable electronics enable high repeatabilities up to very low flow rates (for example 0,1 % accuracy down to 0,1 m/s) including for flowmeters with very small diameters.

Figure 10 Fisheye picture of the water calibration facility at KROHNE Altometer, The Netherlands. Maximum flow rate 3.10^4 [m^3/h], max. diameter 3.2 [m]

The above mentioned capabilities allow us to calibrate with water at low flow velocities for reaching low Reynolds numbers and applications can be simulated with higher viscous liquids at typical flow rate velocities in the field.

The Reynolds number is a function of the mean flow velocity (v), the internal pipe diameter (D), and the kinematic viscosity (ν):

$$Re = (v \times D) / \nu$$

This can be illustrated with a simple example. The Reynolds number with a

- a viscosity of 1 cSt, a diameter of 0,4 meter and a flow velocity of 10 m/s, is is (0,4 x 10) / (1 x 10-6) = 4 x 10^6
- a viscosity of 0,2 cSt, a diameter of 0,4 meter and a flow velocity of 2 m/s, is (0.4 x 2) / (0.2 x 10-6) = 4 x 10^6

This enables us to simulate low Reynolds numbers with the calibration of ultrasonic flowmeters on water (with a viscosity of 1 cSt), with a high accuracy and repeatability while calibration with other hydrocarbons are no longer required. The results of flowmeters calibrated on water can be transferred to other different types of mediums as long as they are in the same Reynolds number area.

See for example the calibration results in figure 11 whereby the same fiscal ultrasonic flowmeter has been tested on water and on naphtha. The flowmeter shows the same linearity curve with water as with naphtha.

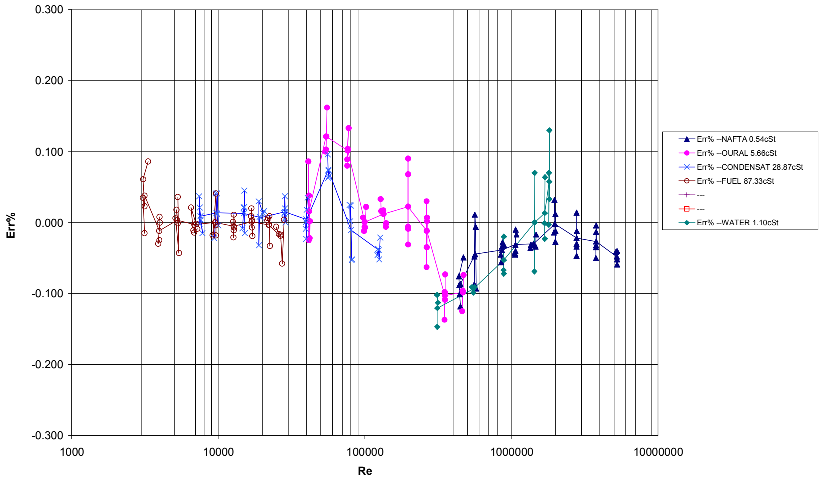

Figure 11: Linearization curves, expressed in Reynolds numbers, of the same five beam ultrasonic flowmeter tested on water, naphtha, oural, condensate and fuel oil.

LNG has a lower viscosity (approximately 0,2 cSt) than water and as a result an ultrasonic flowmeter used for LNG will be operating at higher Reynolds numbers. To transfer the calibration results from water to LNG, it will be necessary to extrapolate the linearity curve.

Based on our experience we know that for the five beam ultrasonic flowmeter the shape of linearity curves becomes more horizontal at higher Reynolds numbers. The physical explanation for this effect is that the shape of the velocity profile does not change much at larger Reynolds numbers.

