On-line comparison of the speed of sound at four Dutch metering stations equipped with ultrasonic gas flow meters.

Henk Jan Panneman, N.V. Nederlandse Gasunie, The Netherlands.

1. Introduction

Ultrasonic gas flow meters are increasingly used for the fiscal flow measurement of natural gas. Advantages of ultrasonic gas flow meters are their rangeability, low pressure drop and the possibility of carrying out bi-directional measurements. Another advantage is the ability to measure the speed of sound of gas flowing through the ultrasonic flow meter. By comparing the speed of sound measured using the ultrasonic flow meter with the speed of sound calculated from gas properties, one can check the performance of the ultrasonic gas flow meter periodically or continuously. Letton et al. [1] previously showed that it is possible to compare the measured and calculated speed of sound. They used ultrasonic flow meters, which were initially calibrated using nitrogen. For these ultrasonic flow meters the measured speed of sound on all chords agreed within 0.1%. In their tests the deviation between the speed of sound measured with an ultrasonic flow meter and the speed of sound calculated with the AGA8 equation of state was less than 0.15%. The reproducibility of the measured speed of sound values was better than 0.03%. However, Letton et al. reported no values for the reproducibility of the On-Line Comparison of the Speed of Sound (OLC-SOS), which is defined as the relative deviation between the measured and calculated speed of sound. Based on the data in their figures, the reproducibility of the deviation between the measured and calculated speed of sound appears to be 0.1 – 0.2%. In their conclusions Letton et al. proposed that deviations of about ±0.3% between the measured and calculated speed of sound should be cause for alarm.

This paper presents the results of field tests at four Dutch metering stations. Measurements at these four stations were carried out using Q.Sonic-5 ultrasonic gas flow meters manufactured by Instromet Ultrasonics b.v. The purpose of the field test was to determine the reproducibility of both the measured and calculated speed of sound, which are necessary to determine the reproducibility of the OLC-SOS system and estimate the alarm limits. The impact of gas composition, gas flow and meter type on the OLC-SOS were also investigated as part of the field tests. Finally, the changes in both speed of sound and gas flow resulting from deviations in the gas flow determining parameters of an ultrasonic flow meter were calculated during a sensitivity study.

2. Principle of On-Line Comparison of the Speed of Sound (OLC-SOS)

The principle of an ultrasonic gas flow meter has been explained in previous papers [1,2]. It is based on the time difference between ultrasonic pulses (≈100khz) travelling downstream and upstream in the presence of a gas flow ($t_{down} < t_{up}$). The flow velocity is proportional to the reciprocal difference between these two transit times:

$$V = L/(2\cos\varphi) \cdot (1/t_{down} - 1/t_{up}) \quad (1)$$

Where φ is the angle between the direction of the sound pulse and the gas flow and L is the length of the acoustic path between the two transducers. The speed of sound is proportional to the average of both transit times:

$$SOS = L/2 \cdot (1/t_{down} + 1/t_{up}) \quad (2)$$

Current generation ultrasonic gas flow meters output both the gas velocity and the speed of sound while readings are updated every second.

The speed of sound can be calculated using a computer program based on the AGA8 equation of state. The required input data comprise a detailed gas composition, the pressure and the temperature. The metering stations where the field tests were conducted are equipped with Daniel process gas chromatographs. Accurate pressure and temperature measurements are also available at these stations.

The continuous determination of the relative deviation between the measured and calculated speed of sound is called OLC-SOS (On-Line Comparison of the Speed Of Sound) and is given by:

$$OLC\text{-}SOS = (SOS_{measured} - SOS_{calculated}) / SOS_{calculated} \quad (3)$$

In the current set-up, the gas analysis is the most time consuming input parameter for OLC-SOS with a cycle time of 15 minutes. The other input parameters (measured speed of sound, pressure and temperature) are updated every few seconds. Therefore, OLC-SOS can be carried out with a frequency of approximately 4 times per hour.

3. Performance of an OLC-SOS field test at a metering station

The OLC-SOS field test was carried out during normal operation of the station and using the existing instruments present at the station. At these stations the ultrasonic flow meters have sufficient straight pipe length (>20D) upstream to ensure a well developed flow profile. Figure 1 shows the field test set-up. The ultrasonic flow meter sends volume flow data to the flow computer. The flow under normal conditions (0 °C, 1,01325 bar) is calculated on the basis of this flow, the pressure, the temperature and data for the compressibility calculation. The Daniel field GC calculates the calorific value under normal conditions. The energy flow, which is the product of the calorific value and the flow rate, is calculated and stored in a second computer-system (see Figure 1).
For the OLC-SOS field test, the speed of sound data were taken directly from the ultrasonic flow meters, while the pressure and temperature and the gas composition were taken from the flow computer and the Daniel process GC respectively .
Quality data synchronisation is a prerequisite for a proper comparison of the measured and calculated speed of sound. This particularly applies if changes in the gas composition can be

expected. The speed of sound, the pressure and the temperature have to be measured at the same moment as the gas sample for GC analysis is retrieved from the pipe.

