Considerations on the influence of deposits or changes in wall roughness on the validity of the calibration and long term accuracy of ultrasonic gas flow meters

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1. Introduction

Due to refined diagnostic capabilities and the lack of moving mechanical parts, ultrasonic flow meters (USMs) provide excellent reliability and long-term stability. These properties lead to high accuracy and low costs of operation in the field. Recent studies [2] have shown how meter performance changes after electronics or transducers are replaced. This demonstrates the high precision of time-of-flight measurement with up-to-date components. Nevertheless, some installation parameters relevant to meter accuracy may change after a long period of operation. For instance, in many situations in the field, inner pipe wall corrosion and contamination can occur. These pollutions of the inner pipe wall may influence the geometrical parameters and/or wall roughness of the pipe and consequently the shape of the flow profile.

Several studies [1], [2], [3], [5], [6] have been carried out evaluating the influence of inner pipe wall roughness or build-up on measurement accuracy. Obviously it would be good to be aware of the measurement shift, relative to the original calibration, as a result of these effects so that corrective action (e.g. cleaning or recalibration) can be taken. As Hall, Zanker and Kelner [2] have already stated: A condition-based instead of a time-based recalibration can save considerable expense and inconvenience.

This paper shows how these changes in inner surface quality in a) the upstream pipe and b) of a complete meter package (upstream pipe and meter) effect the meter accuracy. To achieve this a test was developed and conducted at the SICK ambient-air low-pressure test facility (Germany) and the KEMA high-pressure test-facility (Netherlands). The ability of the inherent meter diagnostic parameter profile factor and the 4+1 check-meter concept to detect the impact of these changes was investigated to generate reliable user information on the meter accuracy. The user can benefit from this additional information to save costs e.g. by extending the re-calibration period or reacting promptly if accuracy is at stake within the re-calibration period.

2. USM operation and diagnostic capabilities

USM technology is based on transit time measurement. The ultrasonic signal emitted by the transmitter travels at sonic velocity through the medium to be measured and is picked up by a receiver. The transmitter and receiver are set at a specific angle to the pipe axis, and their combination is called the "measuring path". The measuring path may either extend directly between the transmitter and the receiver or be arranged spatially with one or multiple reflections within the meter body.

Each sensor can work either as a receiver or a transmitter. The signal is sent with or against the gas flow. This results in a different effective propagation velocity in each direction and helps determine different signal transit times. The difference in the transit times is used to determine the mean flow velocity of the fluid in the sound-penetrated space between the two sensors.

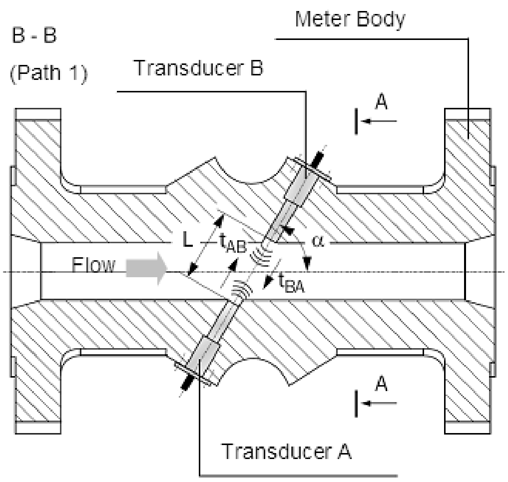


Figure 1: Operating principle ultrasonic measurement technology

Thus, the primary measured variable of ultrasonic gas meters is the signal transit time, which comes from:

- the geometry of the measuring path (path length L and angle α to the pipe axis) and
- the effective propagation velocity (vectorial addition of sound velocity c and flow velocity v_{gas}).

Signal transit time in the direction of flow:

$$t_{AB} = \frac{L}{c + v_{gas} \cdot \cos \alpha} \qquad (1)$$

Signal transit time opposite to the direction of flow:

$$t_{BA} = \frac{L}{c - v_{gas} \cdot \cos \alpha} \qquad (2)$$

Mean flow velocity on the measuring path:

$$v_{gas} = \frac{L}{2 \cdot \cos \alpha}\left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}}\right) \qquad (3)$$

USMs offer the fundamental advantage of diagnosing the device status and hence the quality of the measured value by means of device data acquired internally. As a result, problems caused by device components (ultrasonic sensor, cables, and electronics) or their application (e.g. pulsation, blocked flow conditioner, existence of liquid) can be identified. Multi-path USMs can also compare diagnostic values between the individual paths. They offer a broad variety of diagnostic capabilities. These diagnostic capabilities can be divided into:

Diagnostic values of the Ultrasonic Signal	
Automatic gain control (AGC)	*Describes how much the received signal needs to be amplified. A weaker signal can be an indicator for sensor aging, for example.*
Signal-to-noise ratio (SNR)	*Ratio of undisturbed useful signal to the superimposed noise signal. Can give feedback on changed conditions of the facility.*
Performance	*Ratio of accepted to received Ultrasonic signals.*
Turbulence	*Current fluctuation of the flow velocity around its mean value. Changes in Turbulence can be an indicator of mechanical disturbances in the upstream pipe section.*
Diagnostic indicators of the sound velocity	
Speed of sound (SOS)	*For diagnostic reasons the SOS between different paths can be compared internally (in between paths) and externally (with a theoretical value or externally sourced value).*
Diagnostic indicators of the flow profile	
Profile Factor	*Ratio of inner paths to the outer paths in multi-path USMs.*
Symmetry	*Ratio of upper paths to lower paths in multi-path USMs.*

An alternative diagnostic concept is the check-meter concept. At this concept two ultrasonic meters (a fiscal and a check meter) with different path layouts are connected in series or integrated into one meter body. The respective path layouts react different to upstream perturbations. Comparing the volumes in between the fiscal and the check-meter can provide valuable information [4].

Different concepts and methods have emerged when it comes to analysing these diagnostic data in order to take appropriate action. The depth of analysis varies substantially.

