LNG ALLOCATION METERING USING 8-PATH ULTRASONIC METERS

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1 INTRODUCTION

This paper discusses the requirements and challenges of in-line allocation metering of LNG in facilities with common storage and shared offloading. Field trials conducted at an LNG test site are described and the results and conclusions of these tests are summarised. The design of the Caldon ultrasonic meter for LNG is discussed, with particular reference to the requirements for application at cryogenic temperatures and very high Reynolds numbers. The benefits of using an 8-path transducer arrangement to ensure transfer of calibration from the lab to the field are demonstrated, both analytically and with reference to the field test data.

2 BACKGROUND

2.1 LNG Supply and Demand

With the depletion of existing conventional oil and gas reserves, LNG is becoming an increasingly important source of fuel for many countries. This is illustrated in the UK gas forecast which shows a rapidly increasing supply gap (see Figure 1). Although much of the increasing demand will be met by gas imports by pipeline, LNG will play an important part in meeting future demands.

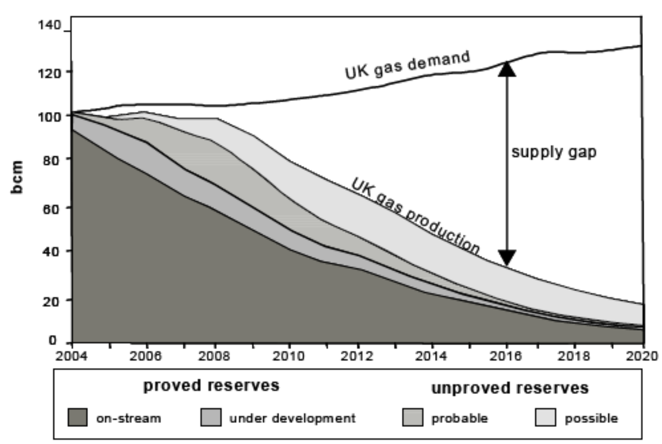


Figure 1 UK gas supply and demand forecast[1]

One of major players in the global supply of LNG is the State of Qatar. For example, the QGII project, which is just one part of the Qatargas facilities, will produce about

15.6 million tonnes of LNG annually. LNG from the first train of QGII is destined for the South Hook Terminal in Milford Haven UK, secured by a 25-year purchase agreement, and will fulfil approximately 20% of UK gas demand.

2.2 Common Facilities

Major savings in capital and operational expenditure can be achieved by using common facilities for storage and shared offloading thus reducing the number of storage tanks and berths required. This is the approach that has been adopted for the Qatar Common LNG Project, as illustrated in Figure 2 below, which comprises five separate joint ventures. Cost savings achieved by adoption of the common facilities approach are estimated to be in the region of 1 Billion US dollars ($1,000,000,000) [2].

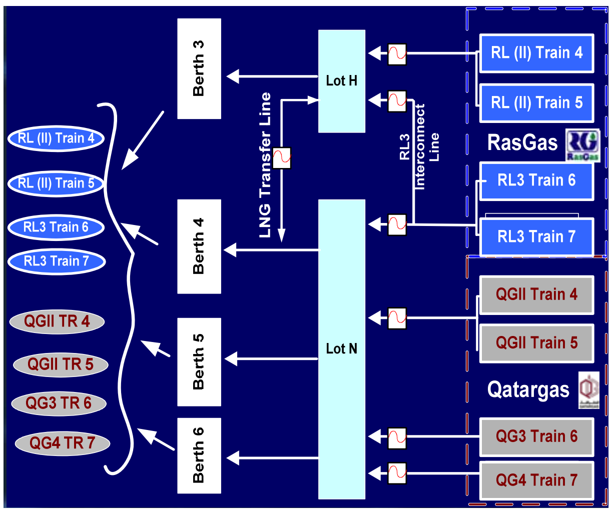


Figure 2 A Schematic of the Qatar Common LNG Project[2]

As a consequence of the fact that LNG from each plant is commingled in the common storage it is necessary to allocate production back to each venture by metering the LNG rundown from each plant. As such, accurate in-line LNG metering is a key enabling technology for this approach.

2.3 Metering Technology Selection Philosophy

As custody transfer measurement of LNG is normally performed by onboard tank measurements, limited research has been conducted regarding the performance of in-line LNG metering systems. In addition to the general shortage of information about in-line LNG metering, there is the added complication that conventional proving systems used for liquid metering can not be used on typical LNG applications. Therefore, a joint funded project was established to evaluate the performance of in-line metering technology for the Qatar Common LNG Project.

The philosophy that the partners agreed upon was to adopt the same technology for all of the metering stations in order that measurement uncertainties would also have a common basis. Basic pre-qualification requirements used in the selection of technologies for evaluation were:

- No rotating parts
- No wetted sensors
- Advanced diagnostics
- Proven reliability in other applications
- Proven accuracy for liquid custody transfer
- Proven performance in (other) extreme temperature applications

On the basis of the above criteria, both ultrasonic and Coriolis technologies were selected by the project team for evaluation.

2.4 Qualification Requirements

In order to qualify for the use in the Common LNG Project, the flow meters would be required to have the following attributes:

- Ability to perform accurately in cryogenic conditions
- High reliability at cryogenic temperatures
- High reliability through large temperature cycles (-161 to +60^{o}C)
- Ability to be used in a duty-and-check configuration
- Built-in diagnostic capabilities for dealing with unforeseen problems
- Low pressure drop to avoid vaporisation

Based on discussions with various manufacturers, two different makes of Coriolis meter and one ultrasonic meter were chosen for evaluation. The ultrasonic meter was a six-inch 8-path meter supplied by Caldon.

2.5 Field Qualification Tests

The qualification tests were performed at the ConocoPhillips LNG plant located in Kenai, Alaska. This location was selected as it was an operational facility with appropriate infrastructure for the meter evaluation. The test line is a bypass loop on the rundown line with double block and bleed valve, allowing installation and maintenance of the test meters without interfering with the production.

This infrastructure allowed the meters to be tested by using them to meter LNG into the plant’s storage tanks. The storage tank measurements were in turn verified against previously certified tanker measurements. Figure 3 shows a schematic diagram and a photograph of the test set up.

