North Sea

FLOW

Measurement Workshop

1998

PAPER # 2.1

AN ULTRASONIC GAS FLOW MEASUREMENT SYSTEM WITH INTEGRAL SELF CHECKING.

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1 INTRODUCTION

Ultrasonic flow meters are becoming increasingly accepted for fiscal measurement of natural gas, as reflected in the latest standards, regulations, and codes of recommended practice such as NPD Regulations and Guidelines 1997 [1] and AGA 9 [2].

Since this is a new method of measurement to many operators, there is a need for diagnostic information which:

- gives confidence that the equipment is functioning correctly,
- shows, e.g. by trending, that there has been no long term shift in the measurement, and
- provides, where possible, 'health checks', i.e. advance warning of any future problems allowing suitable action to be taken in advance.

This need is reflected in the standards, which are moving towards systems which provide continuous on-line quality control and health checks to verify the correct operation of all devices. For example:

NPD, 1997 [1]: Guidelines:

"Trending of various critical parameters should be done"

"When using ultrasonic flow computers, the supervisory computer should calculate VOS (velocity of sound) based on P,T, and gas composition to monitor the VOS calculated by the ultrasonic flow meters."

AGA 9 [2]: Field Verification Tests:

"Some performance aspects of the UM's condition should be evaluated by comparing the Speed of Sound (SOS) value reported from the meter to a SOS calculated from the A.G.A. Report No. 8, Detail Characterization Method Equation of State. A chromatographic analysis ... is required for valid comparison".

For a specific Field Verification Test, this AGA 9 recommendation is met by taking a single sample of gas for off-line chromatographic analysis.

However, a typical field system for measuring energy and mass flow will include a gas chromatograph to provide the gas composition. In this case, full use of the extra diagnostic information available can and should be made by doing the comparison continuously and on-line. Note that the ultrasonic measurement of SOS is a direct measurement based on measured times and dimensions, and thus is totally independent of the SOS calculated from the gas composition, pressure, and temperature.

If a densitometer is also installed, then in a similar way we can compare the direct measurement of density with the density calculated from the chromatographic analysis, also using AGA 8. Figure 1 illustrates this concept schematically.

