Reducing installation effects on ultrasonic flow meters

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1. Introduction

Over the past decennium, Ultrasonic flow meters have gained rapidly a wide acceptance. Main reasons for this are the high repeatability combined with zero pressure loss and extended diagnostic features. During this period meters with different path configurations have been put into the market, each of them trying to obtain the highest accuracy and a multiple of papers have been published on the performance of these meters at the calibration laboratories. Many of them show (often after multipoint linearization) almost ideal straight lines with errors close to the repeatability of the lab.

However, for a user the key question is not how good the meter is at the lab, but what is the accuracy after installation in the field and how can he be sure that the meter's performance is not deteriorating over time. This has been recognized by the coming ISO 17089 standard and also – to a lesser extend - by the AGA9. In the ISO in chapter 6.4 it is mentioned that: "*A meter calibration curve without the guarantee that the meter behaves the same way in the field as in the calibration laboratory is meaningless whereas real world circumstances are generally more complex than those encountered at a calibration facility"*.

In order to ensure that the quality of the calibration curve is transferable to the field, in the ISO 17089 type testing is introduced. There real world circumstances are simulated by series of perturbations tests and the meter has to prove that it can deal with these.

The present paper addresses these items, discusses the flow profile distortions that may occur in real world pipe configurations and present an analyses on the performance of various path configurations. Based on this an optimal path configuration is proposed as well as the test results obtained testing the meter according to the ISO 17089 perturbations as well as those requested by the OIML137-1.

2. Ice berg specifications

When a user is looking for the specifications of ultrasonic flow meters, despite the fact that there are clear differences in their design, the performance of all of them look the same, having specifications such as:

Uncertainty	**≤ ±0.5% of measured value, uncalibrated**
	≤ ±0.2% of measured value, high-pressure flow calibrated (relative to calibration laboratories)
	≤ ±0.1% of measured value, calibrated and linearized
Repeatability	**≤ ±0.1%**

Table 1: The ice berg specifications

What is missing in all of the datasheets are:

1. the transferability of the calibration curve obtained under almost ideal conditions (see figure 1) from the laboratory to the actual conditions in the field (see figure 2.; the installation effects).
2. The impact of the residual condensates and dirt in the gas that affect the conditions at the inside of the meter.

Figure 1: Ideal conditions at a calibration facility. (courtesy of TCC)

Figure 2: Actual conditions in the field.

The transferability of the calibration curve to the field has been investigated, amongst other by T. Grimley (see ref. [4]) and dependentb on the path configuration might lead to installation errors in the order of 0,5% .

The residues of condensates and dirt affect the conditions at the inside of the pipe; notably the cross sectional area and the flow profile. During flow calibration (figure 3) the meter is clean but in operation, after 3 month or 6 months, the meter might be contaminated (see figure 4). The introduced additional uncertainty can easily reach 0,5%; an error which is of the same magnitude as the installation effects.

Figure 3: A clean ultrasonic meter prior toa calibration.

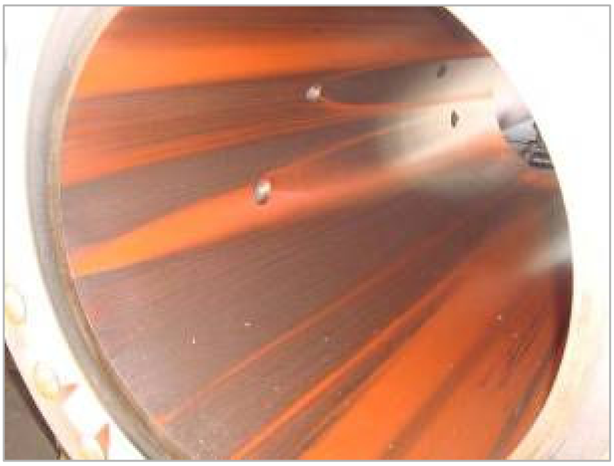


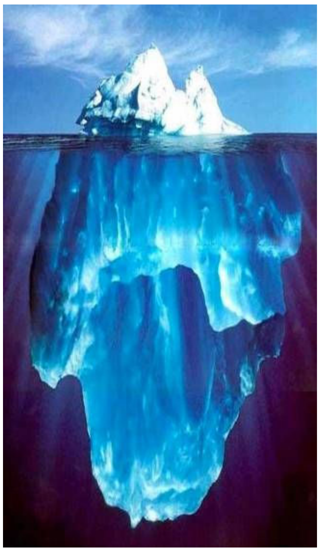
Figure 4: A dirty meter during visual inspection.

The resulting total uncertainty is therefore much larger than the one stated in the datasheet. So in effect, by hiding vital information, the specifications shown in the manufacturer's datasheets are just *Ice berg specifications!*

Figure 5. Typical marketing view, not showing any of the possible inconsistencies with the required specifications.

The real specifications are hidden below the surface; specifications such as:
- The sensitivity to installation effects
- The impact of contamination.

For these reasons, i8n designing the new meter emphasis has been put on reducing the installation sensitivity as well as the detection of fouling.



Uncertainty	**Previous design**	**KROHNE V12 Target**
Due to Meter: Non-linearity, Repeatability	0,15%	0,15%
Due to Installation effects	0,5%	0,2%
Due to possible contamination	0,4%	0,1%
Total √	0,65%	0,25%

Table 2: Real total uncertainty estimation

3. Variations in fouling

Fouling is one of the major concerns of additional uncertainty. This is not only a problem for ultrasonic meters, but it will affect any flow meter installed. The great virtue of ultrasonic flow meters in contrast to all other meters, are their huge diagnostic capabilities. When rightly designed, using the diagnostics, the operator can obtain detailed information on the quality of the measurement.

Looking at fouling, one of the main problems of it is the variety in its manifestations. To show this, in figures 6 to 8 some examples of excessive fouling and pipe conditions are presented. The first one is the result of a production problem, the second one is an example of an off-shore installation and the third one is an on-shore installation.

Figure 6, fouling as a flow on the bottom of the pipe.

Figure 7, fouling intermittently stuck to the pipe wall

Figure 8, fouling evenly distributed over the pipe wall

Looking at the impact that it can have on ultrasonic meters, fouling can be classified into 5 categories; each of them affects the measurement in a different way.

These categories are:

1. Fouling as a small flow on the bottom of the pipe.
2. Fouling intermittently sticking to the pipe wall.
3. Fouling which is as an evenly distributed coating on the inside of the pipe.
4. Fouling as dirt build-up on the transducers (especially on those facing upstream).
5. Fouling as liquid build-up in the transducer pockets.

For ultrasonic flow meters, the major effects of fouling on the measurement are:

- A reduction of the cross sectional area.
- An increased wall roughness.
- The shortening of the acoustic path length.
- The attenuation of the acoustic signal through the reduction of the reflection coefficient.
- The absorbance of the ultrasonic signal due to the layer of fouling on the transducer..
- Increased cross talk when liquid is present in the transducer pockets.

Dealing with fouling

In order to guarantee the quality of the measurement, performance monitoring and especially the detection of fouling has been one of the key elements in the design. The description on how to deal with the fouling follows the sequence of 1- 5 stated above.

3.1 : Fouling as a small flow on the bottom of the pipe

Such a type of fouling can be detected by using a vertical reflecting path. The stability and ability to detect this depends on the viscosity, the density of both the fluid and the gas, as well as the flow velocity.

In wet gas applications the wetness of the gas can be characterized by the so-called Lockhart-Martinelli parameter. This LM parameter, which is equal to the ratio between the Froude numbers of the liquid and the gas, reflects the driving force of the gas to move the liquid and is thereby an indicator for the wetness of the gas.

As an equation:

$$LM = Lockhart\ Martinelli = \frac{Fr_{liquid}}{Fr_{gas}}$$

$$whereby:$$

$$Fr_{liquid} = \frac{v_{sl}}{\sqrt{g \cdot D}} \sqrt{\frac{\rho_{liquid}}{\rho_{liquid} - \rho_{gas}}}$$

$$Fr_{gas} = \frac{v_{sg}}{\sqrt{g \cdot D}} \sqrt{\frac{\rho_{gas}}{\rho_{liquid} - \rho_{gas}}}$$

In these equations is:

- ρ the density
- g the gravitational constant
- D the inner pipe diameter

In principle three different flow regimes can be distinguished as a function of the flow velocity:

1. At lower flow velocities and at higher viscosities, there is a more or less stable stratified liquid layer at the bottom of the pipe. This layer can be detected (and possibly corrected for), using the relative change in the speed of sound of the vertical path in comparison with the other paths.

