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Calibration errors of ultrasonic meters in the Bernoulli laboratory due to non-isothermal flow conditions.

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ABSTRACT

The Bernoulli laboratory (“Westerbork”) in the Netherlands, jointly operated by Gasunie, NMi and KEMA, holds a record of over 30 years in calibrating very large gas meters at high pressure with natural gas. NAM, a major producer of natural gas in the Netherlands, utilises a large number of ultrasonic meters. Elster-Instromet is a world wide operating manufacturer of multi-path ultrasonic meters. Gastransport Services is the national gas transporting company of the Netherlands, who is connected to the network of NAM via several delivery stations utilizing ultrasonic meters.

Due to the results of five calibrations of 24-inch ultrasonic meters in the Bernoulli laboratory early 2008, a quality check procedure (number QC-11) was started by the Bernoulli laboratory. Four out of five ultrasonic meter showed strongly non-linear behaviour at low flow rates, with a maximum at about 560m^3/h (approximately 2% of Q_{max}) with errors peaking as high as +2%. Taking into account, the demands set in ISO/FDIS 17089-1: 2009(E), all four meters would have been rejected had the standard had already been ratified. Together, the manufacturer, the user and the calibration facility decided to give high priority to quickly identify and resolve this problem. After excluding all straightforward errors, two possible causes remained on the short list: a disturbed flow profile at low flow rates, typically below 2 m/s, and meter problems. A series of experiments and improvements to the calibration facility were executed in the course of 2008: an additional temperature measurement at the bottom; dozens of calibrations of one specific 24-inch ultrasonic meter, made available by the user (this meter was even calibrated in the up side down position); thermal lagging was improved; and finally, in January 2009, the full measurement section was insulated. Applying full thermal lagging with 15°C temperature difference between gas and ambient, temperature differences were largely reduced, as was the error of the ultrasonic meter at 800m^3/h. Also the ultrasonic meter diagnostics showed a large improvement of the flow profile. Although the thermal lagging had insufficient heat transmission resistance, which prevented a 100% success, the experiment showed, without doubt, that non-isothermal flow conditions were the root cause of the calibration errors.

Non-isothermal flow conditions have previously been addressed at the 2005 Flomeko conference [3], however, the discussion at that time concentrated on the temperature measurement error and the effect was characterised as “stratification”. In that paper, other effects of non-isothermal flow: non-axial velocity components and an asymmetric flow profile, were not recognised as a problem. The majority of gas meters calibrated in Bernoulli laboratory, turbine meters, are not sensitive to non-isothermal flow conditions. Ultrasonic meters however, measure velocity components and may be very sensitive to a combination of non-isothermal flow, depending on their path configuration. Clearly, the Q.Sonic-4C of Elster-Instromet is sensitive to these non-isothermal flow conditions present in Westerbork.

(Presently, insufficient data on other types of meters are known to the authors to be able to judge their sensitivity to non-isothermal flow. One of the problems in obtaining this information is the likeliness of missing the error peak, since it might very well lie between two calibration points.)

1. INTRODUCTION

The facility:

Established in 1978, the Bernoulli laboratory in Westerbork, the Netherlands, provides research and calibration services with high pressure natural gas under flowing conditions.

Figure 1 - Arial overview of the Bernoulli laboratory in Westerbork, the Netherlands

The facility is among the largest in the world, capable of calibrating 30” gas meters with 120D straight upstream piping. Annually, more than 200 large meters are calibrated.

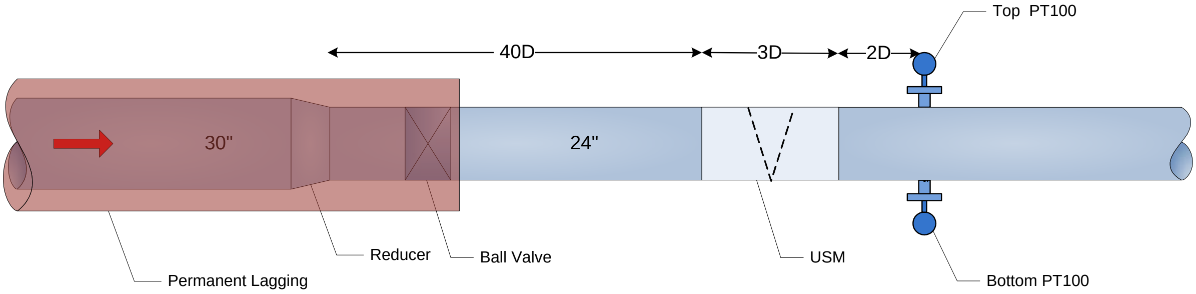

Figure 2 - Schematic lay out of the meter run with a 24 inch ultrasonic meter; valid as from December 2008. Note that the initial results presented, were achieved without the depicted “permanent lagging” and without the depicted “bottom PT100”.

The parties involved:
The Bernoulli laboratory is owned and operated by Gasunie, the Dutch national gas transmission company, transporting more than 80 billion cubic meters annually. Gasunie cooperates with NMi-Nederland and KEMA.

NMi-Nederland is accredited according to ISO17025 for flow calibrations in the Bernoulli laboratory. NMi operates the front- and back office, supervises the calibration, issues the certificate and is responsible for the quality and the traceability of the reference standards.

KEMA, division GCS (Gas consulting and services), until July 1st 2009 part of Gasunie, delivers, among others, services to Gasunie in the field of instrumentation, ict and scientific support.

NAM, is the largest gas producing company in the Netherlands. Almost all gas produced by NAM is transported by Gastransportservices. The majority of the delivery stations are equipped with ultrasonic gas meters, which are calibrated in the Bernoulli lab. The theme of this paper is about some of these calibrations.

Gastransportservices, owned by Gasunie, is on the receiving end of the gas delivered by NAM, which makes the company equally concerned about the flawless determination of delivered volumes.

Elster-Instromet is a market leader in the design, manufacture and supply of gas metering products. In addition to the Ultrasonic meter portfolio, Elster-Instromet offers a full range of turbine meters, frequently utilised as calibration reference meters, as well as a complete range of volume correctors, flow computers, pressure reduction & control equipment, gas chromatographs and energy measurement devices.

A working group was formed with representatives of all parties.

2. PROBLEM DESCRIPTION

In February 2008 a series of five new 24” Q.Sonic-4C Ultrasonic meters were calibrated. They were intended for Custody Transfer station “Sappemeer”, delivering gas from the network of NAM to the network of Gasunie. The calibration curves of four of these meters indicated an unexpected large peak in the calibration curve; see **Figure 3**.

