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AN 8-PATH ULTRASONIC MASTER METER FOR OIL CUSTODY TRANSFERS

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Abstract: This paper describes an 8-path ultrasonic flow meter, with emphasis on how this meter can be used as a master meter with traceability to appropriate standards. In particular the paper describes the methodology whereby transit time measurements and calibration factors can be established in factory and laboratory tests and then verified in the field. Simulations of distorted and swirling flows, and supporting test results are used to demonstrate the insensitivity of the 8-path configuration to installation effects.

Keywords: ultrasonic, flowmeter, multipath, installation effects.

1. INTRODUCTION

Accurate measurement of the total mass or volume of fluid passed is an essential requirement for custody transfer of petroleum products such as crude and refined oils. An error in measurement can result in serious financial losses for either the buyer or seller. For example, at $60 per barrel a 0.1% error in a flow of 50,000 barrels per day would result in a loss of over $1,000,000 over the course of one year. This is what gives rise to the rigorous standards of accuracy and traceability that are applied to oil custody transfers.

Traceability is defined as a process whereby a measurement can be related to a standard via a chain of comparisons. Certain requirements apply:

- The standard must be acceptable to all parties with an interest in the measurement and is usually maintained by a national laboratory such as NIST in the USA, NPL in the UK or Inmetro in Brazil.
- The chain of comparisons must be unbroken, meaning that the field measurement must be connected by one or more links to the standard.
- Every link in the chain involves a comparison that necessarily carried with it an uncertainty. Hence the total uncertainty of the field measurement must account for the uncertainties in each link of the comparison chain.
- There can be no unverified assumptions in the chain of comparisons; clearly a quantitative assessment of each link is required in order to establish the uncertainty in that step.

For oil custody transfers, the required uncertainty for the field measurement is normally less than 0.25% of the total volume at standard conditions of temperature and pressure. In order to achieve such uncertainties in the field, it has been common practice to use a flow meter (normally a turbine meter) in combination with a volumetric transfer standard, commonly referred to as a 'prover'. The use of this type of equipment is well supported by written standards such as the API Manual of Petroleum Measurement Standards (MPMS) Chapters 4.8 and 5.3.

When a turbine meter is used as the primary flow measurement device for custody transfer, the volumetric prover is required in order that the calibration of the meter can be maintained when fluid properties change or if the meter characteristics change as a result of mechanical wear and tear. This ensures that the traceability chain for the measurement is unbroken but it comes at the cost of having to install and maintain the prover, which is an expensive and bulky piece of equipment.

Multipath ultrasonic flow meters can now achieve levels of accuracy that make them competitive with turbine meters. This has resulted in the recent publication of API MPMS Chapter 5.8 - Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters Using Transit Time Technology [1].

Ultrasonic meters possess some significant advantages over turbine meters, as they have no moving parts, are non-intrusive, and can be made to be insensitive to changes in fluid properties. The lack of moving parts and insensitivity to fluid properties creates the potential for use without a volumetric prover, which can result in a 10-fold reduction in the size and weight of the metering system. Obviously the benefits of this can be great, particularly on offshore platforms and floating production vessels.

If an in-situ prover is not available then great care must be taken to avoid introducing too much uncertainty in the transfer of the calibration of the meter from the lab to the field. The API MPMS recognizes this issue stating that "Laboratory proving is normally not preferred because laboratory conditions may not duplicate the operating conditions." However the standard also acknowledges that "While there are more measurement uncertainties associated with laboratory proving, under certain conditions, it may provide the best alternative."

2. TRACEABILITY OF AN 8-PATH ULTRASONIC FLOW METER

The algorithm and corresponding inputs and traceability requirements for a multipath ultrasonic flowmeter are outlined in this section.4

An 8-path ultrasonic flow meter is shown in Figure 1 below. This meter has 16 transducers comprising eight paths arranged in four chordal planes, each at ±45° to the axis of the pipe.