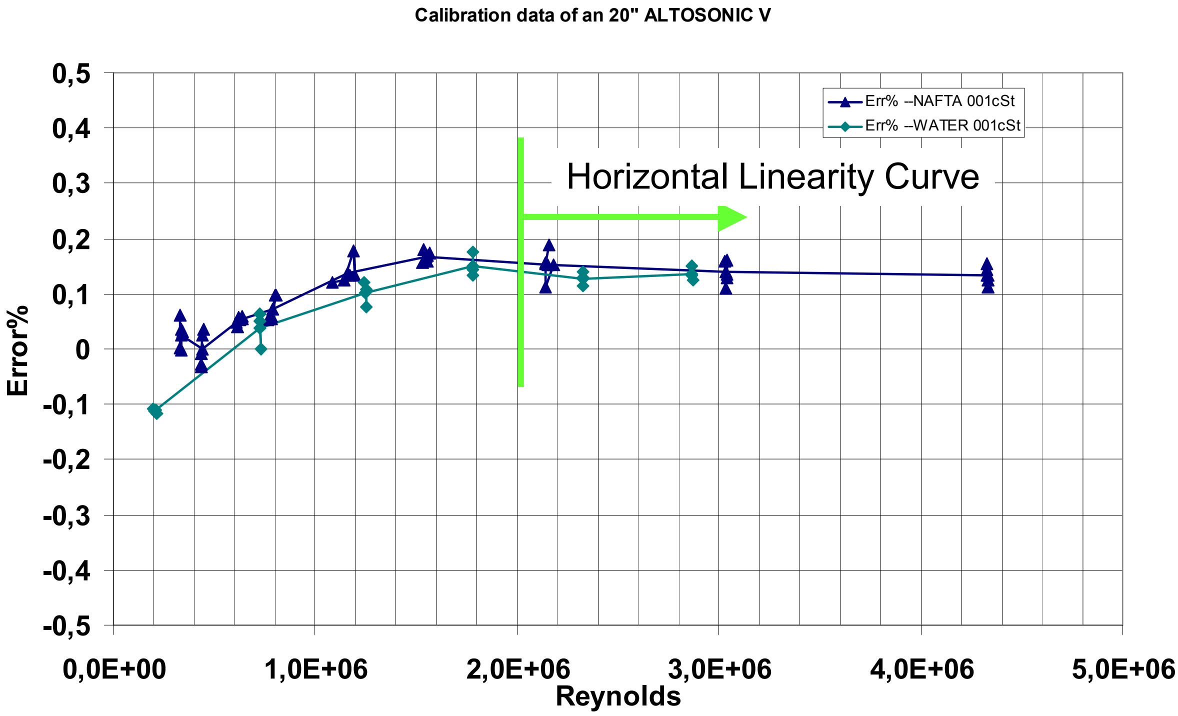

Figure 12: Calibration data of a 20" Five beam ultrasonic flowmeter for custody transfer calibrated on water and on naphtha. The linearity curve has a more horizontal shape at higher at higher Reynolds numbers