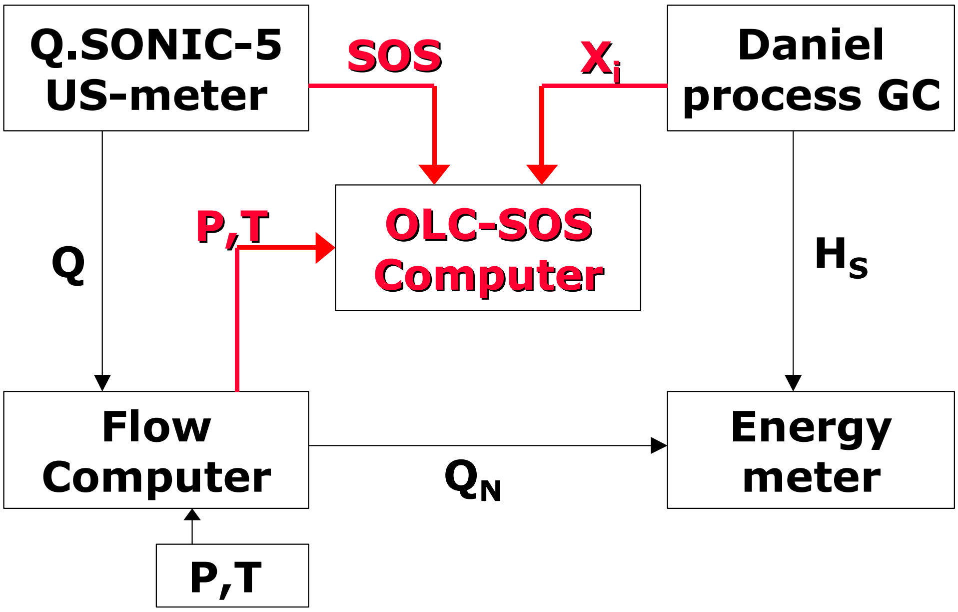

Figure 1. OLC-SOS set-up during field tests at Gasunie metering stations

The Daniel field GC analyses CO_2, N_2, hydrocarbons up to C5 separately and $C6^+$. To determine the calorific value, $C6^+$ is handled as a (pseudo)-component. An average composition of $C6^+$ is derived at following extensive laboratory analyses of many gas samples. This composition was also used for the speed of sound calculations, as part of which minor components were treated according to ISO 12213-2 [3], e.g. neo-pentane and cyclo-pentane are treated as n-pentane.

4. Uncertainty and repeatability of the input parameters

Before the OLC-SOS measurements were carried out, data were collected in relation to the individual input parameters. This data were necessary to gain insight into their uncertainty and repeatability.

4.1 Uncertainty and reproducibility of the measured speed of sound

All ultrasonic flow meters used during the field tests were Q.Sonic-5 QL multi-path flow meters manufactured by Instromet Ultrasonics b.v. These meters have 5 ultrasonic paths; path 1,3,and 5 are single reflection paths, while path 2 and 4 are double reflection paths. The repeatability (2σ) of the SOS measurement and the maximum difference in the measured speed of sound between the chords is presented in Table 1. The gas velocity during the determination of 2σ(SOS) is also shown.
From Table 1 it can be concluded that the repeatability of the SOS measurement is always less than 0.01%. It is well-known that speed of sound measurements are influenced by

Table 1. **The repeatability (2σ) of the measured speed of sound of the individual chords (1 to 5) and maximal difference in speed of sound.**

	Station A	Station B	Station C	Station D
Diameter US meter, m	0.4777	0.4777	0.4777	0.303
Gas velocity, m/s	0.7	1.2	7.5	12
2σ, SOS-1, %	0.0024	0.0024	0.0076	0.0084
2σ, SOS-2, %	0.0026	0.0024	0.0072	0.0088
2σ, SOS-3, %	0.0018	0.0022	0.0078	0.0084
2σ, SOS-4, %	0.0016	0.0026	0.0074	0.0092
2σ, SOS-5, %	0.0012	0.0026	0.0078	0.0082
$(SOS_{max} - SOS_{min})$ %	0.24	0.25	0.1	0.09

the gas velocity. High gas velocities induce large turbulences in the pipe, resulting in a distortion of the acoustic path [4]. In turn, this results in both a small systematic deviation between the measured and "true" speed of sound, which can be accounted for, and a small increase in the random deviation of the measured speed of sound. Indeed, the repeatability increases slightly with the gas velocity. No significant difference in repeatability has been found between the single and double reflection paths during the tests.
The acoustic path lengths of the Q.Sonic meters are directly derived from the pipe diameter, D, and the acoustic path angle. As a result, they are not corrected for uncertainties in the manufacturing process. The length of the three single reflection paths is identical and equals $2D/\sin(\varphi)$. The length of the two double reflection paths is also identical and equals $3D\sin(\pi/3)/\sin(\varphi)$. Instromet claims an uncertainty of ± 0.05% in the inner diameter of the pipe [5]. The uncertainty in time measurement is negligible for the purpose of determining the speed of sound. The uncertainty in the speed of sound measurement should therefore be within ±0.12% for a single reflection path. The maximum difference in the measured speed of sound using a given meter's 5 measuring paths varied between 0.09% and 0.25%, which is in agreement with the uncertainty analysis.
The comparison of the measured and calculated speed of sound is especially suitable for a continuous check during normal operations but can be used for an initial check of the deviations in the individual chords of the ultrasonic flow meter as well. For a continuous check, the somewhat larger differences in the speed of sound measurements of the individual chords are not important.
The differences in the measured speed of sound of the individual chords do not influence the flow measurement; a meter factor is determined after flow calibration, which corrects the errors caused by all parameters and variables involved.

