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Technical Paper

Qualification Testing of an 8-path Ultrasonic Gas Meter

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1 INTRODUCTION AND BACKGROUND

Ultrasonic meters are now commonplace for custody transfer measurement of natural gas, with several established manufacturers and some new entrants. For the end-user the competing claims in terms of meter design can be difficult to unravel, with the result that differentiation between one manufacturer and the next will often come down to knowledge gained from laboratory testing and experience in the field.

While type testing specifically did not feature heavily in the early days of custody transfer metering using gas USMs, the industry did undertake extensive evaluation programmes that set the first benchmarks. More recently, the type testing requirements of international standards, particularly OIML R137 and ISO 17089 have come to the fore. These standards each prescribe a set of tests, with some overlap, which can be taken as the current benchmark for gas USM performance.

In addition to the tests prescribed by international standards, some end-users may choose to prescribe tests of their own design. This has been the case for GazProm where a test using a PTB disturbance plate has been required. A typical installation for GazProm will include 30 diameters of straight pipe upstream of the gas USM, with no flow conditioning. By using the PTB disturbance plate at the inlet of a straight run, a reproducible flow condition with strong swirl and asymmetry can be generated to serve as a benchmark test.

This paper presents a summary and comparison of test results downstream of single and double bends. The results are taken from the larger programme of type testing carried out to certify the 8-path gas meter to the requirements of OIML R137 Accuracy Class 0.5 and demonstrate compliance with the requirements of ISO17089. In addition, results are presented for qualification tests performed for GazProm using a PTB disturbance plate installed at 5, 10 and 30D upstream of the meter, with no additional flow conditioners used to improve the conditions at the meter.

2 DEVELOPMENTS IN ULTRASONIC GAS FLOW MEASUREMENT

Multipath ultrasonic meters have been in continuous development since the 1960’s. In early publications and patents, it was noted how multipath meters that employ numerical integration methods could significantly reduce the sensitivity to distortions in the axial velocity profile caused by upstream hydraulic disturbances. Studies of the accuracy of the numerical integration methods have shown that chordal meters with four chords spaced according to the rules of Gaussian integration could typically be expected to perform with errors of less than one or two tenths of a percent.

In the earliest implementations of chordal integration schemes, it was common to place only one measurement path at each of the prescribed chord locations. In the patents and papers of Westinghouse published in the 1970's [1, 2], the paths of their Leading Edge Flow Meters (LEFM) were shown as residing in a single plane, typically angled at 45° to the pipe axis, as illustrated in Figure 1 below.

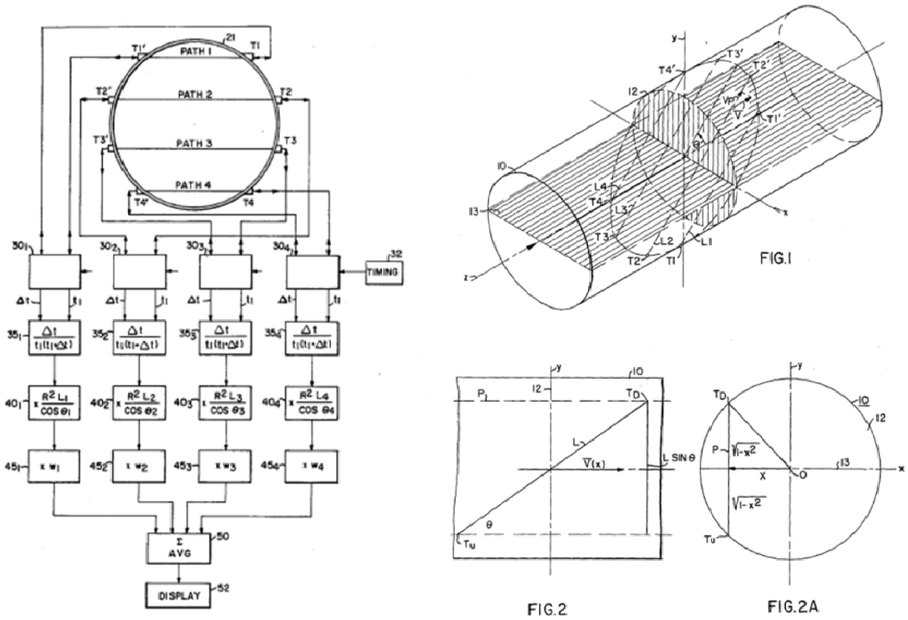

Figure 1 Illustrations of the Westinghouse multipath meter patent

An individual path at an angle of 45° is sensitive not only to the axial flow velocity but is equally sensitive to any non-axial component of flow such as that generated by pipe bends. The result is that in disturbed flow conditions where swirl or non-axial flow exists, the inputs to the integration method are in error, and this in turn results in poorer flow rate measurement accuracy than can be achieved in a non-swirling flow. In some special cases, such as a single-vortex flow that is centred exactly between the two inside paths of the Westinghouse arrangement the errors cancel, but in general they do not.

In the mid 1980's British Gas (BG) began development of a chordal multipath ultrasonic flow meter intended for custody transfer measurement of natural gas. This design was based on a similar arrangement of four horizontal chords to that used by Westinghouse, but with the paths criss-crossed such that the first and third paths were at +45° to the pipe axis and the second and fourth paths were at -45°, as illustrated in Figure 2. This design variation has been justified by technical arguments regarding sensitivity to cross-flow, but the fact that the 1976 patent of Westinghouse [2] was still in force in 1986 when BG filed for their patent [3], suggests that patent considerations may also have come into play.

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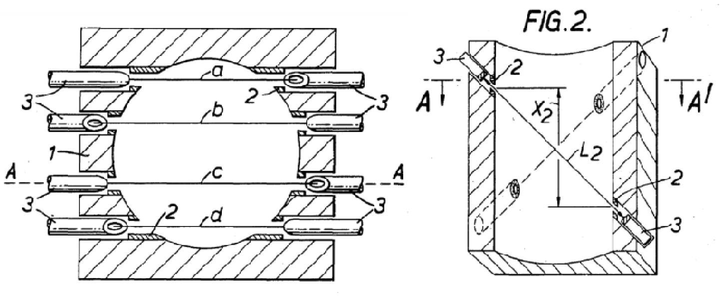


Figure 2 Illustrations of the British Gas multipath meter patent

One particular form of disturbance which it has been claimed the BG arrangement is insensitive to, is a form of cross-flow where the relative magnitude and direction of the cross-flow is equal at each of the chord locations in the cross-section [4]. With a Westinghouse arrangement of all chords at the same angle relative to the pipe axis this would result in a systematic over or under reading, whereas it is shown that for the criss-crossing arrangement of paths in the BG design this cancels. However, this is a hypothetical form of non-axial flow, which is unlikely to occur in practice in closed pipes, as in reality any disturbance that creates a cross-flow in one part of the cross-section is likely to create a counter-rotation in another part.

A more realistic form of cross-flow is that produced downstream of a single bend, where there is a strong cross-flow in the plane of the bend in the form of two counter-rotating vortices. The BG design differs from the Westinghouse design in its response to this situation in that the BG design would in principle be insensitive to the presence of these two counter rotating vortices if those vortices were exactly symmetrical about the line that is centred between paths B and C. However, in practice, owing to a combination of factors including effects from components further upstream, small asymmetries in bend geometry and the fact that the flow wants to recover to a fully developed condition, it is virtually impossible to create two symmetrical counter-rotating vortices. This is borne out in the results presented in paper presented at the 2013 AGA Operations Conference [5]. In the case of the single bend, with both the bend and the paths of the meter aligned horizontally, the resulting errors for the BG 4-path arrangement were significant, and much larger than for the Westinghouse 4-path arrangement [5].