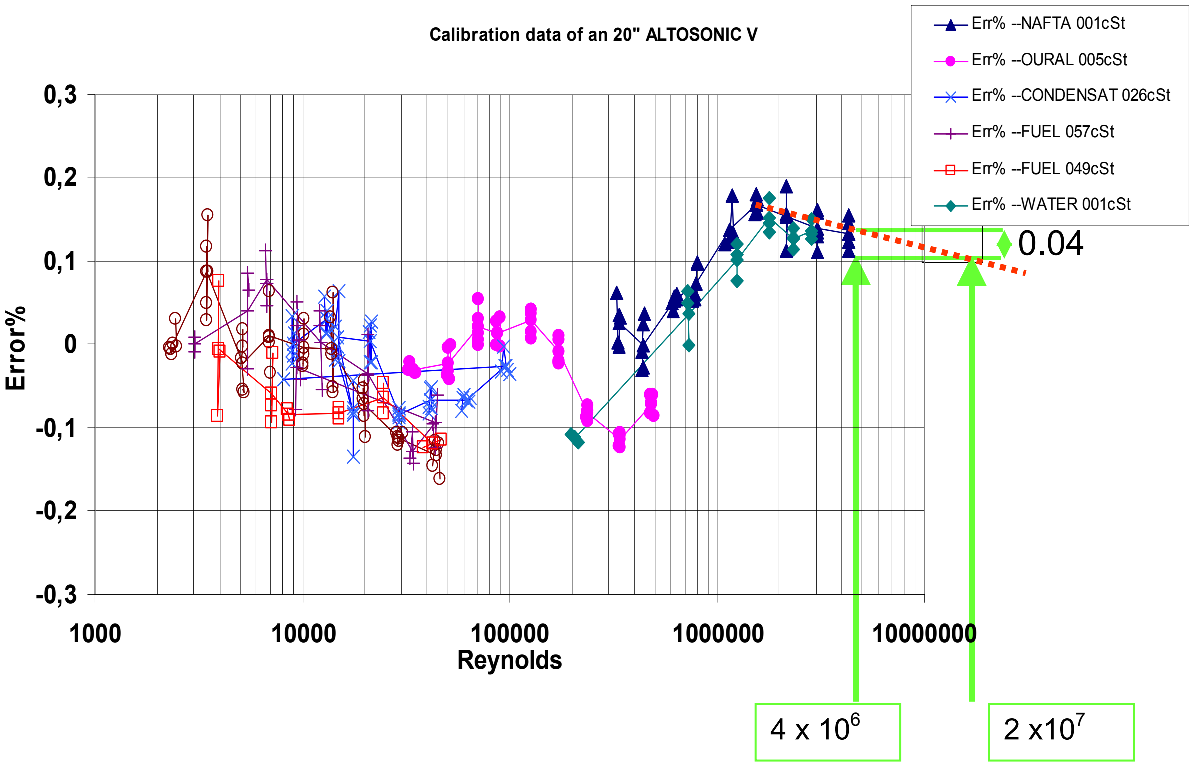

Figure 13: Calibration data of a 20" ultrasonic flowmeter for custody transfer calibrated on water and on naphtha

With water the high Reynolds numbers as required for LNG, cannot be reached to the full extend and therefore we need to add a relatively small extrapolation. This is the reason why the horizontal shape of the linearity curve with higher Reynolds numbers is of such importance. In order to make an estimation of the behaviour at higher Reynolds numbers, the linearity can be expressed as a logarithmic scale (see figure 13).
The calibration results, as shown in figure 13, illustrate that with higher Reynolds numbers the extrapolation even becomes more reliable.

See the following example:

- A ratio of [2 x 10^7 / 4 x 10^6] is a factor 5 (factor of 5 extrapolation in Reynolds numbers).
- The estimated error in this example is 0.04%.

The Dutch Board of Weight and Measures is, however, rather pre-cautionary and advises to use an additional uncertainty of 0,1% when extrapolating with a factor 1.7, and an additional uncertainty of 0,2% when extrapolating with a factor 2.2.

4.2 Thermal expansion of the meter body

There is one other key aspect that needs to be taken into consideration when measuring at very low temperatures. The geometric sizes of a flowmeter change, because of the large temperature changes.
For calculating the average flow velocity over a pipe section, the pipe diameter is assumed to be constant, but in case of very low temperatures the pipe diameter will change.

$$\text{Flow} = A\ (\text{Area}) \times V\ (\text{Flow velocity})$$

$$= [\pi D^3] / [4 \sin(2\beta)] \ * \ [(T_{B \to A}) - (T_{A \to B})] / [(T_{B \to A}) * (T_{A \to B})]$$

Whereby D = Diameter [m]
β = Angle of diameter with average flow velocity [º]
$T_{B \rightarrow A}$ = Upstream transit time from transducer B to A [s]
$T_{A \rightarrow B}$ = Downstream transit time from transducer A to B [s]

In other words the pipe diameter under calibration conditions does not equal to the pipe diameter under operating conditions. Compensation for this will be necessary. Question is how to correct for the diameter at the very low temperature conditions.

$$D_{oper} = D_{cal} * (1 + \alpha \Delta T)$$

whereby
α = Linear expansion coefficient of pipe wall material [K^{-1}]
ΔT = Temperature difference between operating and calibration conditions [K]

Using the meter factor (MF) as a function of D^3 gives:

$$MF_{oper} = MF_{cal} * (1 + 3 \alpha \Delta T)$$

whereby
$MF_{oper} < MF_{cal}$ at cryogenic conditions

Let us look at the following practical example for LNG:

- In case of a calibration at 20^0[C] and operation at - 160^0[C] (-256^0 [F])
- α = 12 ppm; ΔT = - 180^0[C] (-324^0 [F])
- $\alpha \Delta T$ = -2.16 e-3 = -0.216%

This gives a change in meter factor of (3 * $\alpha \Delta T$) of -0,648%. In other words the operating meter factor is 0,648% smaller than the calibrated meter factor.

Based on the above theoretical calculation example it is clear that a correction for the meter factor is required for receiving accurate performance data.

