Ultrasonic flow meter diagnostics and the impact of fouling.

Jan G. Drenthen, Marcel Vermeulen, Martin Kurth & Hilko den Hollander
Krohne Oil & Gas

1. Introduction

Over the past decade, Ultrasonic flow meters have gained a wide acceptance. Main reasons for this are the high repeatability in combination with zero pressure loss and extensive 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. Many of them show (often after multipoint linearization) almost perfect straight lines with errors close to the repeatability of the lab.

However, for a user it is not only important how good his meter is at the lab, far more important is the accuracy after installation in the field and the question how the user can be sure that the meter's performance is not deteriorating over time.

Major factors affecting the performance of a meter installed in the field are corrosion and fouling. This is not only a problem for ultrasonic meters, but it will affect every flow meter installed. The great virtue of ultrasonic flow meters in contrast to all other meters, are their huge diagnostic capabilities. In addition to this, ultrasonic flowmeters that use reflecting paths are also capable in detecting changes of the conditions at the pipe wall. As a result these meters have huge advantages over straight path meter designs which are not capable of detecting anything occurring at the pipe wall.

While there are multiple papers on the performance in calibration laboratories, the impact that fouling and corrosion can have on the performance of an ultrasonic meter is less known. One of the first papers describing the impact of installation conditions was that of Rick Wilsack from TCPL [2]. Recently James Witte has presented a paper including also the impact that it has on the flow velocity profile [5]. Acknowledging the impact that installation conditions and fouling can have on the performance of a meter, was the basis for KROHNE to design their ALTOSONIC V12 ultrasonic flowmeter.

The present paper focuses on the impact of fouling and corrosion and addresses:
- the design considerations
- the ways to detect the various categories of fouling
- the tests performed with dirty meters
- the impact of honed versus corroded upstream pipes.
- the impact of corrosion of the reflecting surface.

Next to this, a first order correction is given, based on information gathered from the reflecting paths.

2. Ice berg specifications

When comparing the specifications of different ultrasonic flow meters, all show similar specifications, despite the obvious differences in the designs:
:

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

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 1 of 16

What all of the different manufacturers do not mention in their datasheet are:
1. the transferability of the calibration curve obtained under almost ideal conditions in the calibration facility (see figure 1) to the actual conditions in the field (see figure 2); the installation effects.
2. The impact of fouling and corrosion.

Figure 1: Ideal conditions at test rig (courtesy of TCC)

Figure 2: Actual conditions in the field

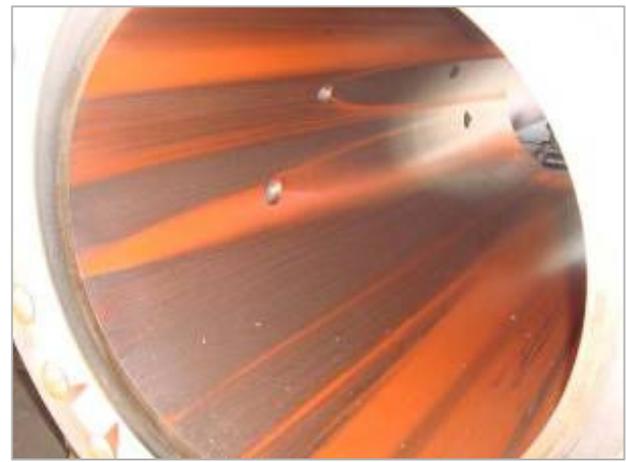Figure 3: A clean ultrasonic meter at a calibration.

Figure 4: A dirty meter during visual inspection

The transferability of the calibration curve to the field has been investigated, amongst others by T. Grimley (see ref. [4]) and is for the conventional meter types, typical in the order of 0,5 %. The Altosonic V12 has been specifically designed to minimize the impact of installation effects. As a result of that the sensitivity has been reduced to a value < 0.2% (see also ref. [2]).

Whereas during flow calibration the meter is clean, after 3 month or 6 months in operation, the meter might be contaminated. The introduced additional uncertainty can easily reach 0,5%, the same magnitude as that of the installation effects. Including this in the equation results in a total uncertainty which is much larger than those stated in the datasheets.

So in effect, the specifications shown in the manufacturer's datasheets are just *Ice berg specifications;* the real specifications are hidden below the surface, meaning:
- The sensitivity to installation effects
- The impact of fouling and corrosion.

Ultrasonic flow meter diagnostics and the impact of fouling. **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 2 of 16

Based on the data on multi path ultrasonic flow meters available in published literature and papers, an estimation of their susceptibility to installation effects and fouling is shown below. (see table 2)

Table 2: Real total uncertainty
estimation
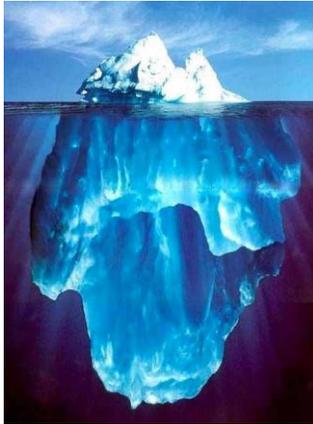
Uncertainty	Direct chord design	Reflective chord design	KROHNE V12
Due to Meter: Non-linearity, Repeatability	0,2%	0.2%	0,15%
Due to Installation effects	0,5%	0,5%	0,2%
Due to possible contamination	0,5%	0,3%	0,1%
Total √	0,75%	0,6%	0,25%

In order to reduce the total uncertainty, the impact of both the installation effect as well as the sensitivity to contamination has to be reduced. These have been the prime targets in the development of the Altosonic V12 ultrasonic gas flow meter.

3. Meter design

As a function of their path configuration, presently 3 different types can be distinguished (see figure 5):

- Conventional parallel chord designs (A)
- Conventional reflective chord designs (B)
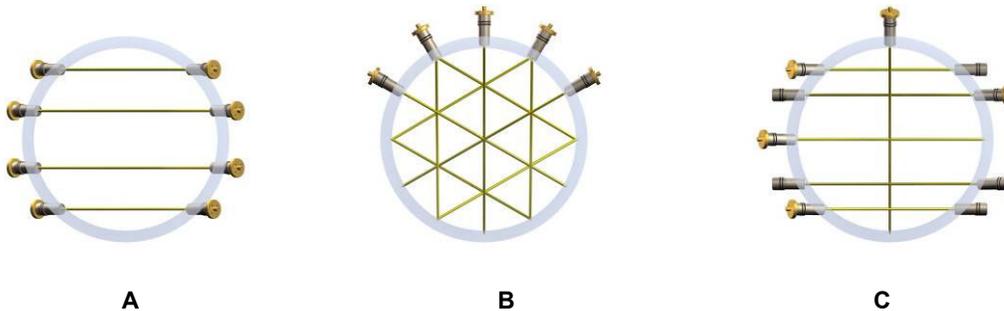- The (patented) Krohne V-12 path arrangement (C)

| A | B | C |

Figure 5: Conventional parallel chord design (**A**), conventional reflective chord design (**B**) & the Krohne V12 design (**C**)

Looking at the conventional meter designs, it must be concluded that despite some occasionally lucky shots, all of them are affected by highly distorted flows and / or fouling. Reasons for this are:

o The conventional parallel chord designs are able to measure close to the pipe wall but lack the interrogation of pipe wall.
o The conventional reflective chord design is able to measure wall built-up, but its triangle shaped path cannot get closer to the wall than the 0.5R position; This position is too far away to effectively deal with changes in the flow profile close to the wall.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 3 of 16