Single-vortex swirl is another basic ‘test case’ for the path layout in an ultrasonic meter. In the Westinghouse 4-path arrangement, if the single-vortex swirl is symmetrical about the centre of the pipe, then the effect on path 1 would exactly cancel with that on path 4 and likewise the effect on path 2 would cancel with that on path 3. This is because the magnitude of the swirl would be the same in the top and bottom of the pipe but the swirl direction would be opposite relative to the path angle. For the BG design single-vortex bulk swirl cancelation relies upon a mathematical quirk of the design, whereby if a solid-body rotation of the flow is assumed, the combined effect on the outside paths (paths A and D) cancels with the effect on the inside paths (paths B and C). The two inside paths in the BG design see the swirl from the same direction and the two outside paths see the swirl from the opposite direction. However, true cancellation does not result in the case of realistic single-vortex swirl, even when the vortex is properly centred and symmetrical, as the BG design relies on the magnitude of the swirl effect on the inside paths versus the outside paths being in inverse proportion to the weighting factors. Owing to mathematics of circular geometry that assumption holds true if the swirl is a solid-body rotation of the fluid. However as Zanker has pointed out, in practice that particular case is unrealistic as the swirl must have its own boundary layer and go to zero velocity at the pipe wall [6].

In the 1990's a gas ultrasonic meter with five chords was jointly developed by Statoil and Fluenta (then a subsidiary of Christian Michelsen Research). The original design had a criss-crossing arrangement of paths, with paths 1, 3 and 5 in the same plane and paths 2 and 4 in the opposite plane. However, a few years later the meter design was altered to a 4-chord, 6-path design in order to account for the adverse effects of symmetrical double-vortex swirl. The new Fluenta/FMC design placed two crossed paths in each of the chord locations in the top half of the pipe, and one path in each of the chord locations in the bottom half of the pipe. This configuration has the benefit of tackling both a single-vortex swirl and the cross-flow caused by symmetrical double-vortex swirl, but similar to some of the 4-path cases discussed above it is truly insensitive only if the vortex pattern is symmetrical about the diametric plane that is parallel with the chord arrangement.

An alternative approach to the issues of swirl and asymmetry was taken by the engineers at Stork Servex (later Elster/Instromet) in their 5-path meter design. Their approach was to use reflected paths with the intent of covering more of the cross-section with a single path. The use of three single-reflection diametric paths and clockwise and counter-clockwise double-reflection mid-radius paths enabled this design to deliver a raw average velocity plus some information about profile flatness, bulk swirl and asymmetry. Using these inputs, empirical relations were applied in an effort to compensate for various forms of non-ideal upstream conditions.

Throughout the 1990s and into the 2000s numerous laboratory tests were carried out on ultrasonic meters for the natural gas industry. Particularly notable are the programmes of GERG in Europe [7] and the Gas Research Institute in the USA [8]. These tests exposed the weakness of 4, 5 and 6-path configurations in some installation configurations and demonstrated that for these particular designs, using either direct or reflected paths, a flow conditioner is generally needed if the requirements of today's standards are to be met.

Despite the clear recognition in the natural gas industry of the importance of installation effects on ultrasonic meters, it appears that developments in other industries either went unnoticed by the gas meter manufacturers, or if developments were noted by some, they chose not to act to improve their meter designs owing to other considerations. The use of flow conditioners has therefore become a de facto standard in many parts of the industry today despite the stated intention in the BG patent to provide a solution that "causes no blockage to the flow and generates no pressure loss". Some movement by end-users in the USA towards including the 'end treatments' of the metering package in the calibration (in addition to the meter run and flow conditioner) represent a further departure from the original promise of ultrasonic technology.

As mentioned in the start of this section, the advantage of the Gaussian integration method, if a sufficient number of chords are used, is that it is relatively insensitive to distortions of the axial velocity profile. It was also stated that the main problem that prevents the method from achieving its potential is the influence of non-axial flow or swirl on the individual paths that are used to provide the axial velocity estimate to the integration method. This problem was recognised many years ago by companies such as by Westinghouse and

ORE/Accusonic who were deploying their ultrasonic meters for large-scale measurements in rivers, hydroelectric and nuclear plants.

A description of the solution to this problem can be found as far back as the 1977 publication by Lowell [9] where the author highlighted the influence of non-axial flow and stated that the resulting error "can be reduced by the addition of one or more acoustic paths, at the same elevations as the original ones but installed at the opposite angle. Exact cancelation of errors can be accomplished on the crossed paths and an estimated of the cross-flow component used to adjust the readings on the non-crossed paths." The significance of this statement is that it encourages pairs of crossed paths at each elevation used in the integration method. It also highlights that for paths that are not crossed in the same elevation the cross-flow can only be estimated by making some assumptions.

The way that swirl or cross-flow interferes with the measurement of axial velocity and how a pair of crossed paths solve the problem can be described quite simply. Swirl or cross-flow introduces an unwanted non-axial component of velocity to the measurement path. This unwanted component of velocity can be additive or subtractive. If the non-axial flow velocity is going in the same 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, as illustrated in Figure 3 below. 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.

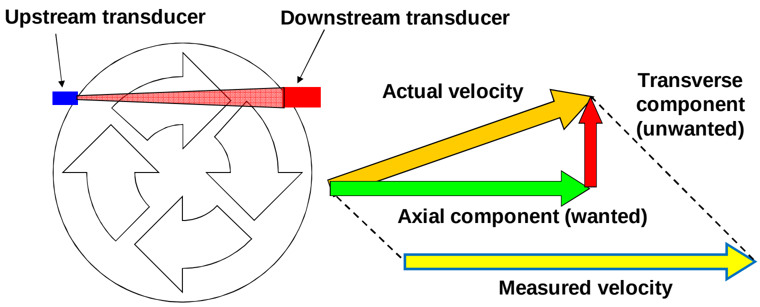


Figure 3 The influence of non-axial flow on an ultrasonic measurement path

As a result, a crossed pair of paths located on the same chord allows the true axial velocity data to be recovered, as illustrated in Figure 4 below.

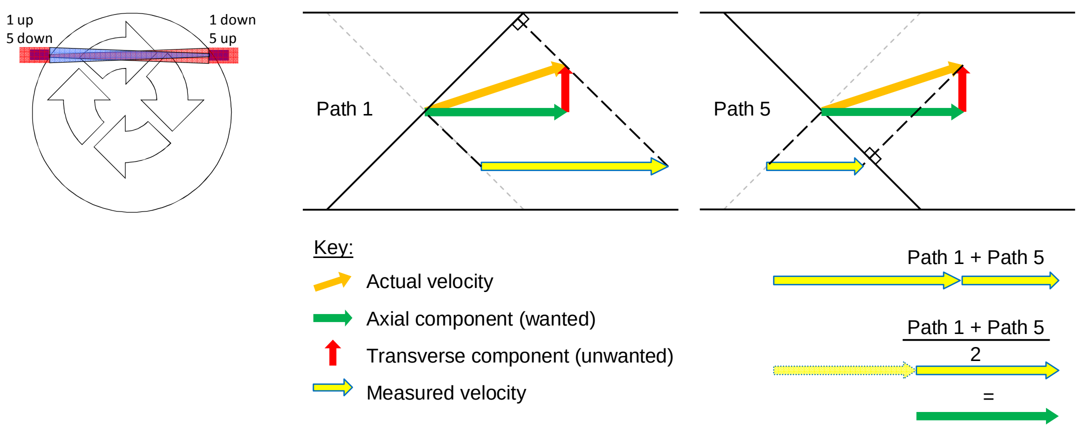
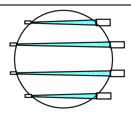
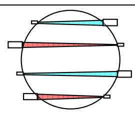
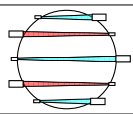
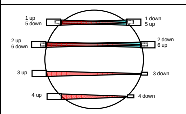
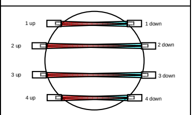
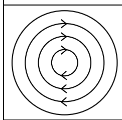
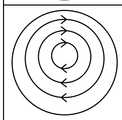
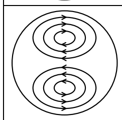
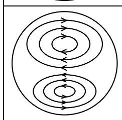


Figure 4 An illustration of how crossed paths cancel the effects of swirl

With this understanding of the fundamentals of how these meters work, it is relatively simple to examine different non-axial flow scenarios or swirl patterns and evaluate whether or not the interfering non-axial flow components would cancel partly or fully. This exercise has been performed for a variety of direct path chordal meter designs and the results are shown in Table 1 below. From this table it can be observed that meters with only single paths in each chordal plane, whether all in the same angled plane with respect to the pipe axis, or in a non-planar criss-crossing arrangement, only cope properly with one particular form of symmetrical swirl. With the addition of a second crossing path at each of the top two chordal planes, the 6-path arrangement is able to cope with both forms of symmetrical swirl but still has problems with asymmetric swirl patterns. However, it is only when a second crossing path is added to each of the chordal planes, and every crossed pair works together to cancel the effects of swirl, that the meter design is able to cope with swirl of any form.

