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DRY CALIBRATION OF ULTRASONIC GAS FLOW METERS

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DRY CALIBRATION OF ULTRASONIC GAS FLOW METERS

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ABSTRACT

At present in most European countries it is customary that turbine meters, or the newer ultrasonic gas flow meters, when used in fiscal metering or custody transfer metering applications, are calibrated in a test facility by comparison to standards or reference devices.

For reason of practical and operational drawbacks, costs involved and availability of only a limited number of calibration facilities, another way of meter verification is advantageous. For orifice metering the practice of dry calibration is well established; that is, meter verification is based upon examination of the geometry and installation of the orifice plate and a function check of the read out devices. Although for turbine meters a flow (wet) calibration may be a necessity, it will be shown that ultrasonic gas flow meters can be dry calibrated in the same way as orifice meters.

As a basis for the acceptance of a dry calibration procedure for ultrasonic gas flow meters, a sensitivity analysis of the relevant variables with respect to the meter's accuracy is presented. Further test results are presented that demonstrate the feasibility of the concept of dry calibration applied to ultrasonic gas flow meters.

INTRODUCTION

Ultrasonic gas flow meters, especially multi path ultrasonic flow meters, become more and more accepted for custody transfer applications. For these applications a calibration or verification of the metering device is often a legal requirement, or a requirement based on the contract between the buying and the selling partner. Ideally such a calibration or verification is performed by comparison of the meter with a standard or reference. Traceability of the standards used to national or international standards is a prerequisite.

Unfortunately, facilities where large gas flows are available, can be controlled and can be measured precisely with standard meters are very rare and also expensive to operate. For the operator it is quite a burden when a meter has to be taken out of the line and sent to a calibration facility for a calibration or verification. Costs for the calibration itself are already high and in addition to this the operators have to face the cost for taking the meter out of the line, transportation and having the production facility shut down. Another restriction, especially for calibrating large size meters, is that test facilities may be limited to flow large flow rates only a short time (some months) a year.

The advantage of a meter being calibrated at a calibration facility is that the owner will get a certificate with a precise statement about the accuracy of the meter and second, it allows to adjust the meter in order to minimize any measuring error or bias relative to the standards used.

However, considering costs and operational drawbacks, the idea of a calibration or verification that does not require a meter has to be sent to a calibration facility is an attractive idea. Similar practices are well established for orifice meters: meter verification is based upon examination of the geometry and installation of the orifice plate and a function check of the read out device. This practice has gained world wide acceptance.

Principle of an ultrasonic flow meter

The principle of an ultrasonic flow meters is illustrated in figure 1.

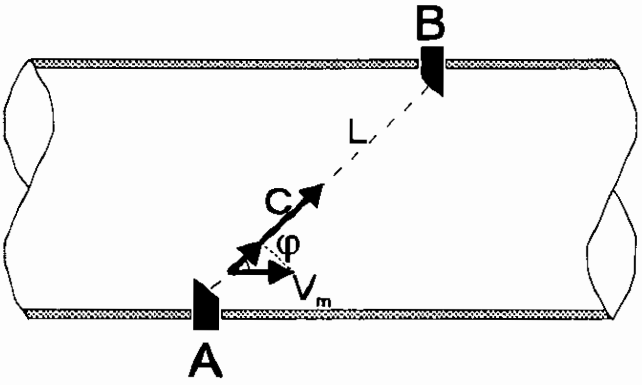


Figure 1: principle of an ultrasonic flow meter

Two transducers capable of emitting and receiving ultrasonic sound pulses are installed in the flow line in such a way that the ultrasonic sound pulses emitted from one transducer can be received by the other transducer, thus creating an acoustic path. The transducers in turn emit and receive pulses. The ultrasonic sound pulses travel, with respect to the gas, at the speed of sound. The velocity of a sound pulse along the acoustic path traveling downstream is increased with the projection of the gas velocity onto the acoustic path. The velocity of the sound pulse traveling upstream along the acoustic path is decreased with a projection of the gas velocity onto the acoustic path. This results in travel times for the upstream and downstream direction as:

$$t_{down} = \frac{L}{C + V_m \cos\varphi} \tag{1}$$

$$t_{up} = \frac{L}{C - V_m \cos\varphi} \qquad (2)$$

where

L : length of the acoustic path

C : speed of sound in the medium (gas)

V_m : velocity of the moving medium (gas)

φ : angle between acoustic path and a vector representing the direction in which the medium moves

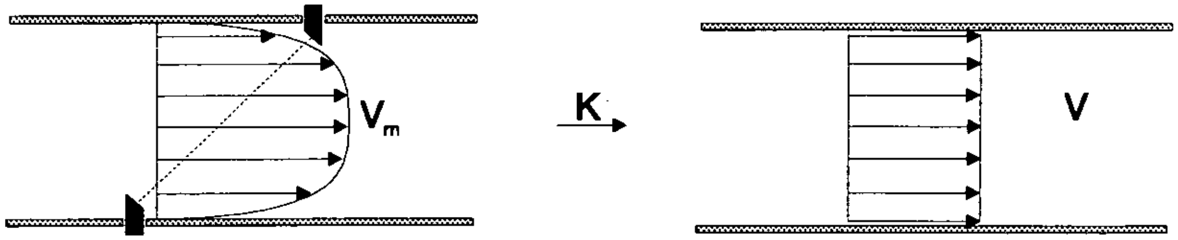
Using (1) and (2) the following expression for the measured gas velocity can be derived:

$$V_m = \frac{L}{2\cos\varphi}\left(\frac{1}{t_{down}} - \frac{1}{t_{up}}\right) \qquad (3)$$

Important to notice is that the speed of sound in the gas is eliminated in this expression. This means that the measurement of the gas velocity is independent of the gas properties such as pressure, temperature and gas composition..