The optimal solution to overcome these issues is a combination of both technologies: *the KROHNE ALTOSONIC V12 design*. (see figure 6)
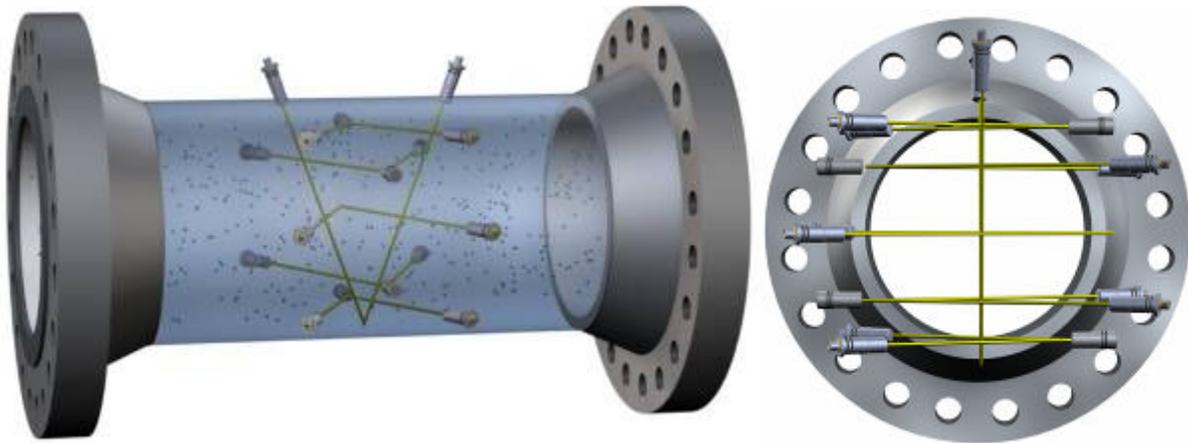

Figure 6: Krohne V12 path configuration.

In this configuration:
- o Each path consists of 2 chords formed into a single V-bounce (in total the meter is equipped with 12 chords, all with a single V shape).
- o The vertical reflecting path is used solely to detect the presence of contamination liquid layers on the bottom of the pipe.
- o All paths are reflecting whereby four of them use small acoustic mirrors at the opposite side of the pipe.

4. Variations in fouling

Looking at fouling, one of the main problems is the variety at which it occurs. In figures 7 to 9 some examples of (excessive) fouling as encountered are presented. Figure 7 is the result of a production problem, figure 8 is an example of an off-shore installation and figure 9 is an on-shore installation.

Figure 7, fouling as a flow on the bottom of the pipe.

Figure 8, fouling intermittently stuck to the pipe wall

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 4 of 16

Figure 9, fouling evenly distributed over the pipe wall

Looking at the impact that fouling can have on ultrasonic meters, it 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 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.

5. Testing at Lintorf

In July 2010 extensive testing have been done at the E-ON Ruhrgas test facility in Lintorf using two 6" ALTOSONIC V12 meters in series (see figure 10).

Figure 10, two 6" Altosonic V12 meters in series at Lintorf

Ultrasonic flow meter diagnostics and the impact of fouling.
15th International Flow measurement Conference, Flomeko 2010, Taiwan

KROHNE

The Lintorf facility is one of the most flexible facilities available. The pressure can be varied between 8 and 45 bar and flows can be generated up to 40.000 m^3N/h (in summer; winter up to 100.000 m^3N/h). As reference meters there a series of 5 parallel runs of orifices as well as a turbine meter (see figure 11). After finishing the tests, an Altosonic V12 meter has been installed as a permanent reference. For the testing described in this paper the repeatability was the most important item rather than the absolute error.

Figure 11 Layout of the Lintorf facility.
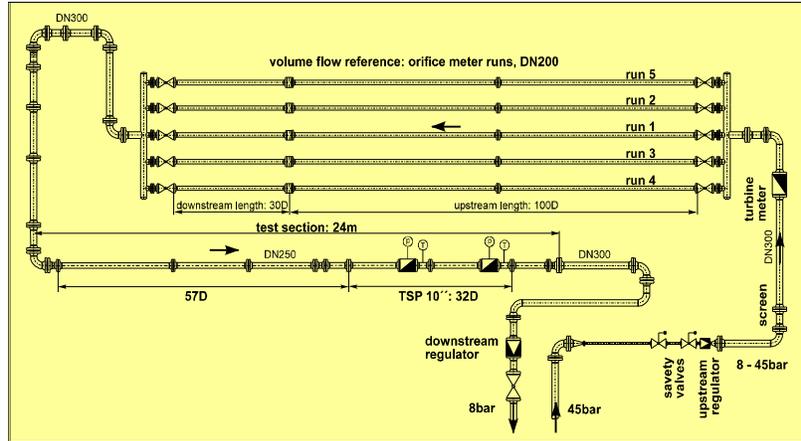
5.1. Test program

The tests were done at the end of July under hot and changing weather conditions. As a result of this stratified flow profiles occurred at - lower flow velocities, affecting the repeatability which manifested itself in a somewhat larger spread in the baselines than usual. The repeatability assessed during the two weeks of testing still remained mostly within the order of 0.1% to 0.15%.

During the tests the following fouling types of fouling and corrosion were investigated:

1. Fouling on the bottom.
2. Fouling intermittently sticking on the pipe wall.
3. Fouling of evenly distributed inside the pipe.
4. Fouling on the transducers.
5. Liquid contamination in the transducer pockets.
6. Reflection on rough (corroded) surfaces
7. Honed and corroded upstream pipes

To create the fouling a variety of products such as water, oil, grease and putty were applied.

5.1.1. Fouling on the bottom of the pipe

Fouling on the bottom of the pipe can be detected by using a vertical reflecting path. The stability and ability to detect this depends on the viscosity, the density of the fluid at the bottom of the meter and the gas in the meter, as well as the flow velocity. The behavior of the bottom layer depends on both the fluid properties as well as the pressure and flow velocity of the gas. A detailed description of the various patterns is presented in [3].

To simulate the bottom fouling and to test the sensitivity of the diagnostic detection, an approximately 4 to 6 cm wide and relatively thin layer of "never-seize regular grade anti-seize and lubricating compound" -further referred to as "grease"- was applied over the whole length of both the inlet spool and the meter.