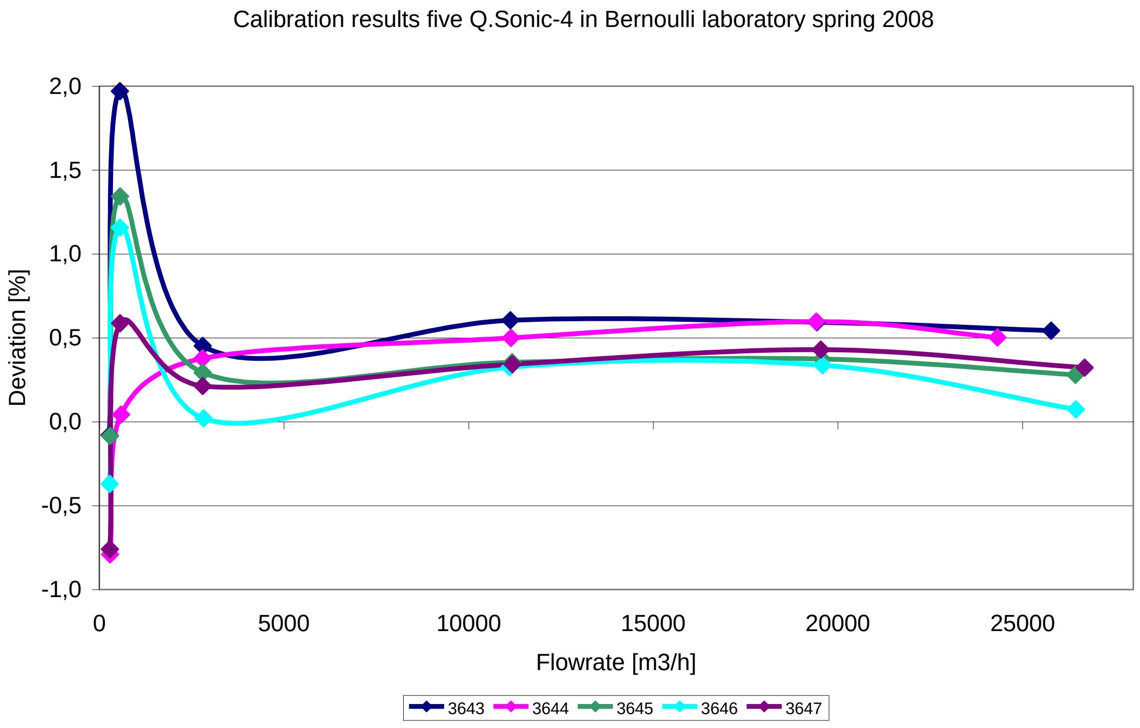

Figure 3 - Calibration results of five Q.Sonic-4 ultrasonic meters

The peak appeared in a flow rate of 560m^3/h in all cases. Curious about the reproducibility of the peak and the absence of the peak in serial number 3644, it was considered that a sharp peak, covering a limited flow range, could be overlooked by the choice of the calibration flow rates. So, with serial number 3646 still installed, the flow region around 560 m^3/h was examined in smaller steps, as is shown in **Figure 4**.

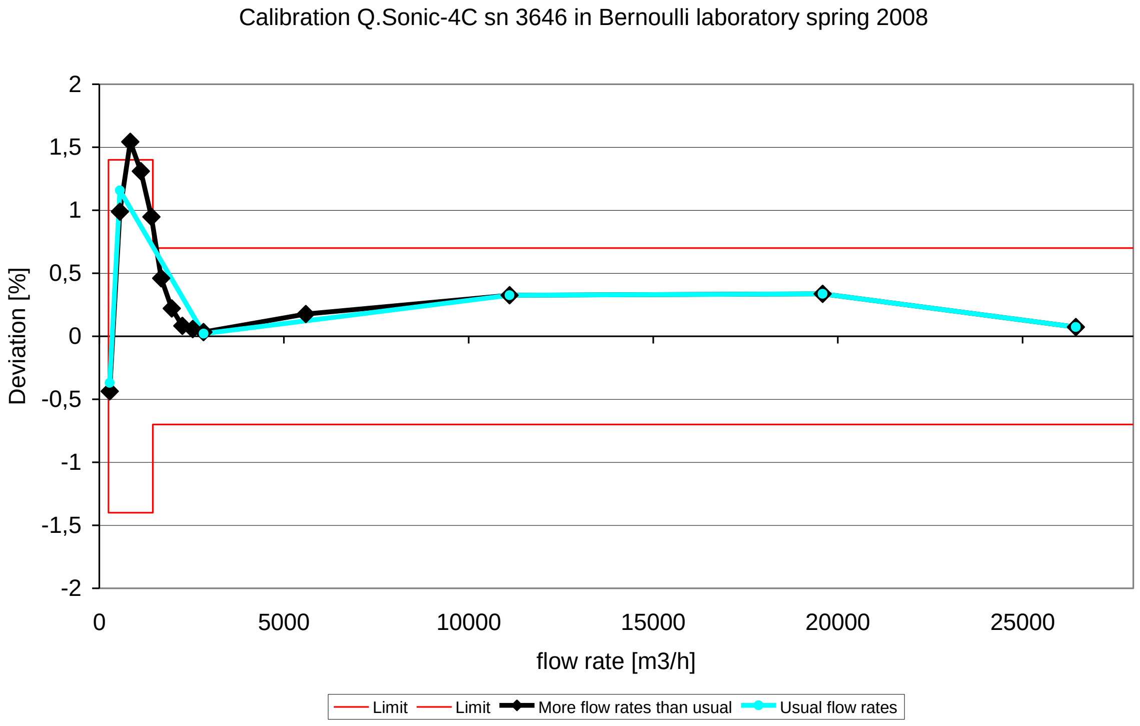

Figure 4 - Calibration result of serial number 3646 with additional flow rates below 1600m3/h

Unexpected calibration results concentrate in the region 300-1800m^3/h, which equals 1-6% of Q_{max}. With a maximum value at 800m^3/h of 1,54%, exceeding 1,4%, the calibration result does not fulfil the requirements of ISO/FDIS 17089-1: 2009(E) [1]; see the relevant table below.