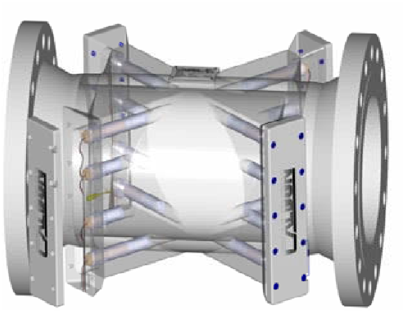

Fig. 1. A Caldon LEFM 280C 8-Path Ultrasonic Flowmeter

The volumetric flowrate Q, is given by the equation:

$$Q = k_h A \sum_{i=1}^{N} w_i \frac{L_i}{2\cos\theta_i} \frac{\Delta t_i}{t_{Ui} t_{Di}} \qquad (1)$$

where:

Q = is the volumetric flowrate (m^3/s)
k_h = the hydraulic calibration factor (or meter factor)
A = the area of the pipe (m^2)
w_i = a constant weighting factor for each path
L_i = the length of each path (m)
θ_i = the angle each path relative to the pipe axis (°)
Δt_i = is the transit time difference for each path (s)
t_{Ui} = is the transit time in the upstream direction (s)
t_{Di} = is the transit time in the downstream direction (s)
N = the number of paths

In the case of a Caldon meter the weighting factors, w_i, are defined by the rules of Gaussian numerical integration and remain constant. Traceability must be established and maintained for the other parameters, which are:

1) the meter dimensions,
2) the transit time measurements, and
3) the meter factor.

2.1. Meter Dimensions

The path lengths, L_i, path angles, θ_i, and pipe area, A, are established in the factory by traceable coordinate measuring machines. As a result the uncertainty in these measurements will be small. However, even though any errors in the measurements are small, they are also compensated when the meter is calibrated against a flow standard in order to determine the meter factor.

Given that the traceability of the dimensional parameters has been established via dimensional measurements and flow calibration, it is now important to consider how these could change in the field.

Temperature is one obvious variable that is not controlled in the field. In order to compensate for thermal expansion effects on the meter geometry, Caldon meters incorporate a traceable platinum resistance thermometer in the meter body. This is used to apply a thermal expansion correction to the relevant measurements. Pressure in oil custody transfer systems does not tend to be high enough to significantly affect the geometry of an ultrasonic meter.

Other changes to the geometry, such as reduction of the cross-sectional area, could occur as a result of fouling or deposition on the inside of the pipe. Chordal multipath ultrasonic meters offer the potential to detect deposition through the use of signal and flow diagnostics as discussed later in the paper.

2.2. Transit Time Measurements

The accuracy and traceability of the transit time measurements are obviously of critical importance in the operation the flowmeter. There are two important aspects to these measurements. The first is ensuring the accuracy of the clock against which the meter makes its time measurements. The second is ensuring that signal detection is being performed properly.

The accuracy of the master clock is assured by calibration against a traceable standard in the factory. To ensure that the calibration is maintained in the field the meter is provided with a second, independent clock which is continuously compared with the master clock. This secondary clock is also calibrated against a traceable standard.

Meeting the uncertainty requirements for the upstream and downstream transit time measurements is easy to achieve using modern electronics. The transit time measurements are compensated for non-fluid time delays in the electronics and cables by factory tests. The corrected time measurements can then be validated by filling the meter body with a know fluid, like water, and checking that the derived sound velocity (L_i/t_i) is within tolerance. Any small residual errors are then accounted for when the meter factor is determined. In the field the integrity of the individual upstream and downstream transit times in a multipath meter can be validated by comparing the sound velocity from individual paths with each other in turbulent single-phase flow conditions.

Errors in the transit time difference, Δt_i, can potentially be much more significant, as the value of Δt_i is much smaller than t_{Ui} and t_{Di}. In order to describe how these measurements are assured in Caldon meters it is necessary to provide a brief description of how the transit time signal detection is performed.

Each pulse that is transmitted is digitized and processed. The transit time measurement is made by detecting the zero-crossing after the first positive peak in the pulse waveform, as illustrated in Figure 2 below. The accuracy of this measurement can be affected by several factors, the most important of these being the level of noise embedded in the signal, and 'non-reciprocal' delays in the upstream and downstream transit times, which would alter the waveform shape. In order to ensure that these effects are within the limits necessary for custody transfer applications, the following continuous checks are performed by the meter.