Table 1 Ability of chordal path configurations to correct for different forms of swirl

	4 paths, 4 chords, planar	4 paths, 4 chords, non-planar	5 paths, 5 chords, non-planar	6 paths, 4 chords, two crossed chords	8 paths, 4 chords, four crossed chords
					
	✓	✗	✓	✓	✓
	✗	✗	✗	✗	✓
	✗	✓	✗	✓	✓
	✗	✗	✗	✗	✓

The ability of the 8-path configuration to cope with a wide variety of disturbed installation conditions has been evaluated in numerous analytical, computational and laboratory studies by the meter manufacturers and third parties. In circular pipes both ORE/Accusonic and Westinghouse deployed 8-path meters with pairs of crossed paths in each of four chordal planes from around 1980. These meters were designed to be inherently insensitive to the swirl and cross-flow that exists in applications where flow conditioning was not practical. Caldon, as successor to Westinghouse, having acquired the LEFM technology from Westinghouse in 1989, then went on to use the 8-path concept in high accuracy liquid meters first in nuclear applications and later for liquid hydrocarbon custody transfer. As a result of this heritage there is a wealth of data validating this design in a wide range of hydraulic configurations, including almost 100 meters for nuclear plants that have been calibrated in a grand total of more than 400 installation configurations.

In Caldon 8-path meters, a crossed pair of paths is located in each of four chordal planes, those chordal planes being located in accordance with the Gaussian integration methods described in the original Westinghouse patents. The four chord selection made by Westinghouse was based on extensive research and although further gains could be made by adding more chords, others have also concluded that a four-chord integration is sufficient to obtain an appropriately small error in integration of the axial velocity profile.

A recent paper by Zanker and Mooney [10] re-examined the choice of the number of chords from the perspective of velocity profile integration in fully developed and asymmetric flows. The analysis is broadly in line with earlier work carried out by Westinghouse and others, and the conclusion the authors appear to reach is that increasing the number of chords beyond four is of questionable value when it comes to obtaining a representative average of the axial velocity profile. However, although the Zanker and Mooney paper discusses fully developed, distorted asymmetric and symmetric axial flow profiles and factors such as the effect of steep velocity gradients and transducer cavity effects, it neglects to examine the effects of swirl or transverse flow and gives these only a passing mention. The paper opens with a discussion involving a 32-path meter design and states later that eliminating the need for a flow conditioner would be an advantage. In the absence of a discussion of non-axial flow there is a risk that the reader could assume that the authors have concluded that increasing the number of *paths* brings little benefit. Adding paths arbitrarily does not necessarily bring a benefit but doing it in a particular way to address a problem using a first-principles approach is different. The purpose of the additional paths in the 8-path design is to cancel the unwanted effects of non-axial flow and allow the numerical integration method to properly do its work of evaluating the mean velocity. Accounting for that fact, the Zanker and Mooney paper is in fact supportive of the 4-chord integration method employed in the 8-path meter.

3 THE 8-PATH CHORDAL GAS ULTRASONIC METER

The 8-path ultrasonic gas flow meter used for the tests we describe here was a Caldon LEFM 380Ci. The Caldon brand covers a family of ultrasonic meters manufactured by Cameron with heritage directly from the Westinghouse multipath Leading Edge Flow Meters first developed in the late 1960's.

The arrangement of paths adopted for the Caldon LEFM 380Ci ultrasonic gas custody transfer meter is similar to that used in Caldon 8-path liquid meters, with the exception that a steeper path angle is used to allow for the effects of high Mach numbers. As illustrated in Figure 5 below, the meter employs 16 transducers to form eight measurement paths which are grouped in crossed pairs of paths at each of the chordal locations associated with the 4-chord Gaussian integration method.

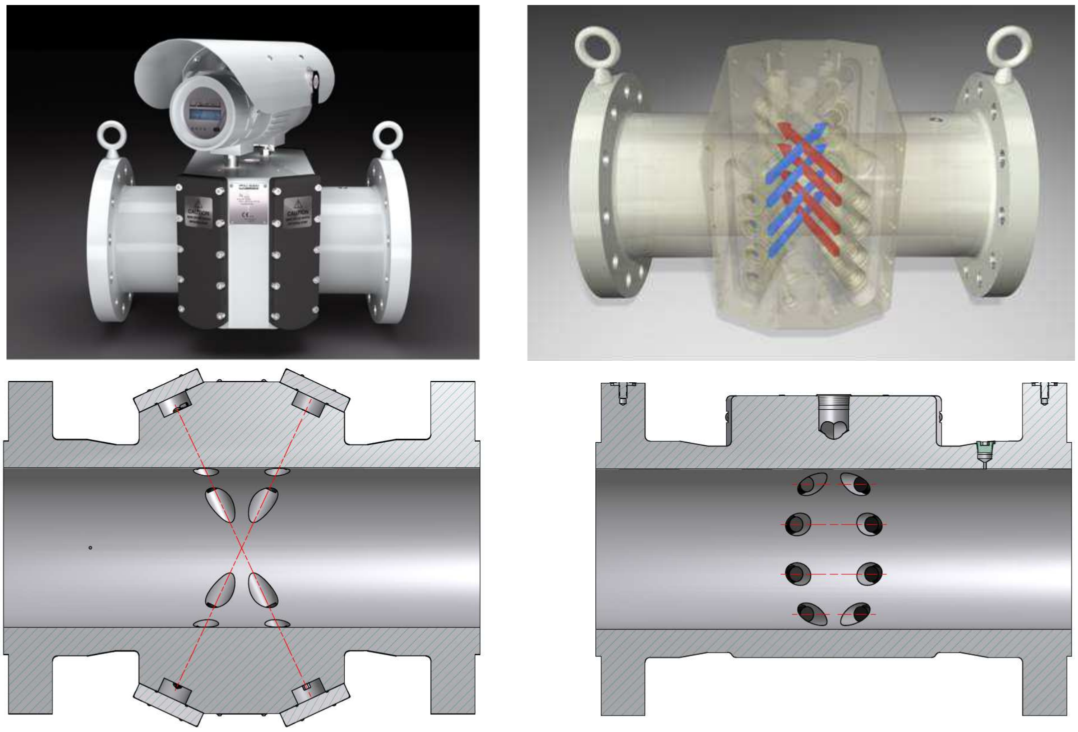


Figure 5 An illustration of the path layout in the 8-path Caldon LEFM 380Ci

When introducing the LEFM 380Ci product for gas custody transfer, three steps were taken in an effort to advance the technology in some of the areas where it had previously been lacking in gas meters.

First, the adoption of the 8-path configuration previously described was seen as a necessary step to enable the meter to perform with high accuracy without the need for a flow conditioner. Eliminating the flow conditioner would not only reduce energy losses, but would also allow metering stations to be reduced in size, and remove the requirement for maintenance of the flow conditioner and the frequently reported problem of partial blockage.

Secondly, the meter body and transducers were designed such that each transducer capsule is placed in a metal alloy housing that is integrated into the meter body and fully isolates the transducer from the process fluid and pressure. This not only results in a very robust transducer by eliminating failure modes associated with aggressive chemical components or rapid depressurisation, it also means that, if necessary, the transducer can be easily removed and replaced without requiring depressurisation of the line. Each metal alloy transducer housing is fully pressure retaining and all work required to replace the transducer is done on the low pressure side. There is no breach of the pressure boundary and therefore no special extractor tools are required; transducer replacement can be performed quickly and safely.

A third enhancement is provided in the form of a proprietary coating that is applied to the inside of the meter to inhibit corrosion and reduce contamination build up inside the meter body. The coating is applied to the bore of the meter and to the wetted surfaces of the transducer housings. The obvious aim here is to minimise changes to the interior of the meter that would otherwise result in changes to its calibration over time.

4 TYPE TESTING TO INTERNATIONAL STANDARDS

In order to be accepted for use in custody transfer applications, it is necessary that ultrasonic gas meters comply with the requirements of the relevant standards. In this case the relevant standards under consideration are AGA9 (2007) [11], ISO 17089-1 (2010) [12] and OIML R137 - 1&2 (2012) [13].

