18th NORTH SEA FLOW MEASUREMENT WORKSHOP 2000

CHALLENGES FOR IMPROVED ACCURACY AND TRACEABILITY IN ULTRASONIC FISCAL FLOW METERING

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SUMMARY

USM technology is today recognized as a competitive alternative for fiscal flow metering of gas, and is also considered for fiscal metering of oil and petroleum products. However, there are clearly un-exploited potentials to reduce systematic errors, achieve higher accuracy, and to improve measurement traceability, robustness and cost/benefit ratio. Some of these possibilities are addressed and discussed.

1 INTRODUCTION

Multipath ultrasonic transit-time meters for gas and liquid flow measurement (USM) have already been developed to a stage where they are considered as competitive alternatives to the more conventional orifice plate, turbine and positive displacement meters for fiscal metering of natural gas and oil products, particularly for transmission line applications. USM technology offers significant operational advantages such as no moving parts, non-intrusive measurement (no obstruction of flow), no pressure loss, and bi-directional operation (reducing need for pipework). Compact metering stations can be constructed on basis of the large turn-down ratio of USMs (40:1 or larger for gas meters, 20:1 or larger for liquid meters (tentatively), reducing the need for a multiplicity of meters to cover a wide flow range), and the short upstream/downstream requirements with respect to bends (10D and 5D for gas meters, typically). Measurement possibilities are offered which have not been available earlier, such as fast time response and flow monitoring (e.g. pulsating flow, flow velocity profile; sound velocity profile), and self-checking capabilities (from sound velocity, signal level, etc). In gas there has been demonstrated potentials of additional information such as gas density and calorific value determination. The potentials of remote operation of USMs is an interesting perspective.

For natural gas, the first generation of USMs have been on the market for about 5-10 years [1-3]. USMs have demonstrated their capability to provide metering accuracy within national regulation requirements [4,5]. Better than ±0.7% uncertainty (of measured value) is being reported, as required for custody transfer in large commercial pipelines. In appropriate applications, multi-path ultrasonic meters can offer significant cost benefits. USM technology is increasingly gaining acceptance throughout the industry, and is today in use in gas metering stations onshore and offshore. ISO standardization work has been started [6].

For metering of oil and petroleum products, USMs for liquids have for many years represented a robust alternative in non-fiscal applications. USMs have recently been introduced also for fiscal metering [7], and 0.15 - 0.25 % uncertainty is claimed, based on *in-situ* flow calibration (using prover). The petroleum industry is at present gaining field experience with this new fiscal liquid metering technology [8].

A relatively small measurement error can easily translate into a large sum of money. For example, an estimate of Norway's export of natural gas in 2000 is about 6000 million USD. Present-day technology for fiscal and sales metering of gas is at a level of 0.5 - 1% uncertainty. A systematic error in the flow measurement of, say, 0.5% (which is still within usual national regulations for gas measurement [5]) would translate into a measurement uncertainty corresponding to an annual value of about 30 million USD for this 2000 gas export estimate.

USM technology is still at a relatively early, introductory stage of development. Significant potentials exist for further development, such as with respect to:

- Technically improved meters (better technical exploitation of the measurement principle),
- Improved cost/benefit ratio,
- Extended applications (gas density and energy (calorific value) measurement [9], check metering, wet gas metering [9-11], etc).

Some challenges for USM technology are higher accuracy, and better control with operational factors not necessarily covered by “dry calibration” and flow calibration (for gas meters), such as pipe deposits, PRV noise, variations in process pressure and temperature, temperature gradients, long-time drift effects, wear, etc. This also includes installation conditions (bend configurations, bend inflow profiles, meter orientation, pipe roughness, flow conditioners, etc.). More complete USM uncertainty analyses and improved use of such may be valuable in this perspective (also taking into account improved basic theoretical description and more complete theoretical functional relationships). The traceability of the in-field USM measurement is an important issue in this respect which needs to be addressed in standardization work. Other significant practical and cost/benefit issues are reduced production and operational costs, improved self-checking, and reduced service needs. Reduced need for flow calibration (for gas meters) and “dry calibration” are also topics presently being addressed.

Important means to fulfil such challenges are through extensive co-operation between highly skilled and experienced users, USM manufacturers and R&D groups. The present paper represents one input from an R&D group to such a co-operation.

The paper addresses mainly systematic effects in USMs due to integration methods and transit time measurements/corrections. Ultrasonic transducer time delays resulting from “dry calibration”, used to correct the measured transit times, may change significantly over the pressure (*P*) and temperature (*T*) range of the meter. The transducer’s diffraction time shift, which is also incorporated in the “dry calibration” measurements, varies with *P* and *T* as well, but in particular it changes significantly with the acoustic path length. This means that “dry calibration” data obtained at a certain *P-T* point, may not necessarily be applicable for transit time correction at another *P-T* point. Moreover, it may not be directly applicable at another path length (or USM size).

For the integration methods, several installation conditions are addressed. The deviation between the output USM flow rate and a reference value may vary with e.g. meter orientation, bend inflow profiles, type of bends and Reynolds number.

The importance and consequences of such systematic effects on USMs are discussed. Examples have been chosen mainly for gas USMs, with a few examples for liquid USMs. However, the principles and methods which are discussed are of more general relevance for USMs.

2 CONTRIBUTIONS TO USM MEASUREMENT UNCERTAINTY

Many factors can contribute to the USM measurement uncertainty. Control with these factors is crucial, to ensure that they do not contribute to deviations in excess of expected measurement uncertainty. It is also important to be able to see how improvements with respect to certain factors can lead to improved measurement uncertainty. For this purpose the *GARUSO* uncertainty model [12, 13] can be used. The model calculates the expanded uncertainty of e.g. the axial volume flow rate (at standard conditions) measured by the USM, *Q*, given by (for USMs configured with parallel chords, cf. Fig. 1) [13].

$$Q \approx 7200\pi R^2 \frac{P T_0 Z_0}{P_0 T Z} \sum_{i=1}^{N} w_i \frac{\sqrt{R^2 - y_i^2}\,(t_{1i} - t_{2i})}{t_{1i} t_{2i} \left| \sin 2\phi_i \right|} \quad . \qquad (1)$$

Here, P and T are the gas pressure and temperature at line conditions, P_0 and T_0 are the gas pressure and temperature at standard conditions, and Z and Z_0 are the compressibility factors at line and standard conditions, respectively. R is the pipe's inner radius. y_i and f_i are respectively the lateral position and inclination angle of path no. i, i = 1, …, N. N is the number of paths, and w_i is the integration weight factor for path no. i. t_{1i} and t_{2i} are the upstream and downstream transit times along the interrogation length, respectively, for acoustic path no. i. L_{pi} is the transducer distance (acoustic path length).