Measuring the thickness proved not to be an easy task and an assessment was made using calipers by weighing the amount of grease applied. Based on these the thickness was estimated as an average layer of about 0.5 mm with peaks of 2 mm. (see figure 12). However the uncertainty of this measurement, especially

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 6 of 16

that of the average thickness, with grease sticking to the caliper is quite large. Using the change in acoustic path length is much easier as well as much more accurate. As a result for all this and all the remaining tests, the speed of sound measurement was used for assessing the thickness.
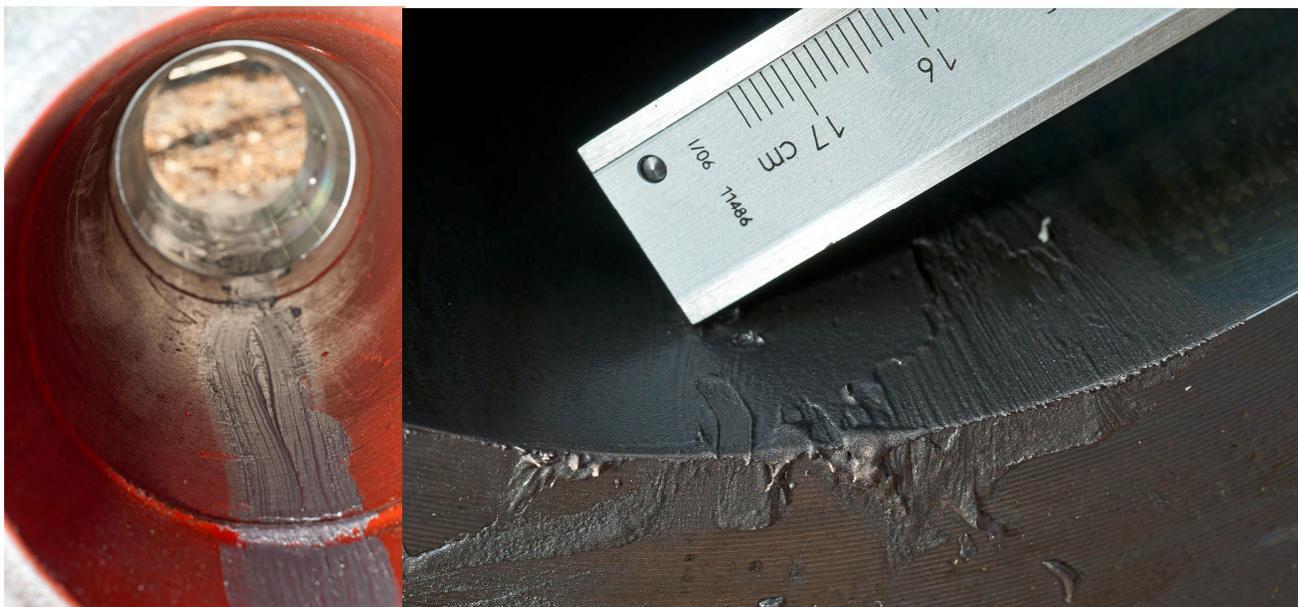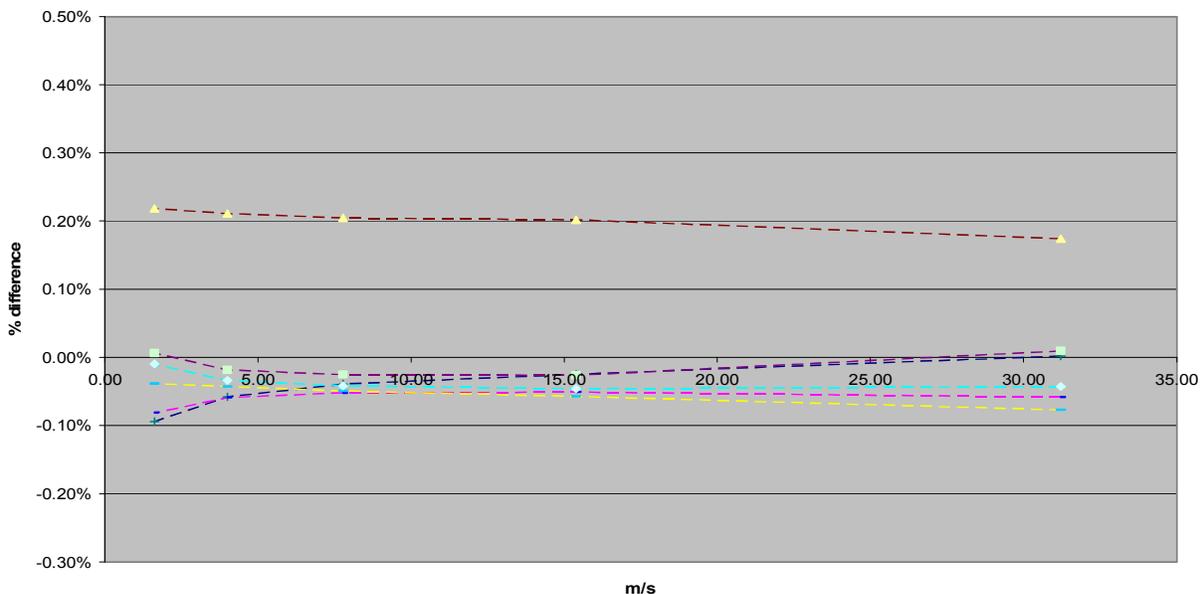

Figures 12 bottom fouling

Figure 13 Speed of sound ratio's

In figure 13, the speed of sound of all the acoustic paths is shown. In this figure it can be seen that the speed of sound of path 6, the diagnostic path reflecting on the bottom of the pipe has shifted approximately 0.2 % in respect to the other paths. Calculated on the shift in the speed of sound, the average thickness of the bottom layer was 0.3 mm; somewhat lower than assessed by the mechanical measurement. As a first order correction, based on the blockage of the cross sectional area, this resulted in a total reduction of the cross sectional area of 0.12%.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