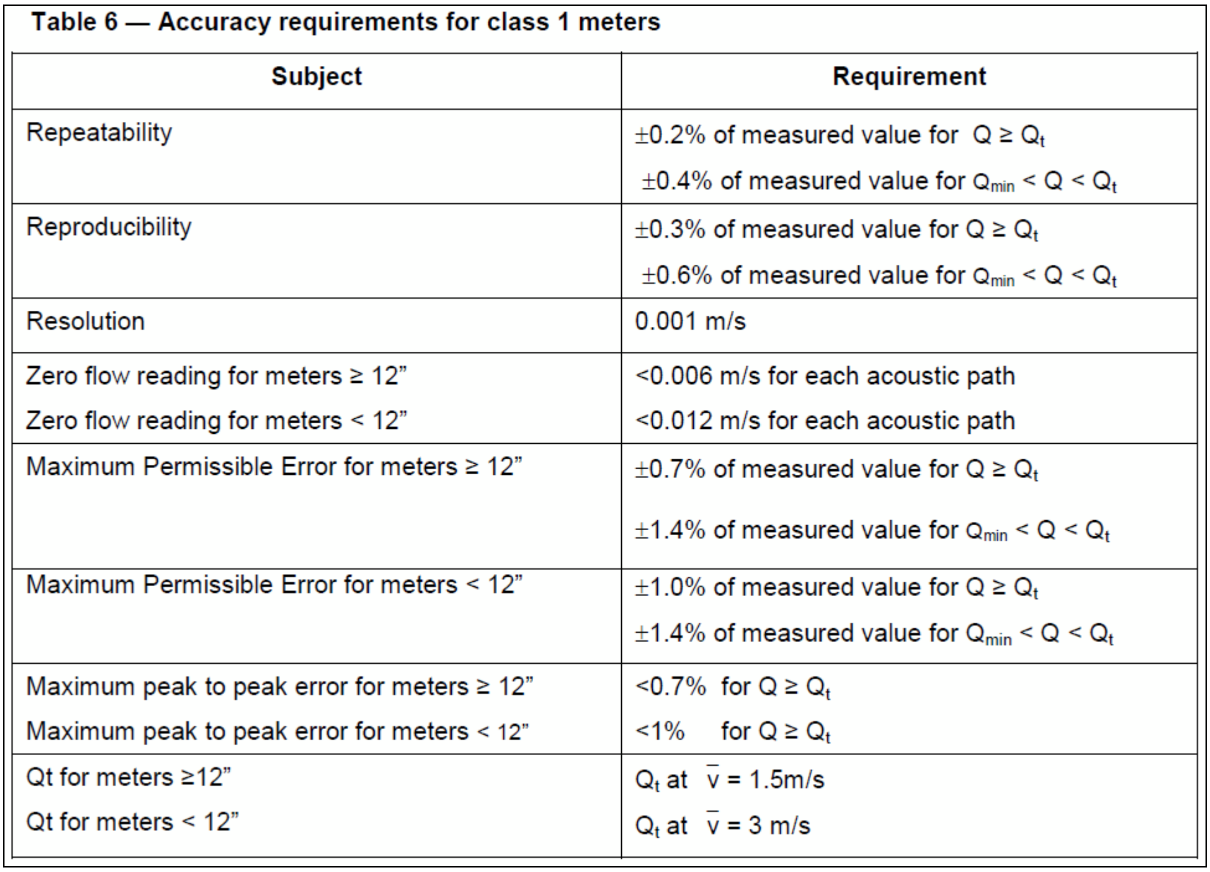

Table 6 — Accuracy requirements for class 1 meters

Subject	Requirement
Repeatability	±0.2% of measured value for $Q \geq Q_t$ ±0.4% of measured value for $Q_{min} < Q < Q_t$
Reproducibility	±0.3% of measured value for $Q \geq Q_t$ ±0.6% of measured value for $Q_{min} < Q < Q_t$
Resolution	0.001 m/s
Zero flow reading for meters ≥ 12" Zero flow reading for meters < 12"	<0.006 m/s for each acoustic path <0.012 m/s for each acoustic path
Maximum Permissible Error for meters ≥ 12"	±0.7% of measured value for $Q \geq Q_t$ ±1.4% of measured value for $Q_{min} < Q < Q_t$
Maximum Permissible Error for meters < 12"	±1.0% of measured value for $Q \geq Q_t$ ±1.4% of measured value for $Q_{min} < Q < Q_t$
Maximum peak to peak error for meters ≥ 12" Maximum peak to peak error for meters < 12"	<0.7% for $Q \geq Q_t$ <1% for $Q \geq Q_t$
Qt for meters ≥12" Qt for meters < 12"	Q_t at $\bar{v}$ = 1.5m/s Q_t at $\bar{v}$ = 3 m/s

Were ISO/FDIS 17089-1: 2009(E) [1] already published, the four meters with a peak exceeding 1,4% would have been declared unfit. Next to that, the meter that does not show the peak, would leave the participants with the considerable doubt that the peak may have remained undetected.

3. STEPS TAKEN TO UNDERSTAND THE PROBLEM

3.1. Initial investigations

The question was, whether the peak was a meter malfunction or the result of an error during calibration. This question triggered the "QC" procedure (Quality Check) of the laboratory. Due to strong similarities with some irreproducible results even dating back to December 2004, the new question was bundled with the earlier questions into the existing, although inactive, QC11. The phenomenon-under investigation is referred to as the QC11 problem.

The "standard" facility checks on the five calibration runs were done, which showed no shortcomings in the set-up of the calibrations, the data acquisition and the calculations.

The only problems that were found, and were thought to be compensated for, were non-isothermal flow conditions, at that time called "stratified flow conditions". By applying two temperature measurements, one of which was at the bottom of the pipe and the other was at the top of the pipe, the temperature measurement was thought to be corrected for.

Non-isothermal flow conditions in the Bernoulli laboratory were already discussed on the 2005 Flomeko conference [3]. It appeared that with sufficiently low gas velocities, the gas flowing along the top of the pipe was warmer than the gas flowing at the bottom of the pipe, due to lack of thermal lagging and temperature differences between the gas and the ambient. Consequently, the temperature measured at top of the pipe was not representative for the average temperature of the gas inside the gas meter. Installing an extra temperature measurement at the bottom of the pipe, allowed the facility to detect non-isothermal conditions and to correct for it by taking the average value. Temperature differences between top and bottom of up to 3 °C were found. However, although considered in 2005, thermal lagging was not introduced, motivated by the demand for user friendliness and unaware of secondary effects. Note that flow conditions were still in the turbulent region ($Re=7*10^5$ @ 280 m^3/h)

Being a heat transfer process, time, location and weather became relevant parameters:

1. Time: It takes time, after changing the gas flow, to reach a new equilibrium.
2. Location: The amount of heat that is transferred, accumulates in the downstream direction.
3. Weather: Changing weather conditions affect the amount of heat that is transferred.

These parameters, together with the chance of missing the peak by the choice made for the calibration flow rates, make the appearance and disappearance of the peak in the error curve seemingly irreproducible.