Flow measurement with single path meters

To measure the gas volume flow the gas velocity must be multiplied with the cross section of the pipe. When the gas velocity is equal over the whole cross section, i.e. has a uniform flow profile, the flow calculated in this way would be the exact value. As this is not the case by law of nature we need to correct with a factor K which is related to the shape of the flow profile.



$$V = V_m \cdot K \cdot$$

Figure 2: Flow profile correction factor

V_m represents the average gas velocity as perceived by the ultrasonic flow meter. This is the linear weighted gas velocity averaged along the acoustic path.

This results in the following expression for the gas flow:

$$Q = \frac{L}{2\cos\varphi} \cdot A \cdot K \cdot \left(\frac{1}{t_{down}} - \frac{1}{t_{up}} \right) \tag{4}$$

where

A : cross section of the pipe
K : flow profile correction factor

From studies, literature and our own research, Instromet established a relationship between the Reynolds number and the flow profile correction factor (also referred to as Reynolds factor) K, which is shown in figure 3.

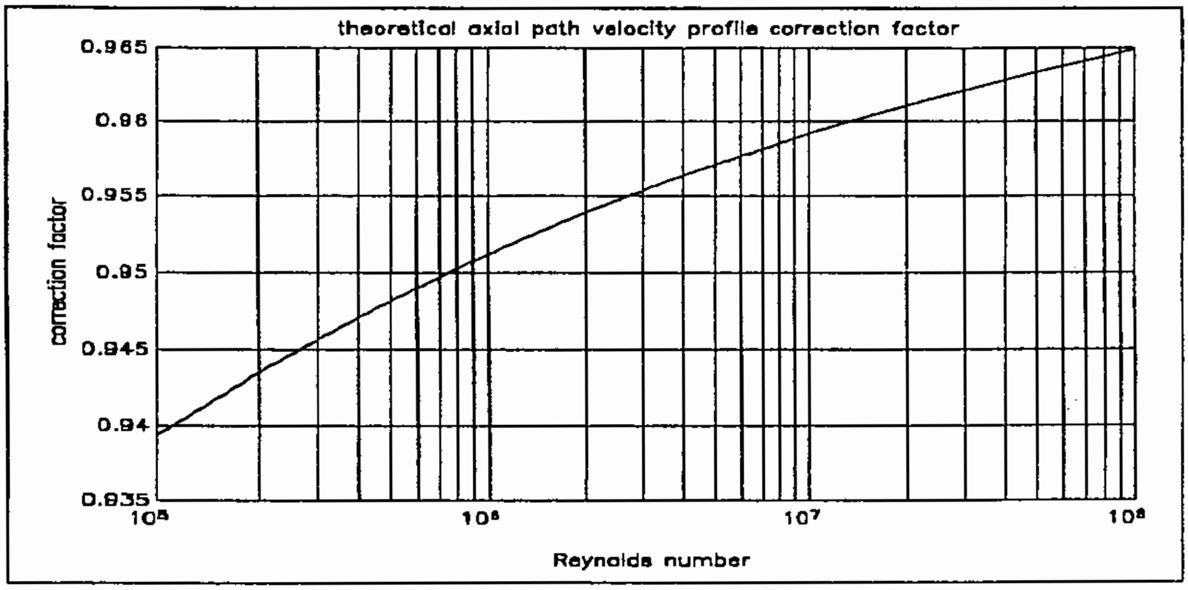


Figure 3: Graph of profile correction vs. Re

This is applicable to a single path meter with an acoustic path through the center of a circular pipe. Dependent on practical circumstances, the flow profile may show some variation resulting in an uncertainty in the flow profile correction factor K. This uncertainty can be estimated based on the residual errors as observed in numerous tests, as shown in figure 4. From this graph it appears that a realistic estimate for the uncertainty in the Reynolds correction factor for a single path meter would be approximately 1 %.

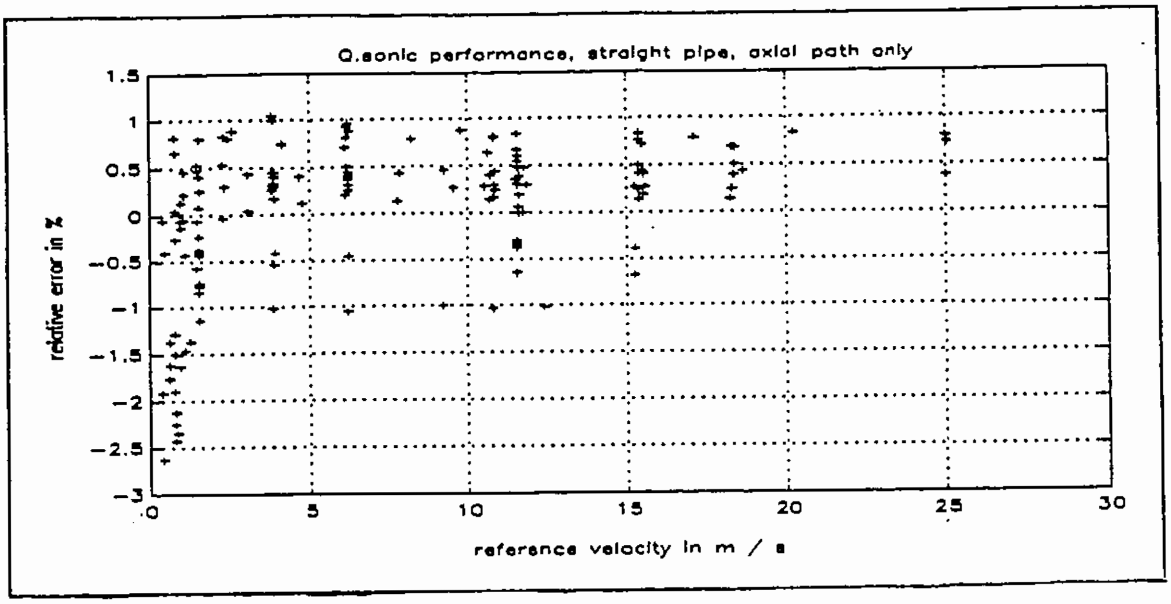


Figure 4: Graph of profile correction error of single path us meter

Flow measurement with multi path meters

Custody transfer applications typically require the use of multi path meters. The reason is the uncertainty of the profile correction factor for a single path meter is not acceptable for custody transfer applications. Multi path ultrasonic flow meters, by implementation of integration techniques, allow to use the data of multiple acoustic paths to improve the accuracy of the flow profile correction. Formally this can be represented with the following expression.