In figure 14, the calibration results of both the "clean" meter as well as that with bottom fouling are shown. From these, it is clear that the first order correction, based on the speed of sound ratios, is in close agreement with the measured offset.
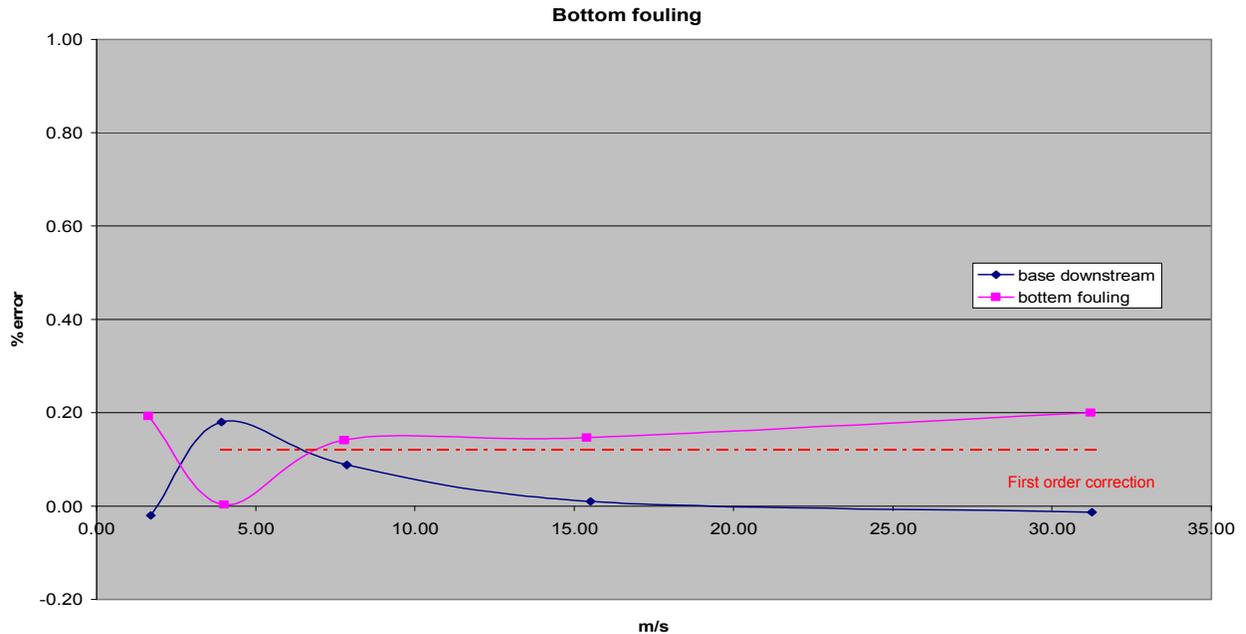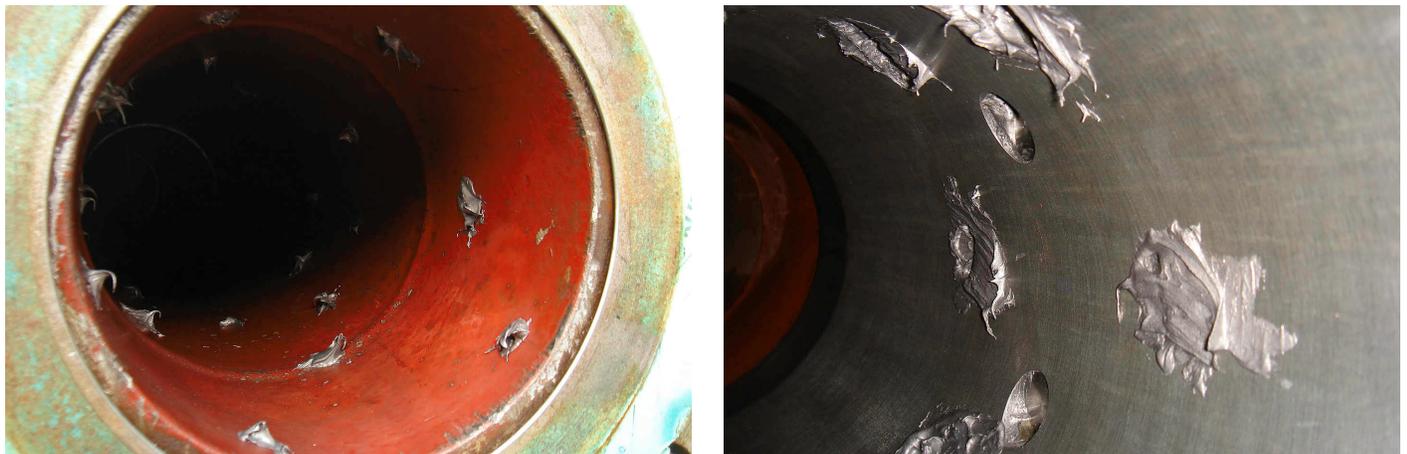

Figure 14 Calibration curves of both the clean meter and with bottom fouling

5.1.2. 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 depends on the gas flow velocity, its density and the characteristics of the fouling itself. 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.

For the tests, generous portions of grease were randomly applied to the pipe wall (see figures 15).

Figures 15: Fouling sticking intermittently to the pipe wall.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 8 of 16

In figure 16, the speed of sound for the 6 acoustic paths as a function of the flow velocity is shown.

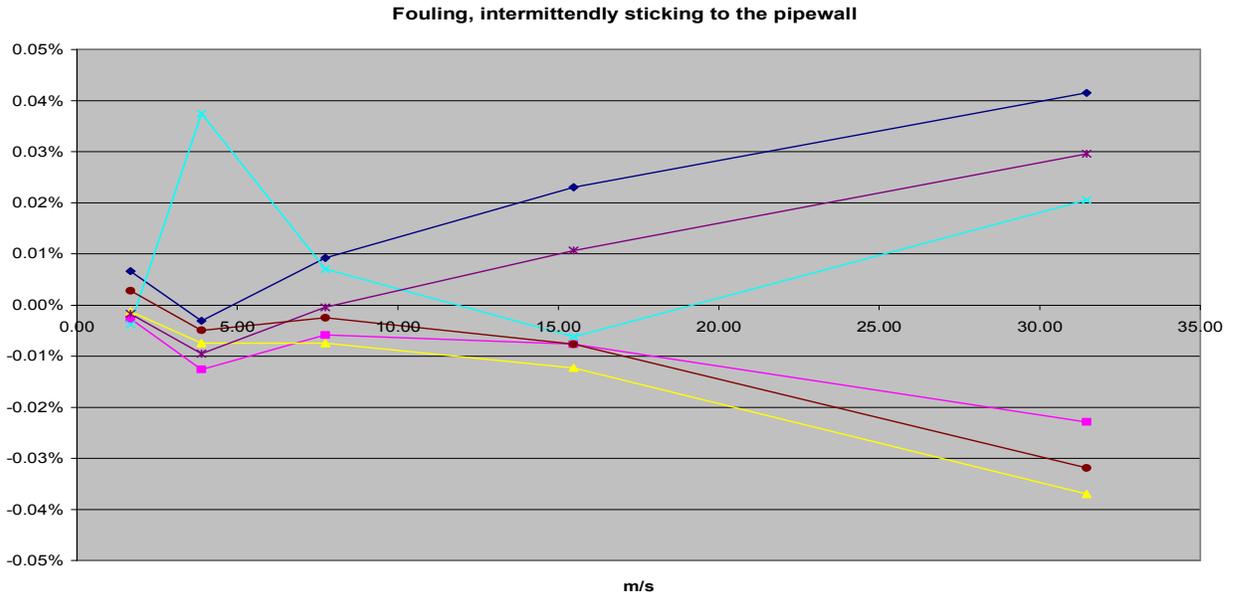**Fouling, intermittendly sticking to the pipewall**

Figure 16, Speed of sound for the 6 acoustic paths as a function of the flow velocity