In addition the following requirements are necessary for an accurate calculation:

- Mechanical behaviour of the flowmeter must correspond with the expansion formula
- Reproducible behaviour of the flowmeter
- Linear expansion coefficient of pipe wall material must correspond with the specifications of the construction material

Together with for example PTB extensive and very accurate measurements with a three beam ultrasonic flowmeter have been done to experimentally verify the above mentioned calculated results. Similar tests have been done with the five beam meter, showing the same results.

The following figures show the:

1. Uncorrected results
2. Test results corrected for thermal expansion 3 $\alpha \Delta T$
3. Test results corrected for thermal expansion plotted as a function of the Reynolds number
4. Linearized test results corrected for thermal expansion plotted as a function of the Reynolds number

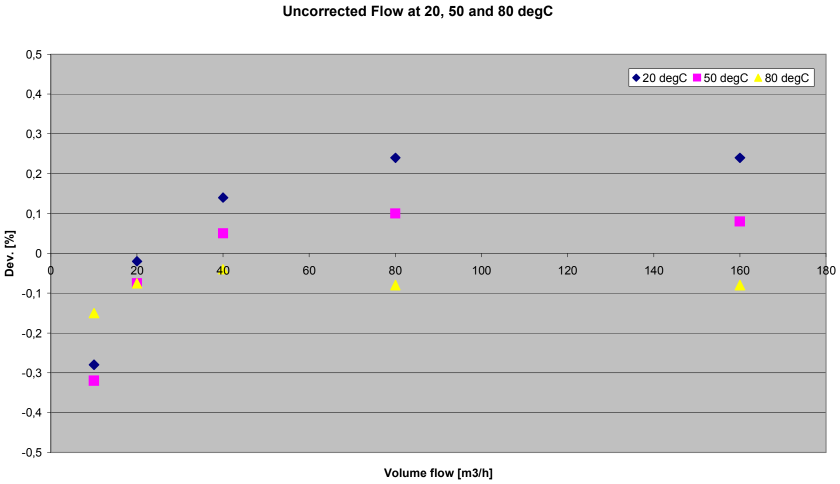

Figure 14 Uncorrected results

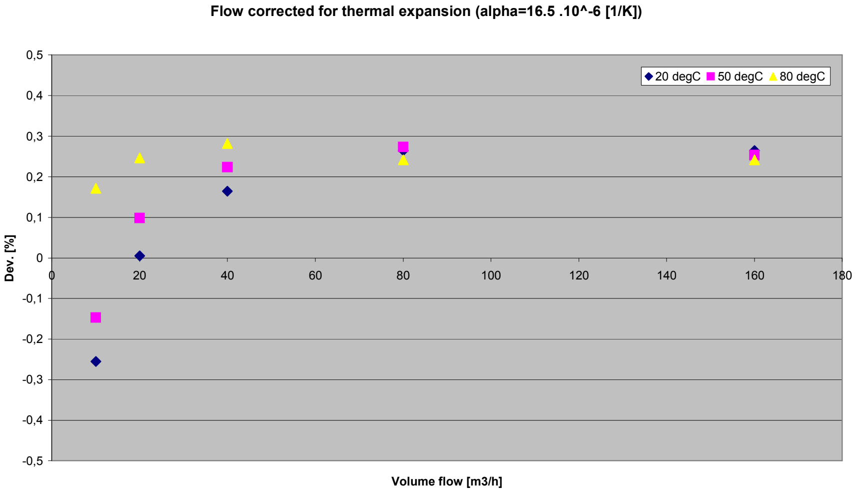

Figure 15 Test results corrected for thermal expansion 3 α ΔT

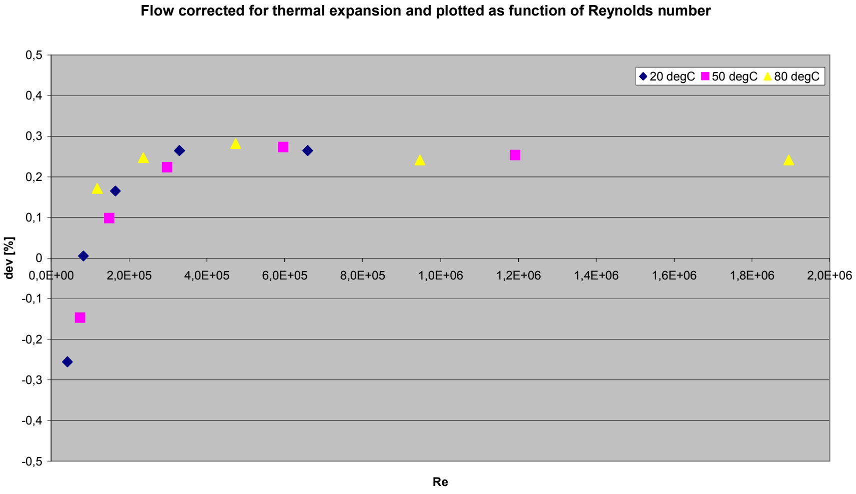

Figure 16 Test results corrected for thermal expansion plotted as a function of the Reynolds number