2. At increasing flow velocities the stratified layer will first become wavy and later been dispersed as a liquid film over inner side of the pipe wall. This process can be monitored by looking at the - from bottom to top - increasing fluctuations of the speed of sound and speed of sound ratio's.

3. At still higher velocities, the fluid will be dispersed as a mist which travels at the same velocity as the gas. Whereas in this case the liquid directly replaces the gas, the associated error in the measurement is now in the same order as that of the percentage of gas being replaced.

When designed for wet gas applications, ultrasonic flow meters should be able to handle wet gas flows up to LM=0.3; a figure that is generally been accepted as the maximum value for wet gas at a production site. The Liquid Volume Fraction (LVF) associated with this number is presented in figure 9.

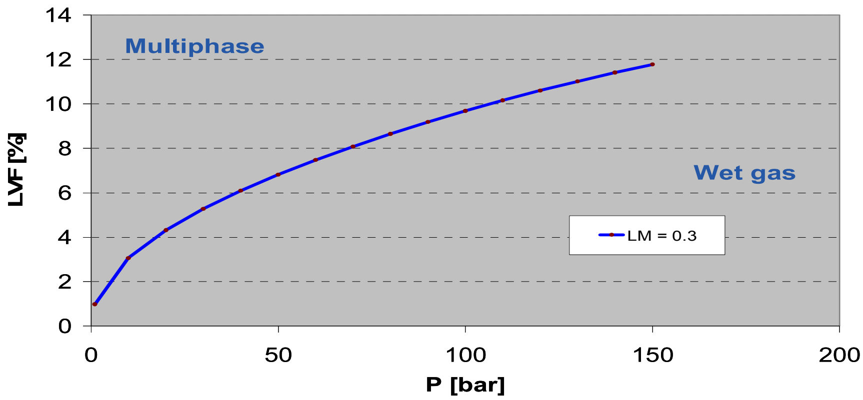


Figure 9 Liquid Volume Fraction as a function of the pressure at LM=0,3

Especially at the higher LM levels, additional information regarding the fluid properties inside the pipe are required for making an estimation on the flow regime.

3.2 : Fouling intermittently sticking to the pipe wall.
The fouling intermittently stuck to the wall is slowly moved forward by the gas through the pipe. How quickly it moves is dependent on the gas flow velocity, its density and the characteristics of the fouling itself. Therefore in practice it is not possible to predict when it will be present at a certain position in the pipe but it is certain that eventually every single point in the pipe will be affected over time.

Using reflective paths, this type of fouling shows an irregular behavior in the speed of sound readings as well as the AGC readings of the various paths. Also the average wall roughness is affected, resulting in a changing average velocity profile.

3.3 : Fouling which is as an evenly distributed coating on the inside of the pipe
This type of fouling, such as the black powder found in many pipes in the southern parts of the USA, is more difficult to detect and trending is necessary. Important trending functions for this are:

- the ratio between the speed of sound of paths with different path lengths
- the flow velocity ratio of the various paths

With the wall build-up being the same for all the paths, the relative impacts for paths of different lengths will be different. With increasing build-up there will be an increasing deviation in the average speed of sound from the different paths. When a gas chromatograph is present, also the absolute speed of sound can be calculated and an estimation of the thickness of the layer can be made.

The build-up affects also the wall roughness, which results in a gradual changing flow velocity profile. Dependent on the path position, there are differences in how much the path is affected:

- the path through the middle of the pipe is the most sensitive to profile changes (and therefore essential in the detection)
- in contrast to this, the paths on half radius chords are highly immune to wall roughness changes.
- The impact on the path close to the wall is very much dependent on its relative position, but different from the others.

As a result, the changes in the flow velocity profile can be detected by monitoring the trending the flow velocity ratio's of the paths close to the pipe wall and the path through the middle of the pipe in respect to the half radius paths.

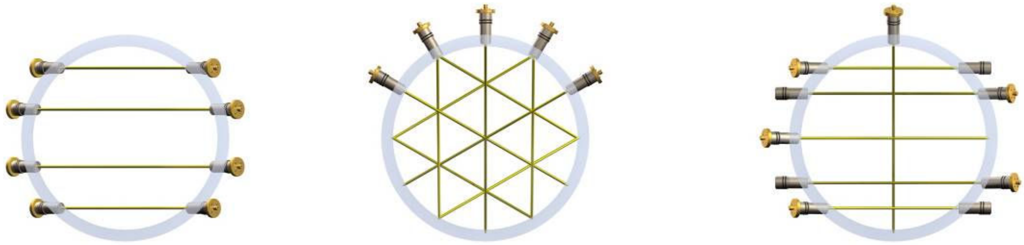
3.4 : The fouling on the transducers
The fouling of the transducer shortens the travel time in the same way as the evenly distributed coating on the wall, but next to that, it also lowers the signal strength. Detecting it is done by looking at the combination of these two parameters and trending those over time. Also a first order estimation of the total thickness of the layers on the 2 transducers can be made.

3.5 : Contamination of the transducer pockets
This category of fouling affects the shape of the acoustic waveform, the signal-to-noise ratio and results in an offset at the lower flow velocities. This category of fouling is difficult to detect and has to be done in the signal processing part.

4. Meter design

When designing ultrasonic meters the development engineer has a variety of possible path configurations. In here there is a mayor distinction between reflective and non-reflective paths. Some examples are presented in figures 10 A and 10 B. Krohne's new path configuration is presented in figure 10C.

A. Non reflective parallel chord designs
B. Reflective chord designs
C: The new Krohne V-12 reflective path arrangement



A **B** **C**

Figure 10: Conventional parallel chord design (**A**), conventional reflective chord design (**B**) & the Krohne V12 design (**C**)

- Whereas strait parallel path designs miss the reflection and thereby the ability for the interrogation of pipe; their benefit is the possibility to measure close to the pipe wall.
- In contrast to this, the conventional reflective chord design is able to measure wall built-up, but it's triangle shaped path cannot get closer to the wall than the 0.5R position; a position that is too far away to be able to deal effectively with changes in the flow profile close to the wall.

The optimal solution is the combination of both technologies*: the new KROHNE V12 design*.

In designing the new meter, the primary goal for the developments was: *The assurance for a customer that the meters performs as expected and his billing is correct.*

As stated, key items in attaining this assurance are:

1. The transferability of the calibration result to the field (the insensitivity to installation conditions)
2. The detection of fouling (dealing with the conditions in the field after installation)

During the design, a variety of possible path configurations have been evaluated using several mathematical models such as CFD models and specially self designed analytical flow models.

4.1 CFD models.

The main problems associated with CFD models are the definition of the boundary conditions and the size of the calculation grid (rubbish in = rubbish out). In order to be sure that the results of the calculations are realistic the outcome of the calculations is compared to real measurements. For this an extended library with flow patterns based on the laser-Doppler measurements from the PTB and others is used. This library, based amongst others on the work done by Bodo Mickan (see ref.[5}), contains hundreds of real life flow patterns ranging from straight pipes to flow patterns behind single- and double-out-of-plane bends as well as expanders and reducers. Examples are shown in figures 11 and 12, showing both the calculated results as well as the Laser Doppler Anemometer (LDA) results from the PTB.

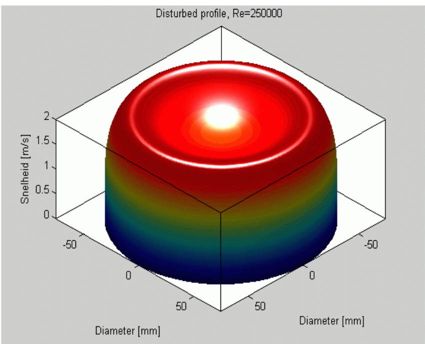


Figure 11, distorted flow pattern

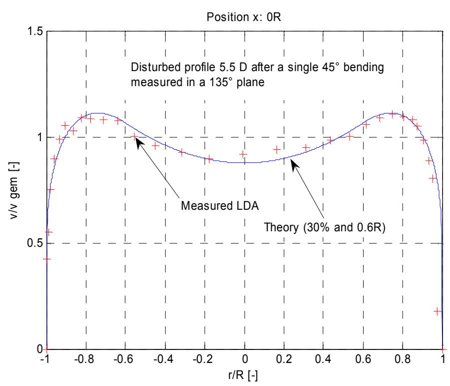


Figure 12, calculated and measured flow profile

4.2 The analytical models.

Due to the limitation of CFD models, also an analytical model has been designed. This analytical model is based on a combination of the fundamental physical laws and mathematical hydrodynamic disturbance functions. As input the data of the LDA measurements are used. In figure 13 this process is schematically shown.