From this it can be seen that the rate of change is not stable, and changes over time and as a function of the gas velocity. As a result, also the errors are not stable and change simultaneously to the changes in the speed of sound. Despite the relatively small changes in the speed of sound, the impact on the error curve is significant (see fig 17) Here the first order correction is not able to predict the error and this type of fouling needs to be investigated further.
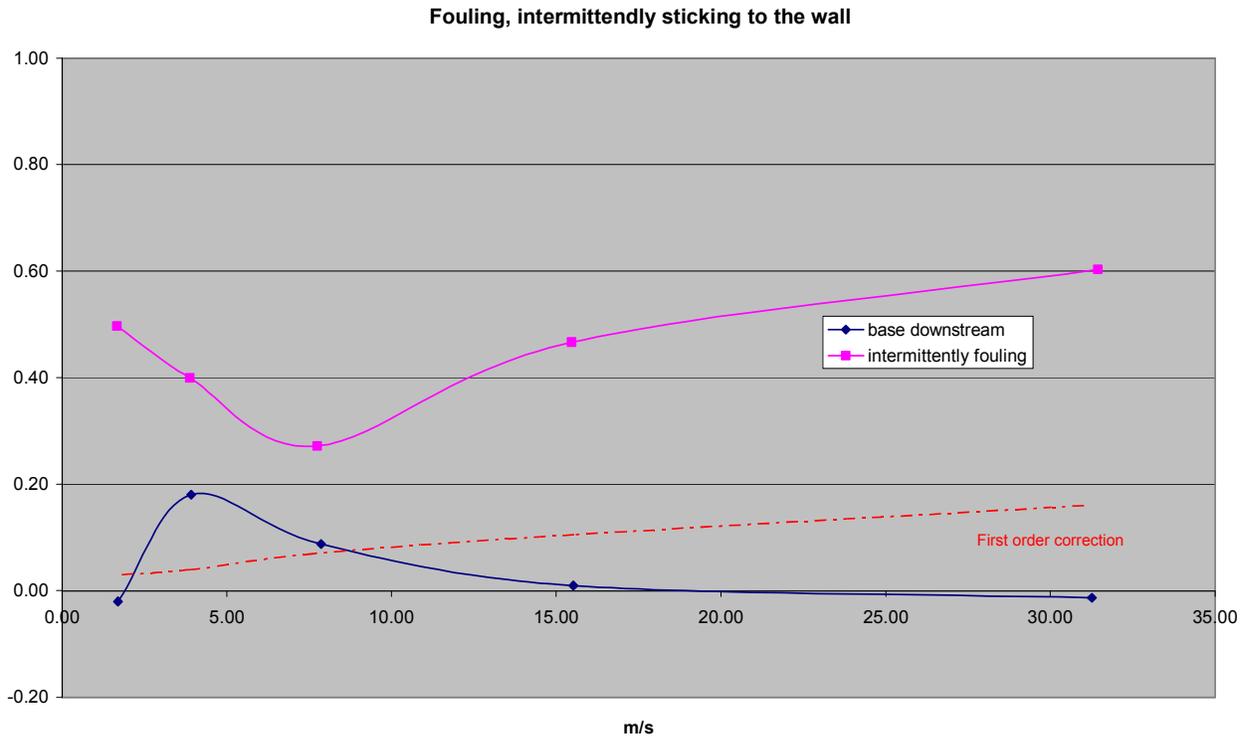
Fouling, intermittently sticking to the wall

Figure 17: error curve with fouling sticking intermittently to the pipe wall

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

5.1.3. Fouling which is as an evenly distributed coating on the inside of the pipe

This type of fouling 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 identical for all the paths, the relative impact 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 paths are 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 ratios of the paths close to the pipe wall and the path through the middle of the pipe in respect to the half radius paths.

To find out how the meter reacts to extreme fouling extensive layers of grease were applied in the same way as that was done to create the bottom fouling (see figure 18).
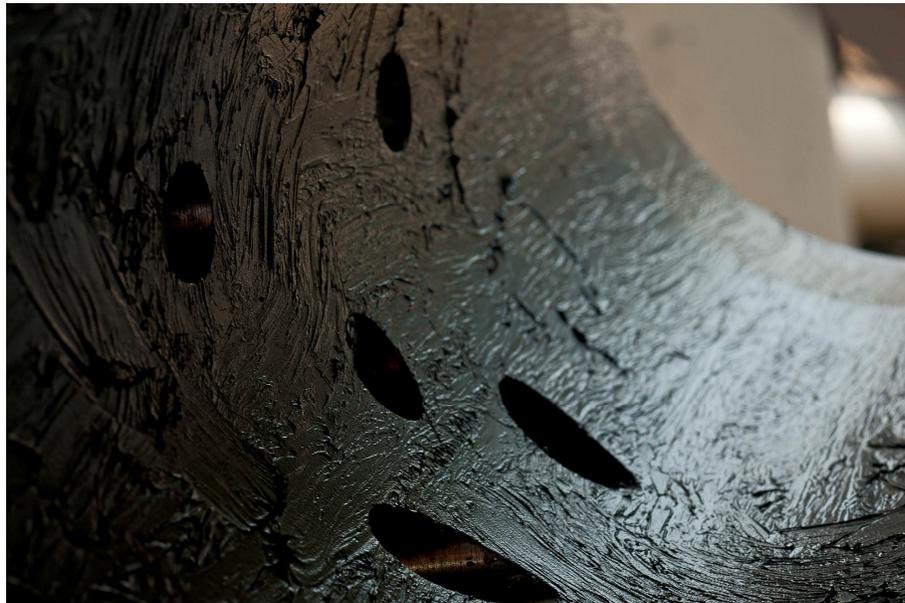

Figure 18 extreme evenly coated fouling.

While no absolute value of the speed of sound available, the ratio of the various paths compared with the average value of all 6 paths was monitored. This is presented in figure 19. As expected, the changes in the speed of sound are of the same magnitude as that of the fouling on the bottom.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 10 of 16
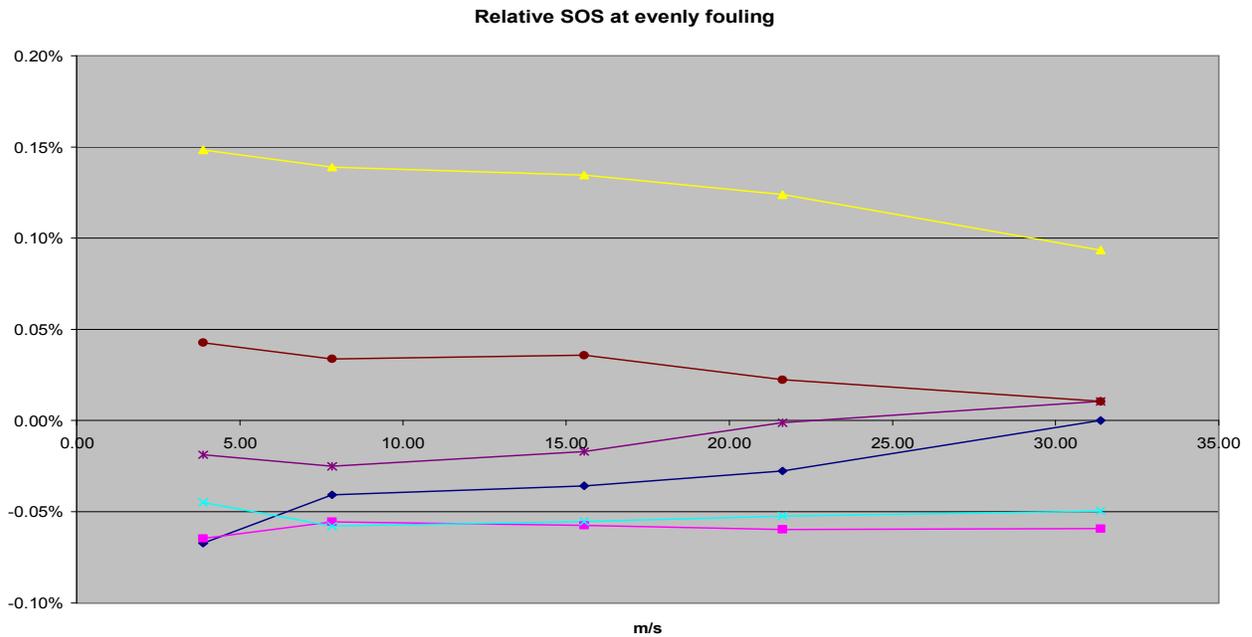
Relative SOS at evenly fouling