Ad hoc analysis	*All diagnostic data from the meter are concisely presented and evaluated in the form of a report showing current values and thresholds.*
Automated user warnings	The USM constantly monitors and checks all diagnostics. A warning will be generated automatically if the threshold value is underrun or exceeded.
Trend analysis	*Evaluates changes in diagnostic data by storing several snapshots of the diagnostics over a specific time frame.*
Fingerprint concept	*Flow rate dependent, adaptive differential analysis of diagnostic data over a specific time. Therefore current diagnostic parameters are compared to the original ones. Diagnostic indicators are classified depending on the current flow velocity instead of globally [5].*

As a diagnostics value parameter, flow profiles have proven to be a good indicator of changes in the inner pipe wall quality due to corrosion or contamination. Papers published so far [1], [3], [5], [6] have shown the ability of the profile factor to indicate corrosion or deposits on the inner pipe wall. Furthermore, research has been carried out into the ability of the 4+1 check-meter concept to determine changes in the inner pipe wall quality. This will be introduced in more detail in the following chapter.

2.1 Profile Factor

By comparing the individual path velocities at multi-path meters, different diagnostic indicators can be derived. One example is the profile factor, presented here in the "Westinghouse" path layout used in the FLOWSIC600, with four measuring paths arranged in parallel (Figure 2).

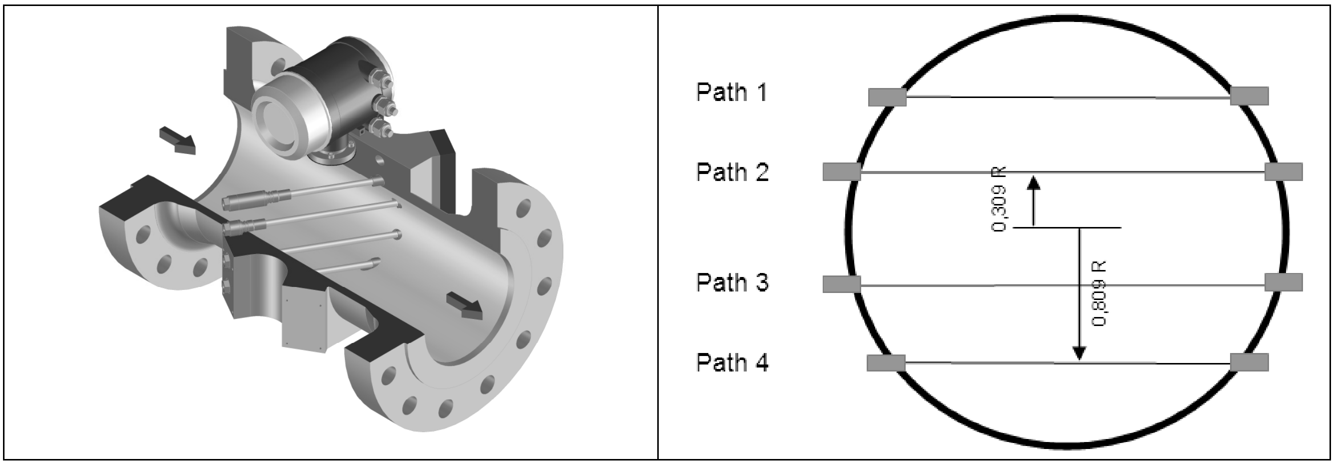


Figure 2: Path layout in a FLOWSIC600

For this specific path layout and a fully developed flow profile, the typical ratios observed are 0.89 for paths 1 and 4, and 1.04 for paths 2 and 3, as compared to the average flow velocity. Due to friction, local flow velocities at the inner pipe wall are lower than at the centerline of the pipe and hence cause a lower ratio.

The *profile factor* indicator itself is calculated from the path velocities by dividing the sum of the inner paths 2 and 3 by the sum of the outer paths 1 and 4:

Profile Factor:

$$PF = \frac{v_2 + v_3}{v_1 + v_4} \qquad (4)$$

For the typical path ratios and a fully developed flow profile described above, the profile factor is 1.17. However, the profile factor can of course vary depending on the design of the upstream piping, the type of flow conditioner (if employed) and the distance of the conditioner from the meter.

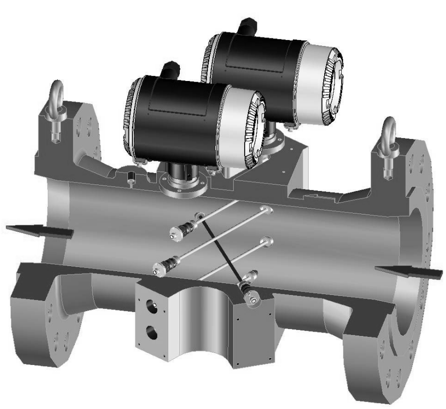
To identify changes it is recommended to observe the profile factor trend over a period of time rather then doing an ad-hoc analysis. By using differential analysis methods, such as the fingerprint concept, for example, the individual profile factor can monitored in comparison to the initial status of the USM. By analyzing the profile factor in the individual velocity class, the thresholds can be set much closer around the mean value. Hence it is more representative for the specific velocity class and for the specific application.

2.2 Check-meter concept

At this concept two ultrasonic meters (a fiscal and a check meter) with different path layouts are connected in series or integrated into one meter body. The respective path layouts react different to upstream perturbations. At the FLOWSIC600 2plex for example a 4-path fiscal meter and a single-path check-meter are integrated into one meter body with two separate electronics. The single-path measurement, is carried out directly in the centerline of the flow profile. The measurement directly in the centerline is known to be more sensitive to profile changes than the standard Westinghouse path locations used at the FLOWSIC600. As soon as, for example, contamination builds up at the inner pipe wall, the flow velocity will be slower at the pipe wall due to friction effects. At the same time flow velocity gets faster in the centerline of the meter. With this concept the meter's response is significantly different from the multipath meter, which is insensitive to upstream perturbations. It reacts much more to perturbations such as blocked flow conditioners, meter and pipeline corrosion and other effects. Several papers have shown and proven this concept [4].

This concept is used to detect flow profile changes very quickly due to the sensitivity of the centerline measurement. Tests [4] with a FLOWSIC600 2plex have shown that the centerline measuring path reacts approx. 30 times more sensitively than the 4-path measuring system when blocking a flow conditioner 40% 10D upstream.

To implement this technique, the flow computer totalizes the volumes from each meter (fiscal meter and check meter). At the end of each hour the flow computer then compares the volume reported by the fiscal meter to the volume from the check meter. If the velocity profile in the meter changes, e.g. due to a blocked flow conditioner or pipeline contamination, the check meter will respond differently, and thus the volumes will be different.