The above standards describe the performance expectations that have been set for gas ultrasonic meters for custody transfer applications. In terms of installation effects, AGA9 requires that the "manufacturer shall ... recommend at least one upstream and downstream piping configuration without a flow conditioner or one configuration with a flow conditioner, as directed by the designer/operator, that will not create an additional flow rate measurement error of the meter of more than 0.3% due to the installation configuration. This error limit should apply for any gas flow rate between qmin and qmax. This recommendation shall be supported by test data."

ISO 17089-1 prescribes a series of disturbance tests that are intended to cover a range representative of the type of conditions that may be encountered in practice. These include a single bend, out-of-plane bends, contractions, expansions and steps. The manufacturer is allowed to specify the length between the meter and the disturbance at which the meter will be tested, and then the meter should be tested at that distance and at a second distance that is ten pipe diameters further away. The requirement in ISO 17089-1 is that above qt, all calculated mean additional errors shall be within 0.3 %. For ISO 17089-1, the tests have to be performed at one flowrate below qt and two flowrates above qt. In addition to the installation tests, ISO 17089-1 requires that tests should be performed to evaluate repeatability, reproducibility, the effect of transducer change out and simulated transducer failure. The general performance requirements in ISO 17089-1 are very similar to those required by AGA9.

A new edition of OIML R137 was issued in 2012. Although the 2012 edition has been partly harmonised with ISO 17089, some differences remain, not only in terms of the tests required, but also in the evaluation criteria by which the flow meter is deemed to pass or fail. Unlike the other standards, OIML R137 allows classification of the meter performance to different levels, the most demanding being Accuracy Class 0.5. In terms of the installation effect testing, the test configurations have a large degree of overlap with those in ISO 17089-1, but for OIML the requirement is that "the shift of the error due to these disturbances shall not exceed one third of the maximum permissible error"; which means in the case of Accuracy Class 0.5 the shift of the error should be within +/- 0.167 %, which is approximately half that allowed by AGA and ISO.

In addition to the general requirements of these standards, and the flow tests mentioned above, the standards also require a series of 'environmental' tests be performed to ensure the that metrological characteristics of the meter are immune to factors such as radio frequency interference, damp heat, vibration and surges on electrical supply lines.

For the 8-path meter a comprehensive test programme jointly prepared by Cameron and NMi, the weights and measures authority of the Netherlands was performed to cover the type testing requirements of the ISO and OIML standards, with minimum duplication.

The flow testing was performed at the CEESI high pressure natural gas calibration facility in Iowa, USA and Euroloop in the Netherlands. All tests were witnessed by NMi as a notified body (issuing authority) for the type approval of gas meters according to the requirements of OIML and the European Measurement Instruments Directive (MID).

The results of the flow tests were described in detail at the 2013 AGA Operations Conference [5] and will only be selectively summarised here.

The tests were performed with three different upstream pipe arrangements between the prescribed disturbance and the meter: 5D of straight pipe with no flow conditioning, 15D of straight pipe with no flow conditioning, and an arrangement where the disturbance was followed by 5D then a CPA 50E perforated plate flow conditioner then a further 10D before the meter, as illustrated in Figure 6 below.

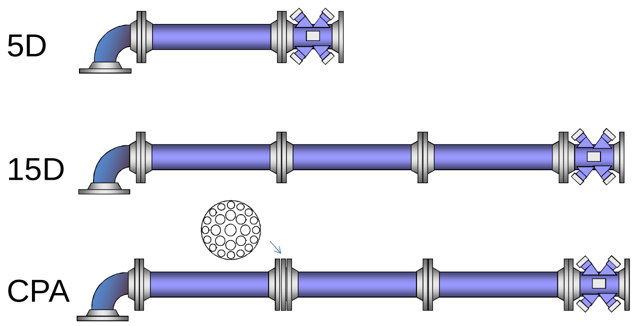


Figure 6 An illustration of the 5D, 15D and 5D-CPA-10D upstream pipe configurations

As explained previously the 8-path meter comprises two planar sets of 4 paths with the paths set at the same chordal heights as in a 4-path design. By making a selection of only some of these paths it is therefore possible to use the 8-path meter to evaluate other path arrangements such as a single-plane 4-path arrangement (Westinghouse) or a 4-path criss-crossing arrangement (BG). Figure 7 shows the path arrangements that were evaluated; Plane A and Plane B being of the Westinghouse type, BG1 and BG2 being of the British Gas type. In all these evaluations, the abscissa (path chordal heights/locations) and weighting factors were the same as prescribed by the 1976 Westinghouse patent [2] and later adopted by BG [3] and others.

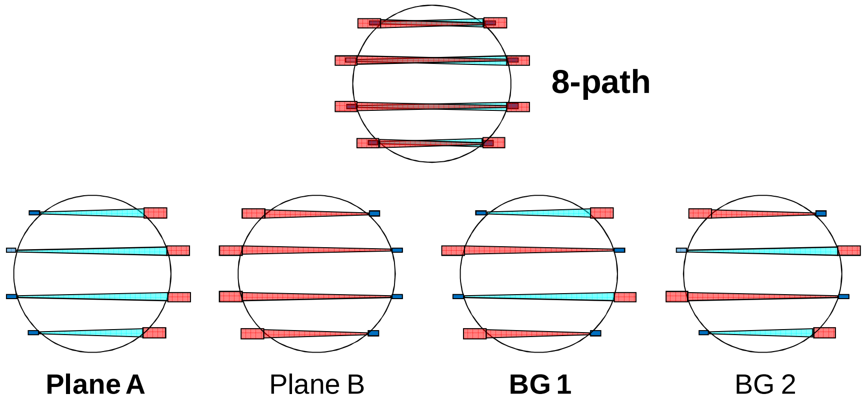


Figure 7 4 and 8-path configurations selected for evaluation

Arguably the most important of the tests prescribed by ISO17089-1 and OIML R137 are those downstream of single and double bends as they are broadly representative of a range of typical piping configurations. The results of the installation effect tests downstream of bends were summarised in the 2013 AGA paper in terms of the shift in the flow weighted mean error (FWME) relative to the straight pipe baseline calibration of the same meter configuration. That method of summarising the results is the same as was used for the data from the GERG and GRI projects referred in section 2 and enables comparison of different installation/meter combinations on the basis of a single number.

The FWME summary of the data obtained with the Caldon meter in both 4-path and 8-path format is reproduced in Table 2 below. For each meter type and upstream meter run arrangement (i.e. 5D, 15D, CPA), the outer extremes of error shift have been highlighted. This table clearly shows that the flow weighted mean error shifts are lowest for the 8-path meter at +/- 0.08% or less and are typically around one third of the 4-path planar arrangement. The 4-path non-planar arrangement produces the largest flow weighted mean error shifts, typically around 4 or 5 times greater than the 8-path meter, but larger still in the 5D configuration. In terms of the flow weighted mean errors, the benefit for the 4-path meters when moving from 5D to 15D and then including the CPA flow conditioning plate is fairly clear, but the improvement for the 8-path meter is not very significant, showing the extremes of +/- 0.06 at 5D reducing to a range of -0.04 to +0.06 % in the 5D-CPA-10D case.

Table 2 Bend summary data in terms of FWME shift for 4 and 8-path meters

Flow Weighted Mean Error Shift			8-path meter	Planar 4-path (Westinghouse)		Non-planar 4-path (British Gas)	
Disturbance	Upstream	Path orientation		A	B	1	2
Single Bend	5D	Horizontal	**0.06%**	-0.08%	**0.21%**	1.02%	-0.90%
		Vertical	0.03%	0.00%	0.07%	-0.86%	0.93%
Double Bends		Horizontal	0.02%	-0.10%	0.15%	**1.17%**	**-1.12%**
		Vertical	**-0.06%**	**-0.26%**	0.14%	0.45%	-0.57%
Single Bend	15D	Horizontal	**-0.08%**	-0.04%	-0.13%	0.30%	-0.46%
		Vertical	-0.05%	-0.02%	-0.08%	**-0.61%**	**0.51%**
Double Bends		Horizontal	**-0.05%**	**-0.24%**	**0.13%**	0.09%	-0.20%
		Vertical	-0.08%	-0.06%	-0.11%	-0.12%	-0.05%
Single Bend	5D - CPA - 10D	Horizontal	-0.02%	-0.06%	0.02%	-0.12%	0.07%
		Vertical	**-0.04%**	-0.01%	-0.07%	**-0.14%**	0.06%
Double Bends		Horizontal	0.03%	-0.05%	0.11%	-0.11%	**0.17%**
		Vertical	**0.06%**	**-0.08%**	**0.20%**	0.12%	0.00%

Perhaps the most important finding when looking at the data in Table 2 is that even when a flow conditioner is used the 4-path meters show FWME shifts that are larger than the results obtained with the 8-path meter at 5D with no flow conditioner, as illustrated graphically in Figure 8 below.