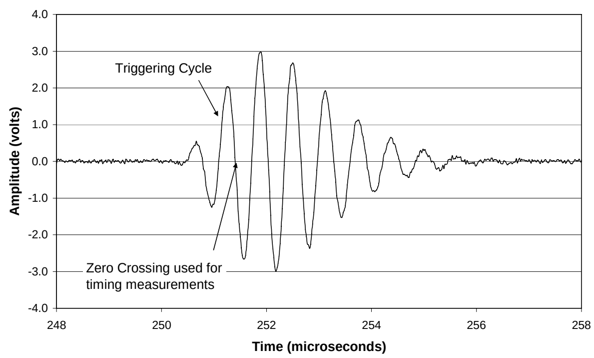

Fig. 2. A Typical Ultasonic Waveform

The magnitude of the noise is measured in the time window just preceding the arrival of the signal waveform and is used to confirm that the signal-to-noise ratio is above the acceptance limit. In addition to this, the shape of the upstream and downstream pulse waveforms are compared with one another to guard against the possibility of non-reciprocal delays. Furthermore, statistical tests are performed on batches of processed signals to ensure the assumptions of the uncertainty analysis remain valid.

2.3. The Meter Factor

Laboratory calibration of an ultrasonic flowmeter serves two important functions. The first is to ensure that the meter as a whole is functioning properly. The second is establish the meter factor. This meter factor is then used to correct for errors that are within the uncertainty limits of the factory calibration process and to account for incomplete assumptions in the theory of operation, particularly those related to hydraulic effects.

From the equation describing the principle of operation, it can be seen that the ultrasonic meter measures velocity on discrete paths and uses these velocity measurements to estimate the mean velocity over the cross-section. As a consequence, the accuracy of the flow rate measurement is a function of the fluid velocity distribution and the path configuration (meaning the physical arrangement of the paths as well as the weighting factors applied). For further details on the relative performance of different path configurations refer to Brown, Augenstein and Cousins [2].

Velocity distributions can vary in four different ways:

1) As a function of Reynolds number
2) As a function of wall roughness
3) By distortion of the axial velocity profile caused by upstream fittings such as bends or valves
4) By the introduction of non-axial flow components (swirl) by upstream fittings

The path configuration used in Caldon 4-path and 8-path flowmeters is, by design, relatively insensitive to the flow profile changes that occur as a result of changes in Reynolds number or pipe roughness. This can be demonstrated by modeling the performance of the path configuration using the well known power law for velocity profiles in a pipe. The meter factor for each meter design has been calculated for profiles with values of *n* of between 4 and 14. This covers a very wide range of application conditions, as it has been shown that *n* = 6 to *n* = 10 spans a Reynolds number range of 4,000 to 3,200,000 and pipes that are hydraulically smooth to pipes that are very rough [3]. The results are shown in Figure 3. It can be observed that for the Gauss-Jacobi integration schemes modeled that the lowest sensitivity to this type of profile variation is achieved when four chords are used (as in the Caldon 4-path or 8-path designs).

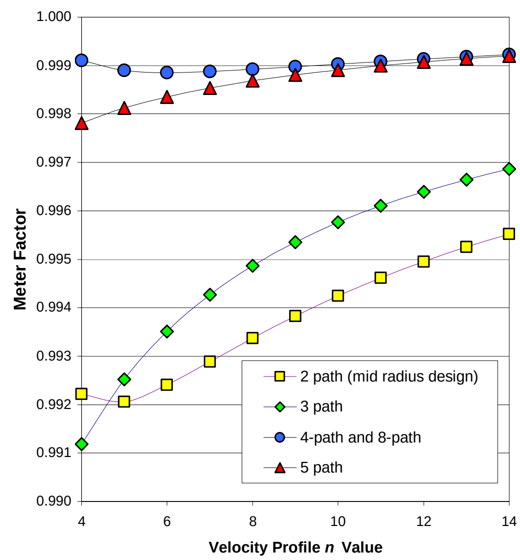

Fig. 3. Meter Factor Sensitivity for Different Numbers of Paths

In practice the meter factor/Reynolds number relationship for a multipath ultrasonic flowmeter can be determined by calibration and then entered into the meter's software. For custody transfer accuracy it is normally required that the calibration spans the whole operating range in terms of Reynolds number, which may mean that several different calibration fluids are used. Once completed, this 'characterization' process ensures that changes in Reynolds number do not affect the calibration of the meter.

When the flowmeter is transferred from the calibration lab to the field, there is the possibility that the traceability of the meter factor could be compromised by the effects of upstream bends and other pipe components on the velocity distribution in the pipe.

In practice it is common for distortion of the axial velocity profile and swirl to occur at the same time. However, in order to understand the effects of velocity distribution on the meter factor it is useful to study these two influences separately.