Picture 1: FLOWSIC600 2plex

3. Effects of surface roughness and corrosion on the measurement accuracy of USM's

To calculate the flow rate correctly it is essential to know exactly the inner diameter of the USM. The inner diameter is measured precisely during manufacturing and stored in the meter electronics for further computing. The measured gas velocity (v_{gas}) multiplied with the cross-sectional area (A) derived from the inner diameter equals the volumetric flow rate (Q).

Volumetric flow rate:
$$Q = v_{gas} \times \frac{\pi}{4} D^2 \qquad (5)$$

Corrosion or contamination of the inner wall of the meter body will lead to a change in diameter and wall roughness in comparison to the original conditions. The changed wall roughness may alter the velocity profile shape. On the other hand the changed inner diameter results in a wrong calculation of the cross-sectional area and hence the wrong calculation of the volumetric flow rate. As there is no indication when a maximum accepted flow rate deviation limit is exceeded, recalibration is usually carried out at pre-defined intervals. This can be cost-intensive for the plant owner. It would be better to know when the meter begins to exceed the deviation limit so that appropriate action can be taken (e.g. recalibration).

Several studies have already been conducted discussing the effects of upstream inner pipe and/or meter body surface roughness and build-up [1], [2], [3], [5], [6]. Some have even gone further, correlating the diagnostics parameters of an USM to the occurring measurement deviation. This paper investigates the effects of either

a) upstream pipe surface roughness changes and
b) corrosion at the inner surface of a meter package (upstream pipe and meter)

on the total measurement accuracy and hence the validity of the calibration. Furthermore the ability to determine changes of the inner pipe wall quality by the USM diagnostics parameter profile factor and the check-meter concept have been researched.

a. Test concept and operation

The first step was to develop a test process (Figure 3).

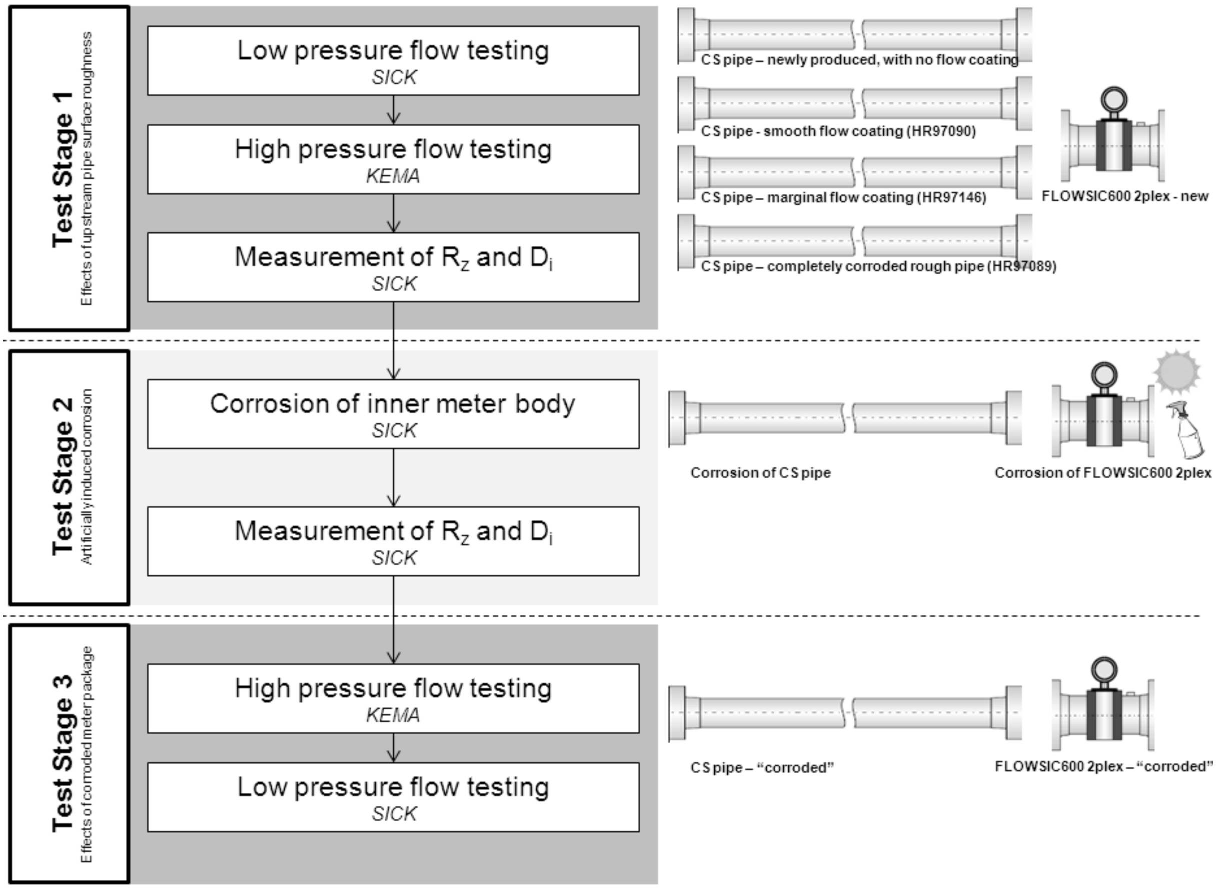


Figure 3: Test process

For testing a 4” FLOWSIC600 2plex was selected. This meter combines a fiscal (4-Path) and a check-meter (1-Path) with two separate electronics in one meter body. The decision to use a small size meter was due to handling reasons and the fact that the diagnostics were expected to be most sensitive to changes of the inner diameter and / or surface roughness.