$$Q = \left\{ \frac{L}{2\cos\varphi} \cdot A \cdot K \cdot \left(\frac{1}{t_{down}} - \frac{1}{t_{up}} \right) \right\} \cdot F \qquad (5)$$

This expression is identical to that of a single path meter except that the part between brackets $\{\ \}$ represents the integration using all acoustic paths.

This expression also includes a multiplier, (F) which represents a correction factor. This correction factor typically has a default value of approximately 1 but can be adjusted based on a flow calibration of the meter in order to minimize the meter error.

DRY CALIBRATION

A dry calibration of a flow meter is not a calibration in the proper sense of the word, since it is not a check of the result - the measured gas volume / flow - based upon comparison with a standard or reference device and if necessary followed by an adjustment. The word “verification” would be more appropriate .

Similar to orifice practice a (dry) calibration of an ultrasonic gas flow meter is based on:

a) verification of geometry
b) measuring differential pressure or travel time differences
c) using tables, equations or mathematical expressions to relate a gas flow to the measured variable.

Ad a) The relevant geometry parameters can be measured for an ultrasonic gas flow meter just as accurate as for an orifice meter. Further, for an ultrasonic gas flow meter, the impact of geometry uncertainty can be assessed and analyzed completely, using fairly simple mathematics, as will become apparent in the following section.

Ad b) It should be appreciated that, using state of the art electronics and good quality quartz oscillators, time measurements can be performed with excellent accuracy and stability, equal or superior to differential pressure transmitters. As an example that demonstrates the basic stability of Instromet's ultrasonic gas flow meters figure 5 is included. This figure shows two error curves:

- one as found initially when the meter was new
- one approximately 2 years later and after the meter having been in service.

Due to the requirements of the application this meter was only calibrated over the low and of its range. It shows very good reproducibility; some more variation (normally random) at the very low flow end is normal and acceptable.

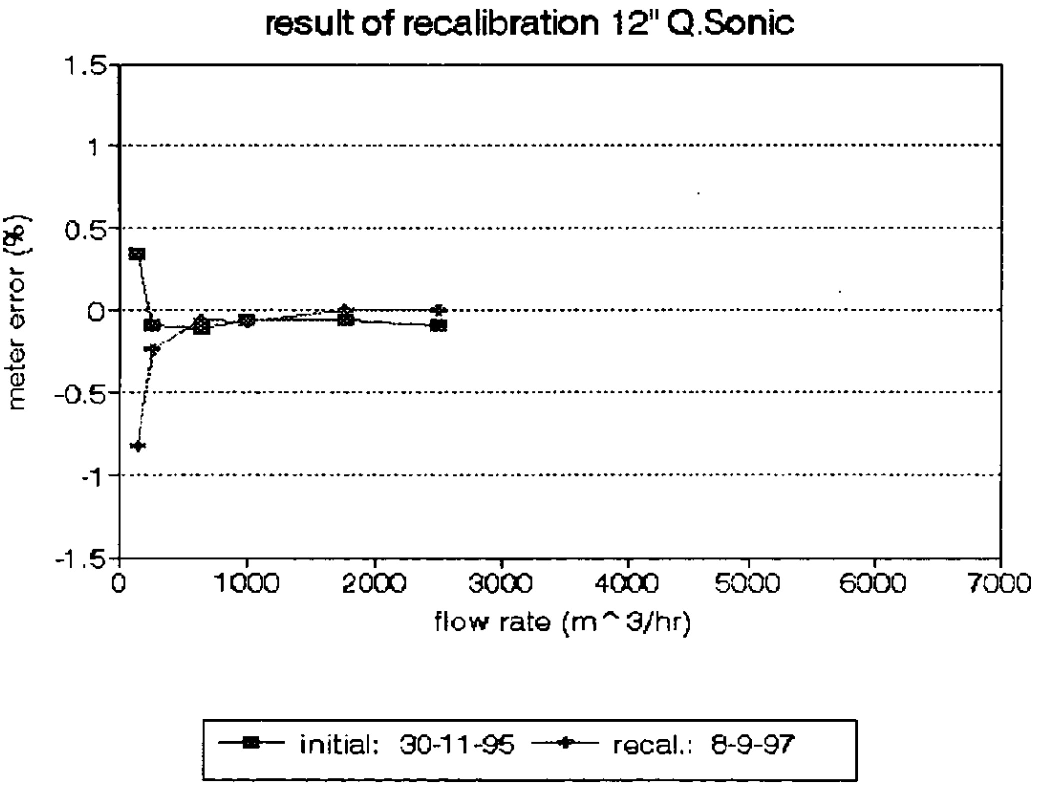


Figure 5: two error curves

Ad c) Discharge coefficients for orifices and profile correction factors for ultrasonic gas flow meters are based on research. For the ultrasonic meters manufactured by Instromet a fast growing database of empirical data is available. Some statistical results will be presented in the following sections.