2.3.1. Distortion of the Axial Velocity Profile

The effects of distortion of the axial velocity profile on different meter designs can be evaluated by using asymmetric profiles described by a function in the form:

$$u = (1-r)^{1/n} + mr(1-r)^{1/k}\, f(\theta) \qquad (2)$$

The detailed methodology applied here is described in a paper by Moore et al [4] and examples of its use can be found in various published papers [e.g. 4 - 7].

The values of the parameters used in Eqn 2 for the profiles analysed in this paper are given in Table 1 below.

Table 1. Parameters for Distorted Velocity Profiles

Profile Id.	n	m	k	$f(\theta)$
C3	9	$\frac{0.02}{\pi}$	4	$(\theta^2-1)(1-\cos\theta)^2$
C5	7	0.34	9	$e^{-0.5\theta}\sin\theta$
C7	9	$\frac{1}{\pi^5}$	4	$\theta^2(2\pi-\theta)^2$
C8	9	$\frac{0.5}{\pi^2}$	4	$\theta(1-\cos^2\theta)$

As these profiles do not have rotational symmetry about the pipe axis, the performance of the design is assessed at a range of orientations relative to the profile, as illustrated in Figure 6 below.

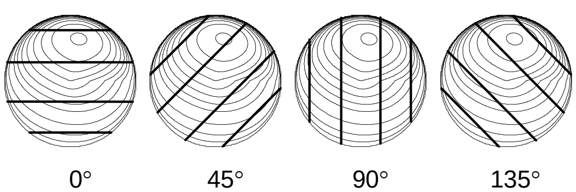

Fig. 4. An Illustration of Changing Path Orientation

This allows us to compute the meter factor for each profile at 0 to 180 degrees of rotation. The results of these computations are shown in Figures 5.

It can be observed that the meter factor for all of these profiles is close to the value of approximately 0.999 calculated for fully developed flow shown in Figure 3, and all results lie within a band of +/- 0.15%.

When there is no swirl present, the 4-path configuration used by Caldon in the LEFM 240C performs in the same manner as the 8-path LEFM 280C meter with respect to distortion of the axial velocity profile. The advantage of the 8-path design comes into play when swirl is present in the flow, as discussed below.

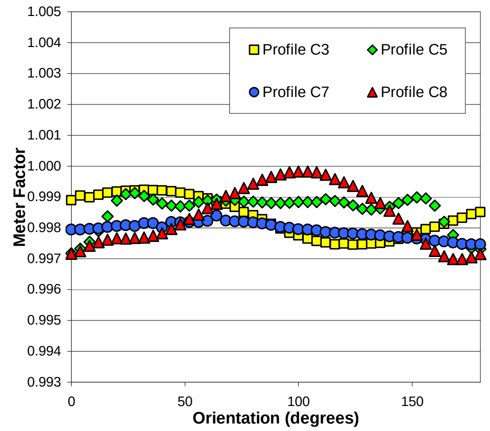

Fig. 5. Meter Factor for Four Distorted Profiles (meters with 4 chordal paths)

2.3.1. Swirl

Swirl interferes with the performance of ultrasonic meters by introducing an unwanted component of velocity in each measurement path. 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 provide some swirl compensation by having opposing paths on opposite sides of the pipe axis. That means that one path will compensate the other for the effect of the swirl, as illustrated in Figure 6 below. However, this is only completely effective if the swirl is a single-vortex swirl that is centered exactly on the pipe axis. If the swirl is slightly off-centre or has a more complex pattern containing multiple vortices, then this form of swirl cancellation is less effective, as we will demonstrate below. Good illustrations of complex off-centre swirl downstream of bends can be found in studies where Computational Fluid Dynamics has been used to investigate meter performance [e.g. 7 - 10].