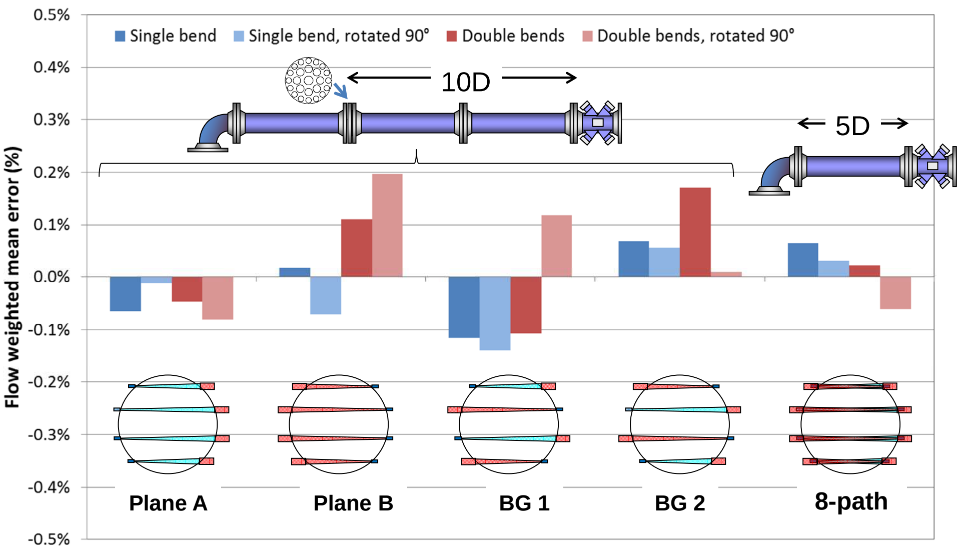


Figure 8 FWME performance comparison for the 8-path meter at 5D with no flow conditioner versus the 4-path meters with 15D inclusive of flow conditioning

Given the fact that ultrasonic meters are commonly used today with flow conditioners, and that this is often put forward as 'best practice', the results shown in Figure 8 may challenge some preconceptions about using meters with or without flow conditioners. It is mainly practical experience that has brought about the common usage of flow conditioners, and that experience is valid, but it is valid only for the meter designs on which that experience is based.

The fact of the matter is that while flow conditioners do reduce non-axial flow velocities, they do not completely eliminate them. What the data presented in Figure 8 shows is that as the 8-path meter is designed to do a first-principles cancellation of non-axial flow, it fares better than a meter design that is adversely affected by non-axial flow, even when the latter is used with a flow conditioner.

Rather than relying solely on the 4 and 8-path data obtained with the Caldon meter, this can be validated by comparing the 8-path results with the data published from the GRI and GERG research progammes. The GERG and GRI results took the most commonly used ultrasonic meters of the day and tested them downstream of bends in configurations similar to those described in the previous section.

Both the GRI and GERG projects selected multipath ultrasonic meters from the same three manufacturers and included single bend and double bend out-of-plane configurations in their tests. The meters were a 4-path chordal design, a 6-path chordal design and a meter with reflected paths which was a 5-path version of the meter for the GRI tests and a 4-path version for the GERG tests. The GRI tests were conducted on 12-inch meters at SwRI whereas the GERG tests were conducted on 8-inch meters at the Advantica (now DNV GL) facility in the UK. The results were summarised in terms of the flow weighted mean error (FWME) shift relative to the calibration baseline, in the same way as was done to produce the data in Table 2 and Figure 8.

The shortest length of upstream pipe without flow conditioning was 10D in the GRI tests and 12D in the GERG tests. Figure 9 below compares the FWME results from the GRI and GERG projects with the 8-path data, all without flow conditioning. It can be observed that for 10 and 12 D without a flow conditioner the GRI and GERG results are typically in the range of +/- 0.5 to 1 % whereas for the 8-path meter the results are less than +/- 0.06 % for 5D and no flow conditioner.

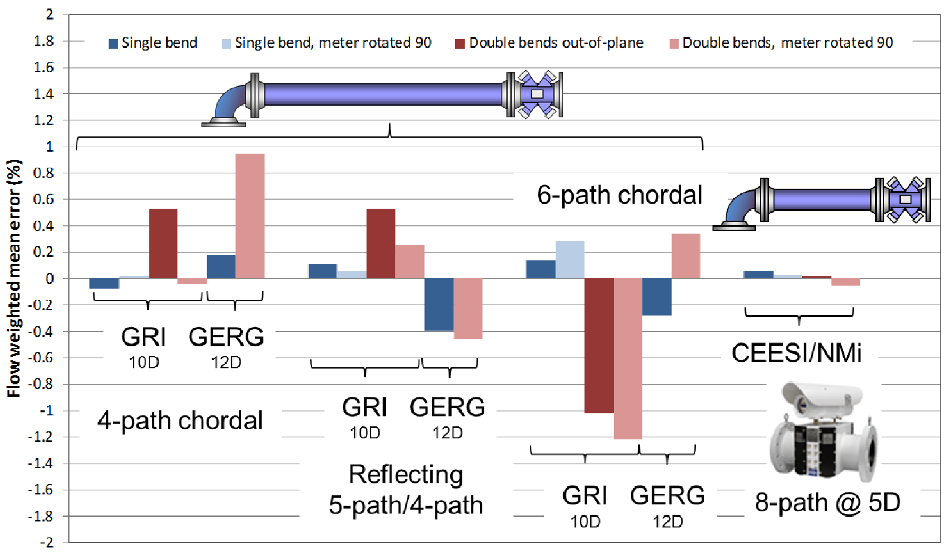


Figure 9 Comparison of 8-path meter at 5D vs GRI and GERG results at 10 and 12 D

Both the GRI and GERG projects also included results where they tested the meters first in straight pipe with a CPA flow conditioner at a distance of 10D from the meter, and then downstream of the disturbance with the 10D location of the conditioner relative to the meter unaltered. Figure 9 below compares the FWME results from the GRI and GERG projects with the 8-path data. It can be observed that although the magnitude of error in the GRI and GERG results is reduced with the CPA plate, they are typically in the range of +/- 0.3 to 0.6 %, still much larger than for the 8-path meter with 5D and no conditioner at +/- 0.06 %.

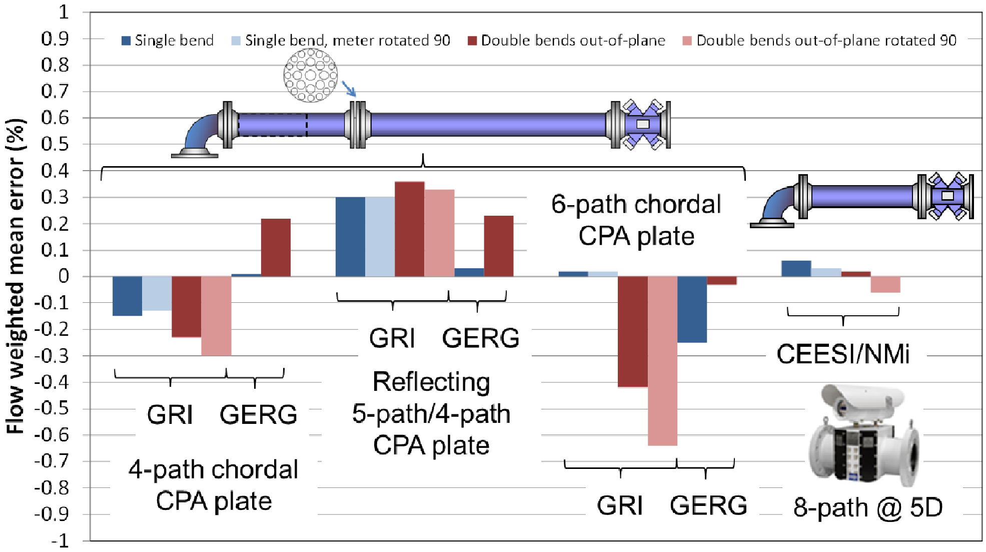


Figure 10 Comparison of 8-path meter at 5D with no flow conditioner Versus GRI and GERG results with CPA conditioner

Although the GRI and GERG data is now a little bit dated, the conclusions that with respect to path configuration still apply, and are consistent with the magnitude of installation effects observed in much more recent testing such as the NAFFMC data reported in 2013 [14].