Therefore, non-isothermal flow conditions were put on the list of possible causes although the working group did not understand the mechanism at that moment of time.

In addition, Elster-Instromet performed standard health checks on the diagnostic data collected during the calibrations. No malfunctions were found, but surprisingly, at flow rates around $800m^3/h$, the average gas velocity of the axial paths and the average gas velocity of the swirl paths did not show the expected 1,05 ratio. This ratio, also known as the profile factor, reduced even to 1,00, making it appear that the flow profile was “flat”.

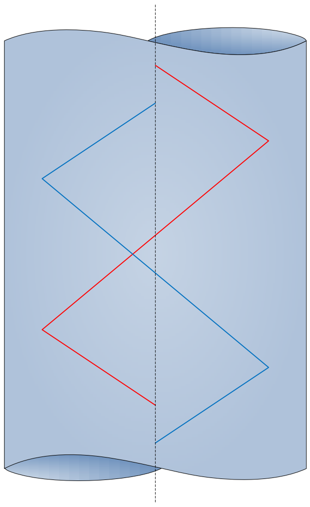

Figure 5 - front view path lay out Q.Sonic-4C

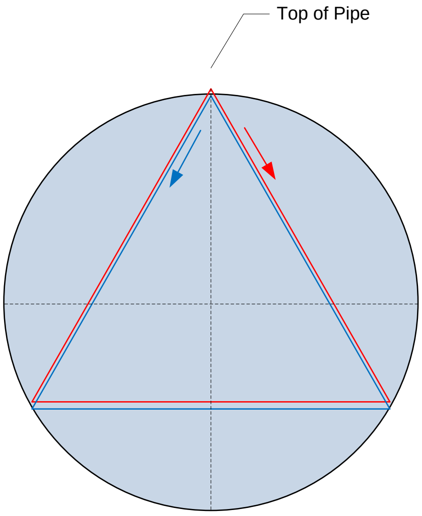

Figure 6 - top view path lay out Q.Sonic-4C

(Axial paths omitted)

Combining the findings of the facility and the meter manufacturer, the focus of the investigations was on the flow profile.

3.2. Further investigations

Before starting any further investigations, the temperature measurement was improved and pulsation measurements were performed:

1. Until spring 2008, a single bottom temperature measurement was installed in the 20” section; not shown in figure 2. At restarting QC11, it was completed with a dedicated 24” bottom temperature measurement, exactly below the top measurement, 2D downstream of the 24” ultrasonic meter; shown as “Bottom PT100” in figure 2.
2. Pulsation measurements were taken during a relevant calibration, confirming the absence of pulsations as was found during earlier measurements.

For the purpose of investigating the QC11 problem, NAM provided a spare Q.Sonic-4C ultrasonic meter with serial number 3015.

First flow profile investigations:

1. 30D upstream of the 24” ultrasonic meter, a full-bore valve is installed. Considering possible flow profile disturbances from a not fully opened valve, the position of the opened valve was recorded. Time after time, the valve showed to be opened for the full 100% after the closure and reopening action. So, this valve was no longer considered as a risk.
2. A reasonably simple experiment that has been performed was the calibration of an ultrasonic meter in the upside down position. No results different from the previous calibration were expected if the peaked curve was caused either by a symmetrical flow disturbance or by a misinterpretation of the flow profile by the meter. A different result was expected with an asymmetrical flow disturbance, since the ultrasonic meter is not symmetrical see figures 5 and 6. As a result of the experiment, the calibration curve showed to be very different; see figure 7. Also the profile factor remained close to the expected value of 1,05; see figure 8.