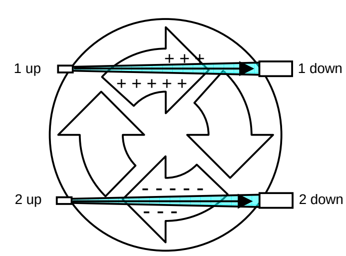

Fig. 6. An Illustration of Swirl Cancellation in a 2-path Meter

To demonstrate the effects of non-symmetrical swirl on 4-path and 8-path meter configurations we have used a

Taylor vortex equation to simulate a sample of swirl patterns. This equation has previously been applied in modelling of ultrasonic meters by Yeh and Mattingly at NIST [11]. The Taylor vortex equation is written as

$$u_\theta = u_0 r_v \exp\left(-r_v^2\right) \tag{3}$$

where u_θ is the tangential velocity, 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. There is a deficiency in this model in that the tangential velocity is not guaranteed to go to zero at the pipe walls. To eliminate this problem we have added a multiplying function that has a maximum velocity in the centre of the pipe and goes to zero at the walls to give

$$u_\theta = u_0 r_v \exp\left(-r_v^2\right)\left(1-r^2\right)^{1/15} \tag{4}$$

where r is the distance from the centre of the pipe normalised to the pipe radius.

Using the above formula we can evaluate the sensitivity of various path configurations to the presence of asymmetric swirl. The Caldon LEFM 240C has a parallel path arrangement, as shown in Figure 7 below.

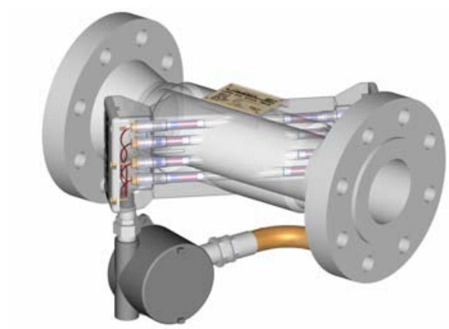

Fig. 7. A Caldon LEFM 280C 8-Path Ultrasonic Flowmeter

The Caldon LEFM 280C differs from the 240C and other commercially available parallel and crisscrossed multipath arrangements by having crossed paths in each of four chordal planes as illustrated in Figures 1 and 8.

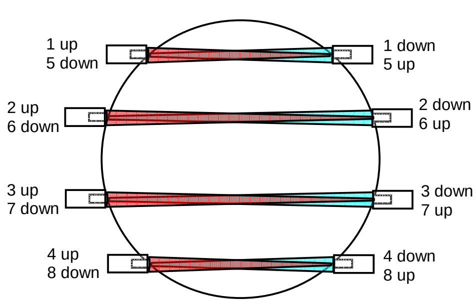

Fig. 8. A Schematic of the Caldon LEFM 280C 8-Path Meter

Figures 9 and 10 below illustrate the velocity profiles measured by and 4 and 8-path meters for the case of asymmetric swirl with a vortex of radius $r_0 = 1$, centered at $x = 0$, $y = 0.1R$, and with a swirl magnitude of $u_0 = 0.1U$, where U is the mean axial velocity. The swirl is superimposed on top of a power-law axial velocity profile with $n = 10$.

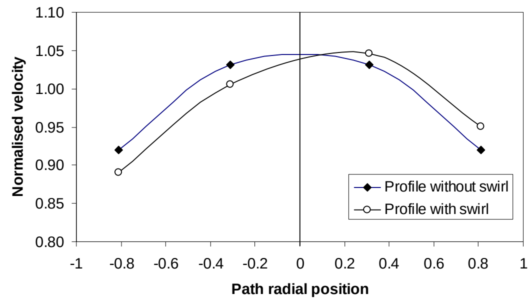

Fig. 9. Measured Velocity Profiles for a 4-Path Meter (0.35% swirl error)

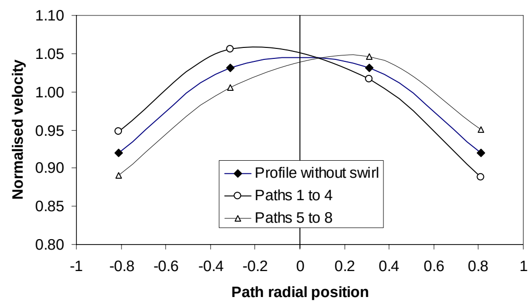

Fig. 10. Measured Velocity Profiles for an 8-Path Meter (zero swirl error)

The impact of the swirl apparent in the measured velocity profiles is an error 0.35% in the case of the 4-path meter and zero in the case of the 8-path meter. This is because the average value of each pair of crossed paths in the 8-path meter is equal to the axial velocity, i.e. the swirl effects cancel.

These results are supported by experimental data from tests on an 8-path meter downstream of out-of-plane bends. Figure 11 shows a photograph of the test set up, and a schematic diagram is shown in Figure 12.