4.2 Uncertainty and reproducibility of the calculated speed of sound

The uncertainty in the pressure and temperature measurement is less then 0.1%. The repeatability (2σ) of the pressure measurement was ±0.01 bar, which results in a contribution of 0.0005% to the repeatability of the calculated speed of sound. The repeatability (2σ) of the temperature measurement was ±20 mK, resulting in a contribution of 0.005% to the repeatability of the calculated speed of sound.
The uncertainty in the calorific value determined by a Daniel process gas chromatograph is 0.25%. However, it is difficult to relate the uncertainty in the calorific value to uncertainties in the component concentrations and, subsequently, to an uncertainty in the calculated speed of sound. Moreover, the average composition of the $C6^+$-fraction used in the procedure for calculating the speed of sound was kept identical during the four tests, even though differences in the composition of $C6^+$ are possible. The uncertainty in speed of sound due to uncertainties in the gas composition was estimated at 0.1%. The repeatability of the gas analysis was better than 0.03%, resulting in a contribution of 0.02% to the repeatability of the calculated speed of sound.
Laboratory measurements of the speed of sound of known gas mixtures using highly accurate speed of sound meters showed that the uncertainty in the AGA8-based computer program that is used to calculate the speed of sound was 0.05% [6].

In summary: the uncertainty and repeatability of the measured speed of sound are 0.3% and 0.01% respectively. The uncertainty of the calculated speed of sound is difficult to determine: the main contributors are the AGA8 E.O.S. (0.05%), the temperature (0.05%) and the gas analysis (0.1%), resulting in a total uncertainty of approximately 0.15%. The repeatability of the calculated speed of sound is approximately 0.02%, and is almost entirely determined by the repeatability of the gas analysis. Therefore, from a theoretical viewpoint, the repeatability for the OLC-SOS should be: $2\sigma_{OLC\text{-}SOS} \leq 0.02\%$.

5. Results of OLC-SOS.

Tests were conducted at four different metering stations. All stations were equipped with the same type of temperature and pressure measurement and a Daniel process gas chromatograph for the analysis. Some parameter properties of relevance to the field test are summarised in Table 2.

From Table 2 it is clear that the experimental conditions varied considerably during the field tests. Ultrasonic flow meters of two diameters were tested and the gas velocity varied between 0 and 13.5 m/s. The gas composition showed large variations, both during tests and between the consecutive tests, resulting in large variations in the speed of sound.

Table 2. Properties and parameters during the field tests

	Station A	Station B	Station C	Station D
Diameter US meter	20”	20”	20”	12”
Flow, $m^3(n)/hr$	0 – 140.000	0 – 117.000	200.000 – 525.000	180.000 – 235.000
Gas velocity, m/s	0 – 1.3	0 – 1.5	4.5 – 13.5	11 - 13
Methane range, mol%	86.5 – 92.2	86.7 – 89.3	82.7 – 84.4	81.24 – 81.29
Temperature range, K	287.6 – 288.6	288.1 – 288.7	287.7 – 286.4	286.2 – 287.1
VOS range, m/s	378 – 401	380 – 391	391 – 396.5	397.5 – 398.5
OLC-SOS, 2σ, %	0.02%	0.02%	0.02%	< 0.01%

Despite these large variations, the reproducibility of OLC-SOS was always within 0.02%. This value is in good agreement with the expected values, based on the repeatability of the input parameters.
The deviations between the measured and calculated speed of sound for the individual chords are shown in Figure 2.

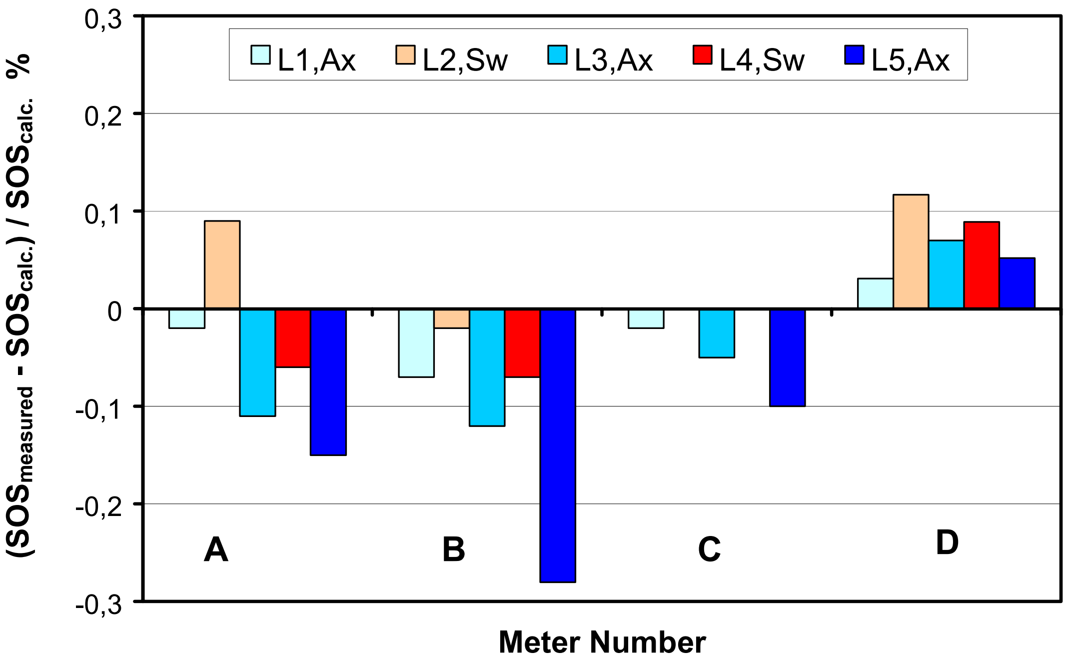

Figure 2. The differences between measured and calculated speed of sound for the individual chords of 4 different ultrasonic flow meters.