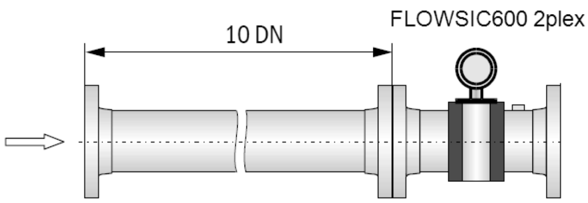
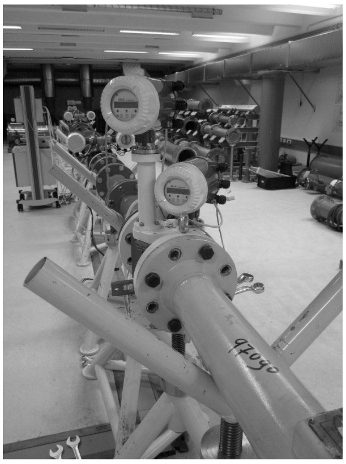


Figure 4: Meter Package

The meter has been assembled in a meter package (Figure 4) consisting of a 10D long upstream pipe section and the meter itself. Different upstream pipes of the same inner diameter (102 mm) and length, but different inner surface roughness, have been used during the tests as listed below.

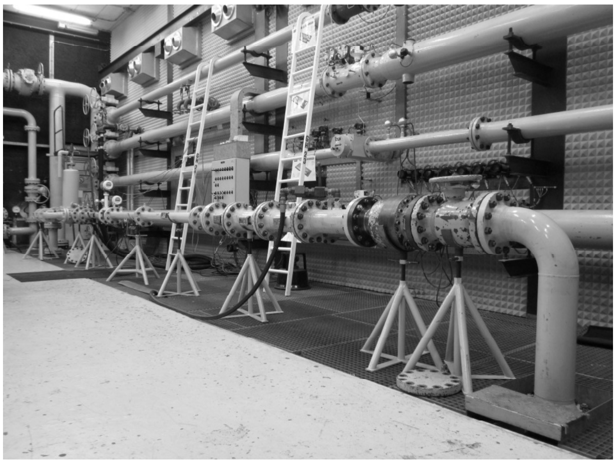
I. Carbon steel pipe (CS pipe) - newly produced, with no flow coating
II. Carbon steel pipe (CS pipe) - smooth flow coating (HR97090)
III. Carbon steel pipe (CS pipe) - marginal flow coating (HR97146)
IV. Carbon steel pipe (CS pipe) - completely corroded rough pipe (HR97089)

Two flow test facilities were used to gain data at different pressures for all test setups. Low-pressure tests were performed at the SICK test facility in Ottendorf-Okrilla, close to Dresden (Germany). This state-of-the-art test facility is used for the quality control of FLOWSIC600 production, for new device development testing and for low-pressure calibrations. The test facility operates with ambient air at ambient pressure and is equipped with three 8-path USM reference meters (4”, 8” and 16” size). Flow rates of up to 10.000 Nm³/h can be measured with a certified uncertainty of better than 0.2 %. For this particular test, the meter package had been installed with 10D upstream piping after a flow conditioner (perforated plate, PTB design).



Picture 2: Low-Pressure test facility at SICK (left picture) and tested upstream pipes with respective different inner surface roughness (right picture)

For high pressure testing at 9 bar(a) and 20 bar(a) the test facility at KEMA in Groningen (NL) was chosen. This test facility can run up to 36,000 Nm³/h at a pressure of 8 to 40 bar(a). The test facility certified measurement uncertainty is better than 0.2%. Meters ranging from small (<1”) to medium (12”) in size can be tested or calibrated here. For this particular test, the meter package had been installed with 30D upstream piping after a 90° bend.



Picture 3: FLOWSIC600 2plex at the KEMA test facility in Groningen (NL)

Test stage 1

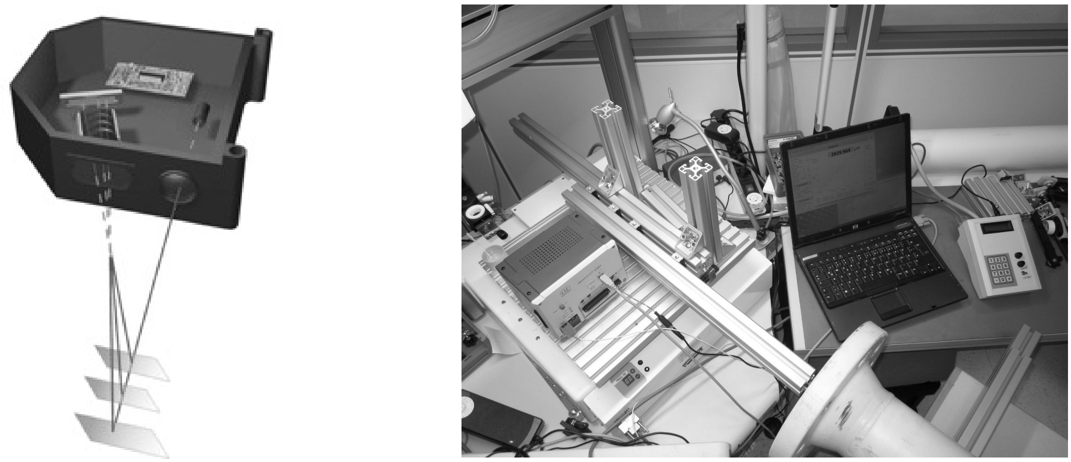
In the first test stage the newly produced meter was tested at ambient pressure at the low-pressure SICK test facility and at 9 bar(a) and 20 bar(a) at the high-pressure KEMA test facility with the different upstream pipes described before. Test flow rates of 10%, 25%, 40%, 70% and 100% of Qmax = 650 m3/h were taken and all diagnostic parameters of the meter were recorded.

Test stage 2

After the initial low- and high-pressure testing, the meter package's (newly produced meter and carbon steel pipe) inner surfaces were corroded over 6 weeks during the summer season. To do so, the inner surface was sprayed with a brine made of sodium chloride every two days, building up a nice even corrosion (Picture 4) at upstream pipe and meter.

Picture 4: Initiating the accelerated corrosion of inner meter and pipe surface using brine

Different technologies were evaluated to measure the inner surface roughness. For reasons of accuracy and practicality, the laser triangulation principle was chosen (Picture 5). The measuring device used offers an accuracy of better than 1 µm and a resolution of 0,03 µm. For the specific requirements of meter surface roughness measurement a special test bench was designed (Picture 5). Over a linear section of approximately 10 mm length, at a representative place in the pipe, the surface roughness number R_z was determined. Additionally the internal diameter of the meter was measured under new, non-corroded conditions and after the artificially induced corrosion. Results can be found in Table 1.