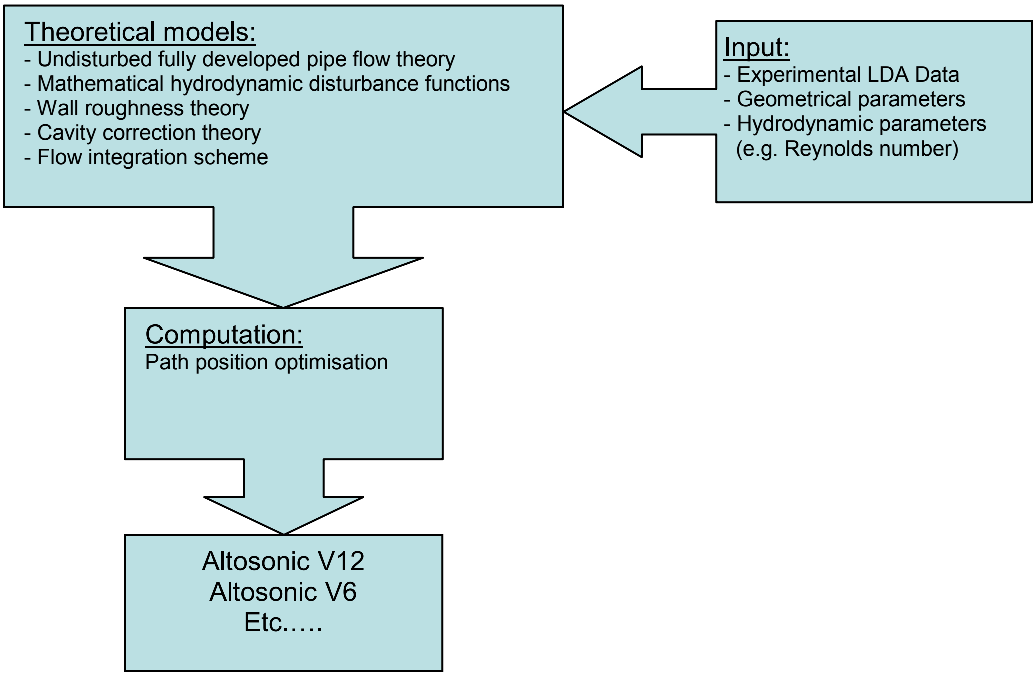


Figure 13. Setup of the analytical model

In this model, the size of the transducers is taken into account and also that the exact path positions can deviate from their nominal positions, a phenomenon which affects the meter performance as a function of Reynolds. As an example in figure 14 the sensitivity calculation of the linearity error is shown. In this figure, the error is presented for both a conventional 4 path parallel path configuration and the new 5-path design. It is clear that the 5 path shows a much smaller and smoother error curve than the 4-path design. Hence the 5-path is much more tolerant to machining tolerances and flow profile distortions.

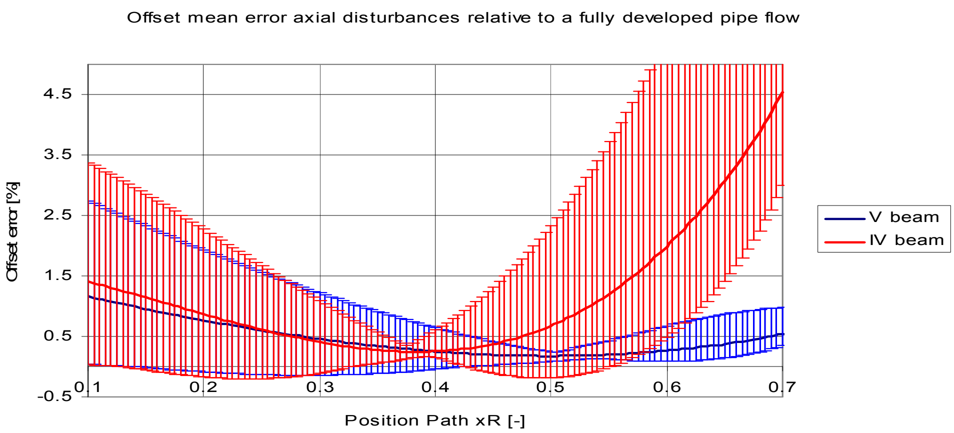


Figure 14. Path sensitivity analysis for 4 and 5 path configurations

4.3 Investigation of the conical reducer.

Based on the successful use of a cone shaped reducer in the ultrasonic liquid flow meters, a similar approach was investigated for the ultrasonic gas flow meters. In creating the necessary input data for the analytical model LDA model tests were conducted. These tests were done using a 4" model made out of quartz glass (see figures 15 to 18).

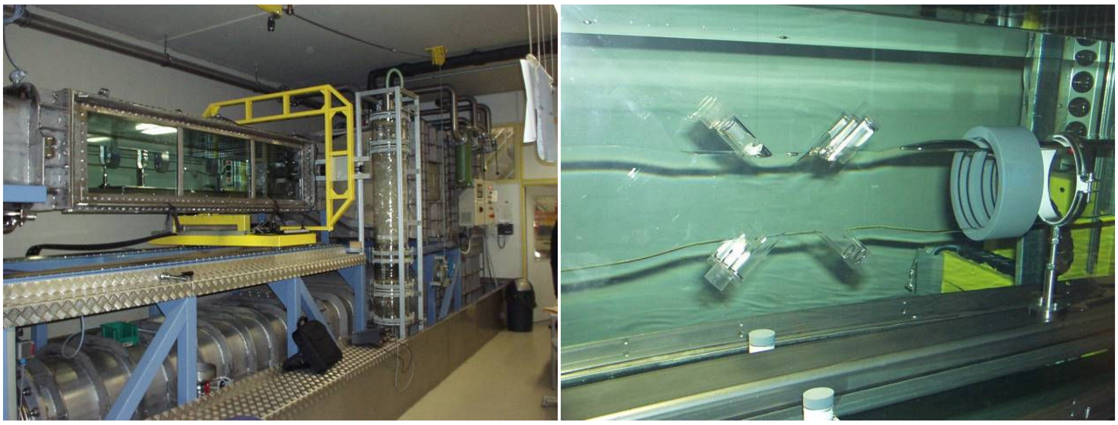


Figure 15 & 16 Experimental set-up at with a quartz glass model.