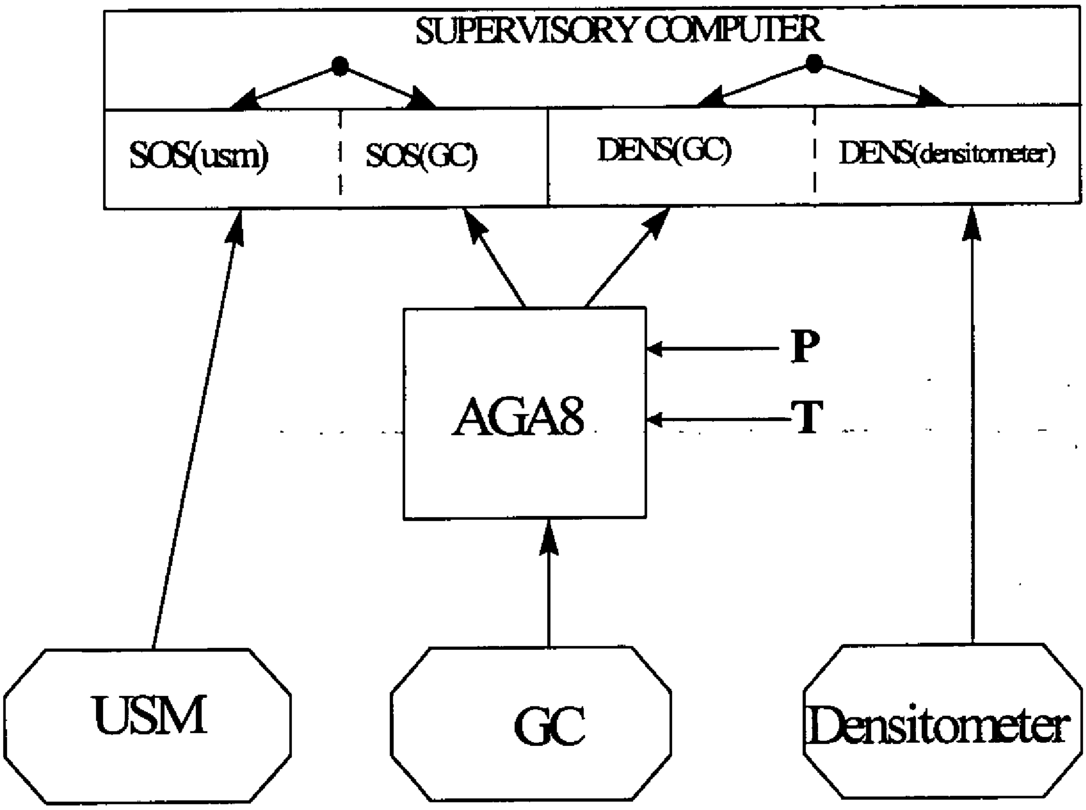

Figure 1 - Ultrasonic gas measurement system

R. Sakariassen [3] has already shown the value of trending Speed of Sound (comparison between 4 paths) and derived density; we now want to look at absolute comparisons using a gas chromatograph and densitometer.

With this system (Ultrasonic meter + Gas Chromatograph + Densitometer), the three main instruments give two independent measures of Speed of Sound and two independent measures of density. It is therefore possible to cross check all 3 instruments against each other, deduce which is the odd one out if there is a disagreement, and also provide some extra redundancy should one of them fail.

The remainder of this paper looks in more detail at the self checking and the diagnostic information available in each component of such a system. Also evaluated are the uncertainties in the dual measurements of Speed of Sound (SOS) and density, and the theoretical limits within which the above components should agree. Finally these theoretical limits are compared with actual data derived from ultrasonic metering systems, to show how cross checking could be used in operational practice.

Specific topics in the rest of this paper include:

- review of ultrasonic flow meter basics.
- self checking in ultrasonic flow meters.
- self checking and uncertainty in gas chromatographs
- accuracy of speed of sound measured by ultrasonic meters
- use of the AGA 8 equation
- the applicability of AGA 8 to rich natural gases
- calculation of the speed of sound using AGA 8
- an integrated configurable system
- experimental data
- field implementation.

2 REVIEW OF ULTRASONIC METER BASICS

Before looking at the main topics of consideration here, it is worth reviewing the basics of ultrasonic transit-time flow measurement. Consider the case shown in Figure 2 below.

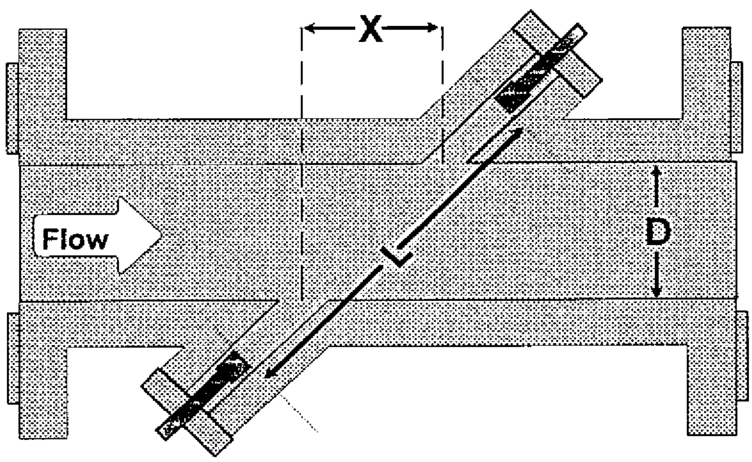

Figure 2 - Ultrasonic Meter

If L and X are the direct and lateral (along the pipe axis and in the flowing gas) distances between the two transducers, C is the Speed of Sound and V the flow velocity of the medium, and T_{12} and T_{21} are transit times in each direction,

then

$$T_{12} = \frac{L}{C+V\cdot\frac{X}{L}} \qquad (1)$$

and

$$T_{21} = \frac{L}{C-V\cdot\frac{X}{L}} \qquad (2)$$

Inversion of these two equations yields

$$V = \frac{L^2}{2X}\left(\frac{T_{21}-T_{12}}{T_{21}\cdot T_{12}}\right) \qquad (3)$$

and

$$C = \frac{L}{2}\left(\frac{T_{21}+T_{12}}{T_{21}\cdot T_{12}}\right) \qquad (4)$$

Thus, by measuring dimensions and transit times in pursuit of the average flow velocity along the path between transducers, we have also measured the Speed of Sound along this path. This will prove to be an extremely useful parameter in determining the overall performance of the meter.