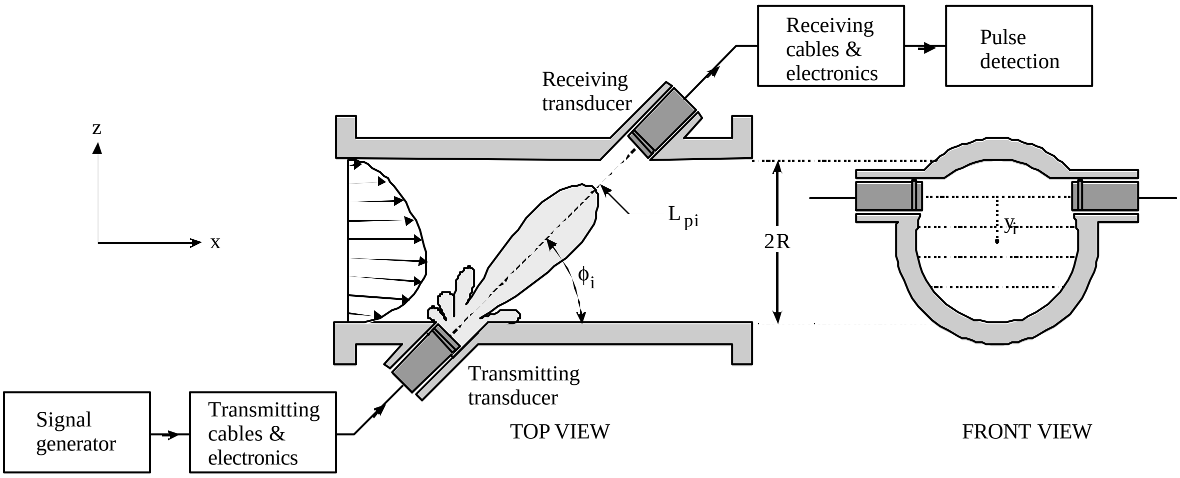

Fig. 1 - Schematic illustration of a single path in a multipath ultrasonic gas flow meter (for downstream sound propagation). (Left: centre path example (y_i = 0); Right: path at lateral chord position y_i.)

Consider the example of a 12" USM configured with 4 paths in an "asymmetric criss-cross" pattern (f_i = ±45°), using the Gauss-Jacobi integration method. Fig. 2 shows the calculated total USM uncertainty (the relative expanded uncertainty) of Q, E_Q, for two axial flow velocities, 0.4 and 10 m/s. The input quantities are grouped in (1) gas parameters, (2) geometry parameters, (3) transit time parameters, and (4) the integration method. The isolated contributions to E_Q from the input quantities in each group are shown (at a 95 % confidence level). The dominant standard uncertainty for each input quantity under the groups (1)-(3) is given in parenthesis in Fig. 2, for the example chosen here. For the integration method, results for a double bend out of plane with no separation between the bends have been used here.

Table 1 summarizes a number of effects which contribute to the uncertainty of these input quantities (for details, cf. Refs. [12,13]). The list of contributing factors/effects is not considered to be complete, but is expected to cover many of the important factors that contribute to the USM uncertainty. The propagation of these uncertainties is described in [12,13], cf. Section 5.

The example given in Fig. 2 demonstrates that several quantities contribute at a 0.1-0.2 % level, and that some quantities contribute at an even more significant level. For instance, typical uncertainties of geometry parameters like the pipe diameter (especially out-of-roundness) and inclination angle contributes significantly. Transit time parameters such as cable/electronics/transducer time delay, Dt-correction, signal-to-noise (SNR) ratio, and time detection are important. With respect to the integration method (accounting for installation effects), the uncertainty contributions from numerical discretisation (incomplete spatial sampling of axial flow profiles and incomplete cancellation of transversal flow effects) are especially important. Some of these contributions are velocity dependent, such as noise effects, Dt-correction and time detection uncertainties.

The influences of systematic effects in USMs due to transit time corrections and integration methods are analysed and discussed in more detail in the following.

3 TRANSIT TIME CORRECTIONS

The measured upstream and downstream transit times, $t_{1i}^{measured}$ and $t_{2i}^{measured}$, contain possible time delays due to signal propagation in the transmit and receive cables, electronics, transducers, diffraction effects, and possible cavities in front of the transducers, cf. Fig. 1. To achieve sufficient accuracy of the USM, these additional time delays may have to be corrected for in the USM. Such transit time corrections have been implemented in different ways by the different USM manufacturers. One possible way of expressing the time corrections is [12,13].

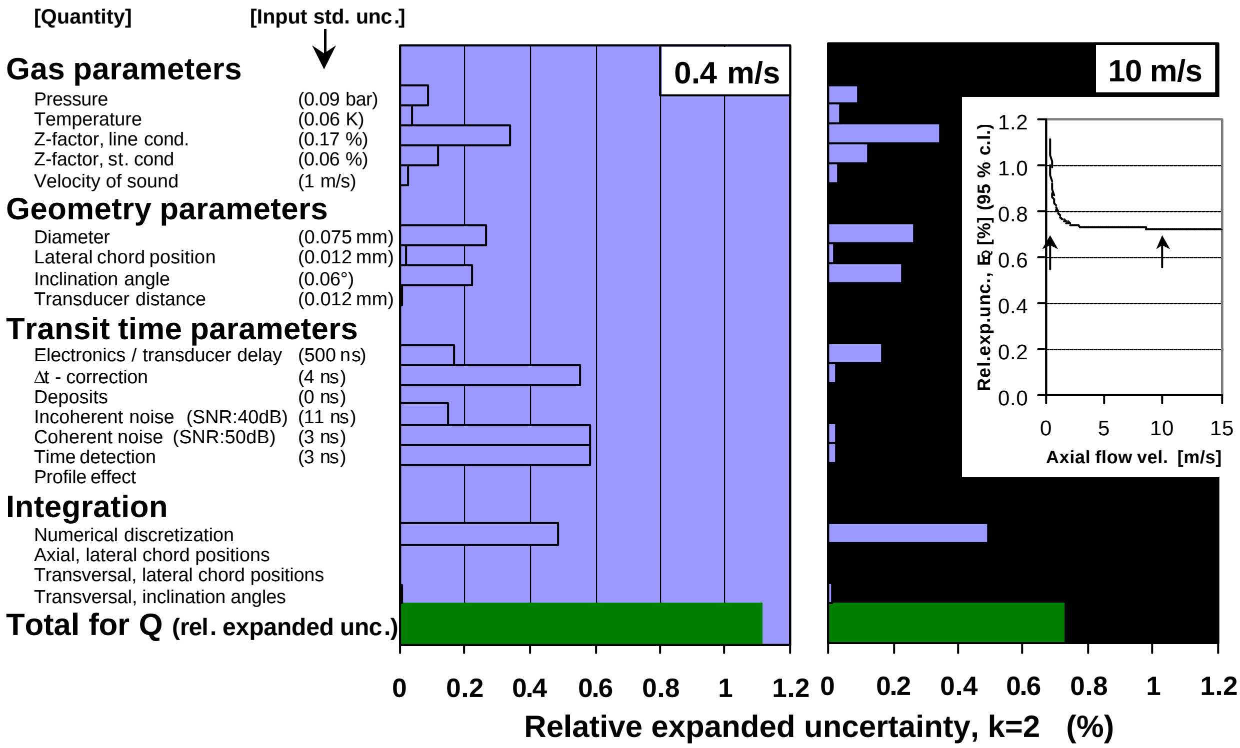

Fig. 2. - Example of uncertainty budget for a gas 12" USM configured with 4 paths in an "asymmetric criss-cross" pattern, using Gauss-Jacobi quadrature. Axial flow velocity: 0.4 m/s and 10 m/s.

Table 1 - Overview of some contributions to the uncertainty of various input quantities.