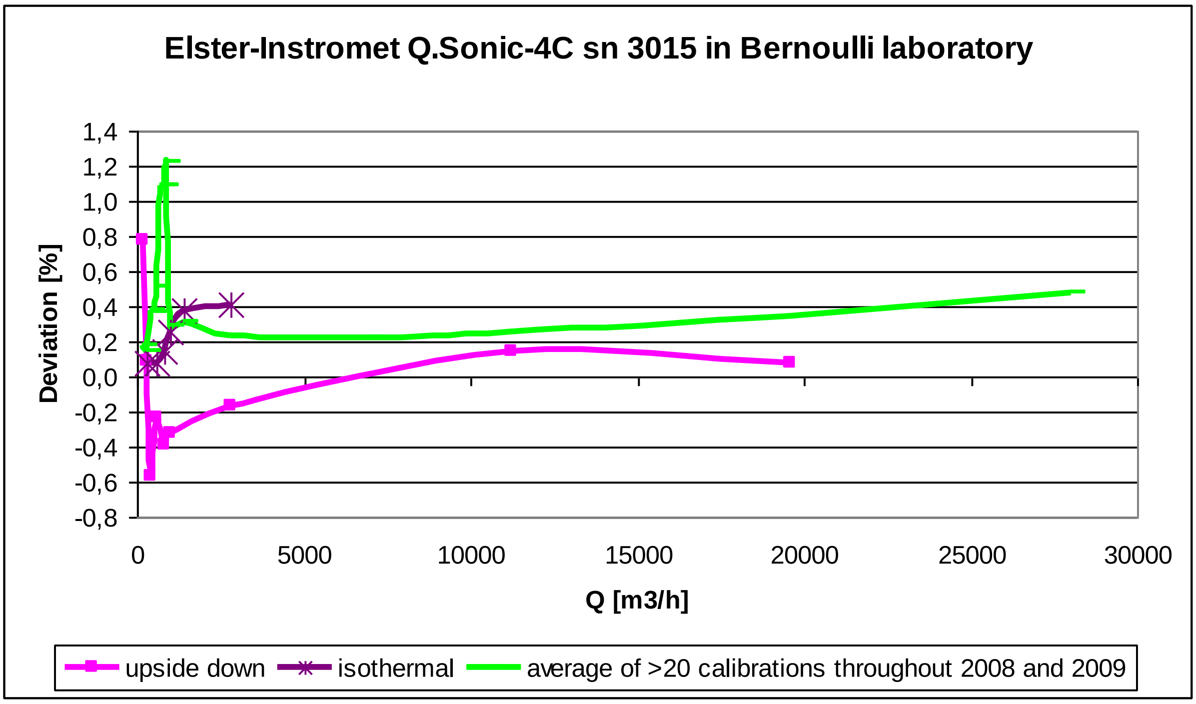

Figure 7 - Several calibration results with sn 3015

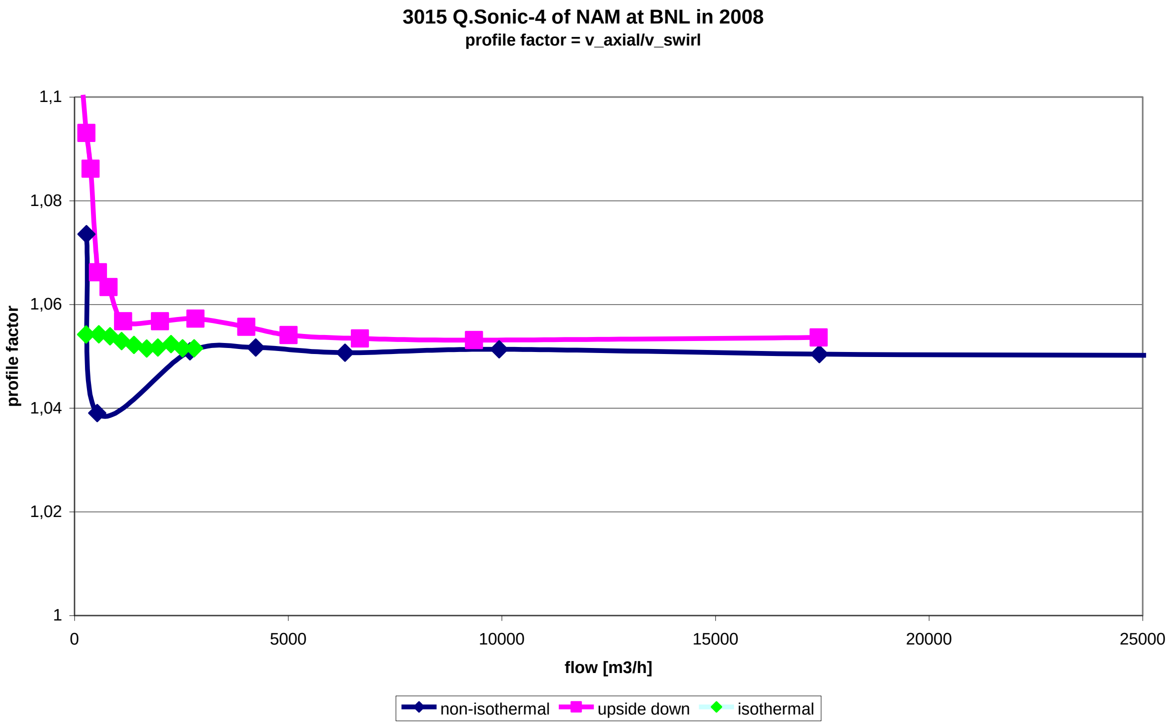

Figure 8 - Profile factors of sn 3015 from several calibration runs

At that phase in the investigations, it was clear that the facility was suffering from a flow profile disturbance, which was asymmetrical, and, from the earlier results, was not reproducible at all circumstances.

3.3. Decisive investigations

Major progress in the investigations came with the consideration that non-isothermal flow conditions must be accompanied with a mechanism to transport warmer gas to the top and colder gas to the bottom; this implies non-axial flow. Since it depends on the ambient conditions whether non-isothermal flow conditions would develop or not, the working group was able to explain the apparent irreproducibility of the earlier results.

Confirmation was provided by the measurements of August 21st 2008, during which the gas temperature was the same as the ambient temperature. With non-isothermal flow conditions absent, no peak in the calibration curve was found, as was the expected profile factor of 1,05.

At this point, the working group was quite convinced that non-isothermal flow, was the root cause of the QC11 problem.

The working group decided to perform a decisive experiment by using thermal lagging to suppress the non-isothermal flow conditions and to summon non-isothermal flow conditions again by removing the thermal lagging. The purpose of this experiment was to demonstrate the decrease of the peak in the error curve and decrease of the dip in the profile factor. Therefore, the quite stationary part of the upstream piping, being the 30” piping and the 24” piping between the 30”piping and the full bore 24” valve was lagged with permanent lagging; see figure 2. Flexible lagging, not shown in figure 2, was used to lag the remaining 24” piping including the ultrasonic meter and the temperature measurements. The experiments performed on January 9th 2009 proved unambiguous, although, the thermal conductivity of the flexible lagging still appeared to be too large. **Figure 9** shows the development of the profile factor during the application of the lagging.

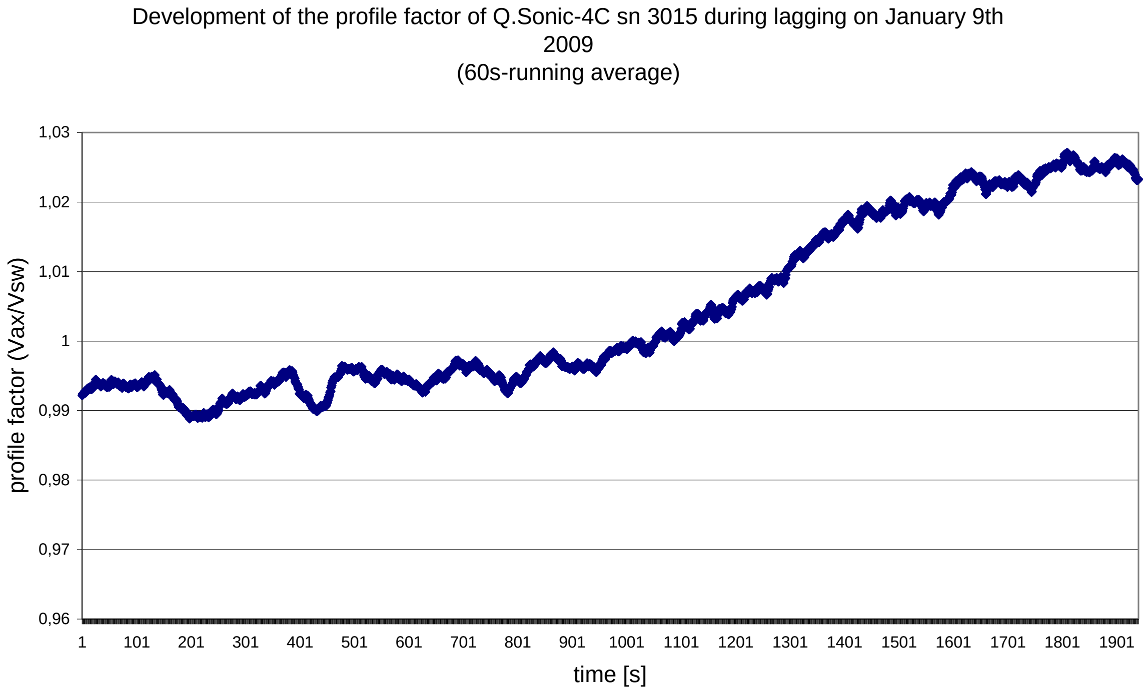

Figure 9 - Effect of the application of thermal lagging on the profile factor

Figure 10 shows the results obtained on January 9th, first without lagging, then with lagging applied and finally without lagging (lagging removed).