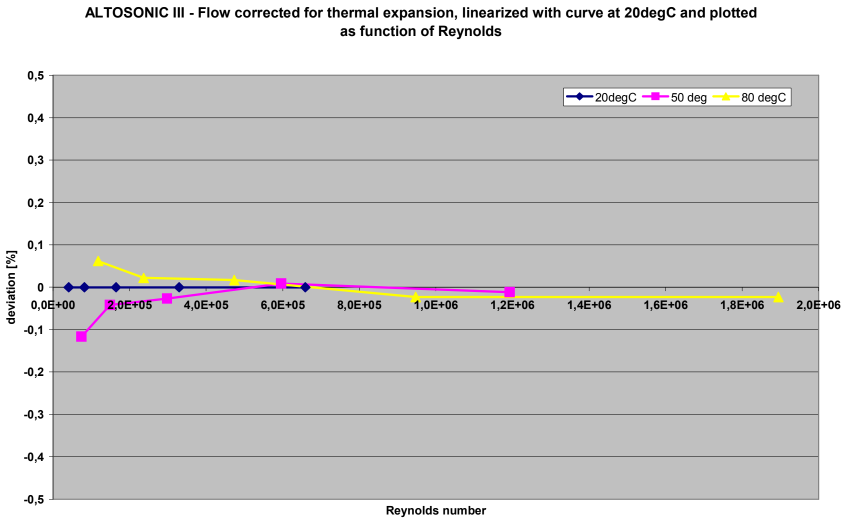

Figure 17 Linearized test results corrected for thermal expansion plotted as a function of the Reynolds number

Based on the above and other test results, the LNG project team decided that the formula (*3 α ΔT*) very well describes the effect of thermal expansion, and more importantly can be used for a reliable correction for the thermal expansion of the five beam ultrasonic flow meter body.

5. TESTS ON LIQUEFIED NITROGEN

Having developed a LNG ultrasonic flowmeter design in combination with the described calibration concept, the next step in the investigation has been to perform tests on liquefied nitrogen. NMi was invited to witness the tests.

5.1 Tests Done at the National Institute of Standards and Technology (NIST)

A flow calibration facility where it is possible to perform tests on cryogenic liquids is located at the National Institute of Standards and Technology (NIST) in Boulder, Colorado [6].

A dynamic weighing system is used to measure totalized mass flow and, with the use of NIST thermodynamic property data for density, volumetric flow. Calibrations are typically performed with liquid nitrogen in a flow range of 0.95 to 9.5 [kg/s], pressure range of 0.4 to 0.76 [MPa], and temperature range of 80 to 90 [K].