Parameter group	Input quantity	Uncertainty contribution
(1) Gas parameters	• Pressure (*P*)	- Measurement uncertainty (at line cond.)
	• Temperature (T)	- Measurement uncertainty (at line cond.)
	• Z-factor, line conditions (*Z*)	- Uncertainty of equation of state
	• Z-factor, standard conditions (Z_0)	- Uncertainty of equation of state
	• Sound velocity (*c*)	- Measurement uncertainty (at line cond.)
(2) Geometry parameters	• Diameter at stand. conditions (D_0)	- Measurement uncertainty (at “dry calibration”) - Out-of-roundness - Deposits at pipe wall - Uncertainty of pressure correction factor - Uncertainty of temperature correction factor
	• Lateral chord position (y_{i0}, $i = 1,\ldots,N$)	- Measurement uncertainty (at “dry calibration”)
	• Inclination angle (f_{i0}, $i = 1,\ldots,N$)	- Measurement uncertainty (at “dry calibration”)
	• Transducer distance (L_{pi0}, $i = 1,\ldots,N$)	- Measurement uncertainty (at “dry calibration”)
(3) Transit time parameters	• Cable / electronics / transducer time delay ($t_{1i,0}^{eltr}$, $i = 1,\ldots,N$)	- Measurement uncertainty (at “dry calibration”) - Variation with *P*, *T*, gas & pipe diameter
	• *Dt*-correction ($Dt_{i,0}^{corr}$, $i = 1,\ldots,N$)	- Measurement uncertainty (at “dry calibration”) - Variation with *P*, *T*, gas & pipe diameter
	• Transducer deposits	- Thickness and sound velocity of possible deposit layer at transducer front (wax, liquid)
	• Incoherent noise	- Signal-to-noise ratio (e.g. electromagn., PRV) - Number of averaged ultrasonic signals
	• Coherent noise	- Signal-to-noise ratio (due to acoustic cross-talk, possible reverberation, etc.)
	• Time detection	- Clock frequency (time resolution) - Possible averaging over several zero crossings
	• Flow profile effects (sound refraction)	- Shape of flow profiles (axial & transversal)
	• Turbulence effects	- Flow velocity fluctuations - Temperature fluctuations
(4) Integration method	• Numerical discretization (spatial sampling)	- Shape of flow profiles (axial & transversal)
	• Axial; lateral positions (y_{i0}, $i = 1,\ldots, N$)	- Measurement uncertainty of y_{i0}
	• Transversal; lateral position (y_{i0}, $i = 1,\ldots,N$)	- Measurement uncertainty of y_{i0}, - Uncertainty of chord parallellity
	• Transversal; inclinat. angles, f_{i0}, $i = 1,\ldots,N$	- Measurement uncertainty of f_{i0}

$$t_{1i} = t_{1i}^{measured} - t_{1i,0}^{eltr} - t_i^{cavity} \tag{2}$$

$$t_{2i} = t_{2i}^{measured} - t_{1i,0}^{eltr} + Dt_{i,0}^{corr} - t_i^{cavity} \quad , \tag{3}$$

where $t_{1i,0}^{eltr}$ is the cable/electronics/transducer time delay for upstream propagation, and $Dt_{i,0}^{corr} = t_{1i,0}^{eltr} - t_{2i,0}^{eltr}$ is the *Dt*-correction. t_i^{cavity} is the cavity delay of path no. *i*, at line conditions.

$t_{1i,0}^{eltr}$ and $Dt_{i,0}^{corr}$ are typically estimated (measured) in a “dry calibration” procedure, in nitrogen, at one or several *P*-*T* points, at zero flow. (The subscript “*0*” denotes that the “dry calibration” values are used in Eqns. (2) and (3)). Besides, the geometrical quantities R_0, y_{i0}, f_{i0}, and L_{pi0} (or equivalent quantities) are measured in the “dry calibration” procedure.

In order to separate various effects in $t_{1i,0}^{eltr}$, Eqn. (2) can be written as

$$t_{1i} = t_{1i}^{measured} - (t_{1i,0}^{el,cab} + t_{1i,0}^{tr} + t_{1i,0}^{dif}) - t_i^{cavity} \quad , \tag{4}$$

where $t_{1i,0}^{eltr}$ has been decomposed into the cable/electronics time delay (transmit and receive), $t_{1i,0}^{el,cab}$, the transducer time delay (transmit and receive), $t_{1i,0}^{tr}$, and the diffraction time shift, $t_{1i,0}^{dif}$. For the definitions of the quantities introduced above, it is referred to Ref. [13].

3.1 Transducer Time Delay

For certain types of USM transducers, the transducer time delay $t_{1i,0}^{tr}$ has been measured in a pressure chamber (Fig. 3), using nitrogen up to 100 bar at 15 and 50/60ºC [13,14]. $t_{1i,0}^{tr}$ has been measured using a reflector method.

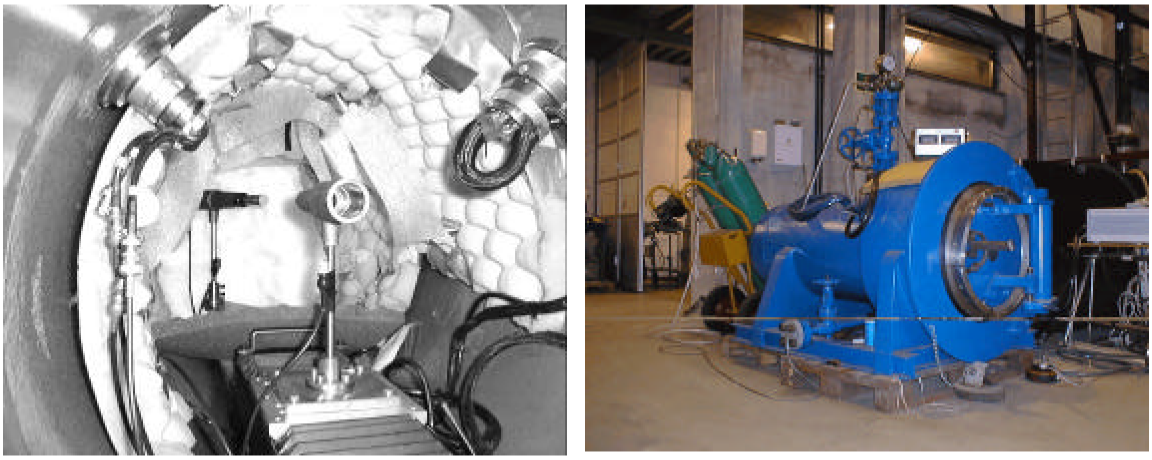

Fig. 3 – Photograph of the positioning system mounted in the 200 bar pressure chamber, with ultrasonic transducers.

One example is shown in Fig. 4, where the change of $t_{1i,0}^{tr}$ is nearly 1 µs over the 20-100 bar range, at 15ºC, and about 1.5-1.8 µs over the 15-50ºC range. The trend of increasing transducer time delay with increasing temperature is typical for transducers employing e.g. epoxy front materials for acoustic matching to the gas, which is a common approach. However, the effect may depend on whether time detection is made in the transient start of the signal, or in the stationary part. The results shown in Fig. 4 relate to the stationary part of the signal.