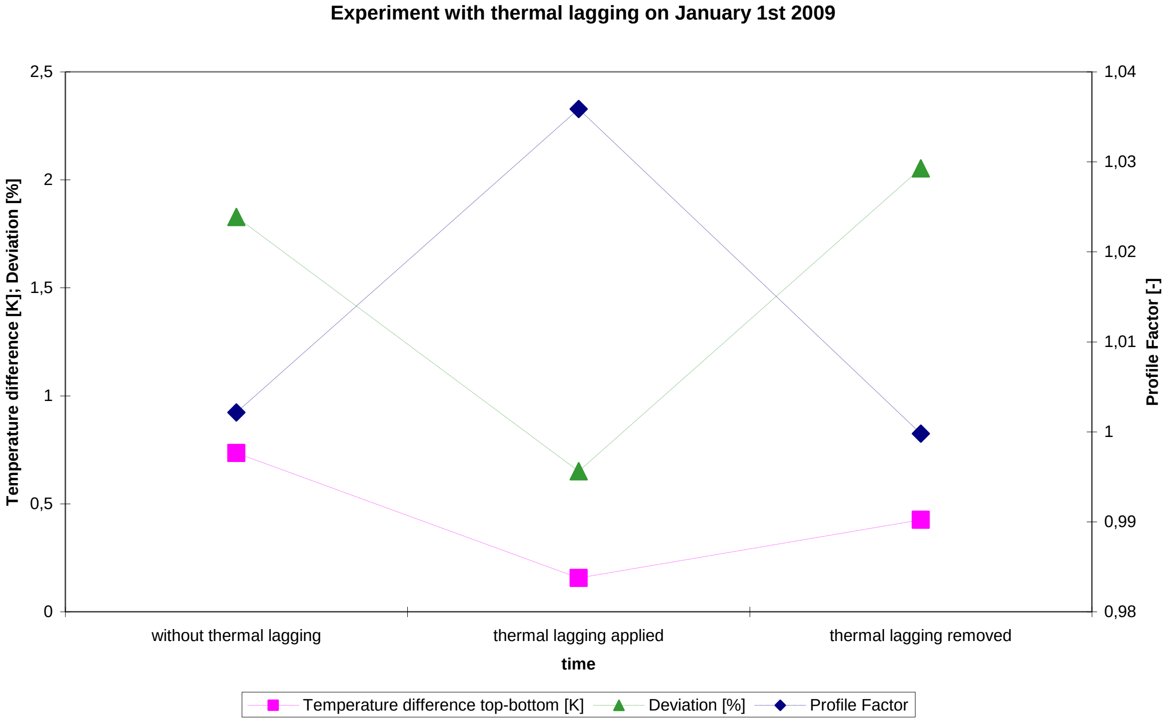

Figure 10 - The effect of thermal lagging on
1. the measured temperature difference at the top and at the bottom,
2. the deviation of the meter,
3. the profile factor of the meter

During the calibration with full thermal lagging the peak @ 800m^3/h was significantly reduced.

Figure 11 - Thermal lagging; Jan. 9th 2009,

Figure 12 - Thermal lagging detail; Jan. 9th 2009

3.4. CFD investigations

In order to gain confidence on the conclusions derived from the experiment on January 9th Elster-Instromet proposed to perform CFD (Computational Fluid Dynamics) simulations of the phenomenon. TNO Science and Industry was asked to perform the analysis. Although a simplified model of the setup and the ambient conditions was used, the results matched the phenomena that were seen in the Bernoulli laboratory. Initially, two cases were simulated, one without a temperature gradient across the top and bottom of the pipes and the other case with a temperature gradient close to the ambient conditions of those of January 9th. Note: ambient conditions such as wind and humidity were not taken into account.

Both the measured temperature differences between top and bottom thermo wells, the established measurement error and the profile factor were predicted quite accurately. The secondary flow profile (perpendicular to the axial direction of the flow) as can be seen in Figure 13 shows two counter rotating cells, one on the left side and one on the right side, transporting warmer gas to the top and colder gas to the bottom.

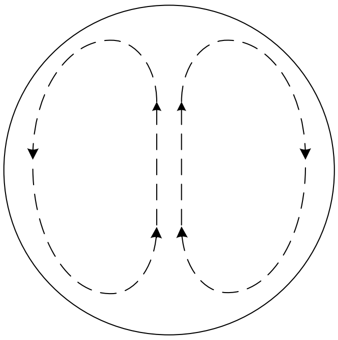

Figure 13 - Secondary flow at meter inlet; the ambient being colder than the gas

Figure 13 shows the rotation direction of two counter rotating cells under the condition that the ambient is colder than the gas. Iit is inevitable that the rotation direction of the cells will reverse when the ambient is warmer than the gas. However, in both conditions, the warmer gas will flow to the top section, while the colder gas will flow to the bottom section.

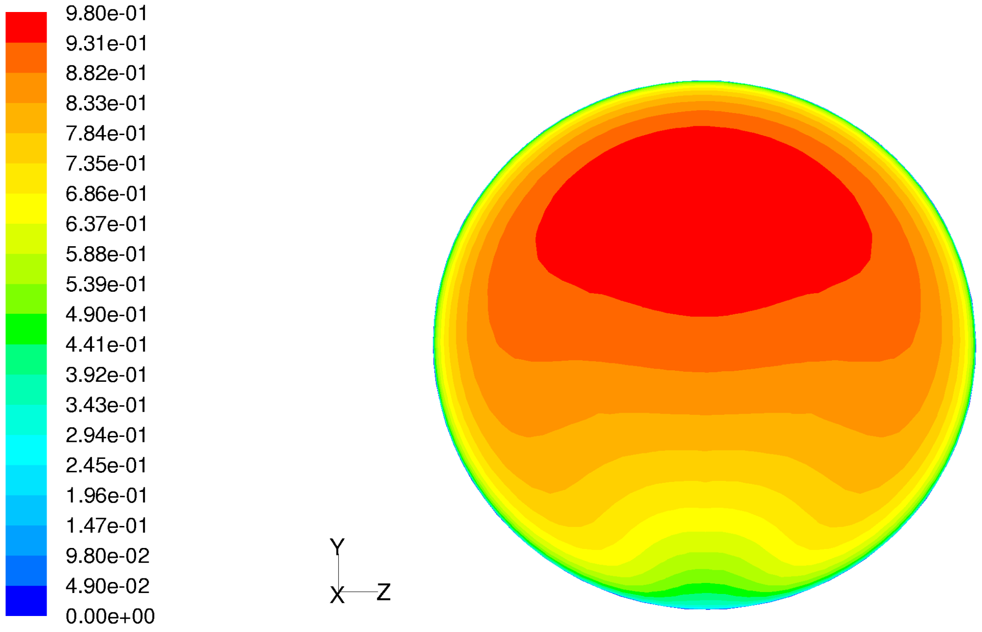

Figure 14 - Axial flow pattern at meter inlet 0.8m/s

This behaviour results in an asymmetric profile as seen in Figure 14 and Figure 15. The gas velocity in the upper (warmer) part of the pipe is higher than the gas velocity in the lower (colder) part.