Meters A, B and C, which were all 20” in diameter, showed a measured speed of sound that is slightly lower than the calculated speed of sound. The fourth meter, D, which was 12” in diameter, showed a measured speed of sound that was slightly higher than the calculated speed of sound. This deviation could be attributable to the ultrasonic flow meter manufacturing process. Alternatively, it may be the result of the uncertainty in the calculated speed of sound (0.15%). The deviations evident in respect of chord 2 from meter A and of chord 5 from meter B are significant compared to the other chords. However, the results are within the uncertainty limits discussed earlier.

The results of the speed of sound measurements for station B are shown in Figure 3. For clarity's sake only the measured speed of sound of a single chord and the calculated speed of sound are shown.

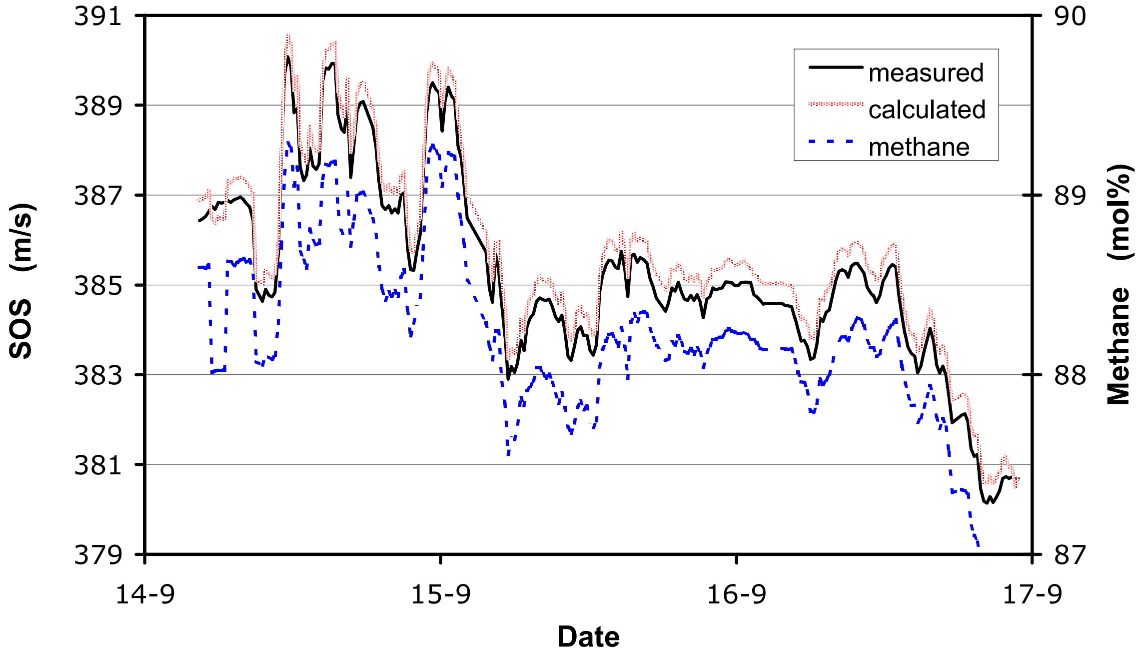

Figure 3. **The measured and calculated speed of sound and methane concentration collected during 3 days at Station B.**

High calorific gas with relatively large differences in composition is measured by station B. The large changes in speed of sound are mainly caused by changes in gas composition. The change in methane concentration shown in Figure 3 follows the same trend as the speed of sound.

The OLC-SOS of measurements by station B are shown in Figure 4. Results for each of the 5 chords are shown. Chord 1 and 4 nearly coincidence. It can be concluded from the graph that all five chords behave identically.
The results shown in Figure 4 can roughly be divided into two parts: the measurements taken on 14 September and the first hours of 15 September show a reproducibility that is significantly higher ($2\sigma = 0.05\%$) than the subsequent measurements taken on 15 and 16 September ($2\sigma = 0.02\%$).

The lower reproducibility corresponds to periods during which fast changes in gas composition occurred (see Figure 3). Further investigation at the metering station showed that the residence time taken for the gas sample to reach the GC was not correctly estimated. This resulted in a discrepancy in time between (a) the moment the gas sample used for the GC analysis was retrieved from the pipe and (b) the moment the speed of sound, pressure and temperature were measured. This discrepancy only resulted in differences in the OLC-SOS if the gas composition changed between these measurements. It can be concluded that measurements must be synchronised properly and that the residence time of the gas in the sample line to the GC must be calculated correctly.