Such *P* and *T* variations of the transducer time delay may give significant errors in the USM measurement, if not accounted for in the transit time corrections of the USM. For a 6" meter, for example, an error in the transit times of 1 µs (corresponds approximately to the change of $t_{1i,0}^{tr}$ over the pressure range 20-100 bar at 15ºC in Fig. 4), gives directly a measurement error of the order of 0.4%. Similarly, a transit time error of 1.5 µs (corresponds approximately to the change of $t_{1i,0}^{tr}$ over the temperature range 15-50ºC in Fig. 4), gives a measurement error of the order of 0.6%. Such errors are influent for all flow velocities.

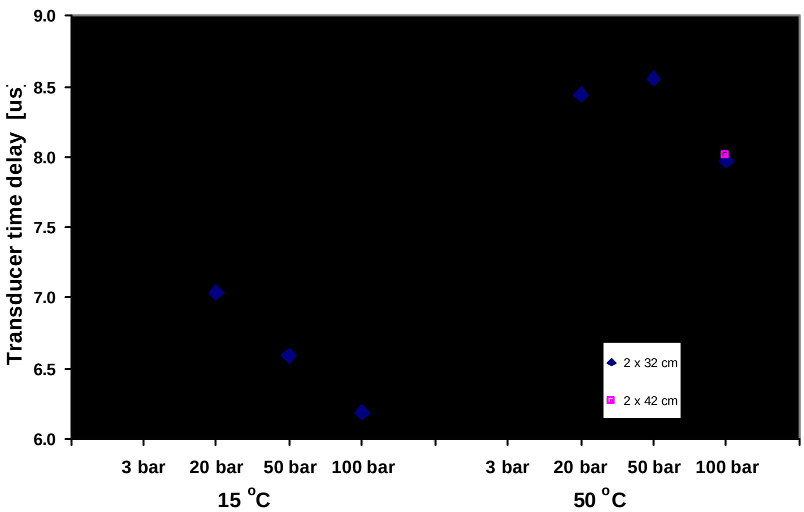

Fig. 4. - Example of transducer time delay measured at pressures 20, 50 and 100 bara, and temperatures 15 and 50ºC, in the 200 bar pressure chamber [13]

An alternative to directly correcting for such systematic errors of $t_{1i,0}^{tr}$ in the transit time correction of the USM, is the use of an empirical meter factor (K-factor), established by a flow calibration of the USM.

Such a K-factor will then need to be a function of *P* and *T*. However, the AGA-9 report states that the USM shall fulfil certain accuracy requirements *before* using a K-factor. The control of systematic changes in $t_{1i,0}^{tr}$ with *P* and *T* is thus very important. Moreover, in possible future USM calibration scenarios based on a reduced dependence on flow calibration and increased dependence on "dry calibration", the control and correction of such systematic changes of the transducer time delay with *P* and *T* becomes even more critical and important (cf. Section 6).

3.2 Diffraction Time Shift

For certain types of USM transducers, the diffraction time shift $t_{1i,0}^{dif}$ has been estimated in the pressure chamber, with nitrogen up to 100 bar at 15 and 50/60ºC. $t_{1i,0}^{dif}$ has been determined indirectly by estimating the "effective piston transducer radius", a_{eff}, by adaptation of the "plane piston transducer model" [15] to measurements of the transducer directivity over the *P-T* range, and using a_{eff} into a model [16] for calculation of the diffraction correction of a plane piston transducer [13,14]. Since the transducer does not vibrate like a plane piston, this simplified method is expected to give only a relatively rough estimate of the diffraction time shift, but has still proved to be useful. In the future, methods should be developed to measure $t_{1i,0}^{dif}$ more directly and more accurately.

One typical example is shown in Fig. 5 (note that $t_{1i,0}^{dif}$ is a negative quantity [13]). The change of $t_{1i,0}^{dif}$ is about 0.2 μs over the 20-100 bar / 15-50 °C ranges, at the transducer distance 20 cm. In addition, $t_{1i,0}^{dif}$ varies significantly with the distance between the transducers, so that acoustic diffraction effects makes the effective transducer delay dependent on the path length (i.e. transducer distance, or USM size). For the example shown here, a change of $t_{1i,0}^{dif}$ in the range 0.5-0.7 μs (dependent on *P* and *T*) is observed over the distance range 20-100 cm. The effect may depend on whether time detection is made in the transient start of the signal, or in the stationary part. The results shown in Fig. 5 relate to the stationary part of the signal.

Such systematic pressure, temperature and distance variations of $t_{1i,0}^{dif}$ may give significant systematic errors in the USM measurement, unless it is accounted for in the transit time corrections of the USM. For the example shown in Fig. 5, diffraction alone causes a change of the effective transducer time delay of the order of 0.4 - 0.55 μs from a 6" USM to a 16" USM. If a "dry calibration" value for $t_{1i,0}^{eltr}$ which is correct for a 16" meter at a given *P-T* point is used in a 6" meter (at the same *P-T* point), that gives directly a systematic error of the order of 0.2 %, unless the distance dependence of $t_{1i,0}^{dif}$ is accounted for in the transit time corrections of the USM.

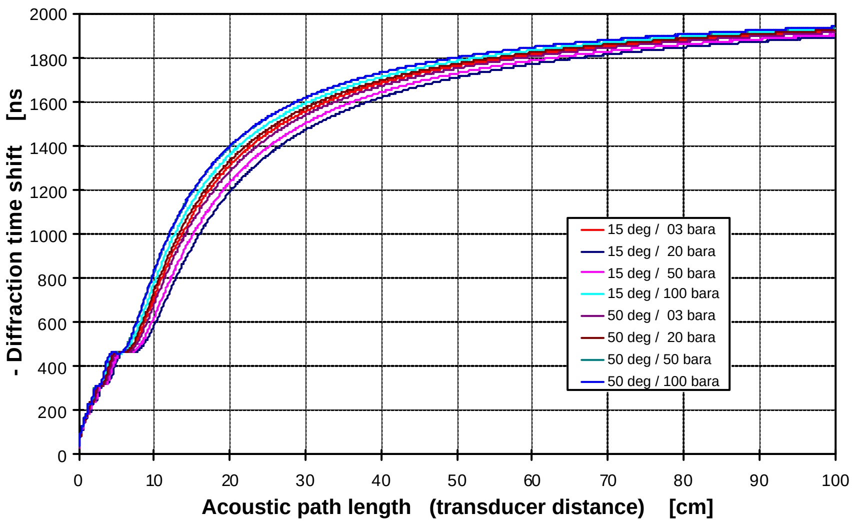

Fig. 5 - Example of diffraction time shift, estimated at pressures 3, 20, 50 and 100 bara, and at temperatures 15 and 50ºC, in the 200 bar pressure chamber [13].

Such errors are influent for all velocities. This point is important e.g. in connection with exchange of transducers in the USM, to avoid systematic timing errors.

With respect to "dry calibration" and flow calibration aspects, the same comments apply to $t_{1i,0}^{dif}$ as discussed for $t_{1i,0}^{tr}$ at the end of cf. Section 3.1.

3.3 *Dt*-correction and Reciprocity

With fluid flow approching zero, the USM method becomes increasingly dependent upon the reciprocity of the electro-acoustic measurement system. If reciprocity is not fulfilled, the measured transit times of upstream and downstream propagation will not be equal at zero flow, $t_{1i}^{measured} \neq t_{2i}^{measured}$, resulting in a zero flow timing offset, which becomes highly important in the low-velocity flow range (cf. Fig. 2).