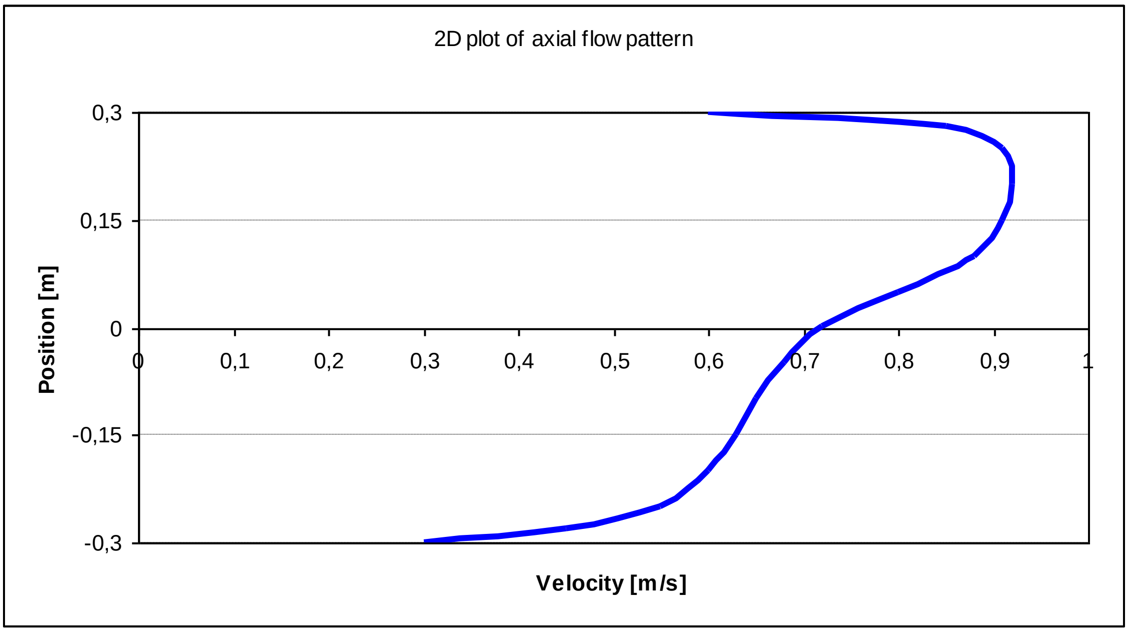

Figure 15 - 2D plot of the axial flow profile (centre line) @ 800 m^3/h

In addition two more cases were simulated, half (0.4m/s) the flow rate and double (1.6 m/s). With double flow rate the non-isothermal profile almost completely disappeared, again being consistent with the measured results obtained.

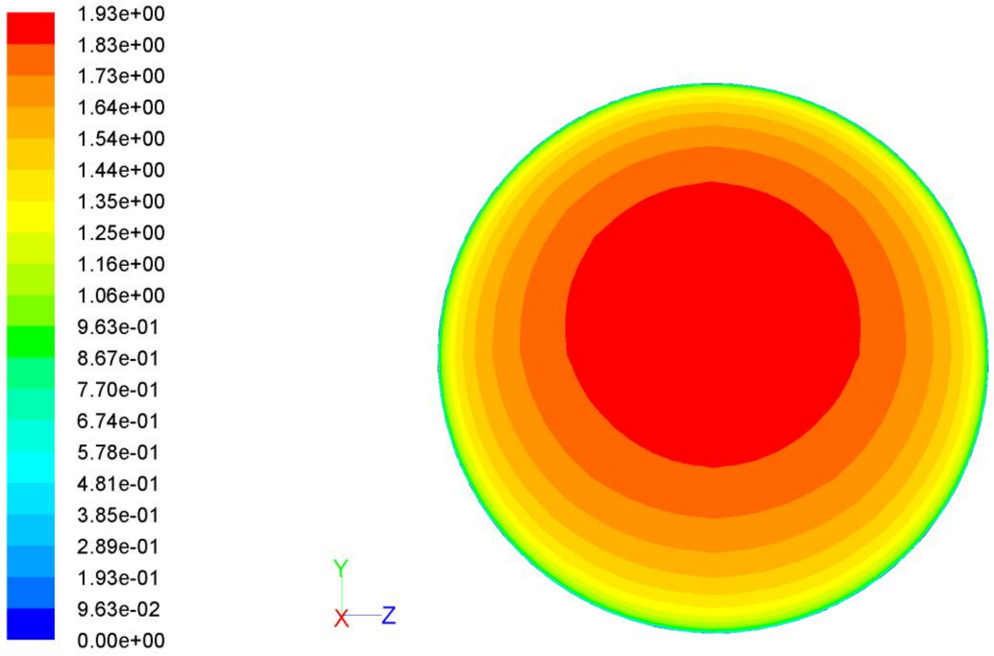

Figure 16 - Axial flow pattern at meter inlet 1.6 m/s

At half flow rate the model showed even more severe non-isothermal flow conditions. However, the model did not match the measured values anymore. It is expected that other effects, not considered in the simulation, overwhelm the non-isothermal flow conditions causing the mismatch between model and reality.

3.5. Concluding the investigations

Our conclusion became final:

1. An asymmetrical flow profile with non-axial flow emerges in the 24” section in the Bernoulli laboratory when:
   a) Flow rates are low (typically<1,6m/s),
   b) There is significant heat transfer between the gas and the ambient due to insufficient lagging, combined with a temperature difference between the gas and the ambient.
2. A Q.Sonic-4C ultrasonic meter under these specific non-isothermal flow conditions calculates a deviating flow rate with errors up to +2%.
3. An asymmetrical flow profile with non-axial flow cannot be characterised as stratified flow conditions as was earlier assumed, but it should be characterised as non-isothermal flow or, flow with natural convection; the flow pattern looks like two counter rotating corkscrews.