Figure 19, relative speed of sound changes

The first order calculated error due to the reduction of the cross sectional area - based on the changes in the speed of sound - is 0.5%; slightly higher than the measured value (see figure 20).
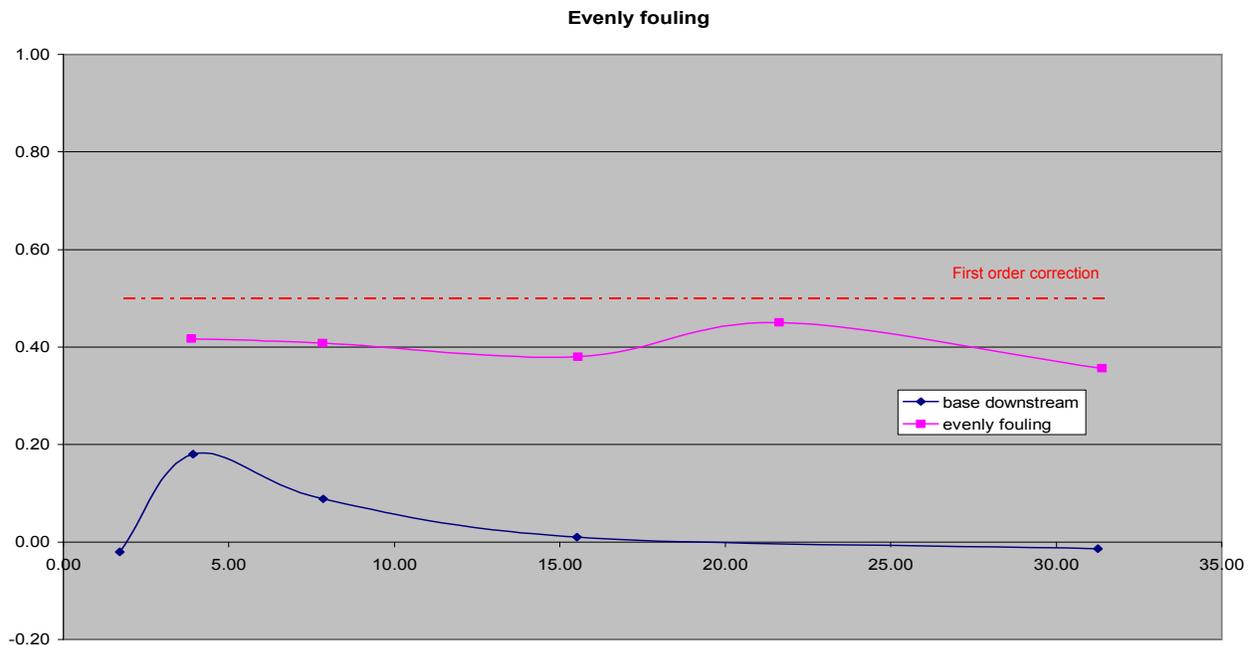
Evenly fouling

Figure 20: error curve at evenly distributed fouling.

5.1.4. Dirt build-up 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.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 11 of 16

For the tests, two different types of "dirt" were applied: one with tape and one with grease covering the top of the transducer (see figures 21)
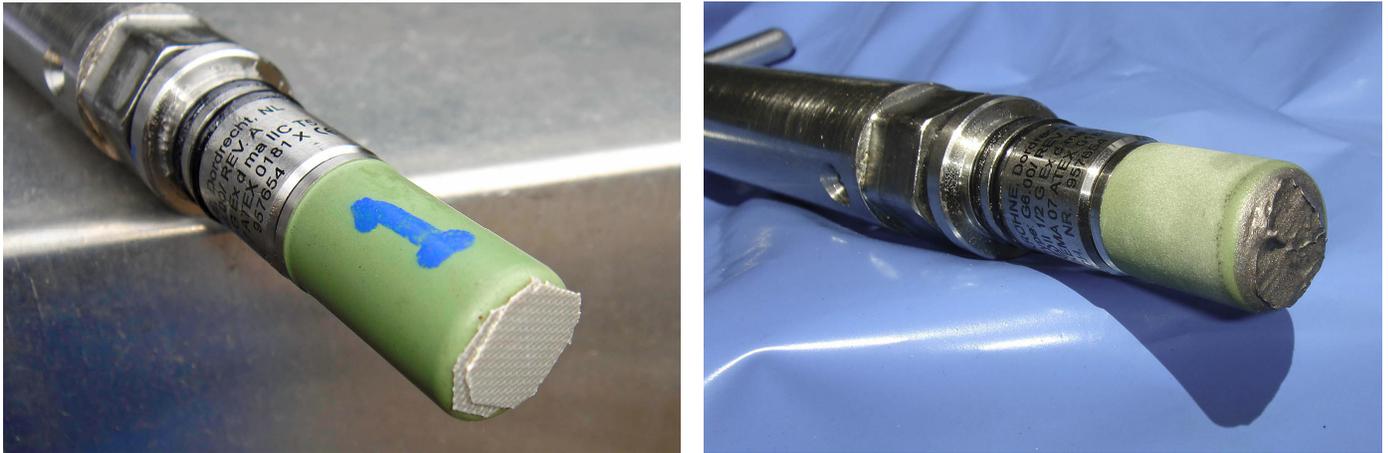
Figures 21: dirt build-up on the transducer.

The impact on the error curve is show in figure 22. It can clearly be seen, that there is hardly any effect on the error curve and all curves are within the repeatability of the test site.
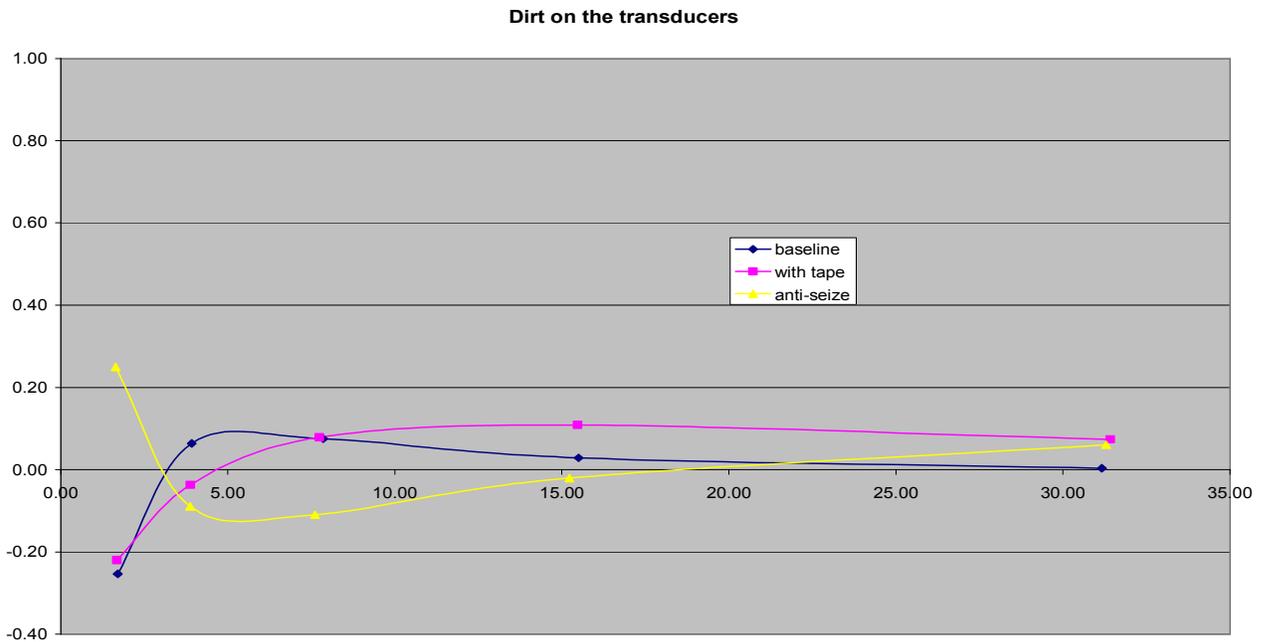

Figure 22: impact of dirt on the transducers.