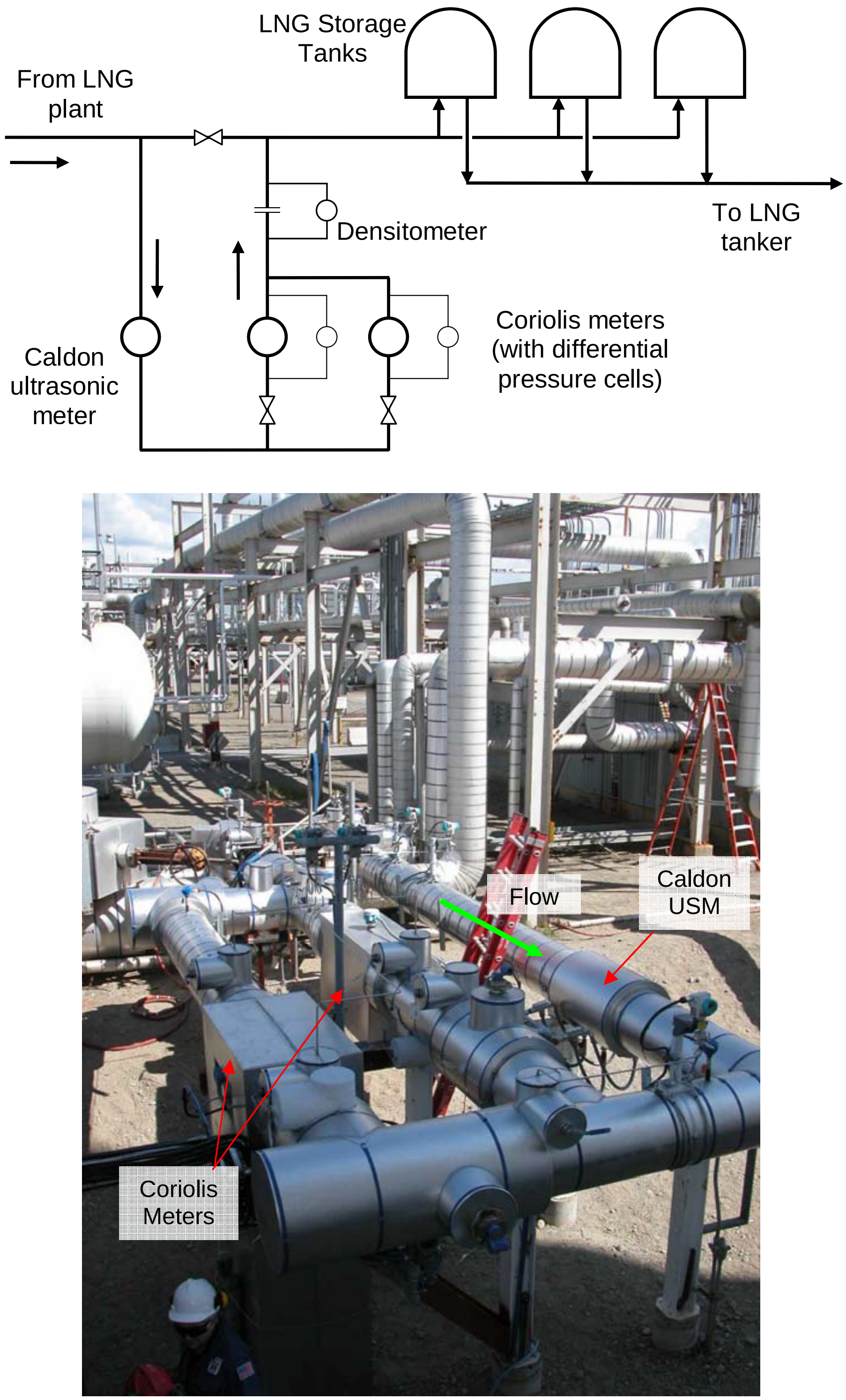


Figure 3 The Kenai test set-up

The qualification tests were performed over a three month period at the end of 2005.

3 CALDON LEFM TECHNOLOGY FOR METERING OF LNG

The Leading Edge Flow Meter (LEFM) ultrasonic technology upon which Caldon meters are based was originally developed by Westinghouse for high accuracy measurement of liquid flows in the late 60's. Following Caldon's acquisition of the LEFM technology in 1989 numerous improvements and additions were made to the product line, including development of transducers for challenging high temperature applications in nuclear power plants. From around 1980 onwards over 70 LEFM systems have been installed in nuclear power plants around the world. These meters are used to measure feedwater flows at temperatures of up to +235°C. In addition, many LEFM systems are now in service in oil custody transfer applications. These applications gave the engineers at Caldon the relevant measurement and design experience required to meet the challenges of high accuracy measurement at cryogenic temperatures.

3.1 Ultrasonic Transducers for Cryogenic Applications

Operation at cryogenic temperatures requires that the materials that are used in the meter body must perform reliably at low temperatures of around -161 °C and be able to withstand large changes in temperature. Furthermore, changes in temperature should not affect the accuracy of the flow rate measurement. The most critical parts of the ultrasonic meter in this respect are the ultrasonic transducers..

When designing an ultrasonic flowmeter for operation at low temperatures the designer must choose between placing the transducers close to the fluid or placing them at the end of some form of temperature buffer rod. Placing the transducers close to the fluid eliminates the buffer but demands that the transducers must produce good quality signals at low temperatures and be robust when subjected to changes in temperature. Using a buffer places lower demands on the transducers themselves but has the disadvantage of influencing the transit time measurements as a consequence of the long transit times in the buffer rods. Furthermore, the thermal gradients in the buffer rods can introduce uncertainties in the transit time measurements.

The approach adopted for Caldon ultrasonic meters is to place the transducers behind a stainless steel window in a welded stainless steel housing. The window, which is less than half an inch thick, serves as a pressure boundary and is in direct contact with the cryogenic liquid. The transducer housings are in turn welded into a manifold as shown in Figure 4. Importantly, this arrangement allows Caldon LNG meters to use the same physical design and path configurations as the standard range of liquid custody transfer meters.

The 8-path Caldon 280C configuration is recommended for LNG applications where high accuracy is important. The main reason for recommending the 8-path design is that it is very insensitive to swirl and distorted velocity profiles, without needing a flow conditioner, which is particularly important when considering pressure drop. A further benefit is that it provides greatest redundancy in case of transducer failure.

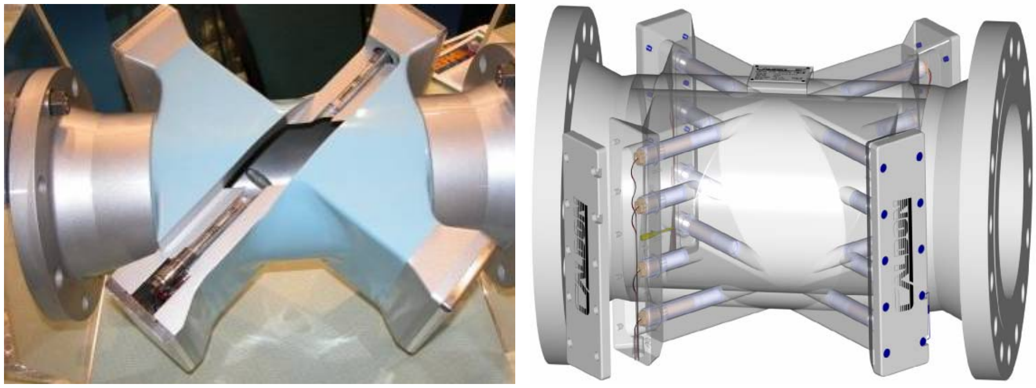


Figure 4 Transducer arrangement in an 8-path meter body

During the development of the transducers, various designs were evaluated by constructing and testing large batches of transducers. The testing included initial cryogenic measurements of signal strength on a large batch of transducers followed by cyclic temperature sample testing to cryogenic temperatures.