UNCERTAINTY OF DRY CALIBRATION

As a general basis for the concept of dry calibration we will investigate the uncertainty in the measured gas flow (volume or flow rate). Using equation (5) we can calculate the impact of the uncertainty of each individual parameter or measured value with respect to the uncertainty of the measured gas flow. In this section we will examine the contribution of these individual parameters and measured values.

The parameter F is a correction factor used only when, - based on a flow calibration-, the reading of the meter is adjusted. In case of a dry calibration this parameter is set to its default value, based upon experience with numerous flow calibrations. In case of a dry calibration this parameter is a constant, therefore it is not associated with uncertainty. This may appear to be a contradiction, since based on a flow calibration this variable may have assigned a value that is different from the default value. However, in case of a flow calibration, this parameter corrects (compensates) the error due to all other parameters and variables. The data presented in this paper is based upon the results of numerous flow calibrations of ultrasonic meters. As a result of these flow calibrations the default value of the correction factor F is adjusted. Since the variation in the correction factors as found reflect the uncertainty due to the geometry and dimension parameters resulting from the manufacturing procedures as currently used as well as the other sources of uncertainty, the frequency distribution of this adjustment factor is a good tool to verify the overall uncertainty for meters manufactured without flow calibration.

Uncertainty of profile correction factor

The Reynolds (profile) correction factor for a single path meter is estimated, based on the graph as presented in figure 4, to have an uncertainty of ± 1.0%. Based upon Instromet's research and test results with Instromet's multi path meters and the path configuration as implemented, we estimate the uncertainty of the Reynolds (profile) correction factor to be approximately 0,3% for a 5 path meter and approximately 0,4% for a 3 path meter.

Uncertainty due to meter body geometry and dimensional variations

As far as the geometry and dimension of the meter body is concerned the relevant parameters that have an impact with respect to the accuracy of an ultrasonic flow meter are (as can be seen from equation 5) :

L : acoustic path length
φ : angle of acoustic path
A : cross section of the pipe

The acoustic path parameters are related to the position of the front side of the ultrasonic transducers, the surface that emits and receives the ultrasound pulses. This position is determined by means of the nozzles (parts marked (C) in figure 6) where the transducers are installed, in particular the center point (figure 6 (3)) of the face of the nozzle, that is used as a reference point.

In order to assess the uncertainty of the acoustic path parameters we need to take a closer look at the manufacturing process. For simplicity we will look at a single reflection path and use the dimensions of a 16" size meter body as an example.

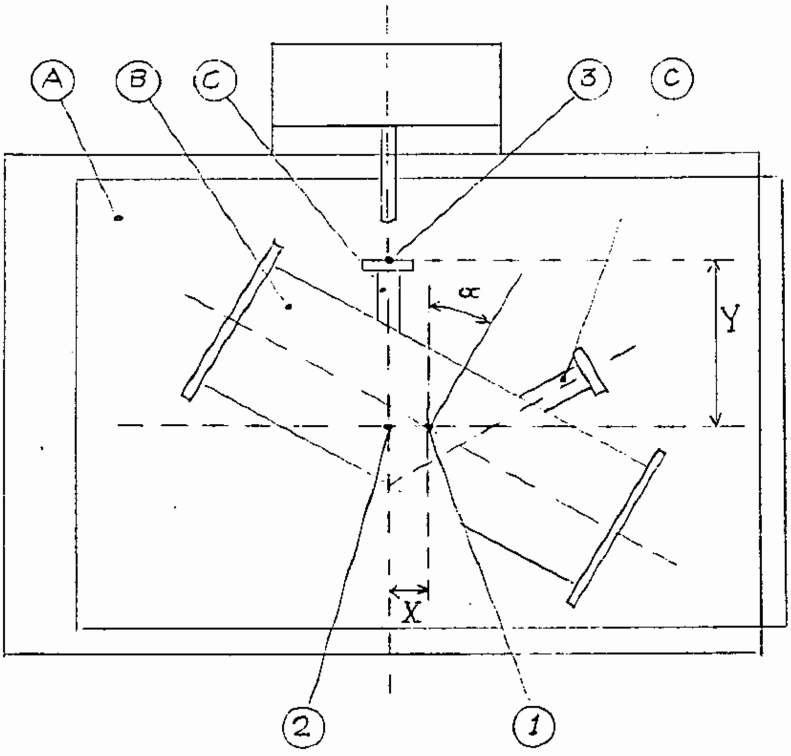


Figure 6: set up for meter body machining

Figure 6 shows a meter body (B) as installed on the support of numerical controlled machining equipment (A). Initially the meter body is positioned so that the center of the body (1) is aligned with the reference point (2) of the machining equipment, having coordinates (0,0).

In order to manufacture the meter body, in particular to machine nozzle C to the dimensions as required, the meter body is rotated over an angle α and the reference point of the front of the nozzle (3) is defined and machined using coordinates X and Y. X represents a translation of the support and Y represents the distance of the nozzle face with respect to the reference point (0,0) of the machining equipment.

These machining parameters are calculated before the machining operation starts and checked during the manufacturing process of each meter body. The result is reported in a certificate provided by the machine shop. Certification of the accuracy of this data and traciblity with respect to national standards, by an independent body, is an option. Based on the machining parameters as reported, the actual path lengths and angles are calculated.

Data applicable to a 16" Q.Sonic used as an example are as follows:

Nominal bore is	406,4 mm
For a single reflection path applies:	
Nominal path angle is	60 degrees
Nominal path length is	469,27 mm

The reference point of the nozzles for the transducers is defined as:

angle : 60 degrees
X : 101.60 mm
Y : 293.29 mm

We estimate that the value of these parameters as realized and reported are subject to an uncertainty as:

angle : ± 0.05 degree
X : ± 0,1 mm
Y : ± 0,1 mm

For the uncertainty of the inner diameter we assume a practical value of ± 0,2 mm, although, depending on manufacturing technology this can be improved when necessary.