Picture 5: Laser triangulation principle [7] (left side) and test set-up for surface roughness measurement

Measured body	Surface roughness R_z (µm)
FLOWSIC600 2plex - newly produced, "non corroded”	32
FLOWSIC600 2plex, "corroded”	114
Carbon steel pipe - newly produced, "non corroded”	56
Carbon steel pipe, "corroded"	111
Carbon steel pipe - marginal flow coating (HR97146)	59
Carbon steel pipe - smooth flow coating (HR97090)	82
Carbon steel pipe - completely corroded rough pipe (HR97089)	128
	Inner diameter D_i mm
FLOWSIC600 2plex - newly produced, "non corroded”	94,91
FLOWSIC600 2plex, "corroded”	94,57

Table 1: Surface roughness and inner diameter measurements

Test stage 3

After surface roughness and inner diameter measurement the corroded meter package was flow-tested again at the high-pressure test facility with the same test setup and test procedure as in stage 1. Flow testing at low-pressure was also planned. Due to the high utilization of the test facility at this time, it could not be finished before submission date of this paper.

b. Results derived from this test

Test stage 1

Figure 5 shows the performance of the newly produced 4" FLOWSIC600 4-path meter with four different upstream pipes varying in surface roughness at different pressures.

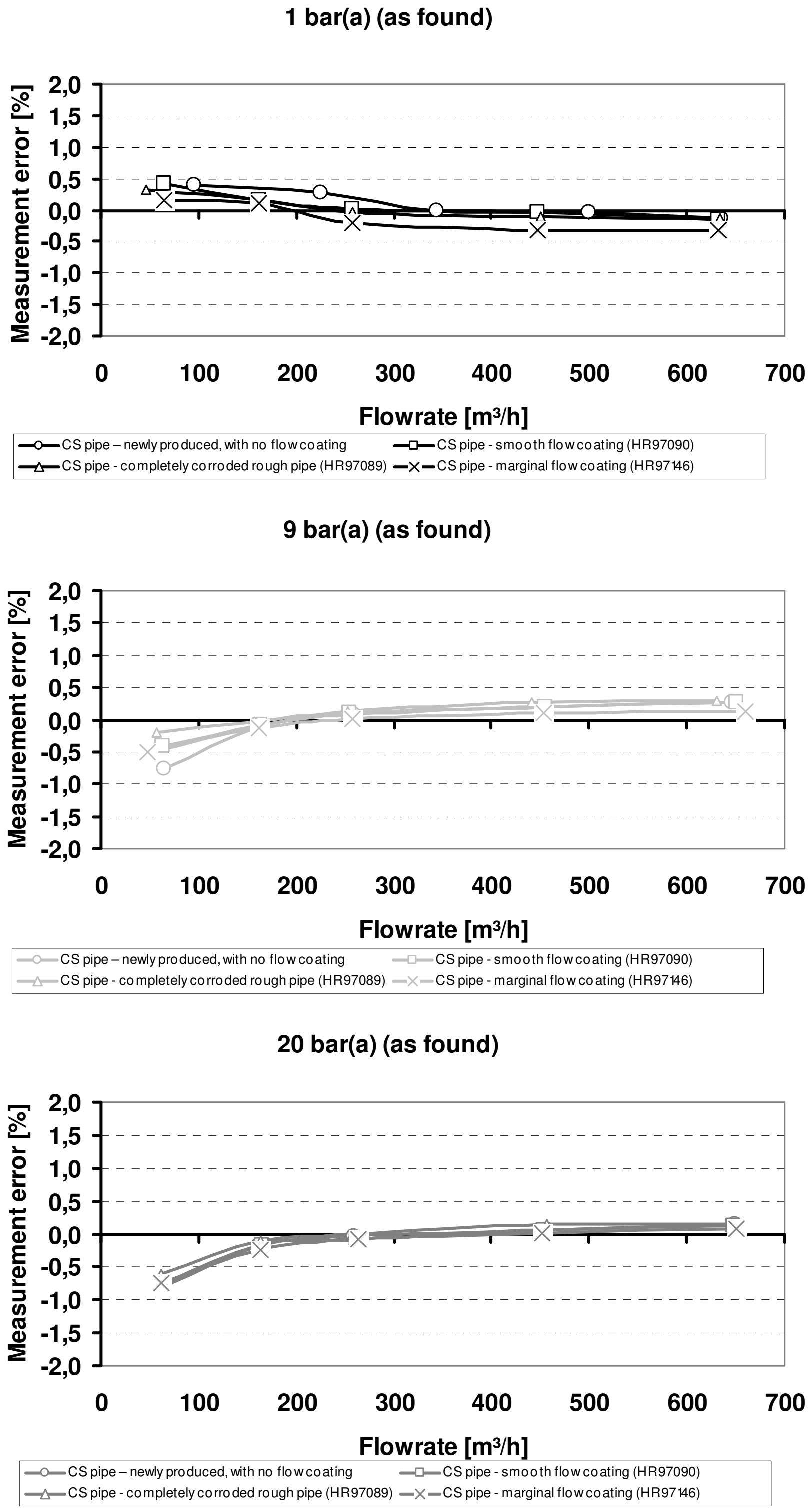


Figure 5: 4" FLOWSIC600 2plex 4-path system - newly produced ("non corroded") with different upstream pipes varying in surface roughness

For better clarity the flow weighted mean error (FWME), calculated according to equation (6), will be used for the analysis of the test results.