Non-isothermal flow is undesirable in any calibration facility, which characterizes the meter deviation as a calibration error rather than a meter error.

Although non-isothermal flow conditions is a typical low flow rate problem, both the flow rate at which the peak appears and the height of the peak, is likely to vary with the already mentioned parameters. At this moment in time it is still not understood why at lower flow rates, it seems that as if the problem diminishes; usually, problems worsen at lower flow rates.

Undoubtedly, all calibration facilities and metering stations without sufficient thermal lagging, combined with temperature differences between the gas and the ambient will suffer from non-isothermal flow at low flow rates.

Prior to discussing the actions that need to be taken by the different parties, the question should be answered whether it is likely or not that other types, sizes and makes of ultrasonic meters detect the same phenomenon.

From the nature of the effect, it may be expected that the problem will appear in all diameters and also in the Q.Sonic-5. This has already been confirmed by the results of the calibration of a 20”Q.Sonic-5 and a 12”Q.Sonic-4. Some historic calibrations may seem unaffected by this effect due to the choice of the calibration flow rates. Other calibrations will be unaffected due to favourable weather conditions. Some historic calibrations however, will be affected by this effect.

Actions by the Bernoulli laboratory: Measures should be taken to eliminate non-isothermal flow or to avoid calibrating ultra sonic meters with non-isothermal flow. So, sufficient thermal lagging should be applied or gas velocities below 1,6m/s should be avoided. Being a calibration facility on the brink of closure, any investment will be hard to defend from an economical point of view.

Actions by the meter manufacturer: The manufacturer may consider to improve its meters by making them (practically) immune to non-isothermal flow or indicate when specific non isothermal flow may exist as detected by the diagnostics.

4. DEALING WITH SUSPICIOUS CALIBRATIONS

Calibration results achieved with non-isothermal flow conditions, may be considered “suspicious” with regard to flow rates below 1,6m/s.

The parties dealing with an ultrasonic meter in full service on a delivery station with an apparently suspicious calibration curve may consider the folliwing actions:

Suspicious curves impact delivered volumes only if:
1. The calibration curve is used as the basis of a calibration curve correction mechanism
2. The meter run has delivered volumes in the flow range affected by the suspicious calibration flow rate. Generally, all flow rates below the next largest calibration flow rate will be affected, e.g. 2800 m^3/h in the case of the five meters with serial numbers 3643 to 3647.

Possible action to detect whether the calibration curve of an ultrasonic meter is suspicious:
- Comparison/monitoring of flow meter diagnostics between calibration and initial field installation. The problem created by non-isothermal flows can be detected by monitoring profile factor, asymmetry and other diagnostics from the flow meter. Changes in the flow meter diagnostics can be used to determine if conditions in the pipe have changed over time or between calibration and field installation

Possible actions to stop the building up of delivered volumes with a suspicious curve correction:
1. Close the meter run and recalibrate the meter
2. Do not operate the ultrasonic meter in the affected flow range
3. Correct the calibration curve correction mechanism by altering the contribution of the suspicious calibration flow rate.

   a. Ignore the suspicious flow rate
   b. Making the deviation of the suspicious flow rate equal to the deviation of the next largest flow rate (2800 m^3/h in the example).

Possibilities 3a and 3b may also be used as the correction mechanism to recalculate the delivered volumes by having the suspicious curve as the basis for the automatic correction.

The working group investigating QC11 appreciates the formulations of ISO/FDIS 17089-1: 2009(E) [1]. This applies for:
1. Warning for discontinuities Ch5.5.2
2. The ultrasonic meter requirements in table 6
3. The stability criteria Ch6.3.2.4
4. The way non-isothermal flow conditions are addressed Ch6.3.2.5

The working group has two suggestions for further improvement:
1. The initial calibration shall contain more calibration flow rates than the standard series, especially at low flow rates
2. Add non-isothermal flow conditions to the type testing section Ch6.4.3

5. CONCLUSIONS
1. At low flow rates and significant heat transfer between the gas and the ambient due to insufficient lagging, temperature differences between the gas and the ambient generate non-isothermal flow.
2. At this moment in time, the working group has only studied the Elster-Instromet Q-Sonic4C, which shows errors up to +2% under non-isothermal flow conditions. However, due to the nature of an ultrasonic meter, meters with other path layouts are also expected to be sensitive to non-isothermal conditions albeit to a different extend. In addition, all types of gas meters sensitive to flow profile distortions are likely to be affected by non-isothermal flow.
3. At non-isothermal low flow rates, a single temperature measurement for volume conversion will not measure a representative value for the bulk flow rate, introducing a measurement error. Even with two temperature measurements it is uncertain whether the average value is representative.
4. Due to the influences of time, position in the meter run, ambient conditions and the chosen calibration flow rates, the adverse effects of non-isothermal flow conditions may either not be present, or may not be detected and therefore may seem irreproducible.
5. The ISO/FDIS 17089-1: 2009(E) [1] has proven itself to be a valuable tool to distinguish calibration errors with ultrasonic meters.

6. RECOMMENDATIONS
1. Calibration facilities should actively search whether non-isothermal flow conditions are possible and if so, should avoid calibration at these conditions, preferably by adding sufficient thermal lagging.
2. Calibration facilities are encouraged to reconsider their temperature measurements.
3. Calibration facilities should monitor and log diagnostic data such as profile factor, asymmetry and swirl angle. When diagnostics are outside acceptable limits, the manufacturer should be consulted. It is recommended to include intermediate calibration points at low flow rates, in order to detect possible non-linearities.
4. Manufacturers of ultrasonic meters are encouraged to make their meters (practically) immune to non-isothermal flow or make the ultra sonic meter indicate when specific non isothermal flow conditions exist as detected by the diagnostics

5. Owners are encouraged to prevent further build up of delivered volumes affected by suspicious calibration curves
6. Owners are also encouraged to calculate the amount of delivered gas that has been affected by suspicious calibration curves
7. Owners are encouraged to lag meter runs in situations where temperature differences between ambient and gas are expected in combination with very low flow rates
8. All parties are encouraged to develop meter diagnostics to detect flow conditions unfavourable for accurate measurement.
9. All standardisation working groups active in flow measurement, like ISO TC30SC5WG1 and CEN TC234WG5, are encouraged to adopt the recommendations of the QC11 working group and to consider the lessons learnt.

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Note:Decimal comma notation is utilized throughout the document except for table 6 and figures 14 and 16.