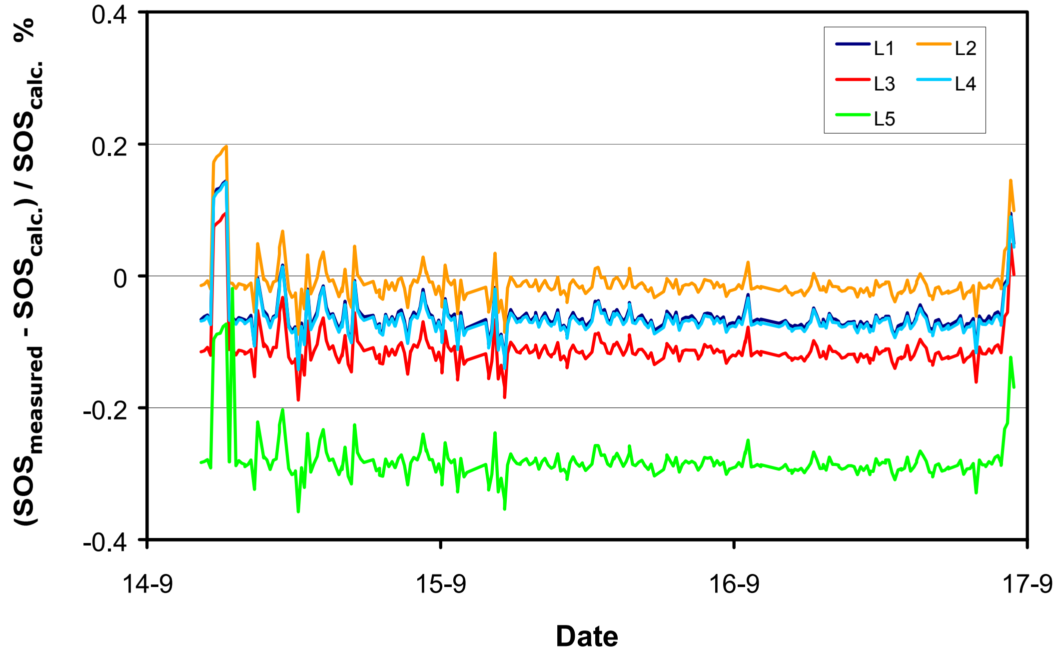

Figure 4. The On-Line Comparison of the Speed of Sound determined at station B.

Figure 4 shows a large deviation in the OLC-SOS shortly after the start of the measuring process. Figure 3 demonstrates that this large deviation is caused by a sudden decrease in the calculated speed of sound. The large deviation in OLC-SOS also coincided with a fall in the methane concentration by approximately 0.6%. It transpired that the GC had been tested with a calibration gas during this period, which gas had a slightly different composition. A decrease of 0.6 mol% in methane and 0.55 mol% in carbon dioxide and an increase of 1.15 mol% ethane results in a change of 0.2% in OLC-SOS. A larger change in OLC-SOS is possible if a decrease in methane (high speed of sound) is compensated by an increase in nitrogen or carbon dioxide (low speed of sound).

A deviation in OLC-SOS can again be observed at the end of 16 September. This deviation coincided with an period of no flow. If the gas flow is zero, the gas temperature near the pipeline wall will be affected by the ambient temperature. As a result, the temperature measured with the PT100 deviated from the average gas temperature in the ultrasonic flow meter, which, in turn, caused the OLC-SOS to deviate.

The field test at station B showed that OLC-SOS easily detects deviations in the GC analysis and temperature. It also showed that synchronisation appears to be important.

During tests at station B, the gas flow varied between 0 and 1.5 m/s. At station D the gas flow was almost 10 times higher. Before comparing the measured and calculated speed of sound, the measured speed of sound was corrected for deviations caused by the high gas velocity.