The contribution of each parameter's uncertainty can be calculated according to equation (5) as:

path length L : ± 0,06 %
1/cos φ (path angle) : ± 0,15 %
cross sectional area A : ± 0,1 %

When all these factors add up to a worst case situation, the uncertainty due to the meter body geometry and dimensions would be ± 0,3 %. However, since each of these contributions are due to independent sources of error, the total error calculated according to the root mean square rule as 0,2% is more appropriate.

Uncertainty due to time measurement

The uncertainty due to the measurement of the travel times can be assessed by distinguishing (similar to DP transmitter practice) between the zero reading and gain errors.

The zero error is related to the resolution of the travel time measurements and small offsets in the travel time measurement. This could introduce a travel time difference being measured even when the gas flow velocity is zero. From equation (4) it can be derived that the following expression is applicable:

$$\delta V = \frac{C^2 \cdot \delta t \cdot \tan(\varphi)}{4D} \qquad (6)$$

where

D : meter body inner diameter
C : speed of sound in the gas
φ : acoustic path angle
δt : error in differential time measurement
δV : error in measured gas flow

The uncertainty in the travel time measurement is at maximum 10 ns. In this example (16" meter body) and using:

C = 400 m/s
D = 0,4 m
φ = 60 degrees
the resulting uncertainty is calculated to be 1,6 mm/sec (gas velocity!)

Using the gas velocity range that can be handled with our ultrasonic flow meters (maximum gas velocity 30 m/s) this can be converted to a relative value (percentage). The next figure (7) presents a graph showing the absolute error (gas velocity error in m/s) and the relative error (in %) as a function of the gas flow. In order to be also applicable to smaller meter sizes the value for the absolute gas velocity error in this figure has been taken as 5 mm/s.

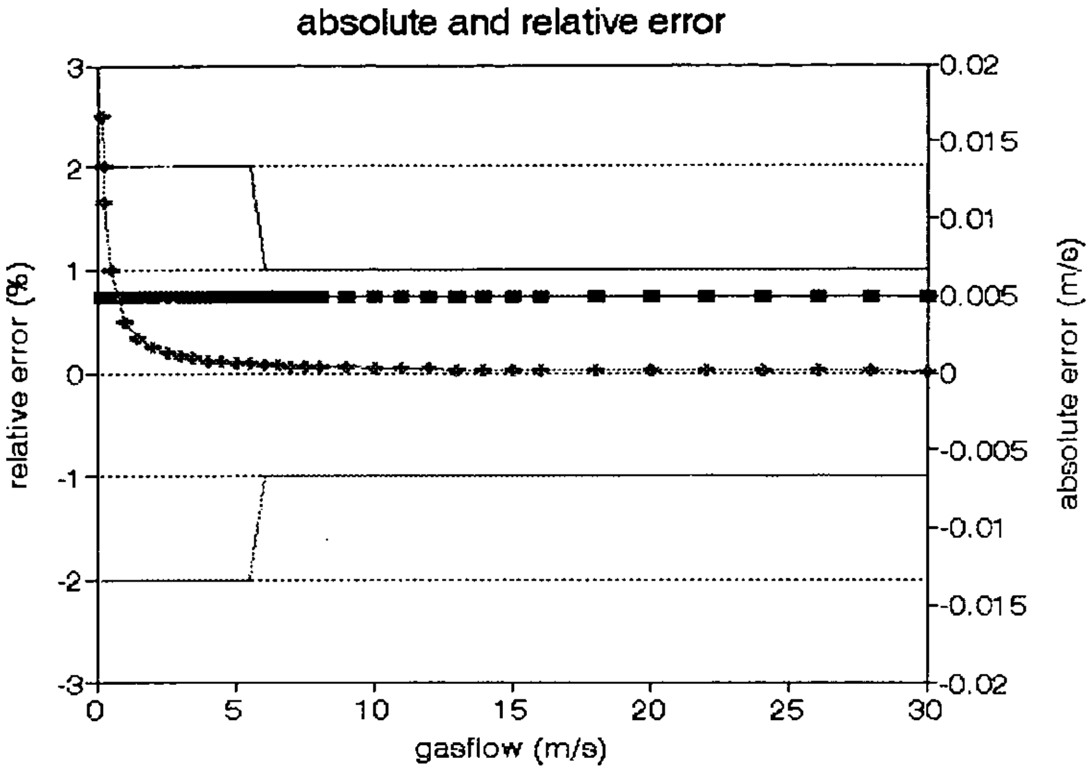


Figure 7: absolute and relative error due to travel time uncertainty / offset

This graph shows clearly that the uncertainty of the travel time measurement is the dominant factor at low flow rates. This imposes a limitation on the low side of the operating range but has no significant effect in the normal operating range.

The travel time measurement is related to a clock signal. When this clock is fast or slow it would have a proportional impact with respect to the measured gas flow. However since this clock is a high stability quartz clock (accuracy ± 50 ppm or 0.005 %) this can be ignored.

Total meter uncertainty

In the previous sections it has been shown that the significant sources that contribute to the total measurement uncertainty of an ultrasonic flow meter are:

Flow profile correction factor K	± 0,3 %
Meter body geometry (rms)	± 0,2 %.

Worst case the combination of both sources of uncertainty would result in a total uncertainty of 0,5 %. Since these are independent sources of uncertainty it is justified to estimate the total uncertainty using the square root rule to calculate total uncertainty as

$$\sqrt{0{,}3^2 + 0{,}2^2} = 0{,}36\%$$

This number is of the same order of magnitude as the uncertainty of the best flow calibration facilities (0,25 - 0,3 %).

Flow calibration results

From many calibrations we calculated the frequency distribution of the magnitude of the adjustment that appeared to be necessary in order to center the meter error around the zero line. This frequency distribution is presented in figures 8 up to and including 11. These graphs confirm the calculated uncertainty to be approximately 0,5 %. Figure 8 presents the frequency distribution of the adjustments for all sizes of meters.