In terms of signal strength, it is vitally important that the signal-to-noise ratio (SNR) be sufficiently high in cryogenic conditions. Noise can be random or coherent. For transit time meters it is the signal-to-coherent-noise ratio (SNR_C) that is most important. As the transducers are such a critical part of the flowmeter, Caldon test each transducer as part of the factory acceptance test procedures and only those transducers that exhibit satisfactory signal strength ($SNR_C > 100$) are used.

Figure 5 below shows the distribution of measured SNR_C values (at cryogenic conditions of -191 °C) for a batch of 98 transducers tested by submersion in liquid nitrogen. In these tests 85% of the transducers had a SNR_C of greater than 100.

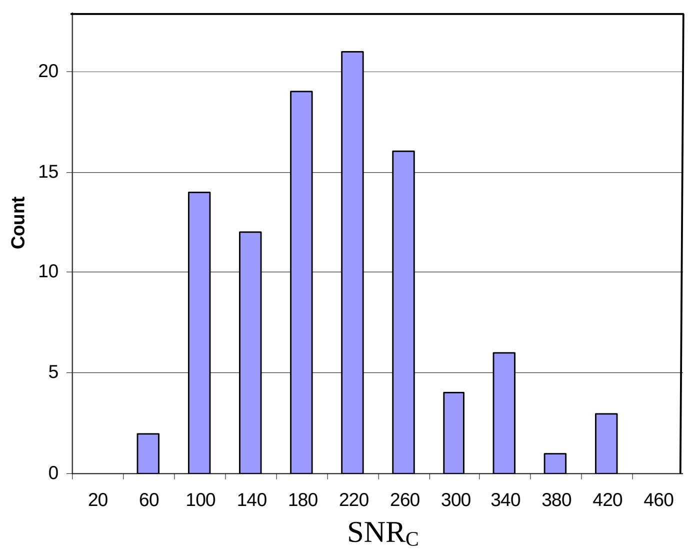


Figure 5 Measured SNR_C in liquid nitrogen

A photograph of the test set up is shown in Figure 6.

Figure 6 Transducer testing by submersion in liquid nitrogen

It can be observed that the average SNR_C in Figure 5 is approximately 200. However, when these transducers were tested in an actual meter (where there are fewer stray echo sources) their performance was much better and the average SNR_C was 740. An example of the cryogenic (liquid nitrogen) test setup with an assembled 10 inch meter is shown in Figure 7.

Figure 7 Cryogenic testing of an assembled meter

In addition to measuring the signal strength during factory acceptance tests, further tests have been carried out to ensure that the signal strength will not degrade if the meters are subjected to multiple thermal cycles. In these tests, the transducers were subjected to a rapid cycle from –191°C to +60°C by placing them in a test cell and submerging them in liquid nitrogen. Once submerged and cooled the signal strength was measured in terms of the gain applied to a transducer pair by the automatic gain control in the flowmeter electronics. The nitrogen was then allowed to boil off and the samples were then transferred into an oven at 60 °C. Once the temperature had stabilised at 60 °C the process was repeated.

Figure 8 below shows the results from three transducer pairs subjected to 70 thermal cycles. It can be observed that there is no significant change in the gain levels over the duration of the test.

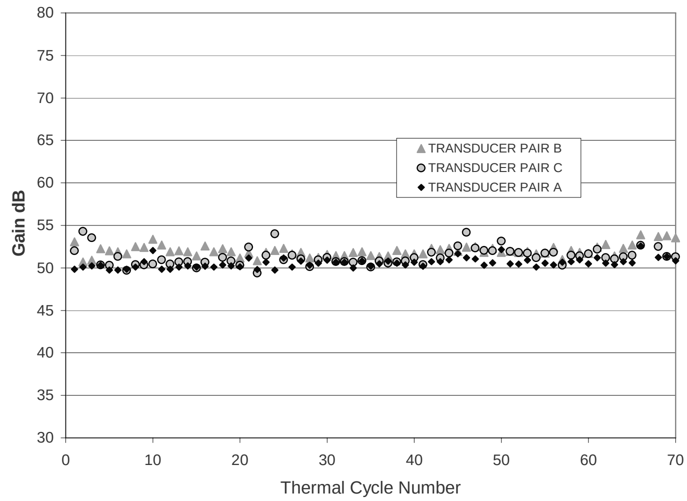


Figure 8 Transducer gain at cryogenic temperature during each thermal cycle

The thermal cycle test is extreme relative to the expected operating conditions for the meter in service for LNG. In general LNG lines will be kept cold to prevent boil-off, and even if the meter does experience temperature cycles the rate of change should be much less than in the Caldon lab tests.

3.2 Maintaining Traceability from the Lab to the Field

3.2.1 Laboratory Calibration and Accounting for Axial Profile Changes

For LNG applications it seems highly unlikely that typically sized ultrasonic meters will ever be calibrated in-situ. Therefore, the calibration must be performed in the factory or at a third-party laboratory. This presents a challenge as currently there are no test facilities using LNG or other cryogenic liquids as the calibration fluid that can achieve the flowrates typically required for ultrasonic meters. For example, the NIST cryogenic calibration facility has a maximum flow limitation of around 45 m^3/hr (or around 14% of the nominal maximum of a 4-inch ultrasonic meter).

To overcome this limitation Caldon have adopted a methodology that allows calibration of LEFM ultrasonic meters using another working fluid. The basis of this methodology is a rigorous analysis of the factors affecting the acoustic signals, and a process that accounts for variations in hydraulic conditions.

The influence of different fluid properties on the acoustic signals can be shown to be relatively small and can be included in the uncertainty budget for the final application [3]. Geometry changes are compensated as a function of temperature, which is measured in the meter body, and again the uncertainty in these corrections can be included in the overall uncertainty budget. This leaves one parameter, the meter factor (or velocity profile factor), to be accounted for.

The meter factor is analogous to the discharge coefficient of a differential pressure flow meter. Ultrasonic meters are velocity measuring devices that sample the velocity on a discrete number of paths. Therefore the 'discharge coefficient' of the ultrasonic meter is a function of the velocity profile of the fluid as it passes through the meter body.

Owing to the low viscosity of LNG, the Reynolds numbers (Re) experienced in LNG applications tend to be high (Re of 500,000 to 30,000,000 could be expected). At these high values of Re the boundary layer is relatively thin and velocity profile is flatter than experienced with a more 'normal' liquid. It is not possible to achieve such high Reynolds numbers in liquid calibration facilities (or at least it is not possible to achieve the maximum application Reynolds numbers), owing to the fact that typical calibration fluids, such as water, have a higher viscosity. Unfortunately achieving a higher Reynolds number by using a gas as the calibration fluid is not appropriate as the acoustic properties of liquids and gasses are too widely different.

However, the important fact is that the calibration of the ultrasonic meter is dependent on the time averaged velocity profile and not some other property of the high Reynolds number flow.

At this stage in the discussion it is important to emphasise some particular characteristics of Caldon 8-path (and 4-path) meters with respect to velocity profile. The first point is that is can be shown in theory (and backed up with laboratory data) that the Gaussian integration method applied in the design of Caldon meters results in a low sensitivity to changes in velocity profile at high Reynolds numbers. The data in Figure 9 below shows the velocity profile factor (or meter factor) for fully developed flow over Reynolds numbers of 32,000 to 35,000,000, calculated using velocity profile data from the Princeton University Superpipe experiments [4, 5]. It can be observed that for Gaussian integration using four chords the change in meter factor owing to profile changes is expected to be less than 0.07%, whereas for meters employing diametric paths the change in the meter factor is 3.9%.