5 RESULTS FROM USM TESTS WITH A PTB DISTURBANCE PLATE

Prior to the tests that are described in Section 6 qualification testing was carried out on behalf of GazProm at the GL test facility in Bishop Auckland in the UK using a PTB disturbance plate. Although no official report of these tests has been published, results purporting to be from these tests have been presented/reported by one of the participating manufacturers at a number of flow measurement workshops [15 - 17]. If the results are to be taken at face value, they make startling reading.

Five well-established manufacturers of gas ultrasonic meters are reported to have participated in the test. The meters were first calibrated in close to ideal conditions, at approx. 28 diameters downstream of a Zanker flow conditioner. Then they were tested with a PTB disturbance plate upstream, with the same straight length of approx. 28 D of straight pipe in between the meters and the disturbance plate.

Only one meter is reported to have performed within +/- 1 % of the baseline calibration when subjected to the flow 28D downstream of the PTB disturbance plate. Two meters are reported to have performed within +/- 2.5 % of baseline and one within 5 %. The fifth meter is reported to have performed with errors of more than 15 %. Experience and common sense would tend to suggest something must have gone badly wrong with the fifth meter to produce errors of that magnitude, but on the other hand, errors in the range of 2.5 and 5 % for the others show that most of the meters were struggling, suggesting that the flow conditions created by the PTB disturbance plate are the common cause.

Whilst these results need independent verification, the suggestion that *any* hydraulic disturbance introduced 28 diameters upstream of a straight pipe section could affect the majority of these meters in such as way as to result in errors of more than 1 % is rather alarming.

The primary claim for the 8-path Caldon LEFM 380Ci is its insensitivity to swirl and distortion of the flow profile. As a late entrant into the running as a potential supplier to GazProm it was therefore necessary for Cameron to submit the 8-path meter to a separate test using a PTB disturbance plate to create the adverse flow conditions. These tests are now described.

6 TESTING THE 8-PATH METER WITH THE PTB DISTURBANCE PLATE

The testing of the 8-path meter with the PTB disturbance plate was carried out at Euroloop using a 12-inch Caldon LEFM 380Ci. The testing was conducted and reported by NMi Euroloop and witnessed by GazProm. The PTB disturbance plate was supplied directly to Euroloop by PTB on instruction from GazProm. The PTB disturbance plate is a thick plate device with an asymmetric distribution of holes, with the holes also made at an angle relative to the face of the plate, such that an asymmetric, swirling profile is produced downstream of the plate. Details of the swirl and velocity profile distortions produced by a PTB disturbance plate have been reported by Pereira et al at 2003 Flomeko conference [18]. A photograph of the PTB disturbance plate used in the Euroloop tests of the 8-path meter is shown in Figure 11 below.

Figure 11 A photograph of the PTB disturbance plate

The tests were conducted at a nominal line pressure of 60 bar gauge. The test points were selected by GazProm and are shown in Table 3 below.

Table 3 Plan of test points

Flow rate m3/hr	Velocity m/s	Velocity ft/s	Baseline calibration repeats	Verification repeats	PTB plate at 10D repeats	PTB plate at 5D repeats	PTB plate at 30D repeats
6700	28.4	93.1	10		10	3	3
5000	21.2	69.5	3	3	3	3	3
4000	17.0	55.6	3		3	3	3
3000	12.7	41.7	3		3	3	3
360	1.5	5.0	3	3	3	3	3
130	0.6	1.8	3		3	3	3

The baseline test was conducted with 30 diameters of straight pipe of 12-inch diameter upstream of the meter, and without any flow conditioning in the 12-inch section. The baseline calibration was performed prior to any meter factor adjustment being made in the meter's electronics, i.e. the meter was set up based on the factory 'dry calibration' measurements alone. Following completion of the baseline calibration, the internal meter factor table was updated. The adjustment was applied using a linear piecewise interpolation of the average meter factor data versus flowrate from the baseline calibration. Following the input of the meter factor data, verification points were run at 360 and 5000 m^3/hr.

The results of the baseline calibration are shown in Figure 12 below. It can be observed that the baseline performance of the meter satisfies all of the ISO 17089 (Class 1) and AGA9 requirements for meters of greater or equal to 12-inch size, namely:

- Maximum permissible errors < 0.7 % for velocities greater than 1.5 m/s
- Maximum permissible errors < 1.4 % for velocities less than 1.5 m/s
- Maximum peak-to-peak error < 0.7% for velocities greater than 1.5 m/s
- Repeatability within +/- 0.2 % of measured value for velocities greater than 1.5 m/s
- Repeatability within +/- 0.4 % of measured value for velocities less than 1.5 m/s

For the 10 repeat points at the highest flowrate, the repeatability can be characterised by the standard deviation of the meter factors, which was 0.026 %.

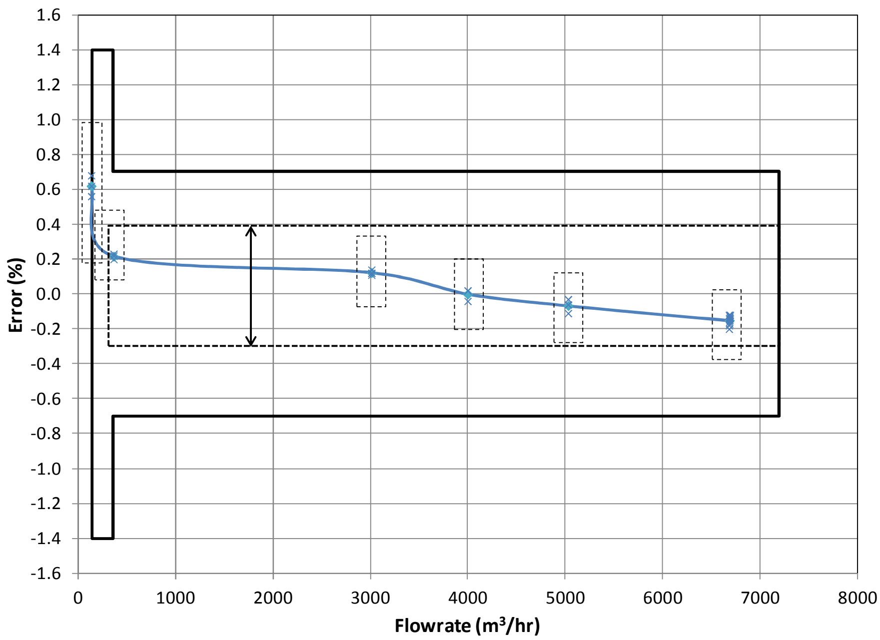


Figure 12 Baseline calibration results

The post adjustment verification points are shown in Figure 13 below. It can be observed that all of the verification points are within 0.1 % of the Euroloop reference standard.