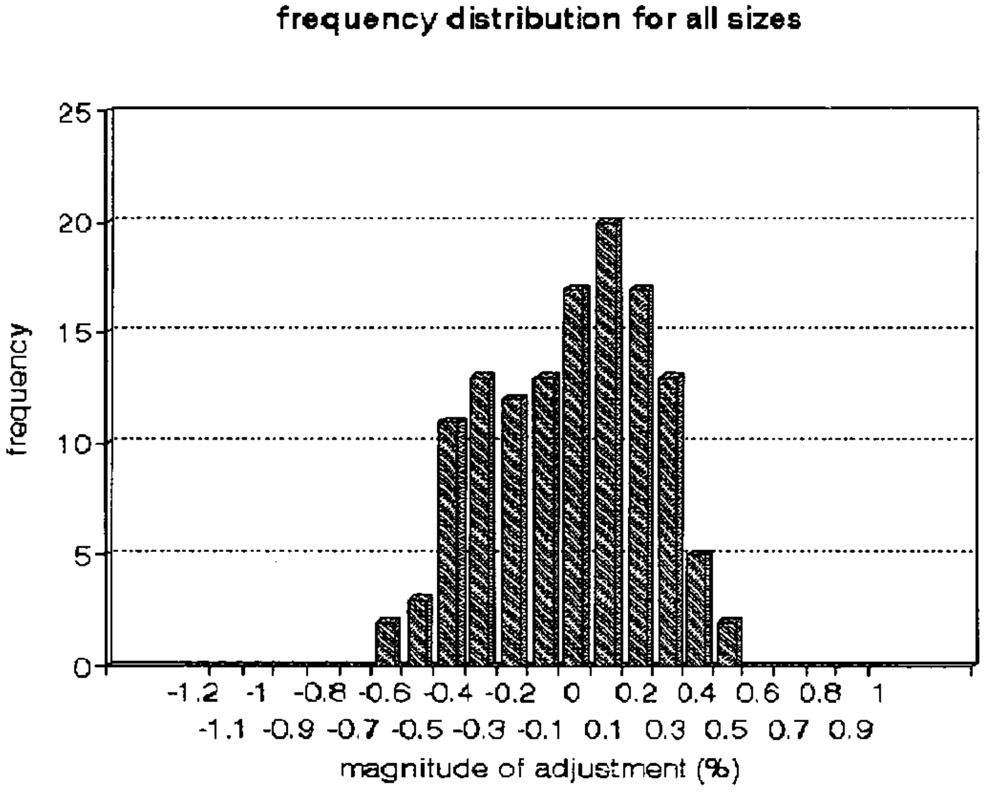


Figure 8: frequency distribution of meter adjustment for various sizes

Figure 9 presents the frequency distribution of the adjustments for meters of 12" nominal size.

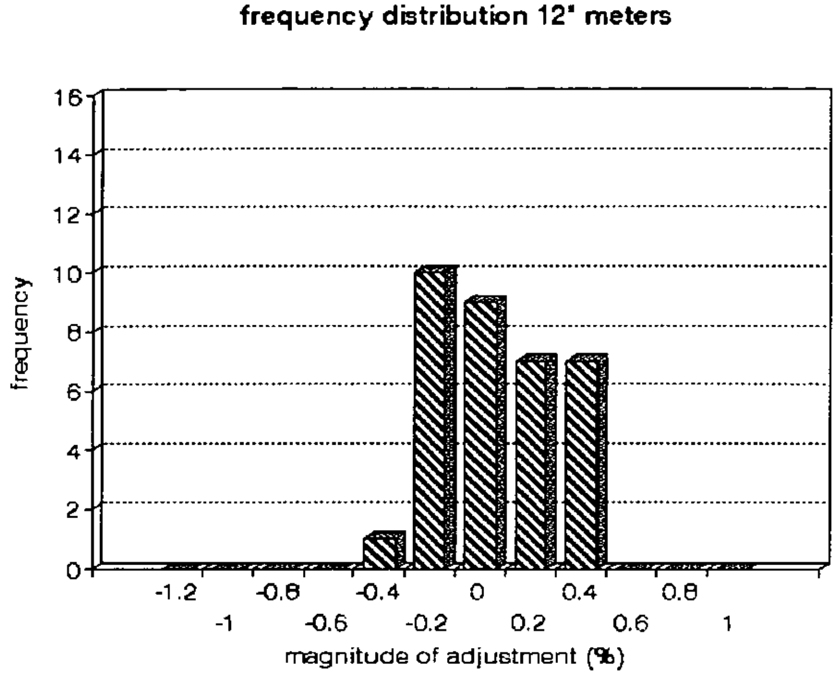


Figure 9: frequency distribution of meter adjustments for 12" meter

Figure 10 presents the frequency distribution of the adjustments for meters of 16" nominal size.