Figure 10 shows results from the calibration of eleven Caldon 8-path LNG meters using water at Reynolds numbers of approximately 700,000 to 3,000,000. This data was obtained after applying a constant meter factor to the raw calibration results, i.e. no linearization was performed. The results demonstrate the excellent inherent linearity of the design, with all meters exhibiting linearity with +/- 0.08%.

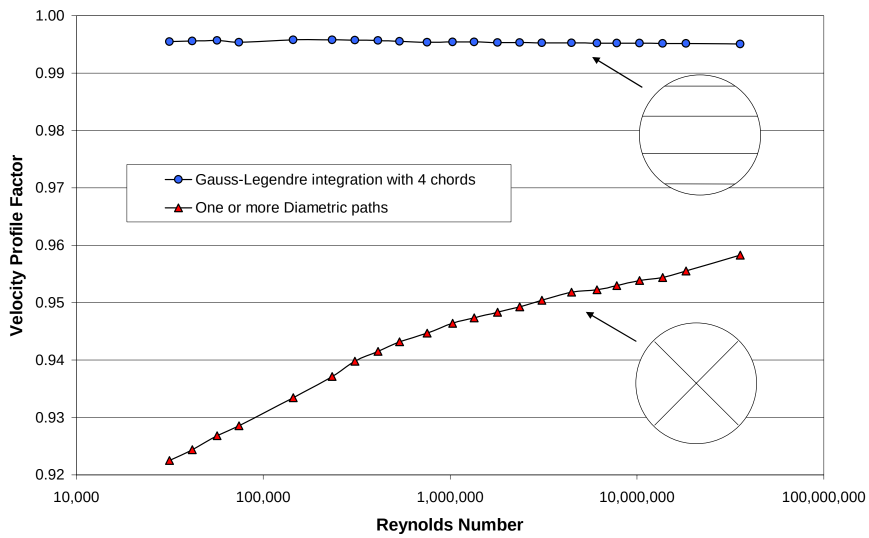


Figure 9 Velocity profile factor vs. Reynolds numbers for two different path configurations

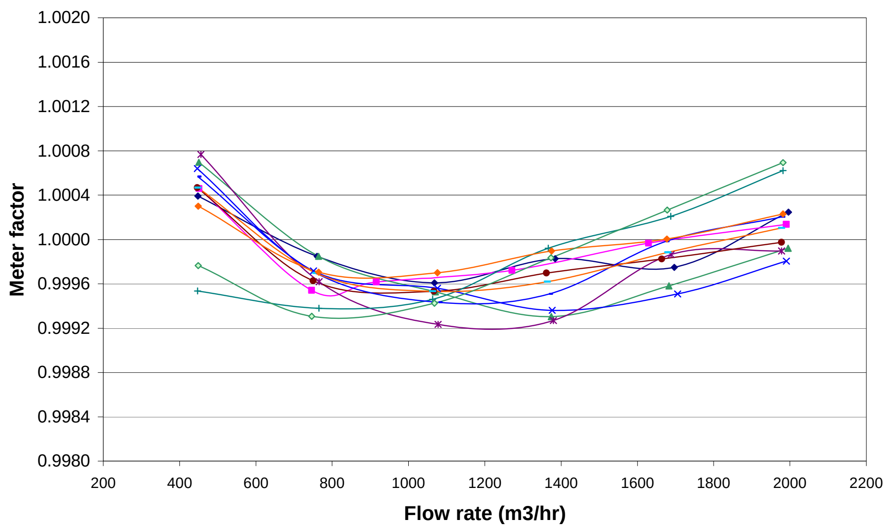


Figure 10 Meter factor versus flowrate for a batch of eleven 8-path LNG meters

The second important point about the Caldon chordal meter design is that the meter itself can characterise the shape of the velocity profile as a 'flatness ratio', which is the sum of the outside path velocities divided by the sum of the inside path velocities. This allows the meter factor to be determined as a function of flatness ratio, as illustrated in Figure 11 below, which shows the flatness ratio and profile factor derived from the Superpipe data for Reynolds numbers from 234,000 to 35,724,000. It should be noted that if two-path diametric or mid-radius designs are used it is not possible for the meter to calculate a flatness ratio, and the correction must rely on inference of Reynolds number.

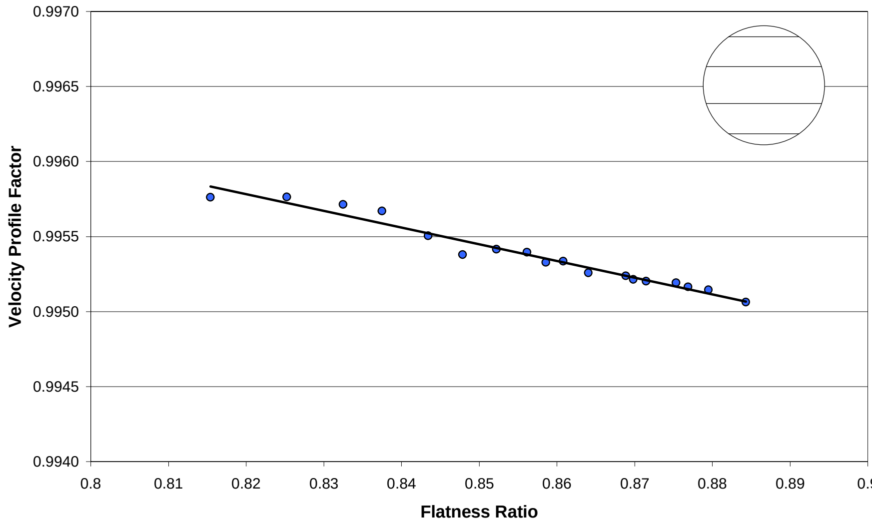


Figure 11 Velocity profile factor vs. flatness ratio for the Gaussian configuration

It is important to recognise that the shape of the velocity profile can be altered not only by changing Reynolds number but also by varying the upstream pipe conditions. For example, out-of-plane bends and reducers tend to thin the boundary layer and flatten the velocity profile. Although such profiles are not identical to fully developed profiles at higher Re, they do produce analogous variations in profile flatness and can be used to validate the calibration method over a range of velocity profile conditions that will encompass the high flatness ratio values seen in LNG applications. It should be noted that this process generates data that includes variation in upstream conditions and therefore also encompasses lab-to-site variations in axial velocity profile. This is in contrast to the limited capabilities of single-path or two-path systems, as illustrated below.