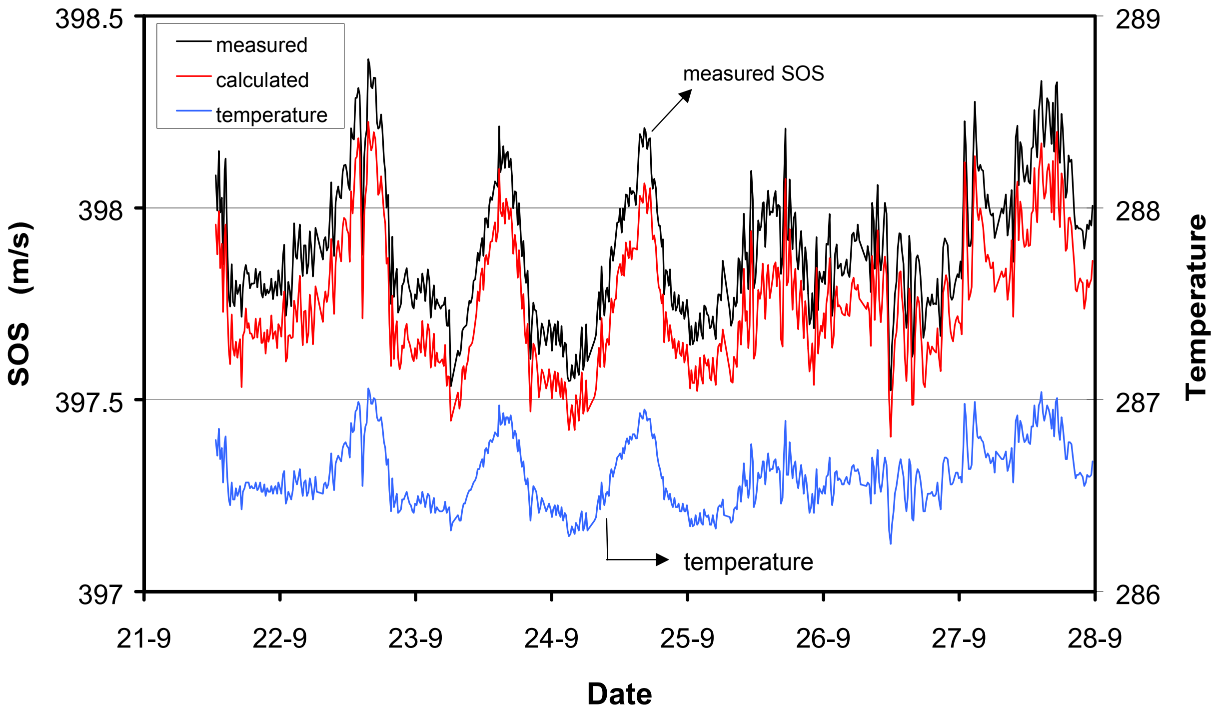

Figure 5. The measured and calculated speed of sound and the measured temperature, data collected over 7 days (Station D).

The results of the speed of sound measurements obtained from station D are shown in Figure 5. Low calorific gas with an almost constant gas composition is measured at station D. During the test, gas velocity varied between 11 and 13 m/s.

The variation in the speed of sound measured at station D was approximately 20 times lower than the variations at station B. In this instance, the variation in the speed of sound is primarily caused by changes in the gas temperature. The results of the temperature measurements are also shown in Figure 5. During the first three days the temperature showed a distinct variation between day and night. This temperature variation was less obvious during the final three days.

There is a very good resemblance between the measured and calculated speed of sound. The results of the OLC-SOS obtained at station D are shown in Figure 6. The reproducibility is both very good, $2\sigma < 0.01\%$, and identical for all 5 chords. The small variations in OLC-SOS are present in all 5 chords. In other words, the variations are most probably caused by the calculated speed of sound. Again, the small variations between measured and calculated speed of sound may be attributable to a small synchronisation error.

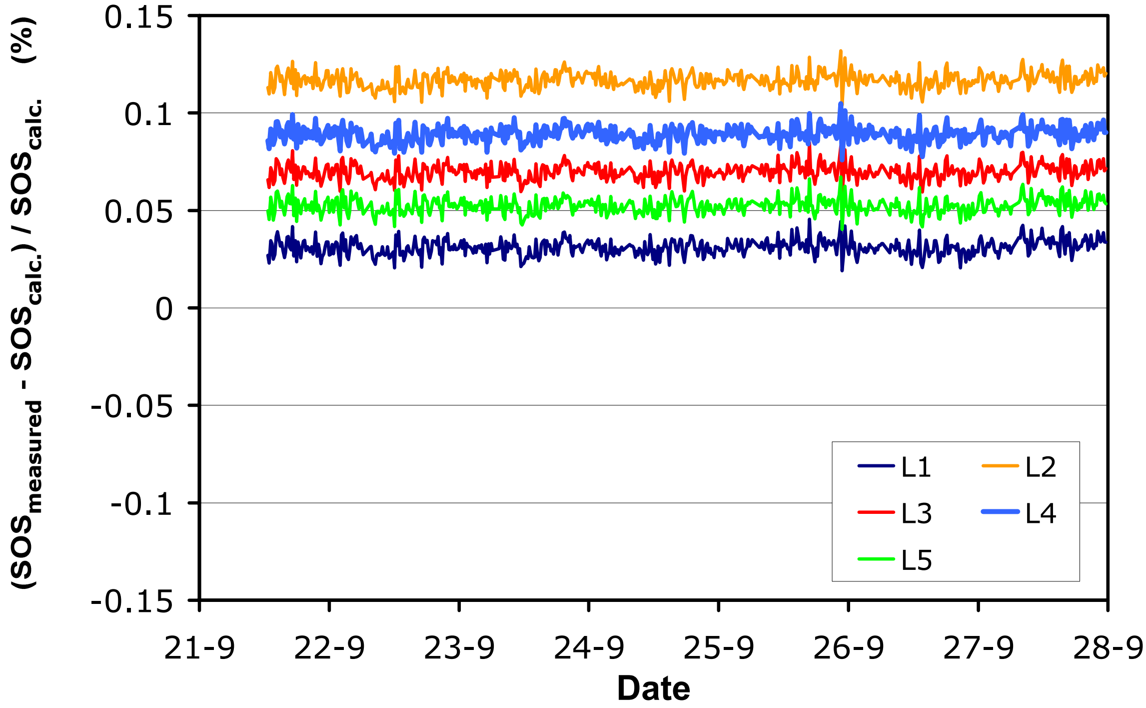

Figure 6. The On-Line Comparison of the Speed of Sound determined at station D.

6. Sensitivity analysis of the speed of sound and gas velocity measurement with an ultrasonic gas flow meter

From the experimental results obtained it may be concluded that the reproducibility of the On-Line Comparison of the speed of sound is better than 0.02%. The results also show that small deviations in temperature and gas composition are detected by OLC-SOS. The on-line comparison of the speed of sound is primarily developed to check the quality of the gas flow measurements by an ultrasonic gas flow meter. As a second step it was therefore necessary to investigate how small deviations in gas flow measurement performance are reflected in the measured speed of sound.