By USM manufacturers, this zero flow timing offset is typically measured in a "dry calibration" procedure and then used in the USM software for active correction of the measured transit times (cf. e.g. Eqns. (2)-(3)). For this reason it is frequently referred to as the "*Dt*-correction", $Dt_{i,0}^{corr}$. For typical ultrasound transducers, the *Dt*-correction may vary with *P* and *T*. Whether the *Dt*-correction is measured at a single *P-T* point, or at a multitude of *P-T* points, common practice varies between the USM manufacturers.

The magnitude and importance of the zero flow timing offset (or *Dt*-correction) may be reduced by optimizing the electro-acoustic system with respect to reciprocity. From the reciprocity theorem [17], it can be shown that reciprocity is fulfilled if (1) the response of the ultrasound transducers is linear, and (2) if special conditions regarding the electrical impedances of the electronics and transducers are fulfilled. If reciprocity holds, the transducers are in principle allowed to be different in their characteristic parameters, such as static capacitance, electrical impedance, resonance frequency, source and receiver sensitivities, directivity, etc. In all cases $Dt_{i,0}^{corr} \approx 0$. This will apply to all conditions of *P, T*, gas composition and acoustic path length, as long as the reciprocity conditions are met.

In practice, compromises may have to be met regarding such reciprocity conditions, in which case the transducers may not be allowed to be very different. However, criteria can be derived to establish requirements for the reproducibility of the transducer production.

By such methods the USM manufacturer can reduce (or eliminate) the need for active *Dt*-correction and "dry calibration", by design. Changes of transducer properties with *T* (or *P*) can be made less influent, so that these do not cause significant zero flow timing errors. This contributes to improve the accuracy and reliability of the USM. Moreover, the need for measuring the *Dt*-correction as part of the "dry calibration" may be significantly reduced (or eliminated), which is an advantage both for the manufacturer and the operator.

Fig. 6 shows examples of measured *Dt*-correction, for periods 1, 2, …, 60 in a measurement signal. Two

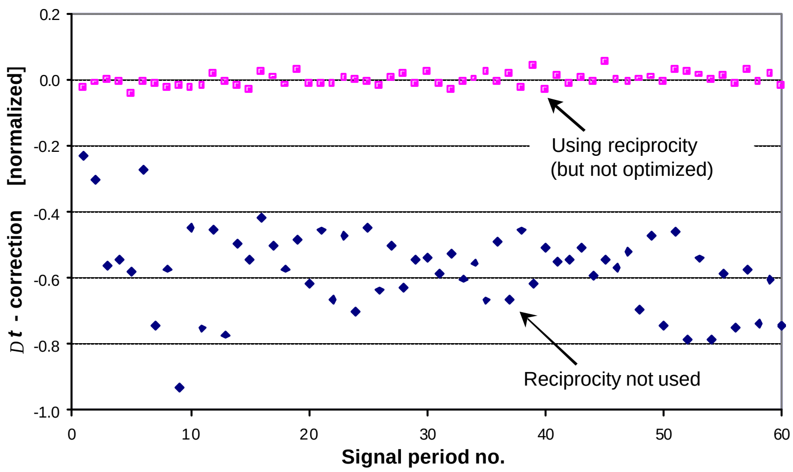

Fig. 6 - Illustration (based on measurement data) on the potentials of utilising reciprocity in the electro-acoustic system (non-optimized example)

data sets are shown: One in which reciprocity is not used, and one in which reciprocity has been considered and used (but yet not fully optimized with respect to reciprocity). The figure demonstrates that a significant improvement (reduced Dt-correction) is obtained when reciprocity is taken into account (by a factor of 250 in the present example, when averaging over all the 61 signal periods). As also demonstrated in the figure, significant improvement is obtained also when only one or a few signal periods are used for time detection (e.g. by a factor of 140 in the present example, when averaging over the signal periods 10-20). By further optimization, even larger improvements will be possible.

In addition to electrical impedance conditions, linearity of the transducer and the measurement system is a necessity to achieve reciprocity. Investigations have shown that for firing voltages used in USMs today, linearity may be violated to some extent [14]. A high firing voltage will cause a larger Dt-correction (a larger systemic timing error) than a low firing voltage [17].

4 INTEGRATION METHODS

In metering stations where compactness is important (e.g. offshore), complex installation conditions (pipe bends, flow conditioners, etc.) cause disturbed flow velocity profiles which influence on the USM measurement. Important factors are:

- Enhanced "robustness" and accuracy with respect to disturbed (asymmetric) axial flow velocity profiles.
- Improved compensation for transverse (non-axial) flow components (swirl, cross-flow, etc).
- Effects of orientation of the meter relative to the flow profiles.
- Reynolds number dependency (in particular for liquid meters).
- Finite acoustic beam effects on the integration method (spatial averaging).
- Pipe roughness effects (influence on flow profiles).

In the present study the former 4 factors will be discussed, using the *GARUSO* uncertainty model [12,13].

For the relative standard uncertainty related to the integration method (integration uncertainty), E_I, five different contributions have been identified [12,13]:

E_{Ida} = The contribution due to numerical discretization of axial flow profile,
E_{Ids} = The contribution due to incomplete cancellation of transversal flow components,
$E_{I\ell a}$ = The contribution due to uncertainty of lateral chord position estimates, effects on axial flow profile integration,
$E_{I\ell s}$ = The contribution due to uncertainty of lateral chord position estimates, effects on incomplete transversal flow component cancellation,
E_{Ifs} = The contribution due to uncertainty of inclination angle estimates, effects on incomplete transversal flow component cancellation.

From considerations on correlated and uncorrelated effects, these terms are combined in the following way to obtain E_I:

$$E_I^2 = \left(s_{Ida} E_{Ida} + s_{Ids} E_{Ids}\right)^2 + E_{I\ell a}^2 + E_{I\ell s}^2 + E_{Ifs}^2 \quad , \tag{5}$$

where s_{Ida} and s_{Ids} are sensitivity coefficients. These sensitivity coefficients will be either 1 or –1 depending on the sign of the deviation from reference for each of the two contributions. In this formula, the two terms E_{Ida} and E_{Ids} have been considered as correlated. The contributions from $E_{I\ell a}$, $E_{I\ell s}$ and E_{Ifs} can be shown to be negligible, for typical uncertainties of the lateral chord

positions and the inclination angles. See Fig. 2 for an example. Improved accuracy is thus obtained mainly through reducing the terms E_{Ida} and E_{Ids}; therefore these terms only will be discussed in the following. The two effects will be presented in a combined way like they appear in Eq. (5).
n
In the literature, the problems and challenges discussed here have been addressed by several authors. Zanker [18] discussed the pipe roughness and the Reynolds number dependency by applying a power law profile. In addition, meter orientation effects were discussed. Only axial flow profiles were used in the discussion. That means that only the term E_{Ida}, and not the term E_{Ids} was discussed. Hilgenstock et al, [19,13] discussed both terms E_{Ida} and E_{Ids}. However, in their work, realistic integration weight factors for multipath flow meters were not used in the discussion. Brown et al. [20] discussed meter orientation effects by using literature 2D (two-dimensional) axial profiles (no transversal flow components). Several transducer configurations and integration methods were used, among others a 4-path Gaussian integration method. The effect on USMs of the distance downstream of bends was studied for one meter orientation by 3D CFD (computational fluid dynamics) simulation results (of axial and transversal flow profiles), and by experiments. Both in the simulations and the experimental work a non-fiscal 4-path meter with two crossing acoustic paths at two lateral chord positions was used. In addition, two clamp-on meters were studied. In the present work, a 3D CFD analysis (involving both axial and transversal flow components) has been used to study influences of meter orientation, bend inflow profiles, bend types, and Reynolds number dependency, for two different fiscal multipath USMs.