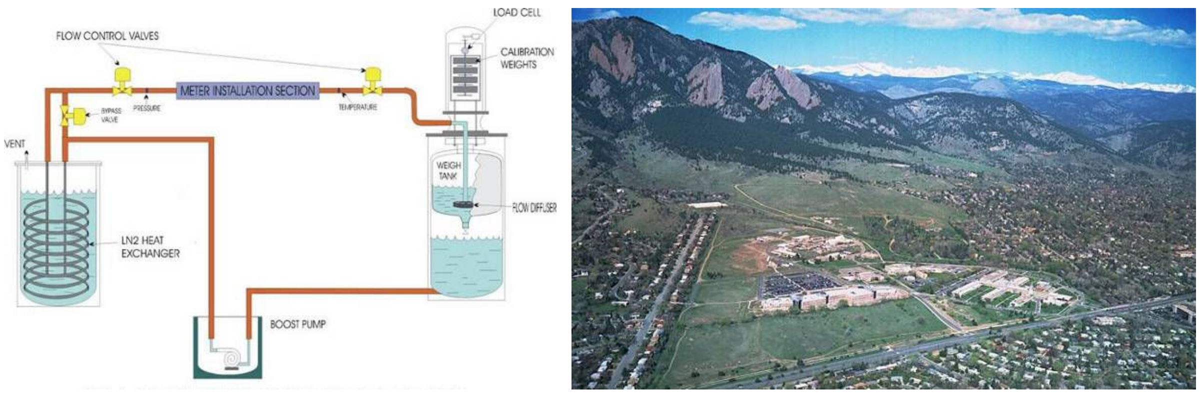

Figure 18 Left hand figure: Schematic overview of Calibration facility for Liquefied Nitrogen at NIST in Boulder. Right hand figure: NIST Location in Boulder, USA.

A schematic of the liquid flow facility is shown in figure 18. Liquid nitrogen is circulated throughout the closed loop by a variable-speed centrifugal pump. The liquid flows through the sub-cooler, a heat exchanger consisting of a finned tube submerged in a nitrogen bath where the thermal energy due to pumping and ambient heat leak is removed. The temperature of the liquid nitrogen in the flow loop can be changed or controlled by adjusting the liquid level and the vapor pressure in the sub-cooler tank. Some of the test fluid also can be diverted around the subcooler, if necessary. After leaving the subcooler and bypass, the fluid passes through a vacuum-jacketed loop containing an in-line heater, through the test section, and into the weigh tank/catch tank system (described below) which represents the heart of the measurement system. The liquid flows into the bottom of the weigh tank through a pipe and diffuser. The diffuser removes the vertical component of the flow. The liquid then flows through the weigh tank valve and into the catch tank, and is drawn back into the circulation pump.The flow system is pressurized with helium gas to prevent the liquid nitrogen from boiling. The nitrogen is always subcooled by 10 to 15 [K].

The facility has an overall uncertainty of 0.17% (k=2) on totalized mass. The overall uncertainty for totalized volume flow is 0.18% (k=2). This uncertainty statement holds for flow rates in the range from 4.5 to 45 [m^3/h].

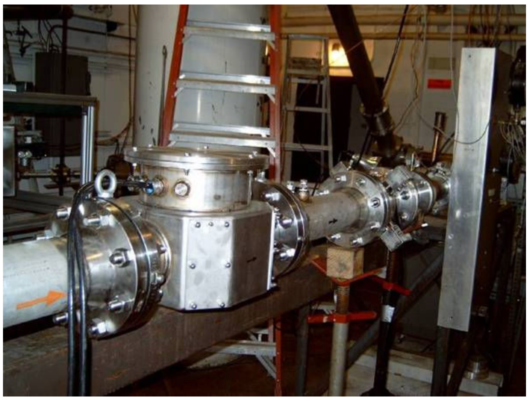

Figure 19 ALTOSONIC V on the calibration facility for liquefied Nitrogen at NIST.

The NIST test facility has been used to evaluate the five beam ultrasonic flowmeter on its sensitivity to pressure, temperature, flow rate and thermal cycling. The average temperature during the test was about 80 [K], the average pressure about 0.34 [MPa]. In addition, the repeatability, reproducibility and stability of the meter have been tested.

The flowmeter has been tested at several flow rates: 4.7, 12.6, 20.9, 29.2, 37.1 and 45.4 [m^3/h]. Single data points were taken at each of the individual flow rates mentioned, the next series of points was taken, followed by a third set of data. This provided three data points at each of the flow rates to be observed. There were also data points taken using small liquid nitrogen mass amounts to observe the meter performance with small sampling.

5.2 Test Results

- **Sensitivity to pressure and temperature**
  No sensitivity to pressure and temperature has been observed. The same holds for the effect of thermal cycling. The meter is still reproducing within the repeatability band after several thermal cycles.

- **Linearity**
  The linearity was well within expectations. The uncorrected linearity was considerably smaller than ±0.20% of M.V.. This corresponds to the experience with other applications at high Reynolds numbers. Since the Reynolds numbers are fairly high (due to low viscosity), a good linearity can be expected.

- **Repeatability and stability**
  The repeatability results have been very satisfactory. Despite the fact that the individual

calibration points have not been collected immediately after each other (a complete flow rate cycle has been run in between), a repeatability of ±0.07% has been obtained in the normal flow range. Even at very low flow rates (1.5% of F.S.) a very good and stable performance has been observed.