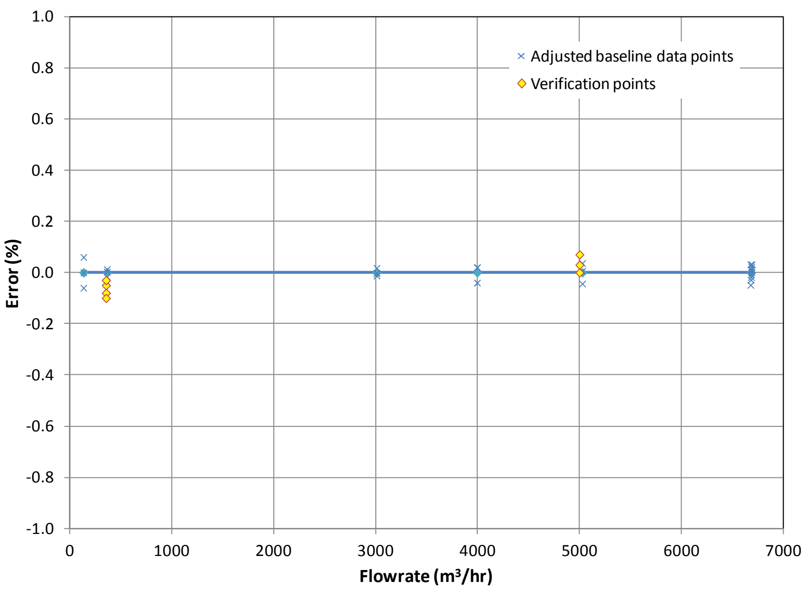


Figure 13 Meter factor adjustment and verification points

Following the verification test, the PTB disturbance plate was installed at 10 diameters upstream of the meter. This distance was selected as a nominal starting distance at which to observe the response of the meter to the asymmetry and swirl generated by the PTB plate.

Figure 14 below shows the results of the meter installed at 10 diameters downstream of the PTB disturbance plate with no flow conditioning between the disturbance plate and the meter. In this case it can be observed that the average errors range from -0.07 to 0.14 %.

For the 10 repeat points at the highest flowrate, the repeatability can be characterised by the standard deviation of the meter factors, which was 0.037 %.

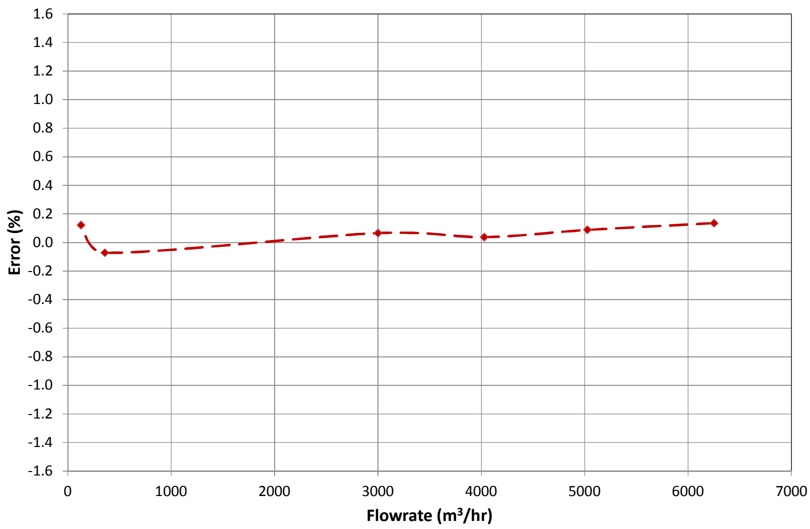


Figure 14 Results at 10 D from the PTB disturbance plate with no flow conditioning

For the second disturbance test the PTB plate was move closer such that it was only 5 diameters upstream of the meter. This distance was selected as it is equal to the minimum upstream straight length recommendation for installation of the 8-path meter downstream of pipe bends.

Figure 15 below shows the results of the meter installed at 5 diameters downstream of the PTB disturbance plate with no flow conditioning between the disturbance plate and the meter. It can be observed that the average errors are within +/- 0.16 % at flowrates greater than Qt and the error is 0.22 % at Qmin. It was observed during the maximum flowrate conditions of this test that, on average, the signal-to-noise ratio values reported by the meter were reduced to around half of their normal values.

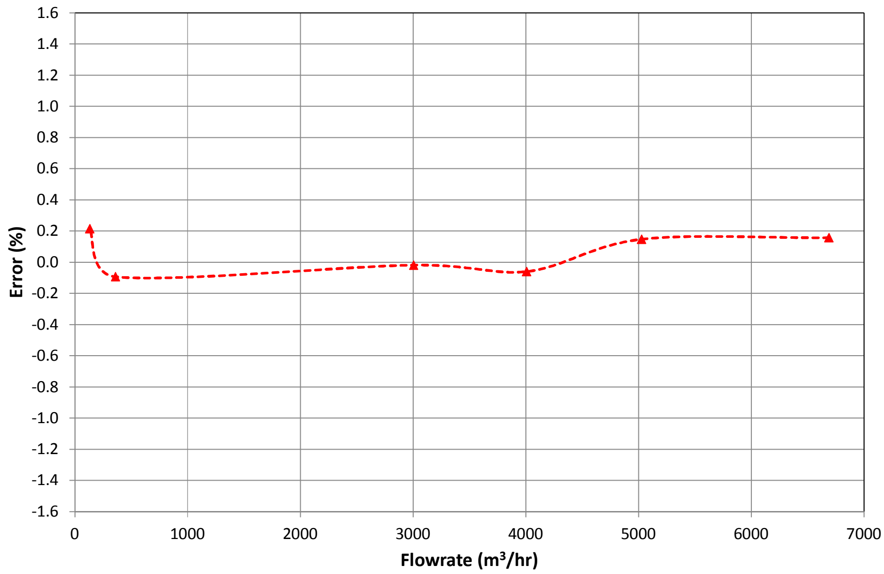


Figure 15 Results at 5 D from the PTB disturbance plate with no flow conditioning

For the third disturbance test the PTB disturbance plate was installed at 30 diameters upstream of the meter. This distance was selected as it is typical of the upstream lengths applied in the custody transfer metering systems of GazProm. A 30D length is used by GazProm as they do not employ flow conditioners in their ultrasonic custody transfer metering systems for gas.

From Figure 16 it can be observed that the average errors are within +/- 0.2 %. One might expect that relative to the results at 5D and10D, the 30D results would show smaller errors. However, as the diagnostic analysis in the following section shows, the degree of profile distortion and swirl still present at 30D is still very significant.

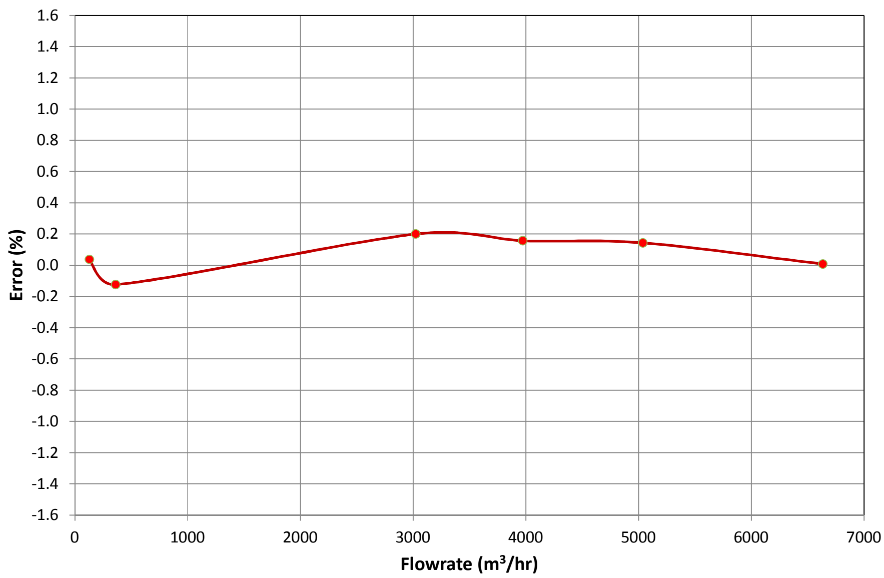


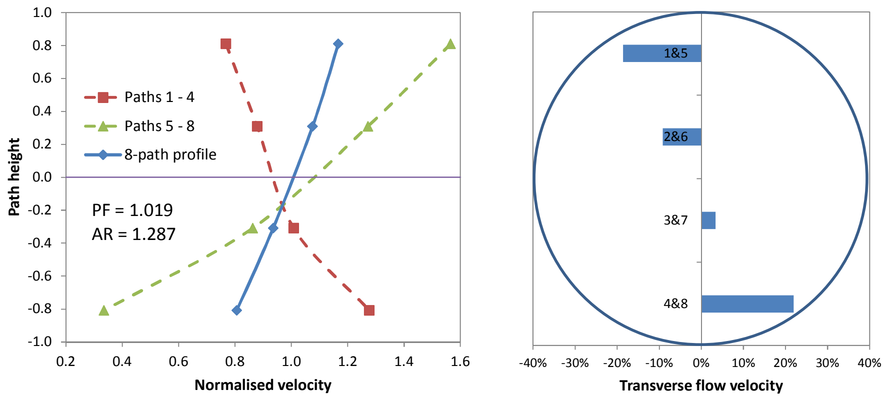
Figure 16 Results at 30 D from the PTB disturbance plate with no flow conditioning