4.1 Meter Orientation Effects

Downstream a bend like e.g. a single 90° bend or a double 90° bend out of plane, the axial flow profile will be asymmetric. In addition, transversal flow components like e.g. cross flow or swirl, respectively, will generally be present in the flow. Fig. 7 shows a calculated example of installation of (1) a 4-path meter with an asymmetric criss-cross path configuration and a Gauss-Jacobi integration method, and (2) an 8-path meter with 2 crossing paths in 4 lateral chord positions across the pipe cross section (not an existing meter at present). Such a meter will nearly cancel out the effects of the transversal flow components, and thus only depend on the axial flow profile. Both meters are installed 10D downstream a double 90º bend out of plane (with no separation between the bends). The bend inflow profile is a power law axial profile with no transversal flow components. The flow profile at the USM installation point has been calculated by the CFD code *MUSIC* [21]. Thereafter, *GARUSO* has calculated the USM performance. The deviation from reference has been calculated for meter orientations from 0º to 360º relative to the bend configuration. 0º and 180º are here the cases where the acoustic paths are in the same plane as the downstream one of the two bends.

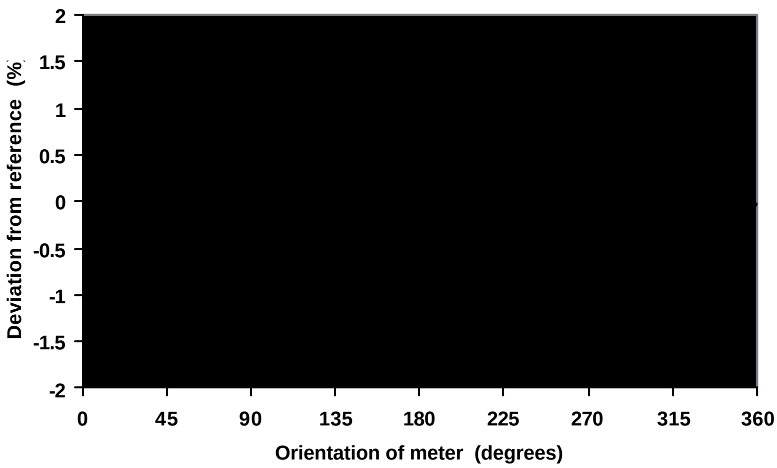

Fig. 7 - Deviation from reference for a 4-path and an 8-path USM installed 10D downstream a double 90° bend out of plane with no separation between the bends.

It can be seen that for the 4-path meter, the deviation from reference depends on the meter orientation relative to the bend. In this particular example, shifts of up to about 0.5% can be experienced due to the orientation of the meter. This is typical for, but not identical to the situation for several other installation conditions, see Sections 4.2 and 4.3. Such meter orientation effects have also been seen in experiments e.g. by Grimley [22]. The 8-path meter will in this example be nearly independent of meter orientation. This indicates that the meter orientation effects of the 4-path meter mainly are due to incomplete cancellation of the transversal flow components, and not so much due to asymmetries in the axial flow profile. This result, in combination with other investigations, indicate that a meter which is able to compensate correctly for transversal flow components thus has a potential of being nearly insensitive to meter orientation. For other meters, it is important that a flow calibration is carried out with the same meter orientation relative to the upstream bend configuration, as in the planned field installation. However, the picture is more complicated than this, as discussed in the following.

4.2 Bend Inflow Profile Effects

In a flow calibration, typically, the flow meter will be calibrated with the same upstream pipe configuration as in the field installation. However, it is not possible to make this installation condition identical to the expected field condition. This is among other factors due to differences in bend inflow profiles to the pipework in question. The flow profile at the USM is dependent not only on the last upstream bend(s), but on the whole upstream history of the flow. Therefore, as illustrated in Fig. 8, a flow calibration can not fully describe a field installation. On the left figure, the deviation from reference downstream a double 90° bend out-of-plane, as calculated for the 4-path meter used in Section 4.1, is calculated for three different bend inflow profiles. An axial power law profile is used in these three cases. For one of the curves, only the axial flow profile is present as bend inflow profile. For the two other curves, there is in addition a transversal swirl in the bend inflow profile (with positive and negative direction of rotation, respectively). This swirl is of the solid body type, and is at the pipe wall 10 % of the value of the axial flow. It can be seen that the various bend inflow profiles can in some meter orientations cause shifts in the meter of up to about 0.8%. Such effects cannot be flow calibrated away by a meter factor. Therefore, it is of relevance to develop a meter which is more insensitive to such changes in bend inflow profiles. To the right in Fig. 8, the same calculations as in the left figure have been made for the 8-path meter described in Section 4.1. It can be seen that such an 8-path meter is about insensitive to this variation in bend inflow flow profiles. Similar results have also been seen for several other bend configurations. An 8-path meter therefore has the potential to reduce the USM uncertainty due to possible deviations in bend inflow profiles from flow calibration to field operation conditions.

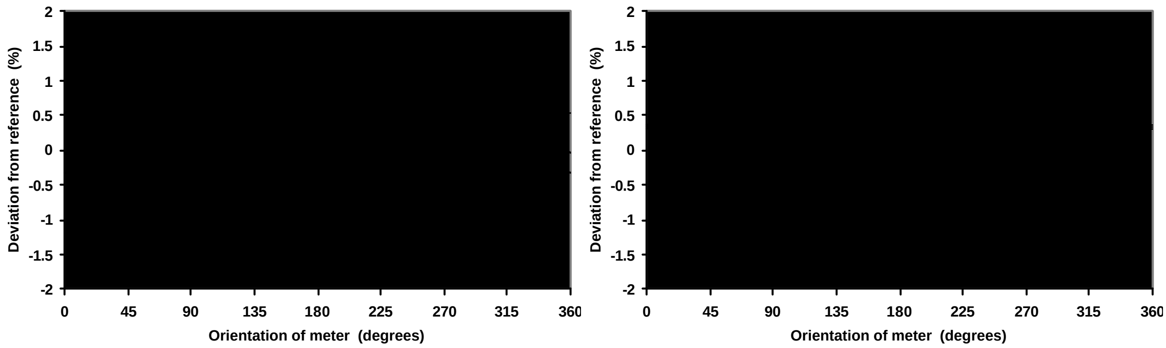

Fig. 8 - Deviation from reference for a 4-path and an 8-path USM installed 10D downstream a double 90°bend out of plane. Three bend inflow profiles have been used.