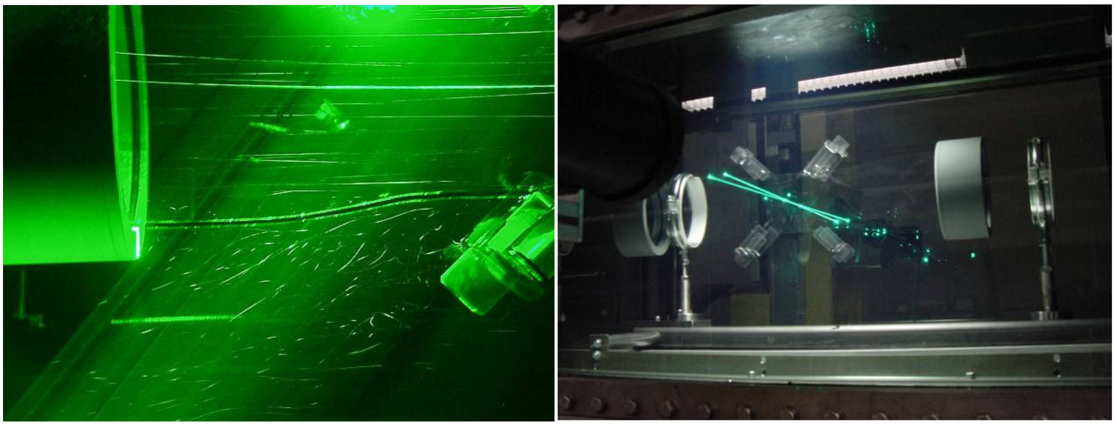
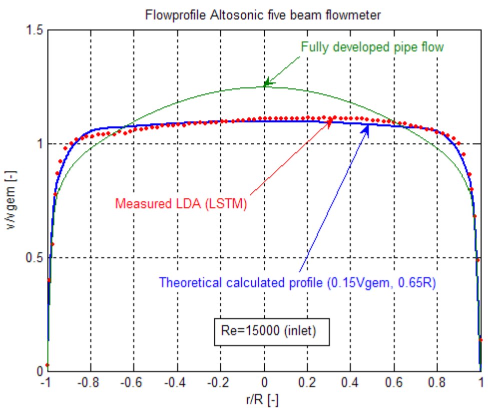
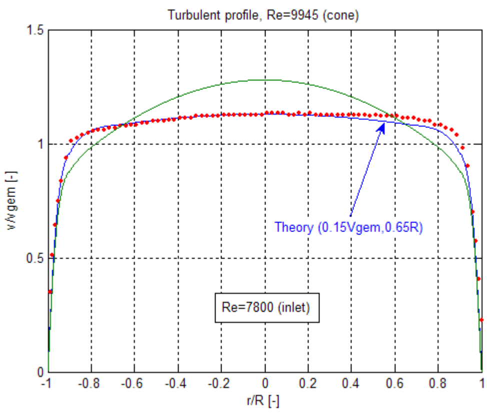
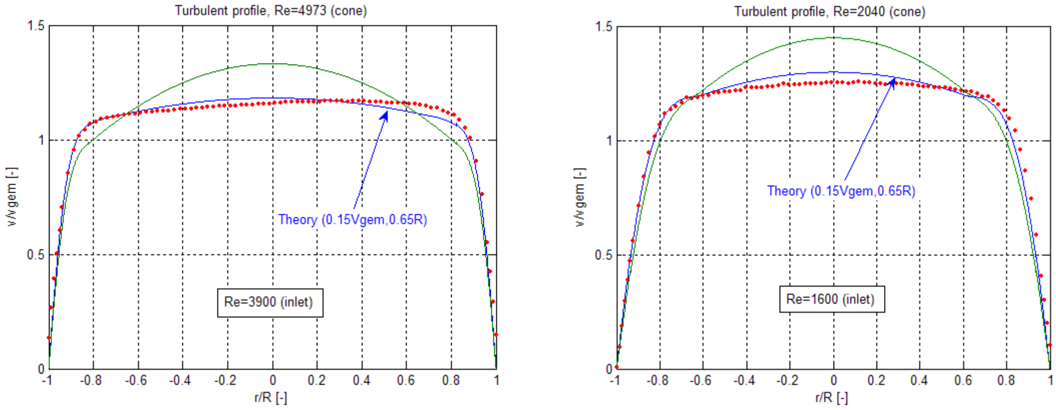


Figure 17 & 18: Flow visualisation in the quartz glass model by using a laser sheet (left) & LDA measurements.

The performed LDA measurements revealed that the shape of a turbulent flow profile in a cone is more flat compared to a fully developed turbulent flow profile in a straight pipe. This can be seen in figures 19 where the measured flow profile for a variety of low Reynolds numbers is shown in combination with those calculated by the analytical model.







Figures 19 to 22: Flow profile at different Reynolds numbers in the cone section; model and experimental data.

4.4 Meter response to conical reducers and expanders.

The key problem in this designs, is the fact that it lacks the information close to the wall and is therefore blind to wall roughness changes as well as pipe size reductions and/or expansions. Although in most installations there are no pipe size reductions and/or expansions present, in the calibration facilities where they have to meet a large variety of different pipe sizes, pipe size reductions and/or expansions are almost a given in any calibration (see figure 23). If the meter can not handle this, *the meter factor as calibrated is flawed*.

Fig. 23 Typical pipe size reduction at a flow calibration lab (photo courtesy of NMi)

4.5 Elimination of the sensitivity to swirl.

Swirl is present in many installations and comes in 2 different variations:

- after a single bend 2 large rotations are created; one rotating clockwise and the other rotating counter clockwise (see figure 24 a).
- after a double out-of-plane bend, the 2 vortices of the single bend merge into a single large rotation (figure 24 b). *An essential difference between these 2, is that the flow velocity vector at the top has changed from direction.*

In addition to this, when for instance a header is present in front of the single or double out-of-plane bend, there is also an asymmetry present in the flow (see figure 22 c: header + double out-of-plane bend)

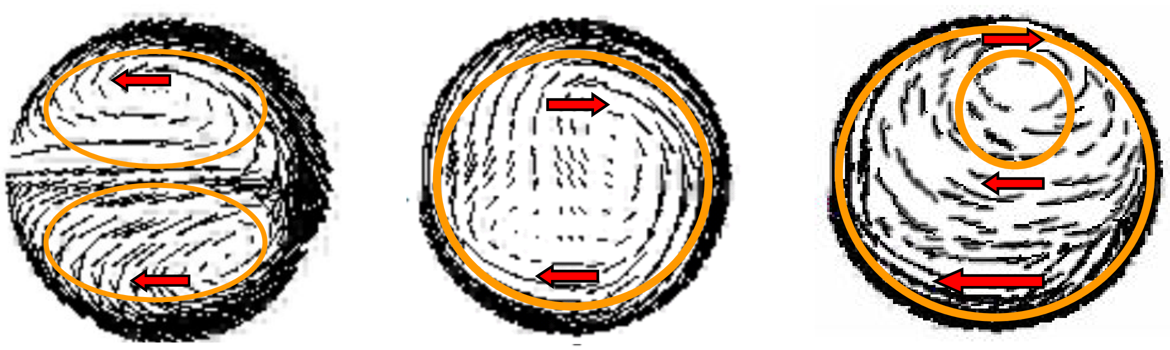
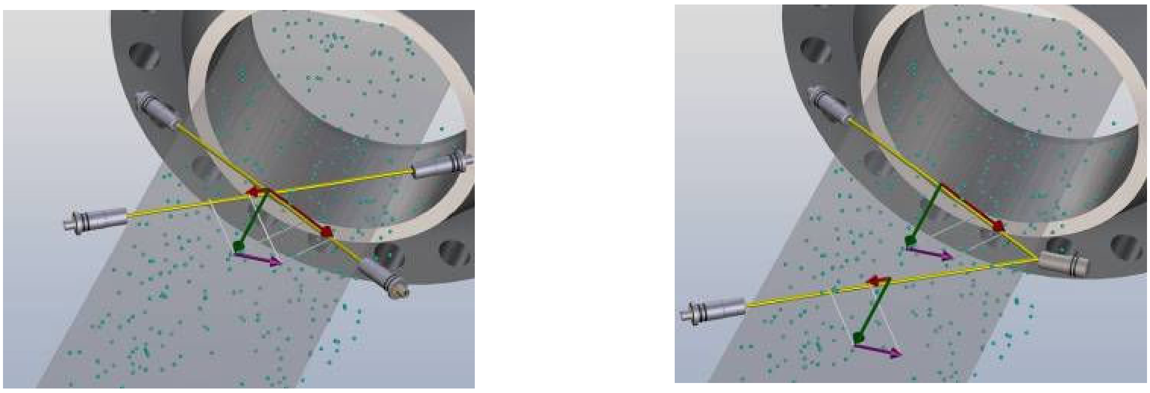


Fig.24.Cross flow **a**: behind a single bend. **b**: behind a double-out-of-plane bend **c**: a-symmetrical swirl

- Being present in many installations, ultrasonic flow meters should be able to handle all these different types of swirl.
- None of them can handle a-symmetrical swirl conditions as in figure 24c, since in that case all paths are subjected to a different swirl strength and by combining the paths the impact of the swirl is never cancelled out.

There is only way to overcome this and that is by eliminating the effect of the swirl *in each of the individual measurement planes.*

Whereas the swirl is stable over hundreds of diameters, such can be accomplished by using either an X or V type path configuration in each of the measurement planes. This is illustrated in figure 26.