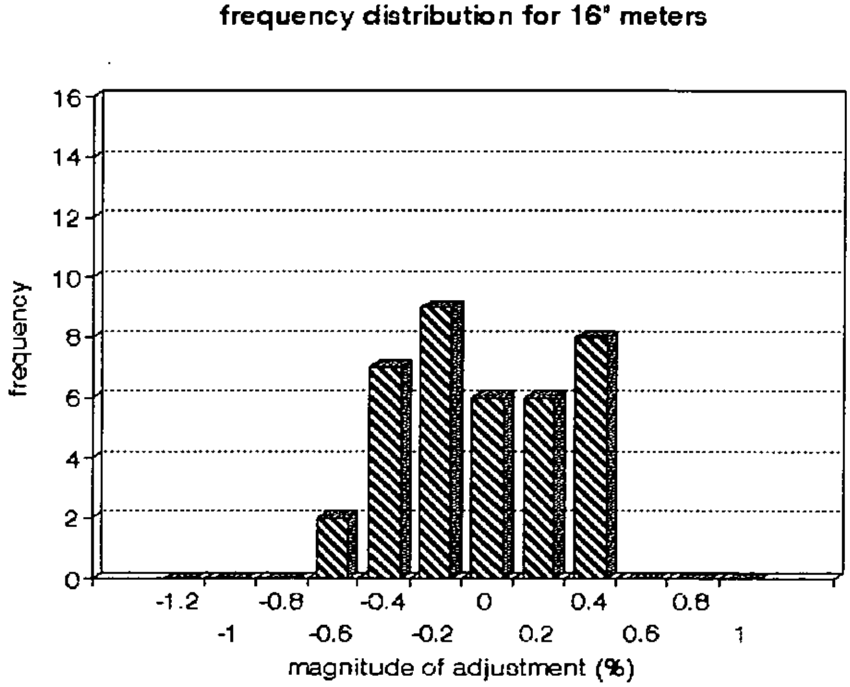


Figure 10: frequency distribution of meter adjustments for 16" meters

Figure 11 presents the frequency distribution of the adjustments for meters of 20" and 24" nominal size.

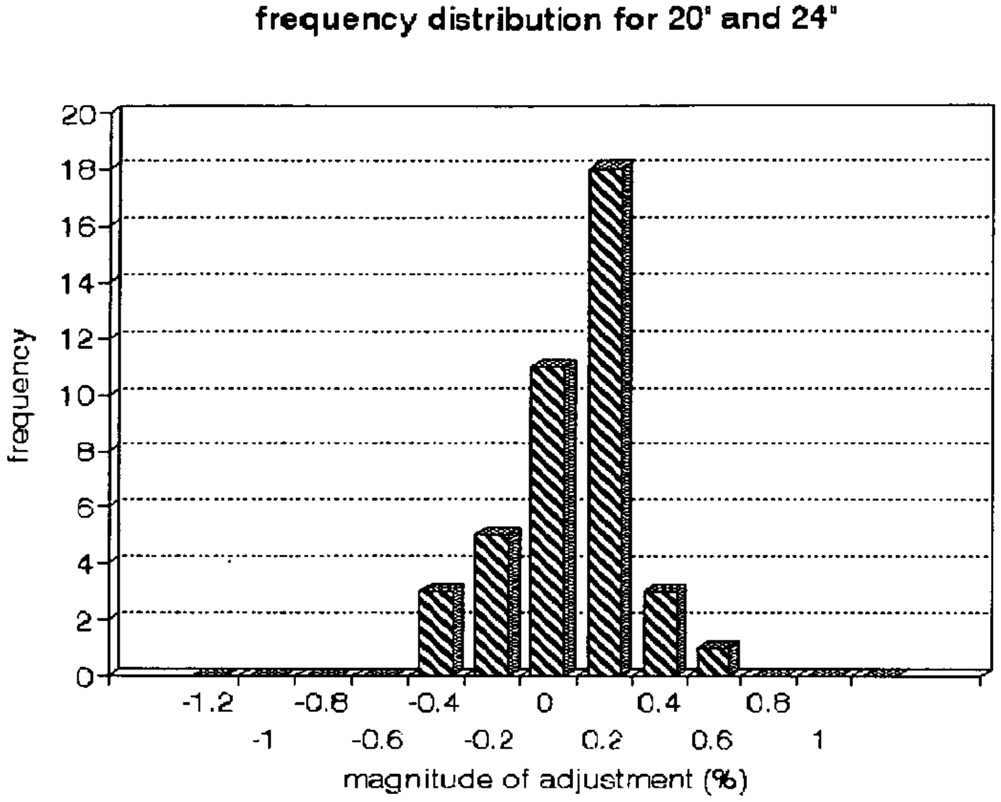


Figure 11: frequency distribution of meter adjustments for 20" and 24" meters

The preceding graphs (figures 9, 10 and 11) show that the frequency distribution of the adjustments is consistent for various nominal sizes. This confirms that the concept of dry calibration, using the calculation methods as implemented in the nominal sizes that have been tested, may be extrapolated to larger sizes as well.

The fact that mainly the geometry and dimensional parameters are determining the accuracy and uncertainty of our ultrasonic meters is further illustrated by the graphs in figures 12 and 13. Both graphs apply to a series of identical meters that have been manufactured in one batch.

Figure 12 shows the calibration result of 6 16" 5 path ultrasonic meters (Q.Sonic) before any adjustments have been made. The meter bodies (spoolpieces) are manufactured as one batch. The electronics and transducers are taken at random from our production and assembled with the spoolpieces.

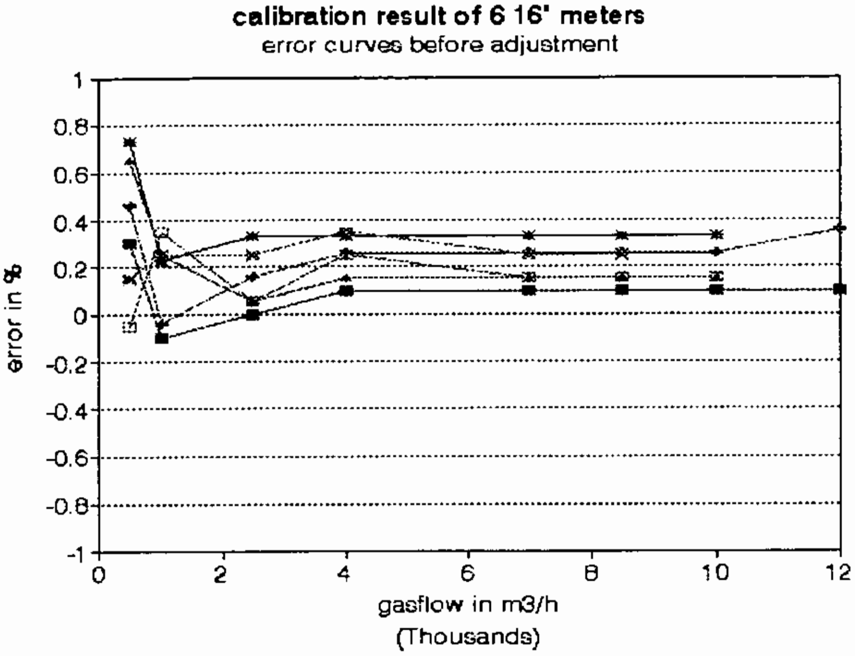


Figure 12: error curves of 6 16" meters (before adjustment)