Fig. 11. Two 8-Path Meters Being Tested at Alden Labs

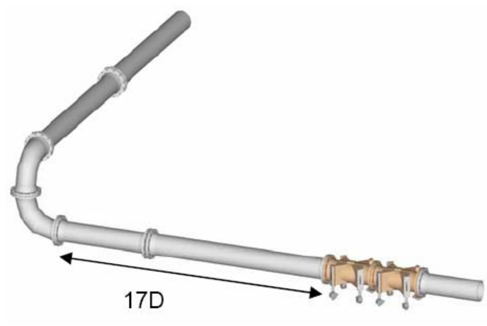

Fig. 12. A Schematic of the Upstream Pipe Arrangement

The tests were performed at the Alden water flow laboratory. Two Caldon 10-inch 280C flowmeters were installed in series approximately 17 diameters downstream of the bends. Here we show results for the first (upstream) meter. Figure 13 below shows the velocity profiles as measured by the meter. It can be seen very clearly that profiles for paths 1 to 4 and paths 5 to 8 are different owing to the effects of swirl. Each of these groups of four paths can be taken to represent a 4-path Caldon 240C flowmeter. It can also be observed that when all of the paths of the 8-path meter are combined the profile is much more symmetrical.

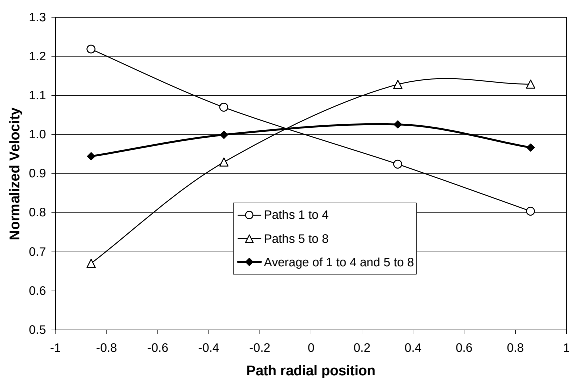

Fig. 13. Measured Velocities from Tests on an 8-Path Meter (Caldon LEFM 280C)

The effect of the swirl on the performance of the two sets of four paths, and the eight paths combined, can be seen in Figure 14 below.

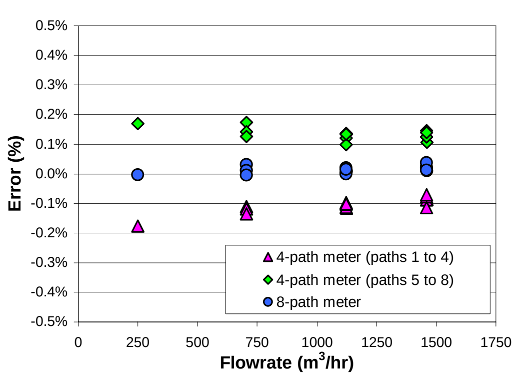

Fig. 14. Error Versus Flowrate for 4-path and 8-Path Meters in Swirling Flow

Figure 14 shows that the each set of four paths has errors of a similar magnitude, of about 0.12%, but opposite sign. These effects cancel in the 8-path meter with the result that the errors for the 8-path configuration are all within ±0.05%.

3. DIAGNOSTICS

So far we have demonstrated how good design and proper practices can be used in order to achieve custody transfer uncertainty requirements with an unbroken chain of traceability. It has also been shown the transit time measurements can be validated in the field. However, we have still to demonstrate how the meter factor can be validated in the field. This is important for custody transfer applications as it is not only necessary for the meter to *be* accurate, it must be *seen* to be accurate.

The fact that multipath meters provide information on individual path velocities creates the potential for powerful flow diagnostics. Such diagnostics are available in most ultrasonic meters but the advantage of the 8-path meter is that it separates and eliminates the effects of swirl. Meters with 4 or 5 paths that are parallel or crisscrossed alternately, can not truly distinguish between swirl and distortion of the axial velocity profile.

To demonstrate this capability of the 8-path meter, we have again taken the four velocity profiles described in Table 1 and have now calculated two diagnostic parameters for each of these profiles, at 4° intervals of orientation between 0 and 180°. The two parameters calculated are described as flatness ratio, and asymmetry. In an 8-path meter flatness ratio is given by:

$$fr = \frac{v_1 + v_4 + v_5 + v_8}{v_2 + v_3 + v_6 + v_7} \qquad (5)$$

where the numerator is the sum of all the outside paths and the denominator is the sum of all the inside paths.