Vline1 and 2 Vaxial Vswirl (unwanted)

Figures 26, Swirl elimination in each of the measurement planes

In the X-arrangement , the swirl is eliminated by adding the 2 measured path velocities together and in case of a V-type arrangement this is done automatically (see figure 27)

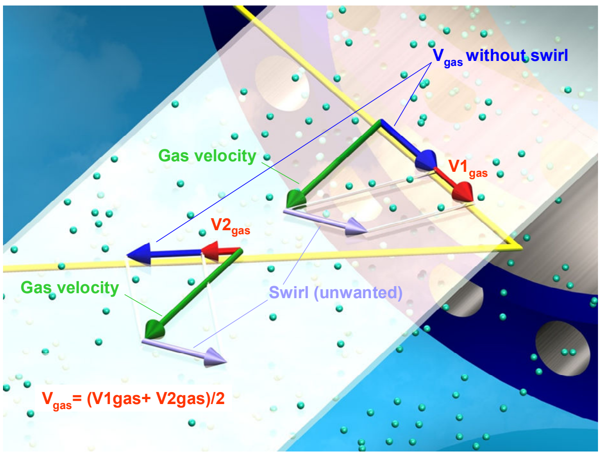


Figure 27 : Swirl cancellation using a reflective V-configuration.

4.6 Final meter design.

Reflective paths have tremendous advantages. Next to their inherent capability to eliminate swirl, the reflecting paths are the only ones capable of detecting intermittent fouling and wall build as discussed in chapter 3. When reflecting on fouling, the signal strength will be affected as a function of the size and shape of the contaminants and the wave length used. The combination of this information with that of the other diagnostic parameters results in a superior diagnostic concept. Obviously, for the path configurations the *reflecting* path design has been chosen.

Also the new meter is equipped with a path through the centre of the pipe. This path is essential for the meter's ability to deal with flow velocity patterns behind single and double-out-of-plane bends. Behind bends, one of the major impacts on the flow velocity profile is the velocity defect in the middle of the pipe (as shown in figures 11 and 12).

Based on considerations as mentioned above, an optimal path configuration was established, whereby:

1. The number of paths have been optimized to attain the lowest uncertainty under a large variety of possible flow profile distortions, including all the ISO 17089 perturbations and all those prescribed by the OIML R137.
2. The combination of path positions and associating weighting factors and algorithms have been designed in such a way, that the meter is to a high degree robust against wall build-up.
3. The path configuration has been optimized to detect the various ways of fouling.

This path configuration is shown in figure 28:

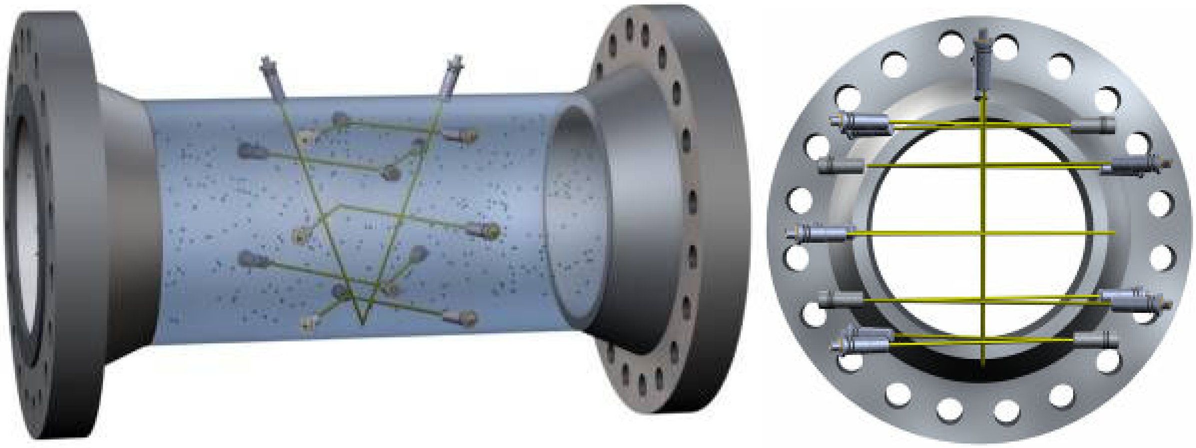


Figure 28: Final (patented) path configuration.

In this configuration:

- Each path consists of 2 chords in a V-category arrangement (in total the meter is equipped with 12 chords, hence the name ALTOSONIC V12).
- The vertical reflecting path is exclusively designed to detect the presence of liquid layers on the bottom of the pipe and is not involved in the flow velocity measurement.
- All paths are reflecting whereby four of them use small acoustic mirrors at the opposite side of the pipe.

5. Test results in relation to the ISO 17089 and OIML 137 flow perturbations

In autumn 2008 the ALTOSONIC V12 was tested at the E-ON Ruhrgas test facility in Lintorf, Germany. The tests performed comply with requirements based on ISO17089 for USM and OIML R137, the latter creating very high swirl conditions (see figure 30).

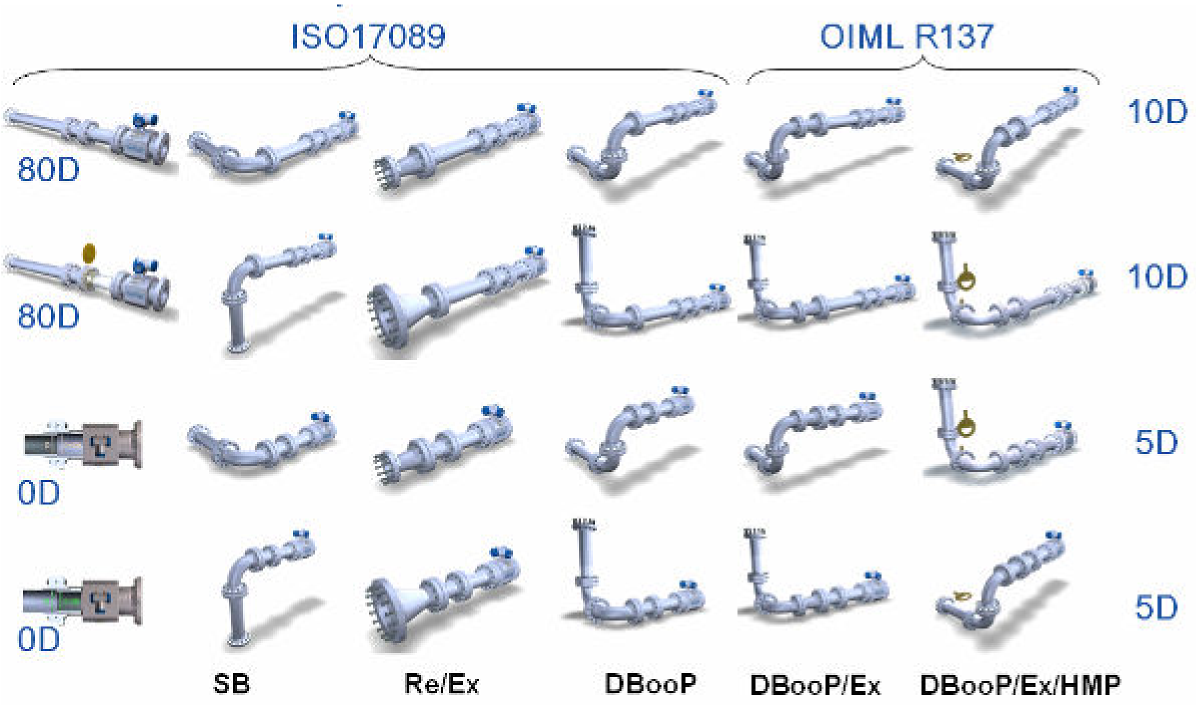


Figure 30 Upstream piping conditions for V12 testing

It is the first time that an USM has been tested under such severe conditions and results are documented. The tests were witnessed by the Dutch NMi and have been used to obtain the MID (Measurement Instruments Directive) type approval for the European Union. The results are shown in the figures 32 – 40 which are the *raw data not linearized or corrected in any other way*.

Figure 31: The V12 tested at 90º rotated with a double bend out of plane at 10D distance.