4.3 Bend Type Effects

In Fig. 9, the deviation from reference has been calculated for (1) the 4-path meter and (2) the 8-path meter for four different bend configurations. These bend configurations include (i) a single 90° bend, (ii) a double 90° bend out of plane with no separation between the bends, (iii) a double 90° bend out of plane with 3D separation between the bends, and (iv) a double 90° bend out of plane with 10D separation between the bends. The bend inflow profiles are purely axial (power law), and identical in all 4 cases. It can be seen that for the 4-path meter, there are significant differences between the performance downstream the various bends. Especially, it should be noted that in the case of a double 90° bend out of plane, a flow calibration should be carried out with the same separation between the bends as in the field installation. It can also be seen that even with a 10D separation between the bends, the upstream one of the two bends still contribute to the flow profile and the output of the USM. It is therefore important to flow calibrate the meter with as relevant bend configuration as possible. The 8-path meter is much more robust against the variety of bend configurations. This may possibly in future simplify the flow calibration procedure.

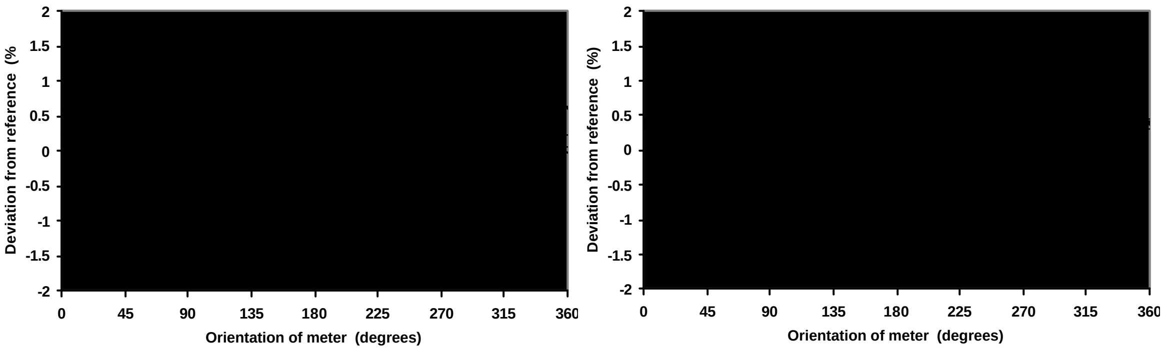

Fig. 9 - Deviation from reference for a 4-path and an 8-path USM installed 10D downstream four different bend types

4.4 Flow Conditioners

In Sections 4.1, 4.2 and 4.3, effects of meter orientation, bend inflow profiles and bend types have been discussed. Traditionally, such effects have often been handled by inserting a flow conditioner. However, experimental results indicate that USMs are not necessarily insensitive to the installation of such flow conditioners [22]. In a baseline situation, flow conditioners may cause a shift in meter performance of several tenths of a percent, relative to a bare pipe installation. An installation downstream bends with a flow conditioner installed, may also cause a shift of several tenths of a percent relative to the baseline test using the same flow conditioner. This demonstrates that the output from a USM may depend on the type of flow conditioner, and that the flow conditioner not necessarily will produce a symmetric and purely axial flow profile. Therefore, even when flow conditioners are considered, the 8-path meter discussed in Sections 4.1, 4.2 and 4.3 can be a realistic alternative. In practice, such an 8-path meter may be more expensive than the commercially available meters today, due to a larger number of paths. Therefore, a trade-off between economy and performance must be done.

4.5 Reynolds Number Dependency

In Ref. [18], the dependency of Reynolds number was discussed with a power law profile approach. It was concluded that a 4-path Gauss-Jacobi integration method was nearly insensitive to the change in Reynolds number in the range from laminar to the highest Reynolds number (Re = 10^3 to 10^8). The lower part of this Reynolds number range is relevant especially for USMs for liquid. In Fig. 10, similar calculations have been carried out by using CFD-calculated profiles in addition to power law profiles for the turbulent flow range. For the laminar flow range, a parabolic profile has been used.

It can be seen that the Reynolds number dependency is larger when using the CFD calculated profiles than when using the power law profiles. The figure demonstrates that, although the CFD results used here may not necessarily be fully representative for the flow profiles at low Reynolds numbers, the USM technology is sensitive to changes in Reynolds number in this range. This result indicates that more study is needed in order to understand the Reynolds number dependency. It should be noted that the Reynolds number dependency shown in Fig. 10 is relevant also for other similar integration methods.

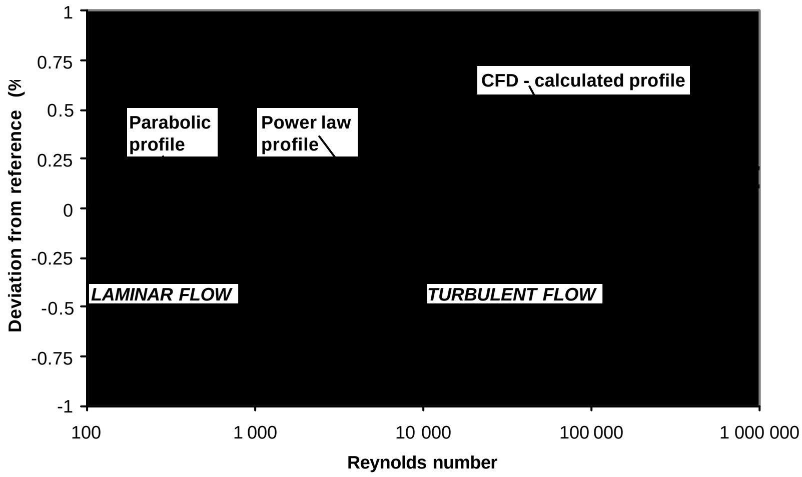

Fig. 10 - Dependency of Reynolds number for the example of a USM with 4 paths arranged in an “asymmetric criss-cross” pattern using the Gauss-Jacobi integration method, in a straight pipe section

5 USM UNCERTAINTY ANALYSIS

In the NPD regulations [4], it is stated that “an uncertainty analysis shall be developed for the oil and gas metering systems within 95% confidence level in accordance with recognised standards”. The uncertainty of the USM is one of the input uncertainties to this uncertainty analysis for the metering station.

To establish the uncertainty of the USM, an ultrasonic meter for gas is today first subjected to a so-called “dry calibration” in the manufacturer’s laboratory, and next, a “flow calibration”, in a dedicated gas flow laboratory by comparison/traceability to national standards or reference devices [5], cf. Fig. 11. The flow calibration is used to verify the meter, or - if necessary - to establish an empirical meter factor to be used in the metering station.