Asymmetry is calculated as follows:

$$ar = \frac{v_1 + v_2 + v_5 + v_6}{v_3 + v_4 + v_7 + v_8} \qquad (6)$$

where the numerator and denominator sum all paths on one or the other side of the pipe.

In fully developed flow, as described by the powerlaw for n = 6 to n =10, the flatness ratio has a value of between 0.826 and 0.892 (however, lower values are also possible at low Reynolds numbers, say below R_e = 10,000). Values of fr greater than 0.892 suggest an unusually flat profile.

In fully developed flow, the flow will be symmetrical and hence the value of ar should be very close to 1. Values above or below 1 show that the axial velocity profile is asymmetric, and the further away from 1 the value of ar is, the greater the asymmetry.

Figure 15 below shows the error in the computed mean flow velocity for the profiles described in Table 1, plotted as a function of both flatness ratio and asymmetry. The size of the circles corresponds to the magnitude of the error, calculated relative to the meter factor for fully developed flow. Also shown are two circles corresponding to error magnitudes of 0.1 and 0.2 % for reference.

What is striking from this figure is that although all of the errors are less than 0.2 %, those that are greater than 0.1 % all fall outside of a given range of *fr* and *ar*. The shaded box corresponds to a range of *fr* from 0.82 to 0.89, and a range of *ar* from 0.85 to 1.15. Therefore it appears that larger errors only occur when the profile is outside of the normal range of flatness expected, or when there is very strong asymmetry.

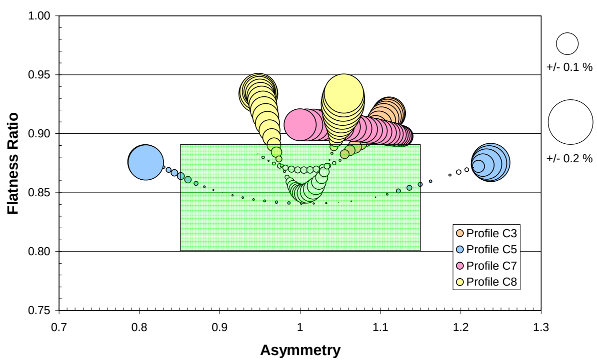

Fig. 15. Error Versus Asymmetry and Flatness Ratio for Four Distorted Velocity Profiles

Further work is required to validate these conclusions for a wider range of profiles. However, what this clearly shows is that flatness ratio and asymmetry can be used as good diagnostic indicators of whether or not the measured flow profile is within an acceptable range. Again, it is worth emphasizing that a 4-path or 5-path meter does not have quite the same capability as the 8-path meter, owing to the interfering influence of swirl.

In application, the values of *fr* and *ar* can be determined when the meter is calibrated in the laboratory and then again when it is installed in the field. When first installed, these values can be checked to ensure the field installation is satisfactory in terms of the incoming flow profile. Once installed, they can be checked again periodically. Significant changes in *fr* or *ar* should only occur if either the Reynolds number has changed significantly or the upstream pipe geometry (or valve positions) have been changed. Any significant change in these parameters that does not correlate with a change in Re or upstream pipework should be investigated further.

In combination with system self-checks and signal diagnostics, these flow diagnostics provide a means of verifying each part of the traceability of an 8-path meter.

4. CONCLUSIONS

The performance of multipath ultrasonic flowmeters is a function of the ability of the mechanical and electronic design to deal with complex variations in flow conditions.

A key feature of ultrasonic meters is the fact that they have no moving parts and a non-intrusive design. It could be argued that if flow conditioning or the use of large volume provers is necessary then one of the major benefits of the technology is lost. If ultrasonic meters are to be considered for use without volume provers and flow conditioning devices, then they must be able to cope with the following common features flow in practical piping systems:

- Axi-symmetric changes to the flow profile (owing to changes in Reynolds number and pipe roughness)
- Asymmetric distortions of the axial velocity profile caused by bends and valves etc.
- Swirl introduced in to the flow by bends and other components that cause the flow to change direction

This paper has presented an 8-path meter design that has been shown to be sufficiently insensitive to the above factors for use in oil custody transfer applications. Furthermore, it has been shown that by use of the signal and flow diagnostics available in an 8-path Caldon meter, the traceability of the calibration from the lab to the field can be validated.

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