5.1.5. Liquid contamination of the transducer pockets.

This category of fouling creates an increased acoustic coupling to the pipe and generates "ghost pulses" which may coincidence with the received pulses. As such it affects the shape of the acoustic waveform, the signal-to-noise ratio and results in an offset at the lower flow velocities. In figure 23 the liquid contamination is shown.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan
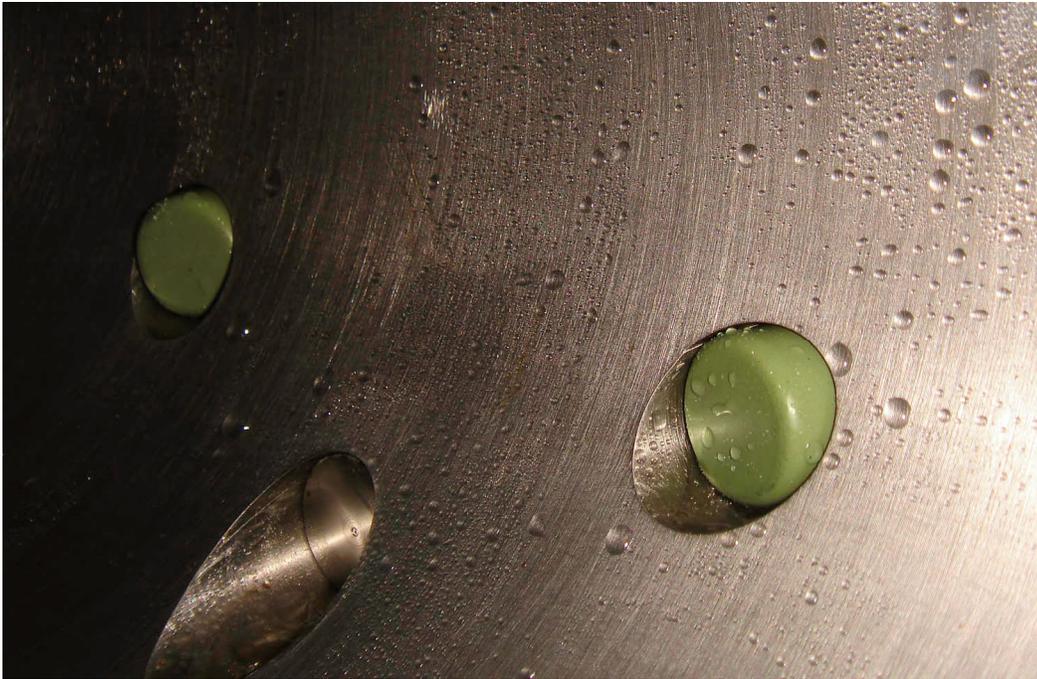
page 12 of 16

Figure 23: Liquid contamination of the transducer pockets

The impact on the error curve shown in figure 24 and is, as expected, most significant on the low flows. In the diagnostics there is a clear change in the S/N ratios which can be used as a warning for the operator.
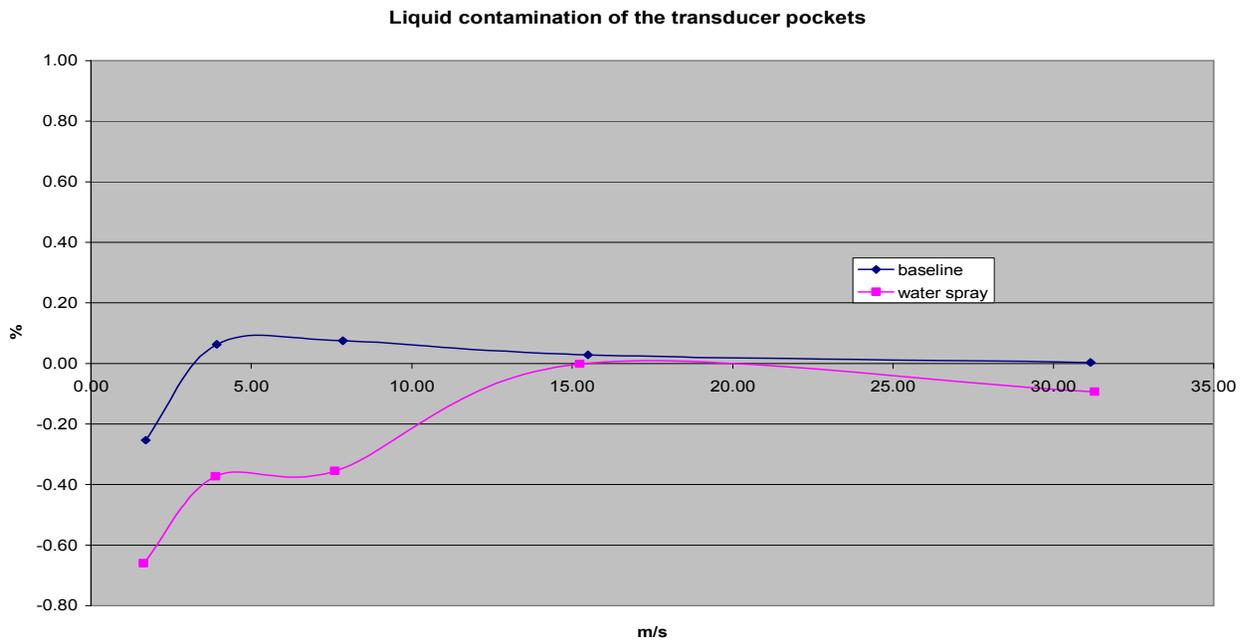

Figure 24: Liquid contamination of the transducer pockets.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 13 of 16

5.1.6. Reflection on rough (corroded) surfaces.

Reflecting technology has huge advantages over direct path meters. Vital diagnostic information on the reflecting surface is retrieved by using reflection technology. With the difference in acoustic impedance between gas and steel being approximately 1 to 1000, the reflection coefficient on clean surfaces is 99.9%. However, when the surface is corroded the reflection coefficient is lower. To investigate the possible impact of corrosion two sets of reflectors with different roughness have been manufactured (see figure 25)

Figure 25 reflectors with different roughness

Despite the huge roughness, the meter functioned flawless showing no impact of the added roughness of the reflector (see figure 26). As expected, both the medium and high roughness reflectors required some more gain in the order of 3 to 6 dB, but the flow measurement was not affected in any way.