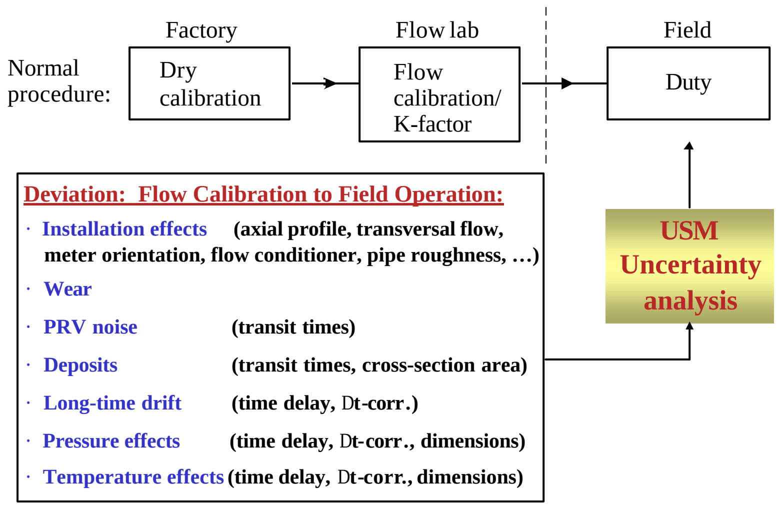

Fig. 11 - Use of uncertainty analysis in connection with USM calibration / field operation (example)

The flow calibration is usually limited, for economical and practical reasons. Consequently, in the field, a number of effects may appear which have not necessarily been accounted for in the “dry calibration” or flow calibration. This may include installation effects (bends, bend inflow profiles, flow conditioners, pipe roughness, etc), wear, noise effects (pressure regulation valves, etc), possible deposits at transducers and pipe wall, possible changes in cable/electronics/ transducer time delay and *Dt*-correction (pressure, temperature and long-time drift effects), etc. Consequently, there is a risk that the flow calibration / meter factor is not representative for the field operation of the USM.

In this perspective, the use of a USM uncertainty analysis would give possibilities to evaluate the influence of such “deviation effects” on the meter’s measurement uncertainty under operational conditions, cf. Fig. 11. That means, to handle the uncertainty implications of deviation in conditions between the flow calibration and the field operation.

Other applications of an USM uncertainty model are: sensitivity analyses, optimization in meter development (in particular for USM manufacturers), design of metering stations (planning of USM localization relative to bends and other installation conditions, etc.).

An uncertainty model for USMs has been developed which is expected to describe many of the important factors that contribute to the USM uncertainty [12,13]. The model, *GARUSO,* has been derived in conformity with the procedure recommended by the *Guide* [23] and the proposed revision of ISO 5168 [24]. Using this model, the relative expanded uncertainty of the USM can be calculated for three different output quantities: the average axial flow velocity (v_A), the volumetric flow rate at line conditions (q), and the volumetric flow rate at standard conditions (Q). Fig. 2 has been made on basis of outputs from this uncertainty model. Today, propagation of the contributions to the USM uncertainty such as those listed in Table 1 and Fig. 2 can be described using the model.

The model should be further developed to achieve a more complete uncertainty model and to improve the description of the influencing effects. This concerns e.g. pipe roughness effects (influencing on flow profiles), turbulence effects (at high flow velocities), finite beam effects (interaction of the acoustic beam with the flowing fluid, with systematic effects on the measured transit times and the integration method), reflection/interaction of the acoustic beam with the pipe wall and transducer cavities (influencing on measured transit times), cavity flow effects, systematic flow profile effects on measured transit times, etc.

It should be noted that at present, improved knowledge on several of the input uncertainties influencing on the USM uncertainty is needed to provide a satisfactory statement of the USM measurement uncertainty. This concerns e.g. a number of those related to transit times. On the other hand, a description and tool to *propagate* many of the important input uncertainties, as far as they are known, *is* already available, as described above.

6 STANDARDIZATION

Work has been initiated to further develop the ISO Technical Report ISO/TR 12765:1997 [6] and the AGA-9 report [5] into an ISO standard. In connection with this work, an accepted uncertainty analysis of the USM should preferably be an integrated part of the standard, such as to account for deviations in conditions between the flow calibration and the field operation, as discussed in Section 5, cf. Fig. 11. Traceability aspects may also need to be addressed in more detail, as discussed in the following.

As discussed in Section 5, traceable flow calibrations of USMs are not extensive enough to cover the operational range specified for the meters. The possible reduction of the use of flow calibration by relying more on “dry calibration” data, also rises the important question of how traceable flow performance data are achieved in such cases. Although the USMs have proven to be accurate, reliable and durable instruments, an omnipresent uncertainty may linger within the measurement community as to whether the meters under certain conditions can possibly be off by more than what is expected and comfortable.

Thus, both in the case where limited flow calibrations are performed, and in the case where a more extensive reliance on “dry calibration” methods and data are used, generally acceptable traceable performance information is lacking. This problem does not seem to have been satisfactorily addressed in relevant available documents such as in the ISO and AGA-9 reports [5,6]. It needs accordingly to be given proper attention in the further work on developing an acceptable international standard on USMs. During such a work, it will be necessary to bring together all relevant research data and experience in order to document and evaluate methods for ensuring traceable measurement data over a more complete measurement range. Such information must be made available and processed in an open and transparent manner, in order for all relevant and interested parties within the measurement community to consider, evaluate and scrutinize it. (Much can be learned here from experiences in the standardization of other meters, such as orifice meters.)

Such a task is not an easy one. Important information may also not be available due to the present state of the art of USMs. To the accuracy considered today, there are still important limitations in the basic understanding and methods for describing the real flow fields in pipe flow, the interaction between the flow and the sound fields, and also the total signal transmission and detection in the measurement system. Simplified methods are being used today for the analyses, supplemented with limited practical measurements and corrections. Thus in the work to ensure an improved metering traceability, the recent and further ongoing R&D work will be of importance.

7 CONCLUSIONS

USM technology is today recognized as a competitive alternative for fiscal flow metering of gas. However, there are clearly un-exploited potentials to further optimize USM technology such as with respect to transit time corrections (transducer time delay, diffraction correction, *Dt*-correction) and integration methods.

There is a need for better control with (and reduced sensitivity to) operational factors not necessarily covered by “dry calibration” and flow calibration (for gas meters). Improved use of USM uncertainty analyses may be a valuable approach in this perspective. This has impact on ongoing standardization work.

Today USM performance is to some extent dependent on meter orientation, bend inflow profiles, type of upstream bends and Reynolds number. Applying a flow conditioner may improve but not necessarily solve these problems. Especially, a flow calibration should be carried out with installation conditions as close to the relevant field installation as possible. Potentials of reducing such installation effects by design have been demonstrated (using an 8-path meter with four chords as an example). Possible increased costs of alternative designs would have to be evaluated in relation to the improved performance.

For possible future USM calibration scenarios based on a reduced dependence on flow calibration, and increased dependence on “dry calibration”, specific requirements regarding “dry calibration” procedures, and means to achieve traceability between the “dry calibration” and the data base of earlier flow calibrations, will need to be addressed. This should be manifested in standardization documents, and not left to the USM manufacturers, if this new calibration approach shall be an accepted and reliable method within the fiscal gas metering industry in the future.

Improvements in the areas mentioned will contribute to higher accuracy and improved traceability in ultrasonic flow metering, a better basis for standardization, and more cost-effective fiscal measurements. Moreover, improved USM technology will lead to wider impacts, such as on the design of gas metering stations, and how these are used in gas exploration, production and transport applications (topside today, and possibly subsea in future scenarios).

ACKNOWLEDGEMENTS

The work has been supported by The Research Council of Norway. The authors wish to thank the group of nine GERG companies participating in the “GERG project on ultrasonic gas flow meters. Phase II” (Gasunie, Statoil, Ruhrgas, BG Technology, Gaz de France, NAM, SNAM, Distrigaz and Enagas, for their support to CMRs four projects in Phases I and II of that programme. USM manufacturers participating in these projects were Daniel Industries Ltd., USA, and FMC Kongsberg Metering, Norway. Also, the present work would not have been possible without the contributions from R. Bø, A. Hallanger, M. I. Andersen and other members of the CMR technical staff.

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