Figure 13 shows the magnitude of the adjustment of a series of 20" meters.

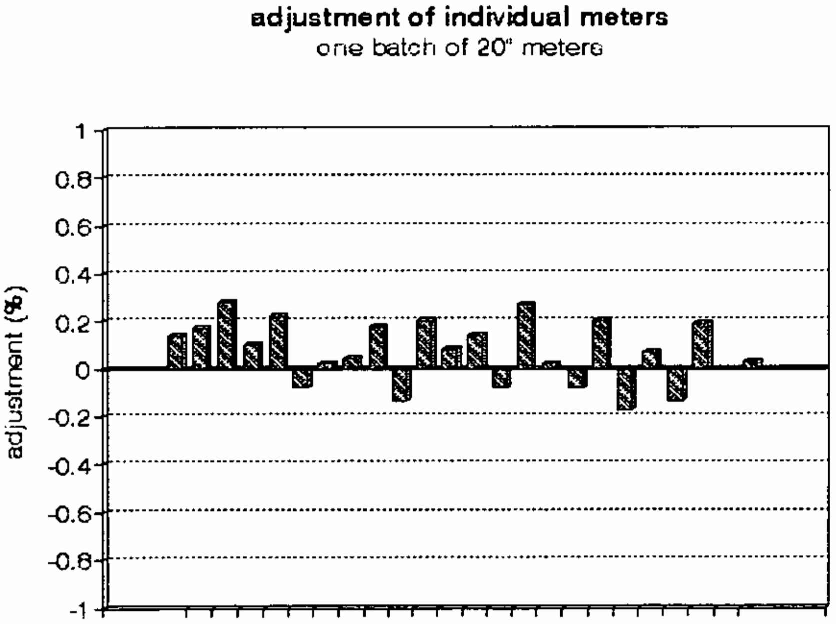


Figure 13: meter adjustment for a batch of identical meters

Both figures (12 and 13) demonstrate that the spread in the average error of individual meters due to manufacturing tolerances is in line with the rms value of ± 0,2 % as calculated before.

DRY CALIBRATION PROCEDURE

In order to implement the concept of dry calibration for our ultrasonic flow meters, Instromet has developed an extensive dry calibration procedure. In this section we will discuss some of the essentials of this procedure.

In the preceding sections it has been shown that geometry and dimension of the meter body and the Reynolds (profile correction) factor are the relevant sources of uncertainty.

The meter body geometry and dimensions reflect in the acoustic path geometry and are calculated using the data reported in the protocol provided by the machine shop where the spoolpiece is manufactured.

When the electronics and ultrasonic transducers are installed on the meter body to complete the ultrasonic gas flow meter, a function test is performed. This test verifies that the meter performs well with respect to all its functions, such as emitting, receiving and detecting ultrasonic sound pulses and the accuracy of the travel time measurement by means of a check of the frequency of the quartz clock.

Further this function test includes a zero flow test and a check based on the measured sound velocity in the gas. In order to perform these tests the ultrasonic gas flow meter is fitted with blind flanges and pressurized with compressed air or nitrogen.

Zero check

Since the meter is fitted with blind flanges, there cannot be any gas flow, and the gas velocity observed on all the acoustic paths should be zero. This test can also be performed with an ultrasonic gas flow meter installed in a practical application, provided that the meter can be isolated. However utmost care should be taken to avoid misleading results since it is our experience that isolation valve are not always perfect and small leakages create minimal but measurable gas flows. Also thermal driven convection currents may easily appear and be perceived as a gas flow.

Speed of sound check

The speed of sound check can be performed as either a function check or a verification. When the meter is to be flow calibrated a function check is sufficient and the check can be performed with compressed air as medium.
For the purpose of verification (dry calibration) the meter needs to be checked with a gas of a known composition, nitrogen is a practical choice. Further accurate temperature and pressure measuring devices must be installed in order to enable a precise calculation of the expected speed of sound at the pressure and temperature at hand. Sufficient time should be allowed in order to reach a state of thermal equilibrum.

The observed speed of sound compared to the expected value will reveal any error in the acoustic path length or the travel time measurement, whereas the latter is highly unlikely since the frequency of the quartz clock has been checked before this test.

The speed of sound of individual acoustic paths may show some variation, but the averaged value is very close to the expected value. Typically the observed value and the expected value agree as close as 0,1 %. This test may be performed in practical applications as well, but it is most critical to know the exact gas composition at the time of the test. Also accurate temperature and pressure measurements are a prerequisite.

CONCLUSION

As presented the concept of dry calibration can be applied to our ultrasonic gas flow meters in very much the same way as with calibrations of orifice meters. Based on the uncertainty analysis in this paper and supported by the results of flow calibrations the uncertainty is of the same order of magnitude of that of the best test facilities. We consider it justified to claim that the concept of dry calibration applied to our ultrasonic gas flow meters is feasible in order to assure the accuracy of the meter as specified. Based on the test results available the concept of dry calibration may as well be extrapolated to larger sized meters.

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.