In Figure 12 the accuracy of Gaussian integration with flatness ratio correction has been compared with meter configurations using two paths for a selection of ten distorted axial velocity profiles. The index numbers in Figure 12 refer to the velocity profiles described in references [6] and [7], but with only half the magnitude of asymmetry (*m*). Contour plots of these profiles are shown in the Appendix. Details of the methodology and further examples of this type of analysis can be found in numerous papers, e.g. [6 -10]. In this case the profile factor was determined for each profile at 5 degree intervals of rotation. For the Gaussian configuration a linear relationship between flatness ratio and profile factor was applied before calculating the root-mean-square (RMS) error for each profile. For the 2-path configurations the RMS error for each profile was calculated relative to the velocity profile factor corresponding to fully developed flow in the form of a power law profile with $n = 7$.

The results presented in Figure 12 demonstrate the excellent performance of Gaussian integration with four chords and flatness correction, and highlight the relative weakness of the 2-path configurations. The Gaussian configuration is about 40 times more accurate than the diametric configuration and ten times more accurate than the mid-radius configuration. The two-path configurations fare so poorly in comparison because they are more sensitive to velocity profile in the first place, and then have no ability to compute useful information about the shape of the velocity profile.

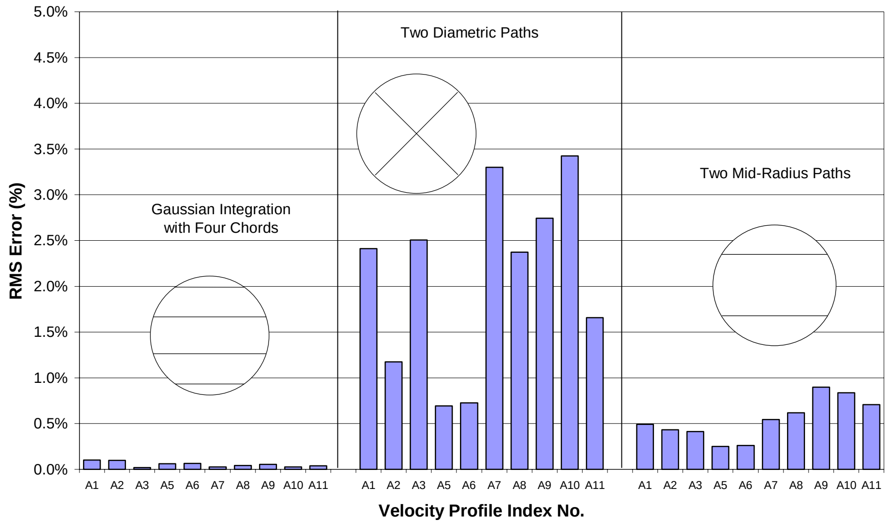


Figure 12 Errors owing to distortion and asymmetry for 10 different axial velocity profiles

For the lowest uncertainty and highest confidence, it is possible to calibrate the meter such that subsequent use relies on interpolation of the meter factor versus flatness ratio data. In that case multiple upstream configurations are required to produce an appropriate range of flatness ratio. However, owing to the low sensitivity of the meter design to velocity profile, extrapolation is possible with very little impact on the overall uncertainty.

The calibration methodology applied to Caldon meters is well supported by theory and an extensive database of laboratory test results obtained with different meter sizes and different pipe configurations. NMi, the Dutch weights and measures authority, have recently reviewed this information in the process of performing independent assessment of this calibration methodology for LNG. The assessment included reviewing uncertainty contributions for the effects of operation at cryogenic temperatures on the dimensional and acoustic aspects of the measurements. NMi's evaluation estimates the uncertainty in volumetric measurement of LNG using Caldon meters to be 0.2% for the case of interpolation using flatness ratio and 0.22% if extrapolation is used [3].

3.2.2 Eliminating the Influence of Non-Axial Flow (Swirl)

The preceding section deals with the issues of calibration and changes of axial velocity profile. It has been demonstrated that a Gaussian integration using four chords can be used to determine the mean velocity very accurately for a wide variety of axial velocity profile shapes, and that under the same conditions 2-path meters are susceptible to significant errors. However, inherent in the preceding analysis is the assumption that the axial velocity is being measured accurately on each of the ultrasonic paths, and that may not be so if there is swirl present.

When flow is forced to change direction, the fluid then travels with forward motion parallel to the pipe axis and motion at an angle to the pipe axis. 'Swirl' is the name generally used for these non-axial components of velocity that are produced downstream of bends and similar pipe fittings.

The means by which swirl interferes with the performance of ultrasonic meters is by introducing an unwanted non-axial component of velocity in the measurement paths. This unwanted component of velocity can be additive or subtractive. If the non-axial flow velocity is going in same the direction as the ultrasound when it travels from the upstream transducer to the downstream transducer then the effect will be to increase the measured velocity. If the non-axial velocity is opposite in direction to the downstream travel of the ultrasound then the effect will be to decrease the measured velocity.

Multipath meters have some in-built tolerance to swirl, but as we will see later, they are limited in terms of what forms of swirl they can tolerate without error.

Single-vortex swirl is a form of swirl that is normally associated with bends in different planes (i.e. configurations that cause a change of flow direction in more than one plane) and can perpetuate for many diameters downstream of the pipeline components that cause it. The rate of decay of swirl can be shown to be a function of the friction factor in the form $\exp(-4fz/D)$, where z is the downstream distance and D is the pipe diameter[11]. The friction factor is in turn a function of Reynolds number, with the result that swirl decays at a slower rate at high Reynolds numbers. This is important for LNG applications as the Reynolds number is typically very high.

Figure 13 below illustrates the rate of decay of swirl at Reynolds numbers of 30,000 (representing an oil flow) and 10,000,000 (representing LNG). An initial swirl angle of 25 degrees has been assumed. It can be observed that at Re = 30,000 the swirl angle is predicted to reduce to less than 2 degrees (the limit set by ISO5167 for orifice plates) in just over 25 pipe diameters. In comparison, at 10,000,000 Re it takes more than 50 pipe diameters for the same reduction in swirl.

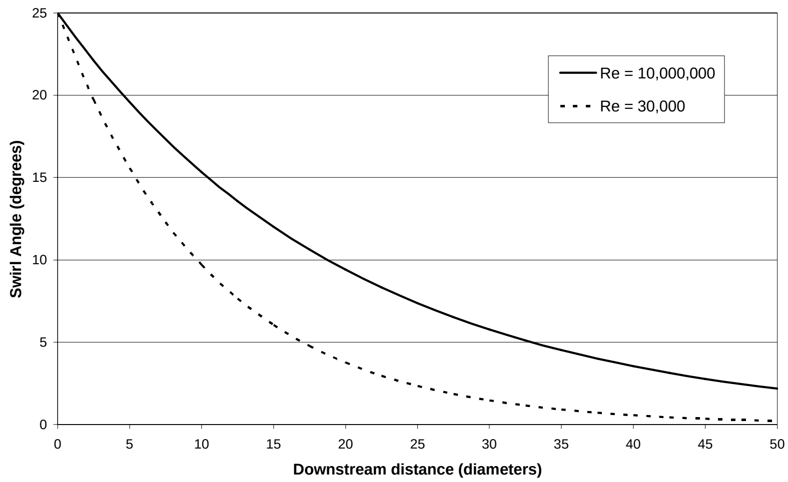


Figure 13 Decay of swirl downstream of a flow disturbance

Most ultrasonic meter designs are unaffected by swirl if the swirl takes the form of a single vortex centred perfectly in the middle of the pipe. However, if the swirl is slightly off-centre or has a more complex pattern containing multiple vortices, then potentially large errors can occur. Good illustrations of complex off-centred swirl downstream of bends can be found in studies where Computational Fluid Dynamics has been used to investigate meter performance [e.g. 12 - 14].