All results have been reported in a test report from NIST [7]).

6. NMi UNCERTAINTY STATEMENT

The test results described in chapter 4 and 5 have been used to further ground the calibration concept for ultrasonic flowmeters at cryogenic applications. NMi (‘Netherlands Measurement Institute’) has performed an overall uncertainty analysis for the 5 beam ultrasonic flowmeter for LNG, which resulted in an uncertainty of 0.26% to 0.33%, dependent on the range of application [5]).

Based on the analysis, NMi has released a written uncertainty statement (see figure 20). This uncertainty holds for the situation of a flowmeter calibration on water at ambient conditions and application on LNG at -163 [ºC].

Nederlands Meetinstituut

C-SP-06-WV-0178
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Date
23 June 2006

Your reference
Meeting 2 June '06

Our reference
C-SP-06-WV-0178

Krohne Altometer
Attn. Mr. Jankees Hogendoorn
Kerkeplaat 12
3313 LC Dordrecht
The Netherlands

Subject
Estimated uncertainty Ultrasonic LNG Volume Measurement

Dear Mr. Hogendoorn,

With reference to the meeting mentioned above, please allow me to inform you that we have carried out a preliminary study on the estimated measurement uncertainty in Volume Measurement by your Altosonic V Ultrasonic flowmeter on LNG.
This preliminary study was based on:

- the test results presented by you
- scientific data provided by NIST
- our experience with the Altosonic V on other media

Please note that in the absence of traceable, volumetric LNG standards, this is the best we could provide on such short notice. We strongly recommend to follow-up on this preliminary study, for instance with accuracy tests on Liquified Nitrogen (-196 °C) in order to obtain more confidence in the Altosonic V for LNG applications.
Also note that broad international acceptance in the field of legal metrology requires all tests to be performed or witnessed by an independent third party such as ourselves, rather than relying on a manufacturer's own test results. Therefore some of the research tests you already performed, as well as all future tests will need to be repeated / performed by, or in the presence of such a party.

With the above in mind, I would like to refer you to pages 2 and 3 of this letter, which summarised show that we expect the uncertainty in Volumetric measurement of LNG by the Altosonic V to be within a range of 0.26 to 0.33% of measured value.

I trust this informs you satisfactorily on this matter.

With kind regards,
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Figure 20 Uncertainty statement of NMi on ALTOSONIC V for LNG. Uncertainty 0.26% to 0.33% of M.V. on basis of water calibration at ambient conditions.

7. SUMMARY AND CONCLUSIONS

This paper describes the development project of the 5 beam ultrasonic flowmeter for measuring cryogenic liquids (e.g. LNG or Liquefied Nitrogen) with fiscal accuracy.

Tests have shown the importance of the acoustical coupling between the piezo ceramic element and the radiating window of the transducer. A thorough investigation has lead to a special design consisting of a combination of an acoustic coupling and a reliable transducer construction. The patent for this solution is pending. Extensive tests under isolated, static and dynamic conditions have shown that the transducer design is stable and generates reproducible and accurate results.

There are two challenges regarding the calibration of any type of flowmeter for use in cryogenic applications. There are no (laboratory) test facilities in the world where flowmeters, with a diameter larger than 4 inch, can be tested on LNG or on liquefied nitrogen against a reliable reference. And, secondly, in most applications it is not possible to calibrate flowmeters on site against a reliable reference. This asked for the development of an alternative calibration method.

The transfer of water calibration to application at cryogenic conditions forms the basis of the calibration concept. LNG and liquid nitrogen have a low viscosity, leading to fairly high Reynolds numbers, which, as confirmed by the tests, improves linearity of the 5 beam ultrasonic flowmeter.
The calibration procedure for calibrating ultrasonic flowmeters for use of custody transfer of LNG has been developed in close cooperation with NMi, the Dutch Board of Weight and Measurement,

This paper also describes tests done at the cryogenic calibration facility at NIST. The performance of the LNG ultrasonic flowmeter with regard to the reproducibility, repeatability and the linearity have been well within expectations and market requirements. The tests at NIST have been witnessed by NMi ('Netherlands Measurement Institute').

Based on this we can conclude that ultrasonic flowmeters form a reliable and highly accurate solution for the custody transfer of LNG. In addition, the developed calibration procedure based on a water calibration offer a good solution for proving the flowmeters.

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