Flow Weighted Mean Error:

$$FWME = \frac{\Sigma Q_i \times e_i}{\Sigma Q_i} \tag{6}$$

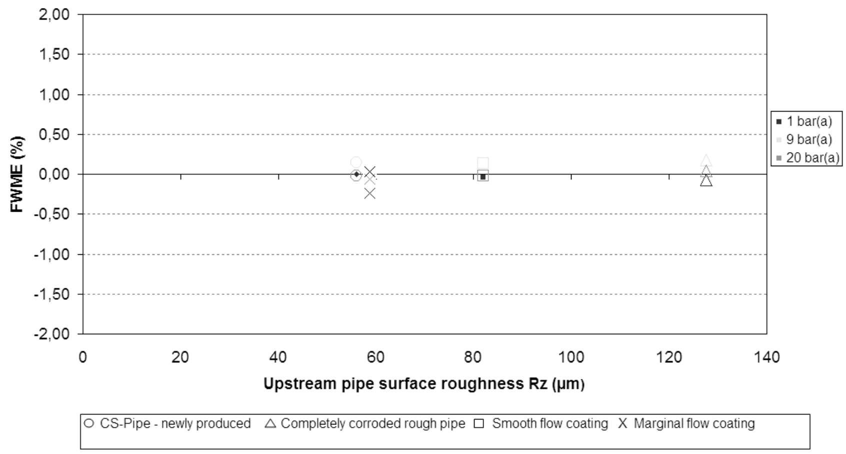


Figure 6: FWME in relation to different grades of upstream pipes surface roughness (newly produced, “non corroded” meter)

Figure 6 shows these average deviations for the different test pressures and upstream pipe wall roughness values. All as found FWMEs are within a band of ±0.2% and the upstream piping surface roughness shows no significant influence on the flow measurement error. Considering the uncertainties of the two different test facilities used it is concluded that the meter’s accuracy is not influenced by the upstream piping. This supports the results already gained by other studies [1].

Test stage 2 and 3

A corroded meter package produces a different picture: the measurement error is significant. Figure 8 shows the flow test results for the corroded meter package at 9 and 20 bar(a) for the fiscal and the check meter in contrast to the flow test results of the clean (newly produced) meter package (Figure 7).

Newly produced meter package

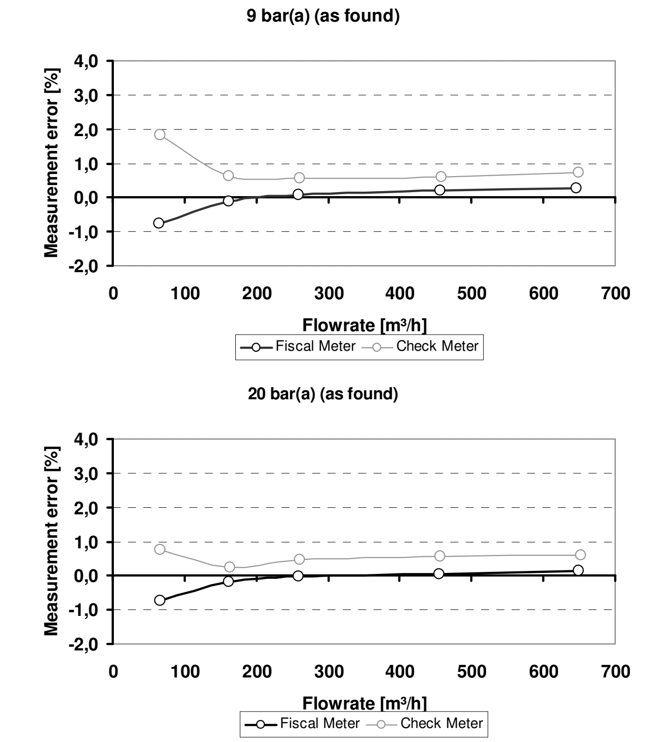


Figure 7: As Found curves at 9 and 20 bar(a) of clean "non corroded" meter package

Corroded meter package

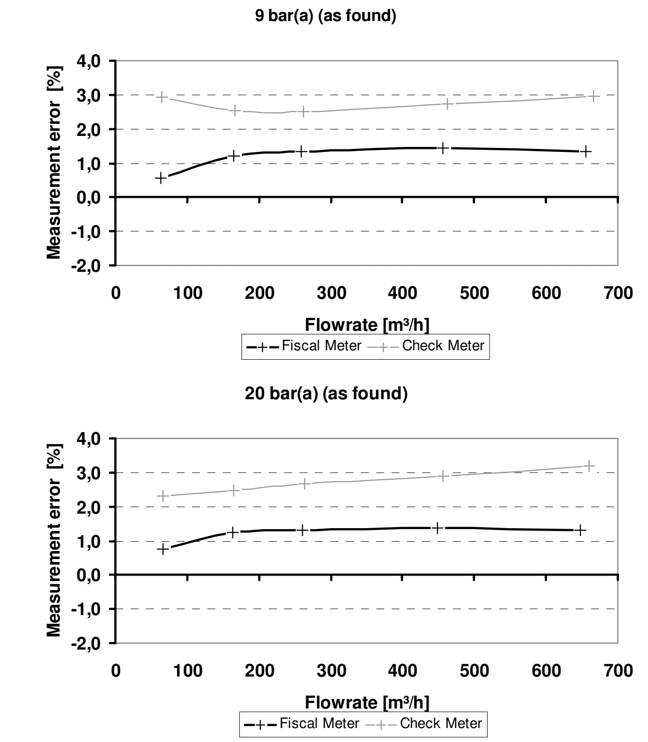


Figure 8: As Found curves at 9 and 20 bar(a) of corroded meter package

The meter FWME of the fiscal meter shifts by more than 1% after the corrosion was induced. This surprisingly large shift needs a closer consideration. As already known, the inner diameter has been reduced by 0.34mm due to the corrosion (see Table 1). Hence it contributed the most with +0,7% (see equation 7) to the whole measurement error (Figure 9). That means, two-thirds of the error results from inner diameter change only.

Influence of diameter change on measurement error: $$k = \left(\left(\frac{D_1}{D_2}\right)^2 - 1\right) \times 100\% \qquad (7)$$

D_1 Inner diameter FLOWSIC600 2plex – newly produced, “non corroded”
D_2 Inner diameter FLOWSIC600 2plex, “corroded”