The potential effect of non-centred swirl on the performance of a meter can be evaluated using simulated swirl patterns such as that given by the following equation.

$$u_\theta = \frac{u_0 r_v \exp\left(-r_v^2\right)}{(1-r+r_c)}\left(1-r^2\right)^{1/n} \qquad (1)$$

where u_θ is the tangential velocity relative to the vortex centre, u_0 is the vortex strength and $r_v = r_c/r_0$, where r_c is the distance from the vortex centre and r_0 is the radius of the vortex. The value of n controls the manner in which the swirl velocity approaches zero at the walls, where r is the distance from the centre of the pipe normalised to the pipe radius.

Using the above model to create a vortex with parameters of u_0 = 0.21, r_0 = 0.9, n = 15, centred at $r_c = 0.1R$, $y = 0.1R$, and adding this to an axial velocity profile described by the power law in the form $(1 - r)^{1/15}$ generates a profile that has non-centred swirl with a maximum swirl angle of about 6 degrees. A plot of the swirl pattern produced by this model is shown in Figure 14 below.

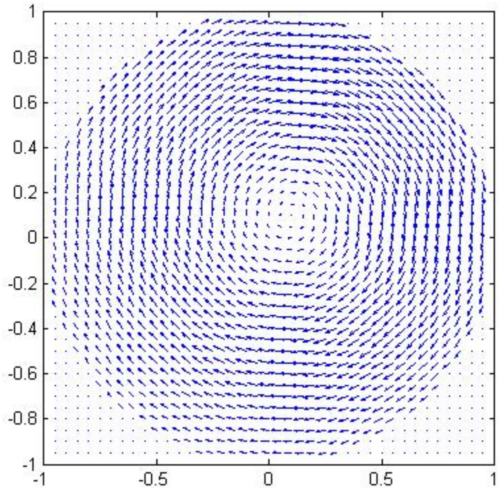
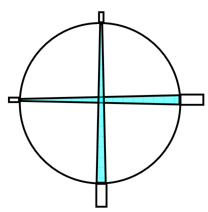
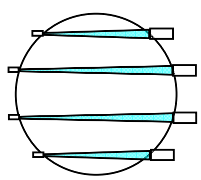
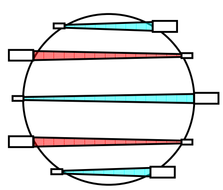
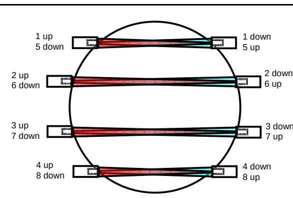


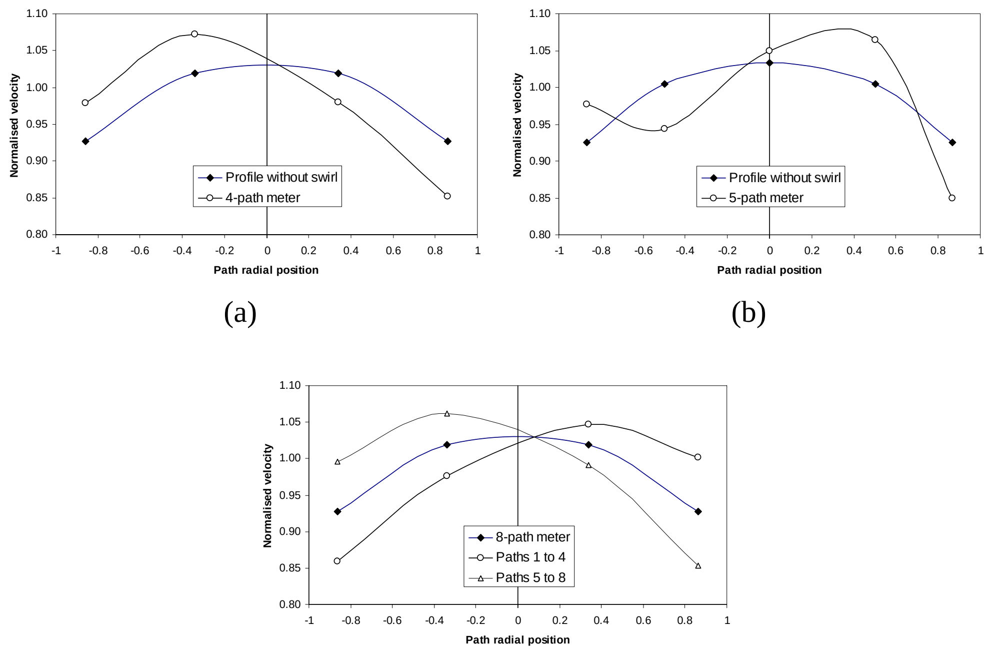
Figure 14 An example of non-centred swirl generated using Equation 1

In terms of the magnitude of effect on various meter configurations, the swirl pattern shown above would result in the errors given in Table 1 below.

Table 1 Swirl induced errors for the swirl pattern shown in Figure 13

Path configuration		Swirl Error Magnitude
Dual diametric paths		1.5%
4-Path Gauss-Legendre integration (single tilted plane)		0.26%
5-Path Gauss-Jacobi integration (criss-crossed)		0.33%
8-Path Gauss-Legendre integration (two tilted planes)		0%

The reason for the zero swirl error in the case of the 8-path meter is illustrated in Figure 15 below, which shows the path velocities for the 4-path (a), 5-path (b) and 8-path (c) meter designs. It can be observed that by averaging the paths in pairs the 8-path result is the same as the profile without swirl in (a) and (b), and hence the influence the swirl is eliminated.



(a) (b)

(c)

Figure 15 Path velocities for (a) 4 paths, (b) 5 paths and (c) 8 paths with swirl

4 FIELD TEST RESULTS AND CONCLUSIONS

The Caldon meter and the two Coriolis meters were tested at Kenai over a three month period by using them to measure the LNG rundown to the storage tanks. The Kenai plant produces approximately 50,000 barrels/day of lean LNG. Photographs of the Caldon meter are shown in Figure 16. The right-hand photograph shows the two sets of electronics that are currently used for the 8-path meter. Each set of electronics produces an output corresponding to one set of four paths (the four paths are grouped in a single tilted plane, like a conventional Caldon 4-path meter, and are referred to as plane A or plane B). The two outputs were averaged externally in the Kenai data acquisition system.