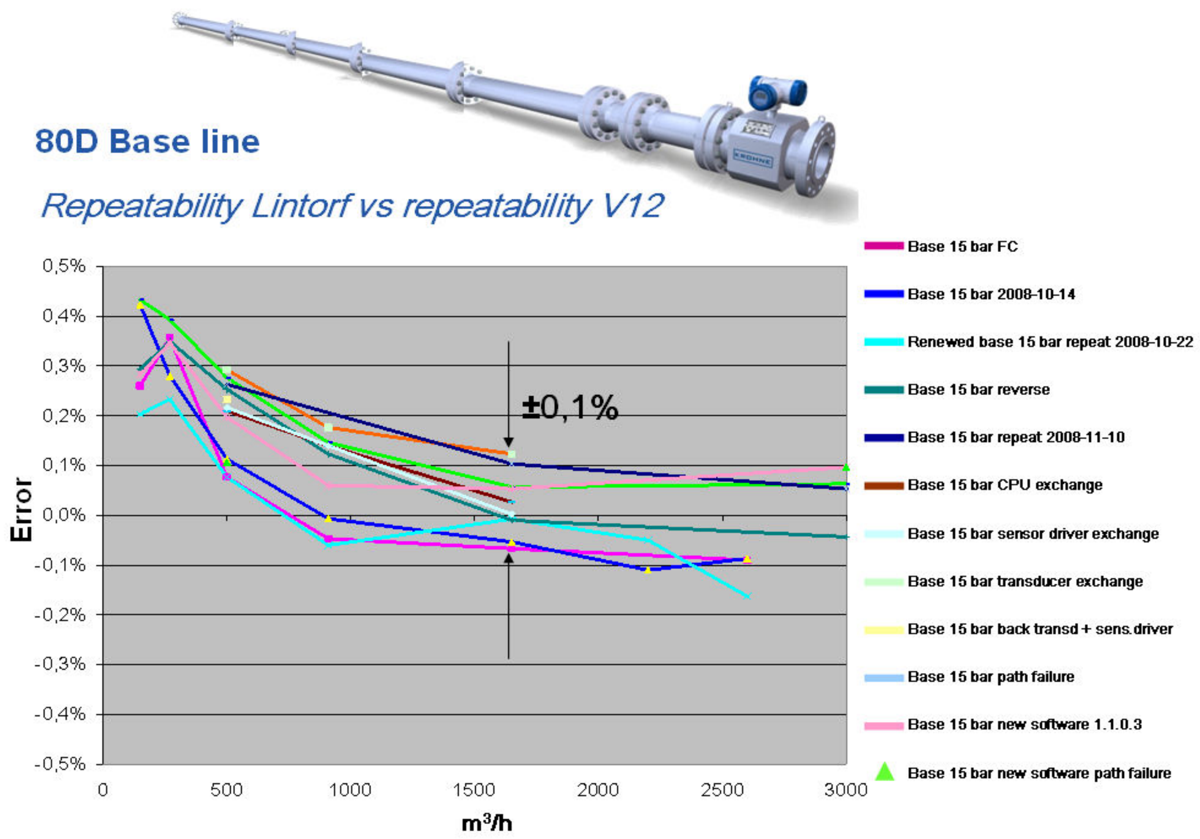


Figure 32: Base line tests

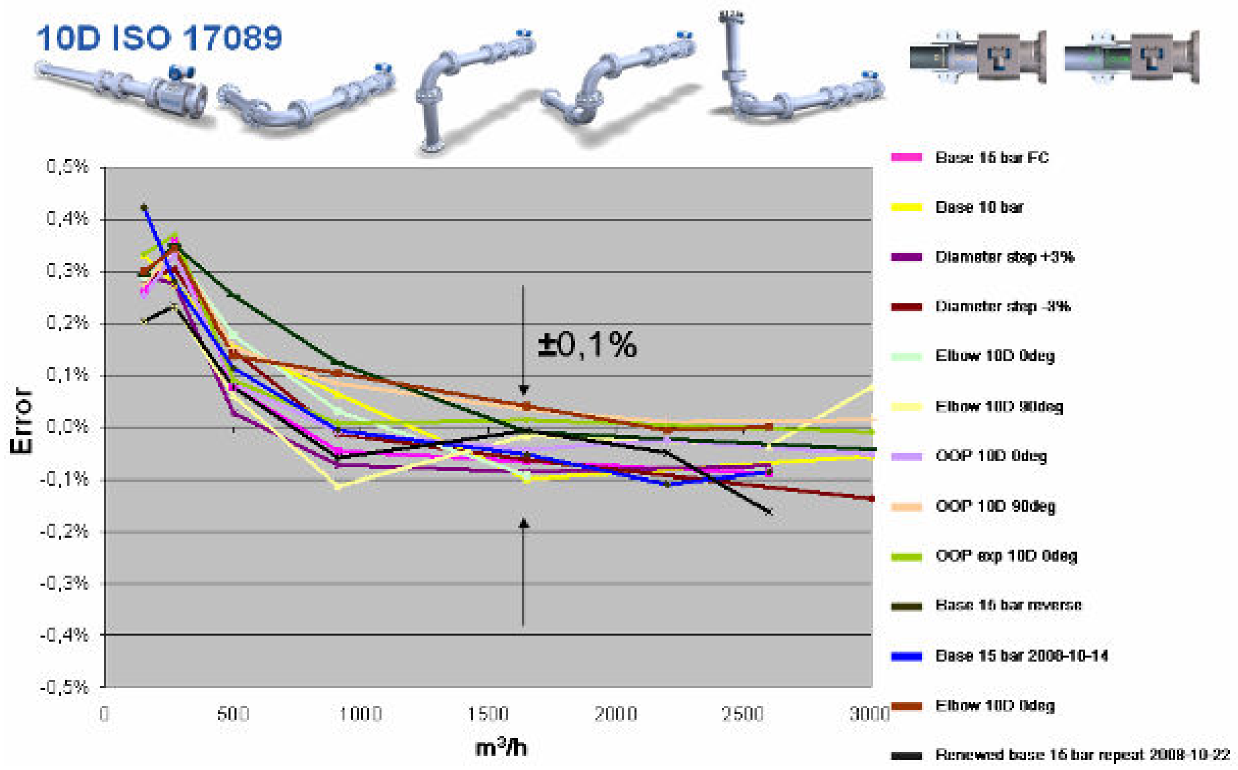


Figure 33: Distortion tests in compliance with ISO17089 at 10D

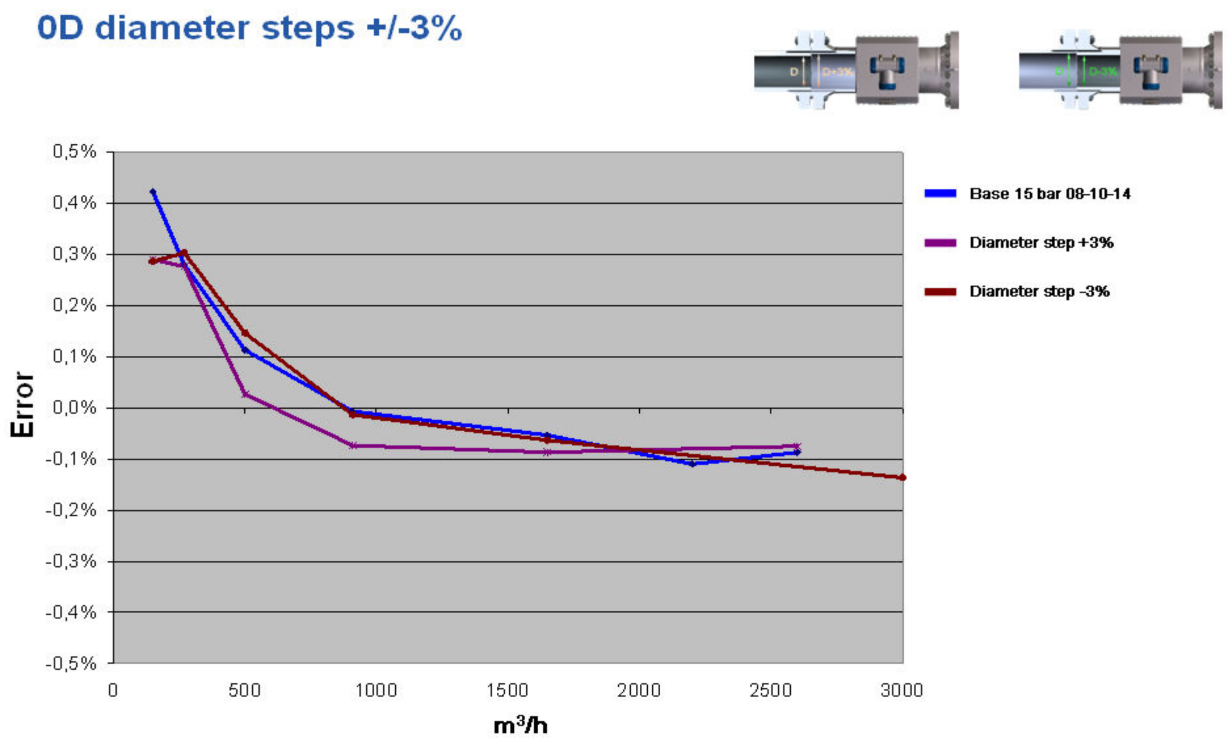


Figure 34: Diameter steps +/- 3%

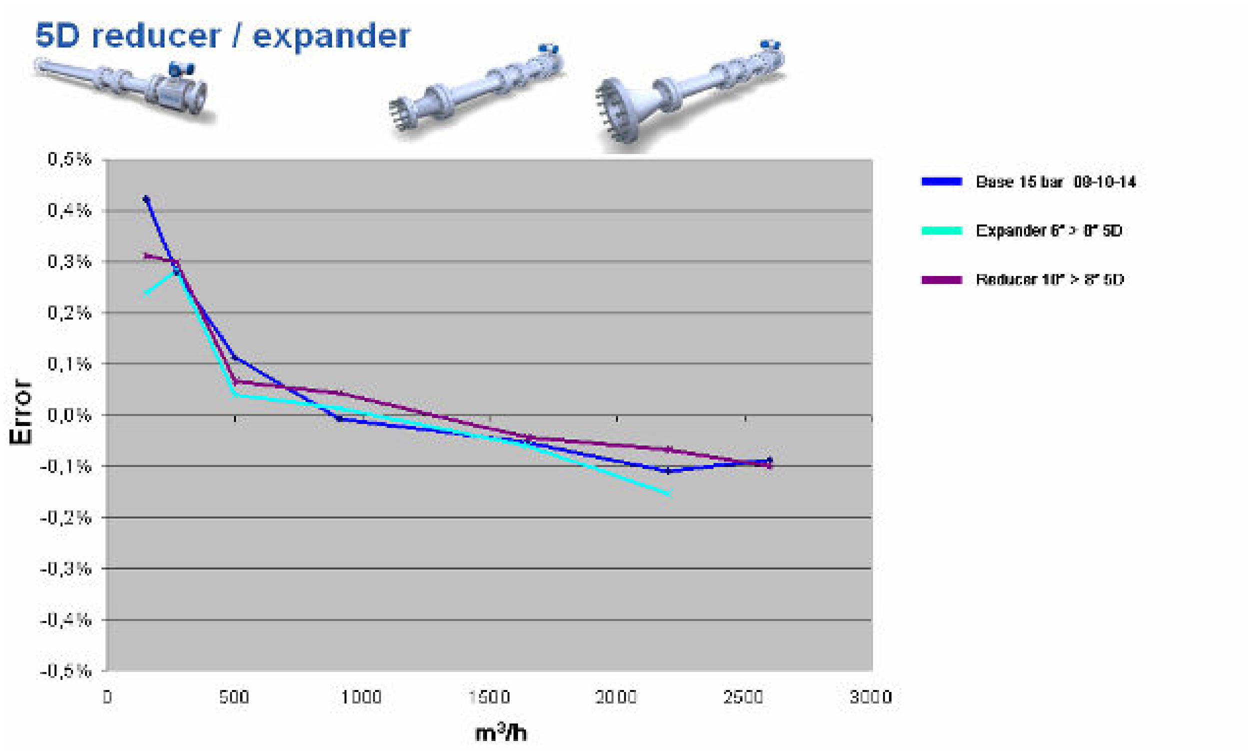


Figure 35 Pipe reduction and expansion at 5D distance

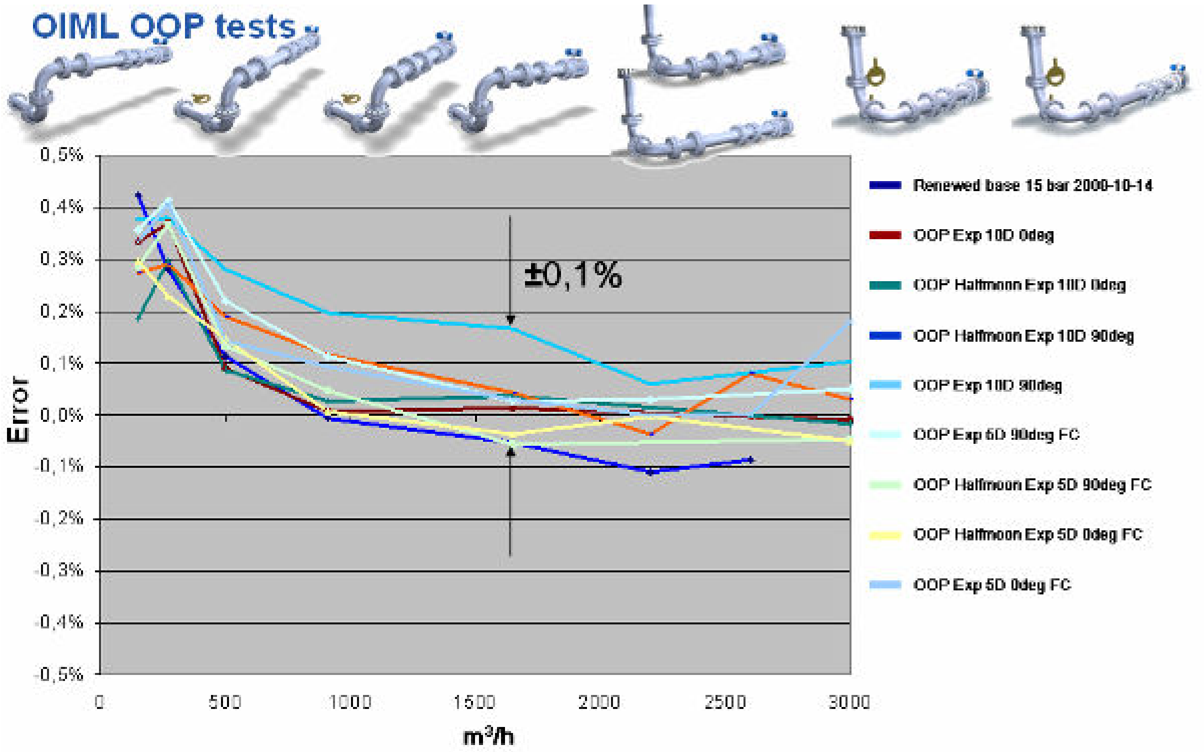


Figure 36: OIML R137 distortions at 10D

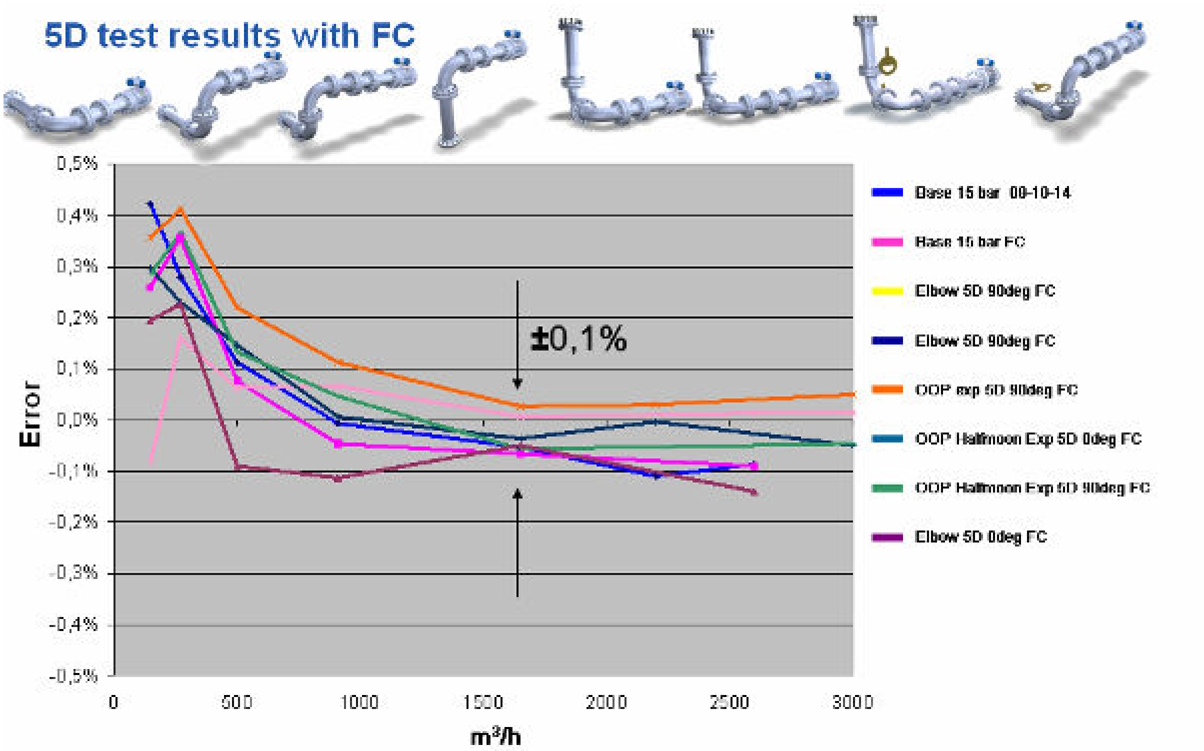


Figure 37: OIML R137 distortions at 5D with KROHNE flow conditioner at 3D

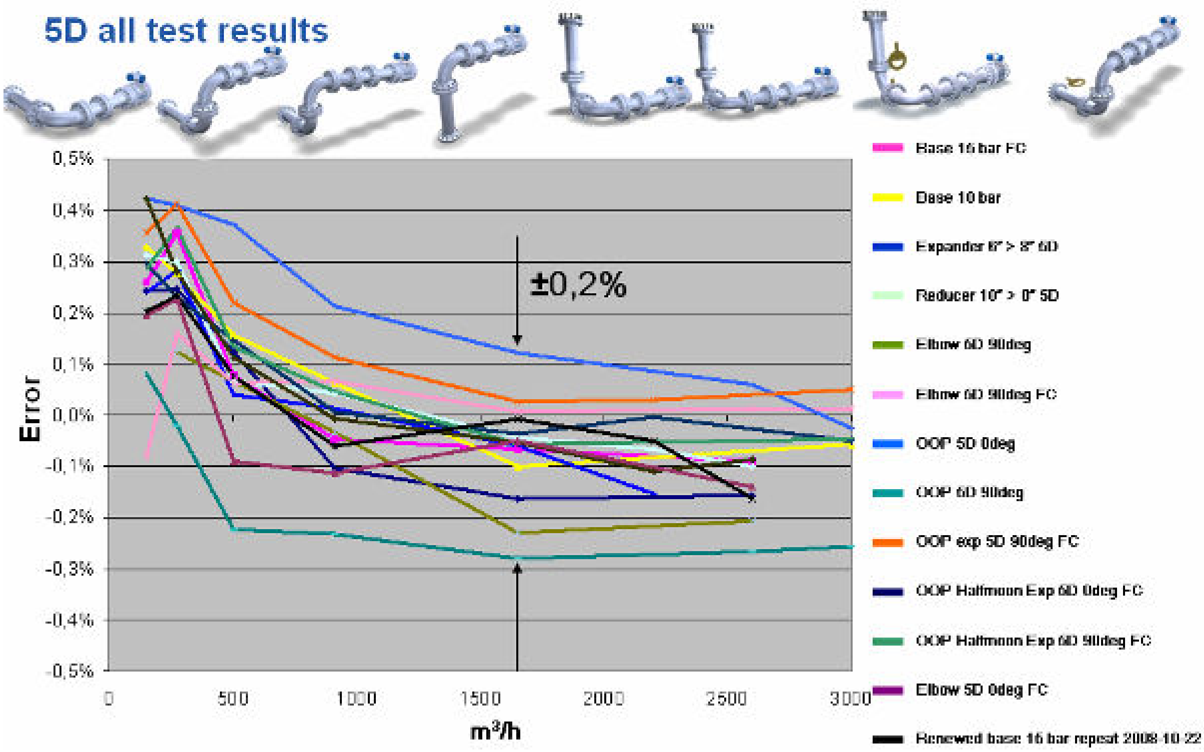


Figure 38 OIML R137 distortions at 5D without flow conditioner

The tests described above have all been conducted at the Ruhrgas Lintorf test facility. This test facility was chosen based on the excellent flexibility; its traceability to the European national standards and its very good short term reproducibility. With a row of 5 parallel orifice meters being used as reference meters the only weak point of the facility is its low flow characteristic and performance where in that case only one orifice is used..