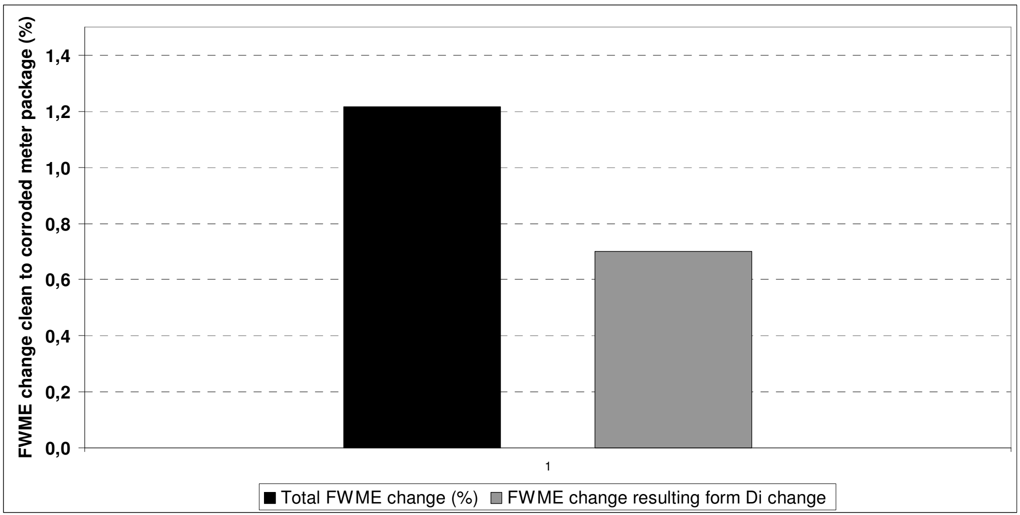


Figure 9: FWME change clean to corroded meter package (%) (Pressure averaged)

Indication of FWME shift through Profile Factor

As already stated, one of the purposes of this paper is to give user advice on when the meter is out of the original calibration range and needs to be recalibrated. For early indication the ability of the inherent meter diagnostics to detect surface roughness and build-up effects was investigated. Therefore the profile factors were logged with the FLOWSIC600's integrated log-functionality throughout the testing procedure and evaluated. Figure 11 shows the shift in the FWME of the fiscal meter relative to the shift in the flow profile from clean to corroded meter package. Based on these results and assuming a linear correlation one can say for this particular setup that a profile factor shift of 1% indicates a FWME shift of 0,55%.

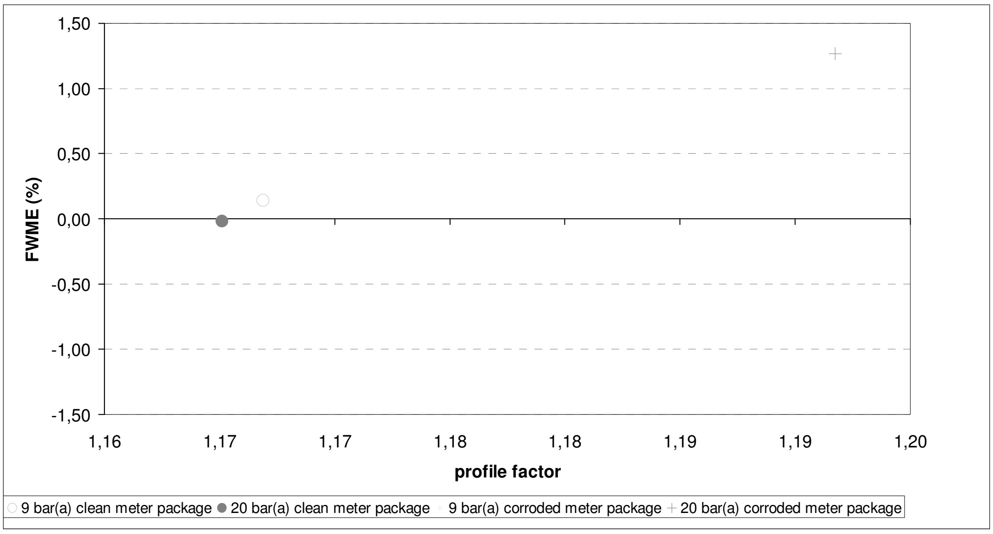


Figure 10: Profile factor in relation to FWME for clean and corroded meter package

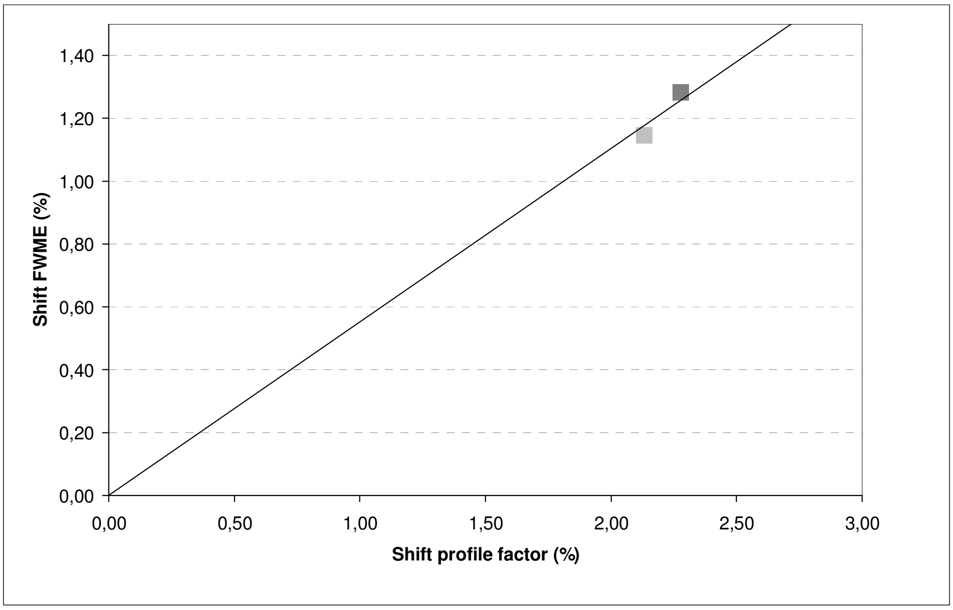


Figure 11: Profile factor shift (%) in relation to the FWME shift (%) clean to corroded meter package

Indication of FWME shift through 4+1 Check-meter concept

Additionally the ability of the FLOWSIC600 2plex check-meter concept to identify build-up or surface roughness changes was analysed. Therefore the FWMEs of the fiscal and the check-meter have been compared, practically representing the difference in the respective hourly volume flow readings. First the individual flow-measurements of both meters were evaluated (Figure 8) and the respective FWMEs calculated. Second, the difference between these FWMEs (FWME - △4+1) was computed: One for the clean meter package and one for the corroded meter package. The shift of FWME - △4+1 in between these both setups was plotted relative to the FWME shift of the fiscal meter itself. Based on the these results and assuming a linear correlation one can say for this particular setup that a FWME - △4+1 shift of 1 %, indicates directly the FWME shift of the fiscal meter.