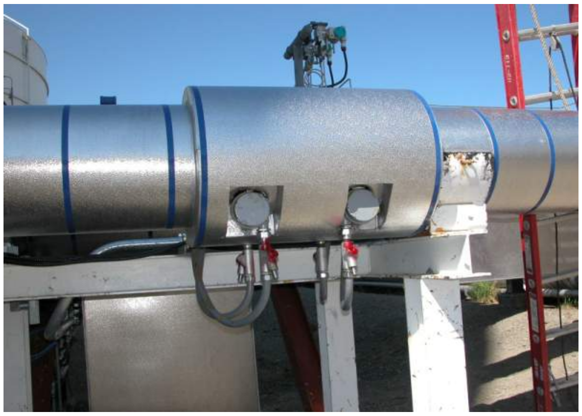


Figure 16 Caldon LNG meter installed at Kenai in Alaska

4.1 Comparison Results

A limited number of runs were performed by comparing data taken directly against the shore tanks between shipments. The storage tank measurements were in turn verified by comparison with onboard measurements from a tanker load performed during a plant shutdown. There was good agreement in the shore tank to ship comparison (within +/-0.3%) but the small number of runs and the scatter in the comparison of the meters with the shore tanks gave rise to a greater statistical uncertainty in these results. Nevertheless there was still reasonable agreement between the three meters and the shore tanks, with the results coming within approximately +/- 0.5%, which was considered acceptable given the limitations of the test.

The main part of the test programme involved comparing the Caldon ultrasonic meter against both of the Coriolis meters in order to assess the reproducibility of the results. The philosophy behind this was that any lack of reproducibility in either technology would be apparent, given that the comparison was between two completely different technologies, including two variants of Coriolis design. The stated aim was that the day-to-day reproducibility should be better than +/- 0.25%.

In terms of reproducibility the comparisons were similar in the case of both Coriolis meters. In terms of the absolute values there was good agreement between the Caldon ultrasonic meter and one of the Coriolis meters, with a more significant bias existing between these two and the second Coriolis meter. Figure 17 below shows the comparison of the Caldon ultrasonic meter and one of the Coriolis meters, using the percentage deviation in 8-hour totals taken over a period of twelve days. The average agreement between the two meters was better than 0.1%, with a statistical uncertainty of less than +/- 0.15%.

These results were taken as a positive confirmation of the performance of both technologies.

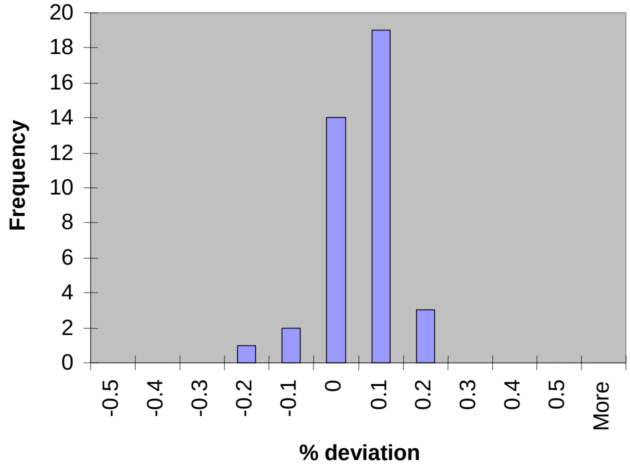


Figure 17 Comparison of Caldon USM and Coriolis meter totals on LNG [2]

4.2 LNG Density Measurement

In order to compare the ultrasonic meter with the Coriolis meters, a density input was required. Various methods of determining the density were compared. These included direct measurements from the Coriolis meters and a Solartron densitometer, calculations using equations of state (e.g. Klosek-McKinley), and density calculated by the Caldon meter. The differences between these different methods were generally less than 0.1%, as shown in Figure 18. The output from the ultrasonic meter was offset from the other results by approximately 0.4%, but tracked the changes in density closely. This result from the Caldon meter shows promise for further development either as a primary or check measurement of LNG density.

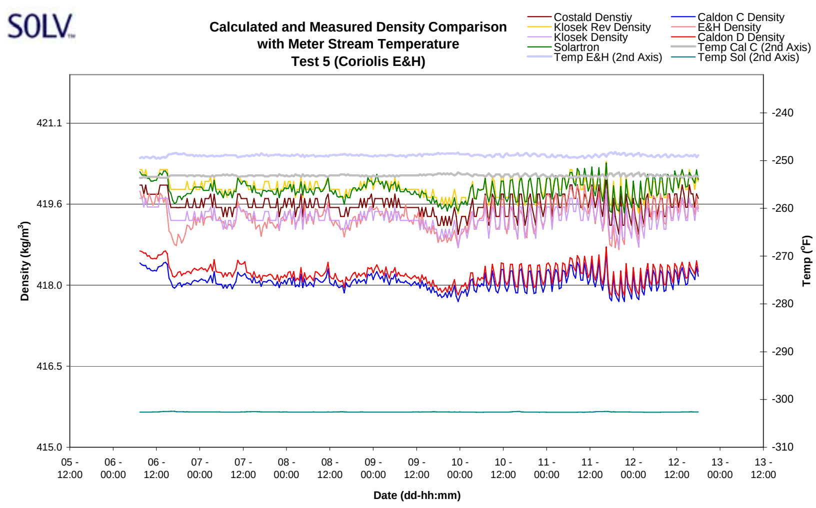


Figure 18 Comparison of calculated and measured densities [2]

4.3 8-Path Swirl Compensation in Action

As two outputs were logged from the Caldon meter, it was possible for the project team to evaluate the outputs from both plane A (i.e. paths 1 – 4) and plane B (paths 5 – 8) separately. When this was done it was found that, relative to the Coriolis meter, one plane was biased by approximately +0.4% and the other by approximately -0.4%, as illustrated in the results shown in Figure 19 below.

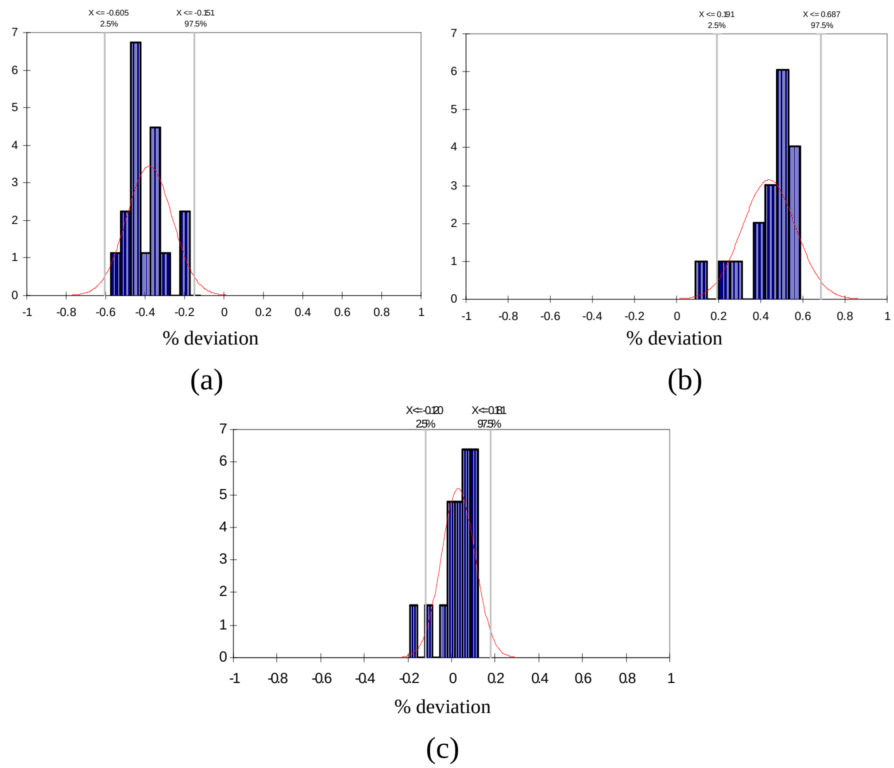


Figure 19 Eight-hour totals, compared with the Coriolis meter
(a) Plane A, paths 1-4, (b) Plane B, paths 5- 8, and (c) 8-path meter results[2]