7 VELOCITY PROFILE DIAGNOSTICS

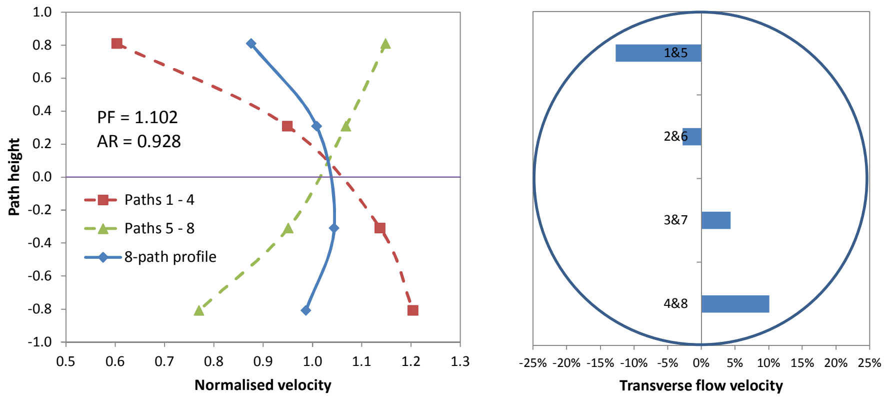
Figure 17 below shows the averaged velocity profile diagnostics recorded by the 8-path meter. As described in a paper presented at the 2014 AGA Operations conference [19], the 8-path meter has powerful velocity profile diagnostic capabilities that enable calculations of non-axial flow as well as accurate determination of symmetry and flatness without requiring flow conditioning. A fuller discussion of diagnostics can be found in the referenced paper. In Figure 17, the left hand plot shows the individual path velocity indications and the 8-path average profile along with numerical values of the asymmetry ratio (AR) and profile factor/flatness (PF). The right hand plot shows the calculated non-axial or transverse flow velocities as a percentage of the mean axial flow velocity. Note that the scaling used for the 5D graphs in Figure 17(a) is different to that used for the 30D graphs in Figure 17(b).

What is interesting to note here is the very severe degree of profile distortion and swirl generated by the PTB disturbance plate. The results show that there is still a significant amount of profile distortion and swirl at 30D downstream of PTB the disturbance plate. When compared in terms of the asymmetry ratio (AR), the value of 1.287 for the PTB disturbance plate at 5D (i.e. an asymmetry of approx. 29 %) is greater than anything observed when the 8-path meter was placed at 5D downstream of the disturbances prescribed by ISO 17089 and OIML R137. At 5D downstream of the severe OIML R137 disturbance which comprises two out-of-plane bends with a half-moon plate between them, the asymmetry registered was only 1.15 or 15 %. Likewise when the 8-path meter was moved further away from the OIML R137 severe disturbance, the asymmetry reduced to 1.03 or 3 % at 15D. In the case of the PTB disturbance plate the asymmetry parameter at 30D was 0.928, or roughly 7 %.

These diagnostic indications, particularly the large magnitude of asymmetry observed, tend to suggest that the PTB disturbance plate creates a very high degree of velocity profile disturbance. This severity of disturbance could explain the unusually high errors from the earlier tests that were discussed in section 5 of this paper.



(a)



(b)

Figure 19 Velocity profile diagnostics at (a) 5 D and (b) 30 D downstream of the PTB disturbance plate

8 CONCLUSIONS

The results that have been presented in this paper show that the 8-path chordal meter design is highly tolerant of swirl and velocity profile disturbances introduced upstream of the meter. Performance to the requirements of OIML R137 Accuracy Class 0.5 can be achieved downstream of bends with only 5D of straight pipe and no flow conditioning.

Qualification tests mandated by GazProm were carried out at Euroloop using a disturbance plate designed and provided by PTB to create adverse conditions in terms of swirl and velocity profile distortion. The 8-path meter performed to within +/- 0.2 % without flow conditioning over a range of distances from 5D to 30D downstream of the PTB disturbance plate. These results compare very favourably with previously reported results describing large errors incurred by ultrasonic meters tested at approximately 28 diameters downstream of a PTB disturbance plate.

Analysis of diagnostic data shows that the PTB disturbance plate produces a strongly swirling flow. Furthermore, the observed magnitude of asymmetry was worse than that observed downstream of the OIML R137 severe disturbance test that uses two out-of-plane bends with a half-moon plate between them. This suggests that the PTB disturbance plate does indeed create conditions that are more severe than would be expected in typical custody transfer piping arrangements.

9 REFERENCES

[1] Malone, J T and Whirlow, D K (1971) Fluid Flow Measurement System, US Patent no. 3,564,912, Assignee: Westinghouse Electric Corporation, Filed Oct 1968, Issued, Feb 1971

[2] Wyler, J S (1976) Fluid Flow Measurement System for Pipes, US Patent no. 3,940,985, Assignee: Westinghouse Electric Corporation, Filed April 1975, Issued, March 1976

[3] O'Hair, J and Nolan, M E (1987) Ultrasonic Flowmeter, US Patent no. 4,646,575, Assignee: British Gas Corporation, Filed July 1986, Issued, March 1987

[4] Zanker, K J and Mooney, T (2013) "Celebrating quarter of a century of gas ultrasonic custody transfer metering" Presented by M Schlebach at the 2013 European Ultrasonic User's Workshop, Lisbon, Portugal, April 2013

[5] Brown, G J, Freund, W R, and McLachlan, A (2013) "Testing of an 8-path ultrasonic meter to international standards with and without flow conditioning" AGA Operations Conference, 21 – 24 May 2013

[6] Zanker, K J (2000) "Installation effects on single and multipath ultrasonic meters" Flomeko, Salvador, BRAZIL, June 04-08, 2000

[7] Delenne, B et al (2004) "Evaluation of flow conditioners – ultrasonic meter combinations", North Sea Flow Measurement Workshop, St. Andrews, Scotland, October 2004

[8] Grimley, T A (2000) "Ultrasonic Meter Installation Configuration Testing," AGA Operations Conference, 7 – 9 May 2000, Denver, Colorado

[9] Lowell, FC (1977) "The design of open channel acoustic flowmeters for specified accuracy: sources of error and calibration test results" Flow measurement in open channels and closed conduits, NBS Special Publication 484, Vol. 1

[10] Zanker K J and Mooney, T (2013) "Limits on achieving improved performance from gas ultrasonic meters and possible solutions" North Sea Flow Measurement Workshop, St. Andrews, Scotland, October 2013

[11] AGA9 (2007) Measurement of Gas by Multipath Ultrasonic Meters

[12] ISO 17089-1 (2010) Measurement of fluid flow in closed conduits - Ultrasonic meters for gas - Part 1: Meters for custody transfer and allocation measurement

[13] OIML R137 - 1&2 (2012) Gas meters - Part 1: Metrological and technical requirements - Part 2: Metrological controls and performance tests

[14] Hanks, E and Miller, R (2013) "Installation Testing NAFFMC Research", CEESI Ultrasonic Meter Users Workshop, Denver, 2013

[15] Drenthen, J G (2011) "Installation Effects on Ultrasonic Flowmeters", CEESI Ultrasonic Meter Users Workshop, Bolivia, November 2011

[16] Drenthen, J G, Kurth, M, Vermeulen, M and Hollander, H d (2012) "Verschmutzung auf dem Prüfstand", KÖTTER Workshop Gasmengenmessung, March 2012

[17] Drenthen, J G (2012) "Installation Effects on Ultrasonic Flowmeters", CEESI Ultrasonic Meter Users Workshop, Kuala Lumpur, February 2012

[18] Pereira, G. M., Mickan, B., von Lavante, E. And Kramer, R. (2003) "Investigation of Flow Conditioning in Pipes", Proceedings of Flomeko, Groningen, Netherlands, May 2003

[19] Brown, G J and Freund, W R (2014) "Analysis of diagnostic data from an 8-path ultrasonic meter" AGA Operations Conference, Pittsburgh, 20 – 23 May 2014