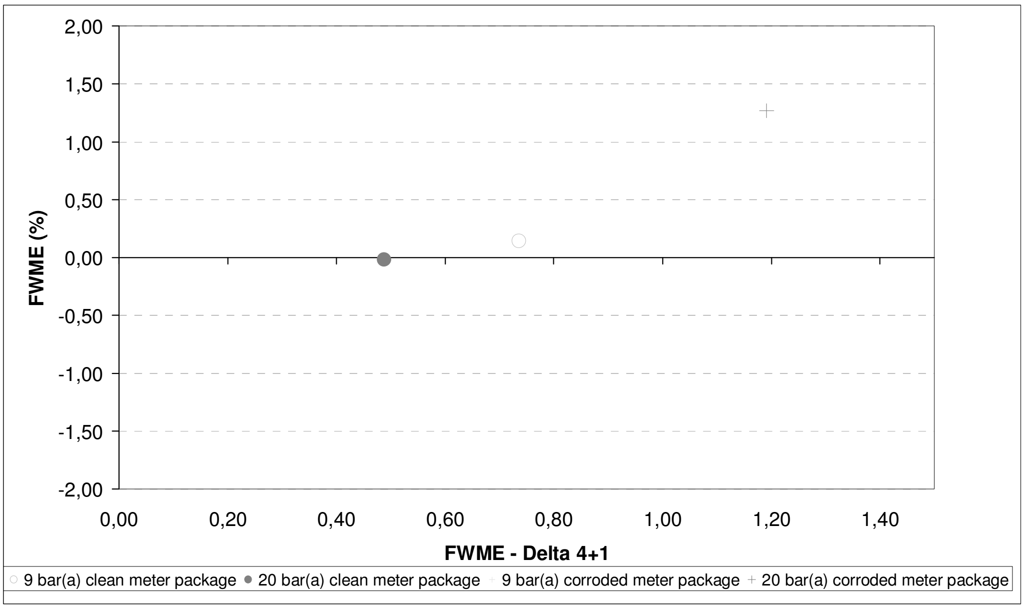


Figure 12: FWME - △4+1 in relation to FWME for clean and corroded meter package

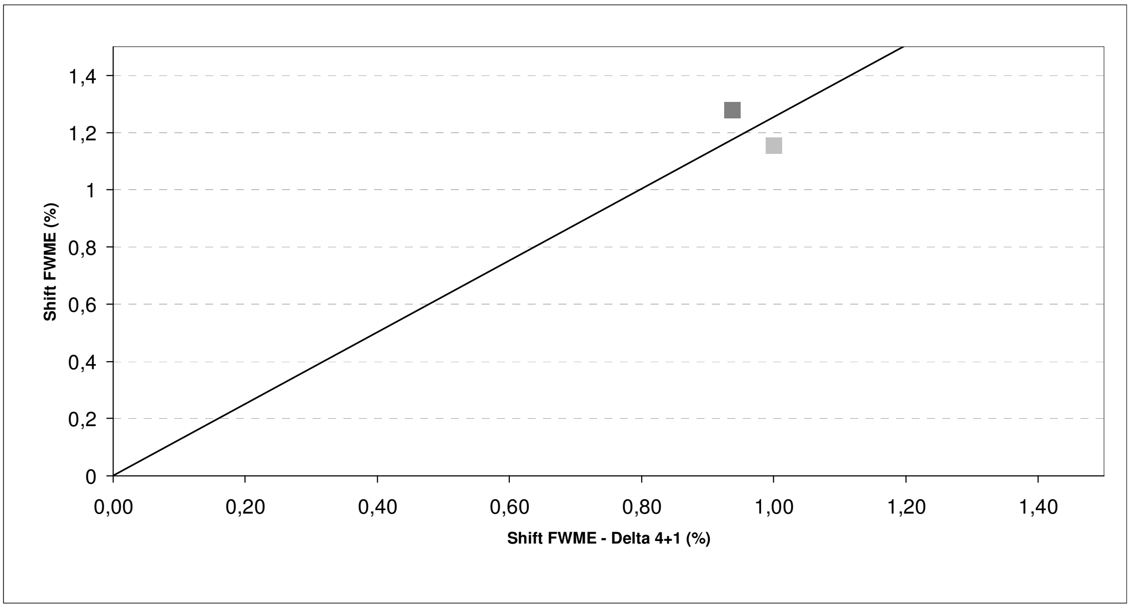


Figure 13: FWME - △4+1 shift (%) in relation to the FWME shift (%) clean to corroded meter package

4. Conclusion

The test results lead to a better understanding of how the validity of the calibration and the long-term accuracy of an USM is influenced by build-up or/and changes in wall roughness and how this can be diagnosed. By comprehensive testing of typical field situations the effects of a) upstream pipe surface roughness and b) corrosion of a meter package on the meters accuracy have been shown.

The results lead to the conclusion that a calibration respectively recalibration of this type of USM as a package (upstream pipe with meter) is not required, as the change of the inlet piping due to corrosion and different wall roughness's doesn't influence the meters accuracy. This saves handling costs for the initial and the future recalibrations of the meter.

For the given 4" meter package the impact on the accuracy due to corrosion within the meter body has been significant – two-thirds of the FWME change were identified to be due to the change of inner diameter and only one-third due to the change of the wall roughness. For large size meter packages, due to the smaller relative diameter change of the build-up, the meter body roughness will be more dominant to the meters accuracy, but decreases the FWME change.

Today's diagnostics (e.g. profile factor) or check-meter concepts (such as the 4+1 concept) clearly identify changes in the nearby installation of the meter due to corrosion or contamination. This means that no maintenance is required as long as there is no indication from the diagnostics or variance in volume reading with the 4+1 check-meter concept.

The type of change in the installation (e.g. pulsation, blocked flow conditioner, existence of liquid) can be identified using different diagnosis parameters within the meter (e.g. profile factor, symmetry, turbulence) combined with a check-meter concept (e.g. 4+1). Before the accuracy of fiscal metering gets significantly affected the right activities can be scheduled (e.g. cleaning of piping vs. recalibration of a meter).

In the past several studies quantified the changes in the nearby installation of the meter by diagnostics. The user should make more field data available to the market in order to get a comprehensive picture over all meter sizes and application data occurring in the field.

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