A symmetrical bias of this magnitude between the two planes of an 8-path meter is normally indicative of strong asymmetric swirl. The Caldon meter was installed at Kenai with approximately 37 diameters of straight pipe upstream and no flow conditioning. This would normally be considered an acceptable installation condition. However, immediately upstream of the straight pipe there were three out-of-plane bends. This sort of configuration is notorious for producing swirl. Add to this the fact that low viscosity of LNG results in such high Reynolds numbers that swirl perpetuates for longer than is usual in liquid applications (see section 3.2.2) and it is perhaps not so surprising that there would be a significant level of swirl present at the location of the meter.

The presence of swirl was confirmed by logging the path velocities from the meter. Figure 20 shows the normalised path velocities obtained during logging at a flowrate of approximately 400 m^3/hr. Note the general similarity of the data in Figure 20 to that of Figure 15(c), typical of a swirling flow. The information in the graph below can be used to estimate the swirl magnitude. The pair of path velocities at each radial position can be used to yield a transverse velocity, which can in turn be converted to an equivalent tangential velocity at the pipe wall. Performing this calculation for the data shown in Figure 20 results in an average equivalent tangential velocity that is 6.5% of the axial velocity. Similarly, the data can be used to estimate the maximum swirl angle, which is calculated to be approximately 5 degrees. Another way of interpreting the data is to say that the flow undergoes one complete rotation every 48 pipe diameters/every 1.2 seconds.

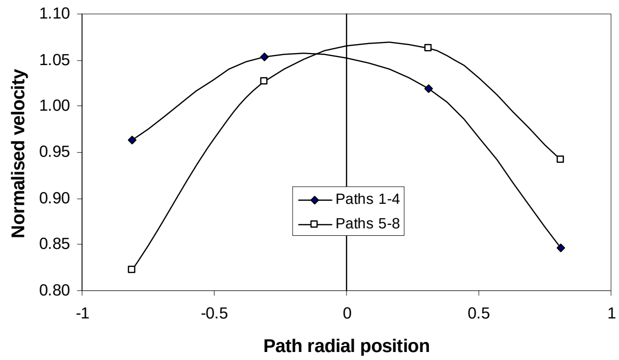


Figure 20 Path velocity information confirming the presence of swirl

The most important thing to note about this data is that despite the biases that are present in the results from each plane, the combined 8-path results shown in Figure 19(c) were within 0.1% of the Coriolis meter. This illustrates the benefits of the 8-path meter configuration with overlapping crossed paths at each chordal location. Similar performance can not be achieved with single-tilted-plane, or staggered criss-crossed path arrangements unless swirl-removing flow conditioners are used.

4.4 Final Meter Selection

The project team responsible for the trials at Kenai were satisfied with the flow measurement performance of the Caldon ultrasonic meter and the Coriolis meters. However, other factors proved to be important in the final selection.

Ensuring minimum pressure drop was the biggest factor in the final meter selection. The importance of this issue was increased further by the project requirement for check metering. Two Coriolis meters in series would have created too much pressure drop. On the other hand the Caldon 280C is non-intrusive. It also has two 4-path planes that operate independently and can be used in a duty and check arrangement. Furthermore, the 8-path, dual electronics design makes the meter extremely fault tolerant.

On this basis the Caldon meter was selected for the Qatar Common LNG Project, and has continued to be used in service at Kenai since the end of 2005.

5 SUMMARY AND CONCLUSIONS

A Caldon ultrasonic meter and two makes of Coriolis meter were evaluated by a joint venture project team in field trials at Kenai in Alaska. All three meters tested were found to have acceptable flow measurement performance for the final application. However, the Caldon ultrasonic meter was selected as it had much lower pressure drop than the Coriolis meters, particularly if two Coriolis meters were to be used in series to provide check metering. The built-in redundancy and diagnostic capabilities of the Caldon 8-path meter also featured in the decision.

The Caldon meter uses transducers that are housed behind a stainless steel pressure boundary in the meter body. It has been demonstrated, both in the lab and in field trials, that this design is suitable for robust and accurate measurement of cryogenic liquids. This includes the large temperature cycles that the meter will experience whenever the line is warmed up or cooled down.

The configuration of the Caldon 280C is such that there are two sets of fully redundant electronics, each operating a different ‘plane’ of four measurement paths. This results in a compact metering installation that can be used in a duty and check arrangement and is extremely fault tolerant.

The particular arrangement of paths used in the Caldon 8-path meter makes the meter very insensitive to velocity profile changes and swirl. As a result, this meter design can easily transfer its calibration from the lab to the field, without use of a flow conditioner, and still achieve better than +/- 0.22% uncertainty. As such this technology is suitable for allocation measurement and also has the potential to be used for tanker loading.

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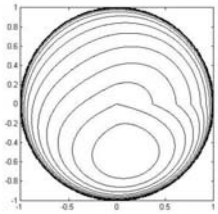
APPENDIX – VELOCITY PROFILE CONTOUR PLOTS



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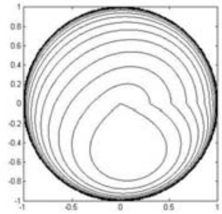

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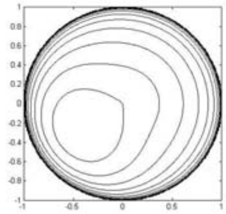

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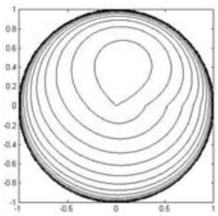

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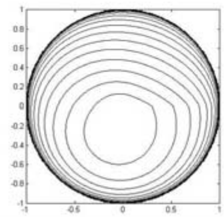

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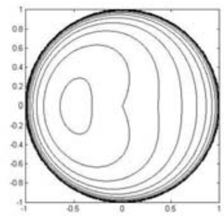

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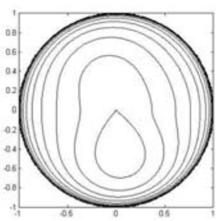

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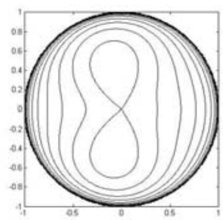

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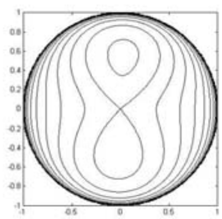

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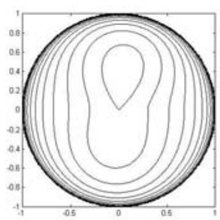

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