Modern ultrasonic gas flow meters have a number of self-diagnostics tools, such as a signal quality monitor, a detection window with warning limits for some parameters, a pulse quality check and of course the speed of sound itself [7]. Except for the speed of sound, these diagnostics tools will not detect small deviations in the parameters, which are influencing the gas flow measurement. These parameters are: the path length, L, between the two sonic transducers; the transit time measurement, t_i; the electronic delay-time, t_d; the transducer's angle, φ and contamination of the transducers and/or the pipe wall by oil, grease or solids.

The sensitivity analysis was carried out for an ultrasonic flow meter with an axial measuring chord and a single reflection. A realistic path length of 1 m was taken, the speed of sound was set at 400 m/s and the gas velocity was fixed at 10 m/s unless indicated otherwise.
Table 3 gives the changes in the speed of sound and the measured gas velocity for small changes in the relevant parameters. The last column indicates whether or not the change in parameter is detected by OLC-SOS.

Table 3. Sensitivity of speed of sound and gas velocity with respect to the flow determining parameters of an ultrasonic gas flow meter.

parameter	Δ(parameter)	ΔVOS %	ΔV %	OLC-VOS Detection
L	+ 1%	-1%	-1%	Yes
t_{ab} (+10ns), V=10 m/s	$+8\cdot10^{-4}$%	$-4\cdot10^{-4}$%	-0.033%	No
t_{ab} (+10ns), V=1 m/s	$+8\cdot10^{-4}$%	$-4\cdot10^{-4}$%	-0.33%	No
t_{ab} and t_{ba} (+ 5 μs)	½λ shift	-0.2%	-0.2%	Yes
time delay, t_d	+1%	-0.01%	-0.02%	Yes
φ (- 0.1°)	-0.17%	-0.1%	+0.2%	Yes
Wax (on transducer)	0.5 mm	+0.08%	+0.08%	Yes
Oil (on transducer)	0.5 mm	+0.07%	+0.07%	Yes
Wax (transd. + wall)	0.5 mm	+0.16%	+0.16%	Yes

Deviation in the path length L:
A +1% deviation in the path length of a chord gives a different transit time, which causes the gas velocity and the speed of sound to be determined incorrectly. If, for example, a transducer of a slightly different length is mounted, and OLC-SOS is used, the error in length will be easily detected. Based on the reproducibility of the OLC-SOS, it may be concluded that changes of 0.05% in the length of the sonic path will be detected.

Deviation in the measurement of the transit time, t_{ab} and t_{ba}:
The uncertainty in the travel time measurement is at most 10 ns [2]. The corresponding uncertainty in the gas velocity is strongly flow-dependent. A deviation of +10 ns in the transit time results in deviations of –0.033% and –0.33% for gas velocities of 10 m/s and 1 m/s respectively. The deviation in the speed of sound is negligible.

The transit time is measured by detecting a predetermined zero crossing in the voltage signal received. Under unfavourable conditions, the determination of the zero crossing of both transit times (t_{ab} and t_{ba}) can shift by half a wavelength. A shift of +½λ results into a deviation of –0.2% in both the measured gas velocity and speed of sound, which deviation is easily detected by OLC-SOS.

Deviation in the electronic time delay:
The transit times measured also contain delays on account of the electronics, the cables, the transducers, and diffraction effects. A +1% change in the time delay will affect the gas velocity by –0.02% and the speed of sound by –0.01%. The effect of changes in the time delay on the gas velocity and the speed of sound depends on the absolute value of the transit times and the absolute value of the time delay. Significant deviations in the time delay, due to changes in the electronics for example, will be detected by OLC-SOS.

Deviation in the inclination angle:
The inclination angle between the direction of the sonic wave and the direction of the gas flow is determined by the position of the transducers on the meter body. Deviations in the angle of the acoustic path will affect both the gas velocity and the speed of sound measurement. A –0.10° deviation in the angle of the acoustic path results in a +0.2% deviation in the gas velocity and –0.1% deviation in the speed of sound. During normal operations changes in the inclination angle are unlikely. However a small change in the angle of the acoustic path might occur following the mounting of new transducers.

Wax or liquid deposits:
During the transport of natural gas heavy hydrocarbons (condensate), compressor and seal oil and/or fine solid particles can be deposited inside the gas flow meter. Depending on the nature of the contamination and the total amount of contamination present, a thin layer of grease or wax can be present on the transducer surface and/or on the inner surface of the meter body.
Contamination on the transducer and meter body surface causes the path length of the sound wave in the gas phase to be reduced in comparison to the original path length. Furthermore, the speed of sound in liquid or solid contamination is significantly higher than it is in natural gas. Therefore, the resulting transit times will be smaller when contamination is evident. If the transducers and the surface of the meter body are covered with a grease layer of 0.5 mm, the deviation in the gas velocity and speed of sound amounts to 0.16%. Based on the results obtained in the field tests, OLC-SOS will thus detect deposit layers of 0.2 mm and above. Therefore, contamination will be detected before significant deviations in the gas velocity are obtained.