In order to investigate the low flow behavior of the meter as well, additional tests were conducted at the Bergum facility of the NMi which has an outstandingly low flow capability. There the same 8” meter, as well as a 4” meter, was tested (see figure 39). The results show the outstanding capability of the meter design to deal with very low flow velocities.

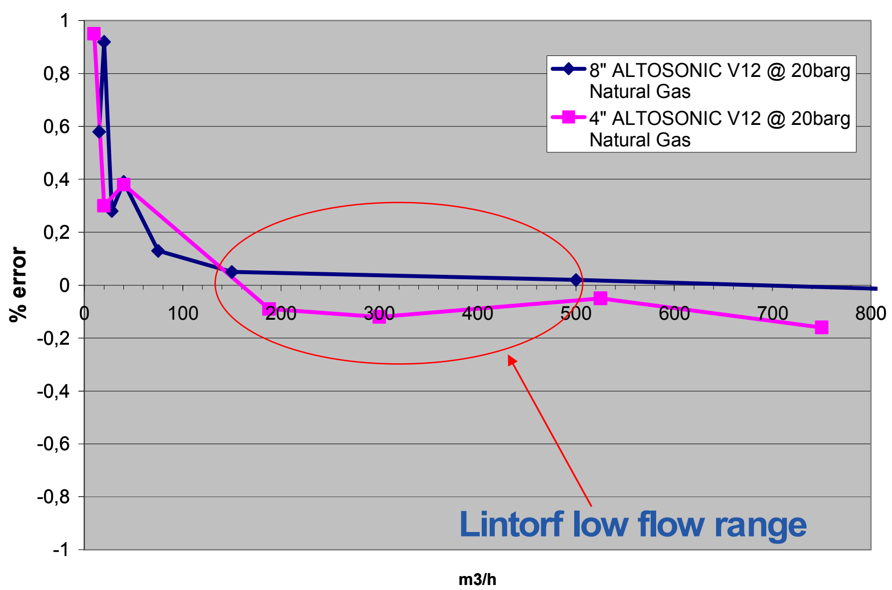


Figure 39 Low flow test results at NMi Bergum calibration facility

8” ALTOSONIC V12 @ 20 bar Natural Gas	4” ALTOSONIC V12 @ 20 bar Natural Gas

Flow rate [m³/h]	Qmax [%]	Error [%]	Repeatability [%]
1600	53	-0,10	0,16
500	17	0,02	0,06
150	5	0,05	0,06
75	2,5	0,13	0,03
40	1,3	0,39	0,14
28	0,9	0,28	0,20
20	0,7	0,92	0,12
15	0,5	0,58	0,13
Weighted mean error: -0.03%			

Table 5: NMi Bergum results 8” V12

Flow rate [m³/h]	Qmax [%]	Error [%]	Repeatability [%]
750	94	-1,06	0,08
525	66	-0,05	0,05
300	38	-0,12	0,01
188	24	-0,09	0,10
40	5	0,38	0,04
20	3	0,30	0,18
10	1	0,95	0,22
Weighted mean error: -0.09%			

Table 6: NMi Bergum results 4” V12

As a result of all tests tests, it can be concluded that the V12 performs excellently under all test conditions. The V12 is the first ultrasonic meter to be able to be installed in applications having only a 5D straight upstream inlet length where uncertainties better than ±0.2% are required. As a result, the Altosonic V12 is world-wide the first ultrasonic gas flow meter receiving the OIML Class 0.5 approval.

In table 7 the conclusion of the uncertainty to installation conditions is presented. Based on this the operator can be assured that the quality of the calibration curve is transferred to the field.

Upstream condition	Uncertainty installation effects
10D straight length	± 0,1%
5D straight length	± 0,2%
5D straight length with flow conditioner	± 0,1%

Table 7 Conclusion on the uncertainty to installation effects

6. *Conclusions*

Based on the extensive research on installation effects, using CFD, in-house developed analytical models and the Laser-Doppler measurements, a new ultrasonic meter has been designed which is extremely robust to installation conditions. Also the meter’s diagnostics has been optimized for the use under harsh conditions. Through this, the user is continuously informed that the meter performs as expected and his billing is correct.

The end result is a state–of-the–art measurement concept that combines the best attainable accuracy with an unsurpassed performance monitoring guaranteeing that the quality of the calibration curve is transferred to the field.

7. *References*

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