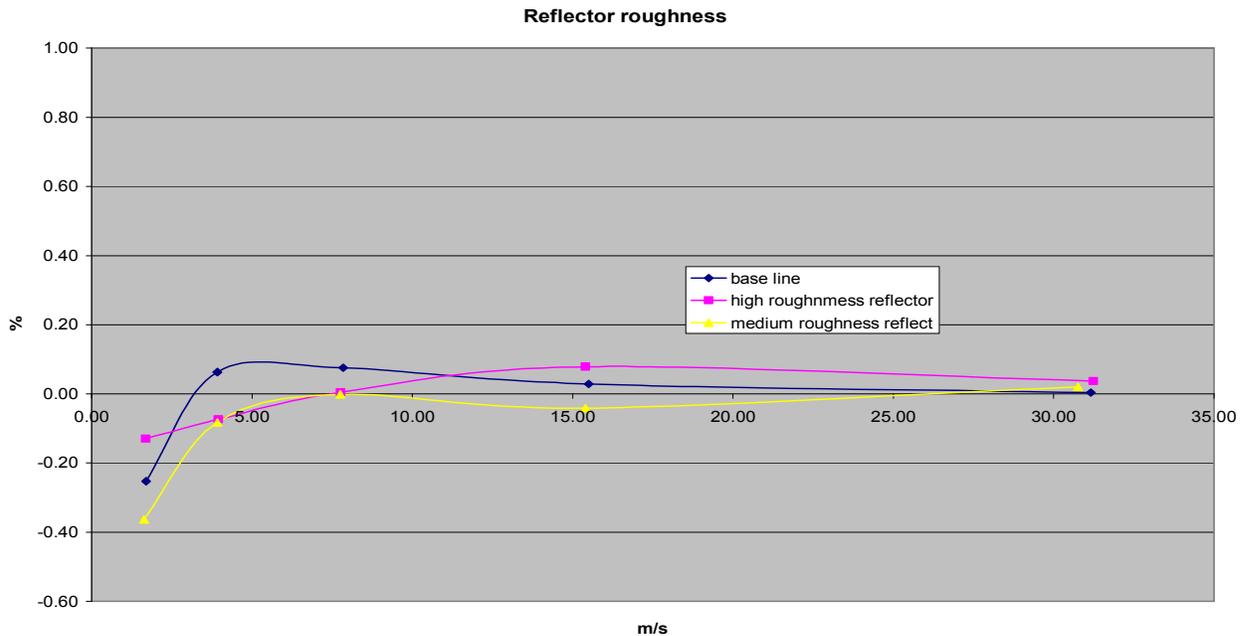Figure 26: error curves with reflectors of different roughness.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 14 of 16

5.1.7.Honed versus corroded inlet spools.

Unless specific attention is paid to the inlet spools, the roughness of the spools can vary widely and other meters such as orifice meters are extremely vulnerable for this.

In contrast, for ultrasonic meters this seems not the case. Looking at the requirements for the connected piping, both the ISO 17089 as well as the AGA 9 does not make any statement regarding the roughness of the upstream piping. Reasons for this were amongst other the tests done by Wilsack & co, finding no shifts when very corroded or smooth pipes were used (see [4]). With these tests done at an older design it was decided to repeat these tests (courtesy of Eon-Ruhrgas). In figures 27 & 28 the test results from the corroded pipe as well as the honed pipe are shown.

Figure 27 corroded inlet spool   Figure 28 Honed inlet spool

Despite large differences in the upstream piping, the ALTOSONIC V12 calibration curves were not affected at all (see figure 29).
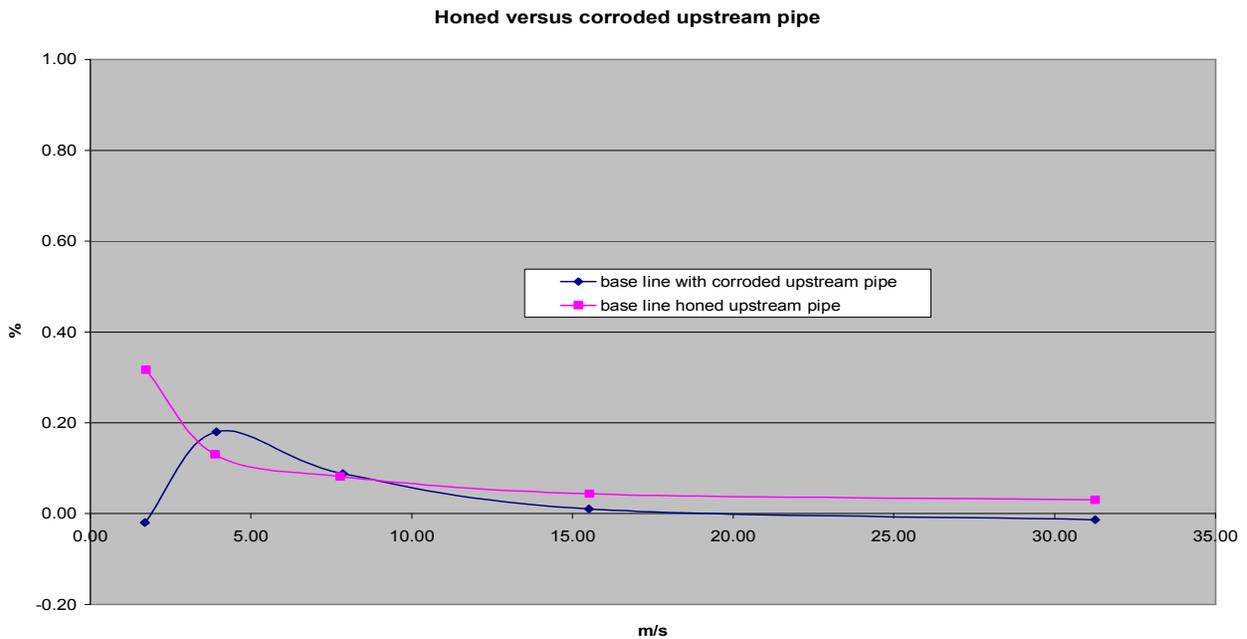

Honed versus corroded upstream pipe

base line with corroded upstream pipe
base line honed upstream pipe

Figure 29: calibration curves with honed and corroded inlet spools.

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 15 of 16

6. Conclusions

- By using reflection technology, vital information on the conditions at the pipe wall is gathered and even small changes can be detected; long before it affects the accuracy of the custody transfer.

- Exclusive to the patented design, even very small fractions of bottom fouling can be detected by the vertical path.

- When changes are reported the developed first order correction functions give a reasonable correction for both the bottom fouling as well as that of the evenly distributed fouling on the wall. For intermittent fouling the correction curve could not be fitted with the error curve and will be further investigated.

- Reflective technology is in respect to accuracy and diagnostics far superior to direct chord designs.

- When using the Altosonic V12, if there is no change, the user can be confident that the original calibration curve is still valid.

7. Acknowledgments

8. References

[1] Diagnostics for reflective multipath ultrasonic meters. Jim Robertson, Pacific Gas and Electric Company, AGA Operations Conference, Dallas 2007

[2] A novel design of a 12 chords ultrasonic gas flow meter with extended diagnostic functions
Jan G. Drenthen, Martin Kurth & Jeroen van Klooster. KROHNE New Technologies, AGA Operations Conference, Dallas 2007

[3] Reducing installation effects on ultrasonic flow meters. Jan G. Drenthen, Martin Kurth, Hilko den Hollander, Jeroen van Klooster & Marcel Vermeulen; Krohne. 7th International Fluid Flow Symposium, Anchorage 2009

[4] Wilsack, R., "Integrity of custody transfer measurement and ultrasonic technology." CGA Measurement School 1996

[5] Witte, James " Predicting Ultrasonic Meter Error in Dirty Service Conditions." Ceesi Ultrasonic flow meter workshop Colorado Springs, 2010

Ultrasonic flow meter diagnostics and the impact of fouling.   **KROHNE**
15th International Flow measurement Conference, Flomeko 2010, Taiwan

page 16 of 16