The sensitivity analysis showed that small deviations in the parameters, which are relevant for the determination of the gas flow, will be detected by OLC-SOS. An exception is the random uncertainty in the transit time measurement. A disturbed flow profile will not be detected by

OLC-SOS as well. To detect this phenomenon, the velocity measurements of the individual chords may be used.

7. Field implementation On-Line Comparison of the Speed of Sound

For economical and practical reasons, ultrasonic gas flow meters are not frequently recalibrated. Consequently, a number of deviations may arise between two calibrations. These have a negative impact on the measuring characteristics of an ultrasonic gas flow meter. Possible sources of deviation include the contamination of transducers and/or pipe walls, changes in delay times, an exchange of transducers or electronics and changes in gas properties. A sensitivity analysis showed that OLC-SOS will detect almost all effects that occurr during the normal operation of an ultrasonic gas flow meter. A first indication of alarm limits will be given next.

AGA-9 [8] recommends that the ultrasonic gas flow meter must meet specific minimum measurement performance requirements before a calibration factor adjustment can be applied. These requirements are a meter deviation (from reference) of at most ±0.7% and a reproducibility of ±0.2% or less for flow rates between 10% and 100%.

The experimental results presented in this paper show that the OLC-SOS has a reproducibility of within 0.02%. The sensitivity analysis showed that changes in the relevant parameters result in changes of the same magnitude in gas flow and speed of sound, except for the inclination angle and the time delay. For the latter parameters the change in speed of sound is only half of the change in gas flow.
Evidently, OLC-SOS detects deviations up to 10 times faster than an on-line flow comparison. The warning limits should be set at a level that avoids false alarms. In practice, a CUSUM (Cumulative Sum) or a EWMA (Exponentially Weighted Moving Average) control chart including a spike filter can be used.
It is also possible to use OLC-SOS for checking the performance of the process gas chromatograph and temperature measurement. It is shown that a 0.3% deviation in gas composition or 0.3K in temperature corresponds with a 0.1% change in OLC-SOS. A practical operational limit for initial warning alarms could be set at ±0.05% in the OLC-SOS, which corresponds to $\pm 5\sigma$. Assuming these values are used, the number of false alarms is minimal, while deviations of 0.15% in the gas composition and a change of 0.15K in the temperature are nevertheless detected. If an alarm occurs, the deviation in gas composition and temperature are much larger than the reproducibility of the process gas chromatograph (0.03%) and the temperature measurement (0.02K).

8. Conclusions

Speed of sound data were collected at four metering stations using Q.Sonic-5 ultrasonic flow meters. Although the experimental conditions, e.g. gas velocity and gas composition, varied strongly, the repeatability (2σ) of the measured speed of sound was always within 0.01%. The mutual differences between the individual paths were always within ±0.12%. Differences will be caused by the uncertainty in the meter dimensions.

The speed of sound was also calculated, on the basis of gas composition (measured using a Daniel process gas chromatograph), temperature and pressure. The uncertainty and repeatability of the calculated speed of sound were within 0.15% and 0.02% respectively.

The difference between measured and calculated speed of sound (OLC-SOS) was always within 0.3% and showed a reproducibility that was at all times better than 0.02%. The reproducibility (a) appears to be path independent (b) is the same for the 4 meters tested and (c) does not dependent on the gas composition, the gas flow and the pipeline conditions. The difference between measured and calculated speed of sound will be caused by deviations in the dimensions of the flow meter and the uncertainty in the gas analysis used to calculate the speed of sound.

During the implementation of OLS-SOS specific attention must be paid to proper synchronisation. The residence time of the gas in the sample line leading to the GC must be know. Speed of sound, pressure and temperature must be measured at the exact moment that the gas sample is retrieved from the pipe line.

Small deviations (0.05%) in the temperature (on account of zero gas flow) and the gas composition (GC is calibrated using a slightly different gas composition) could easily be detected easily with OLC-SOS (during the field tests).

A sensitivity analysis showed that small deviations in nearly all parameters that influence the performance of the flow measurement lead to changes of the same magnitude in both the gas velocity and the speed of sound. These parameters are: the diameter of the flow meter, the path length between the sonic transducers, the manner in which the transit time is determined, the electronic delay-time, the transducer's angle and contamination of the transducers and pipe wall on account of oil, grease or solids. Variations in the random error in time measurement and a disturbed flow profile are not detected by OLC-SOS.

Based on the field tests and the sensitivity analysis, it can be concluded that OLC-SOS detects small changes in the performance (dimensions, electronics, contamination) of the ultrasonic flow meter. OLC-SOS additionally detecs small changes in (a) the performance of the GC, (b) pressure or temperature measurements. Therefore, OLC-SOS offers higher reliability of all fiscal measurements, without using additional instrumentation.

The measurements taken during the field tests made it clear that the reproducibility of speed of sound measurements is roughly 500 to 1000 times better than the reproducibility of the gas velocity measurements. Therefore, small deviations in the gas flow, which are caused by small changes in the flow determining parameters (except random errors in the transit time measurement t_i), will be detected far more easily by comparing speed of sound than by comparing the gas flow using a second gas flow meter. Assuming equipment for the determination of gas composition, pressure and temperature is present, the OLC-SOS method is much cheaper than the latter method.

The practical usability of OLC-SOS is mainly determined by the repeatability of the measured speed of sound data and the repeatability of the input data for the calculated speed of sound. Systematic deviations are of lesser importance, on the assumption that the systematic deviations are small and remain constant.

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