3 SELF CHECKING IN ULTRASONIC METERS

One of the principal attributes of modern ultrasonic meters is their ability to monitor their own health, and to diagnose any maladies which may be detected. Multipath meters offer the ultimate in this regard, as they can compare certain measurements between different paths, as well as checking each path individually.

Measures which can be used in this self-diagnosis include the following.

Gain. One of the simplest indicators of a meter's health is the presence of strong signals on all its paths. Properly designed multipath meters will have automatic gain control on all receiver channels, hence an increase in gain on any channel indicates a smaller signal on that channel, perhaps due to transducer deterioration, fouling of the transducer ports, or even liquids in the line [4]. Caution must be exercised to normalize for other factors which affect signal strength, such as pressure and flow velocity. Whatever the cause, if it persists and threatens good signal detection, it is a cause for further investigation.

Signal Quality. This expression simply refers to the influence a detected signal has on a meter's ability to make a proper detection. Since this is highly dependent on the detection scheme employed by a given meter, one cannot simply jot down general equations which describe this parameter for any meter. The vendor of any given meter should, however, be able to supply some figure of merit describing how good his signal detection is for each ultrasonic path, i.e. the signal quality for this path. Note that this measure may be either statistical (percentage of good detections) or structural. A good instrument will monitor both.

Signal to Noise Ratio. This should also be monitored as an independent indicator. Note that the noise may be gas borne, (e.g. from pressure reduction valves), or from coupling of sound from the transducer to the meter body, or electrical. Stacking can be used to overcome some kinds of noise problems.

Sanity Checks. Correct meter operation dictates that certain parameters will have well-defined ranges, and that any measurement or estimate outside that range indicates that an error has occurred. Likewise, ranges exist for parameter changes. Alarms or warnings can be raised for out-of-range values for either.

Velocity Profile. Once a meter is placed in a specific gas pipeline configuration, the velocity profile of the gas for a particular average velocity should not vary a great deal. If the multipath meter in use is capable of measuring the velocity profile, then significant departures of this profile from normal should be viewed as a cause for concern.

Speed of Sound. Since an n-path ultrasonic meter has **n** paths of the type shown in Figure 1, it has **n** independent means of measuring and comparing the Speed of Sound (SOS) of the gas in the pipeline.

Statistical Measures. An ultrasonic meter will typically fire pulses and measure the transit times at as high a sampling rate as possible, then average the results from a 'batch' of several measurements. The standard deviation of the individual readings in the batch from the mean values can be used to indicate meter operation. Deviations can indicate the onset of problems.

4 SELF CHECKING AND UNCERTAINTY IN GAS CHROMATOGRAPHS

4.1 Self checking in Gas Chromatographs

Most on line process gas chromatographs have a variety of self checking procedures, the exact details of which are dependent on the manufacturer. Listed below are a set of self checks suitable for a process gas chromatograph operating with a thermal conductivity detector.

Status of Detector. The thermal conductivity detector has to be balanced to provide a good analytical measurement. Detector voltage balance is checked at the start of every run when only carrier gas is present. Deviations from the balance point indicate a change in detector circuit conditions and if the signal drifts beyond pre-set limits this should be investigated.

Signal from Detector. The analogue signal from the thermal conductivity detectors is subjected to various degrees of amplification. Limits on the allowable range of this signal, for example, between 5% and 95% of full scale, are automatically set and checked during data acquisition. Values outside the limits will indicate a fault condition.

Analysis Results - Un-normalised Total. There are always small variations between successive gas chromatograph analyses of the same gas. Furthermore, with atmospheric pressure sample injection systems the size of sample injected changes proportionally with variations in ambient pressure. However, in a correctly configured and calibrated system the un-normalised component total (i.e. the actual quantity of component detected) should always be close to 100%. Significant deviations from 100% indicate that there is a potential problem with the analytical set up. In the UK it is normal fiscal metering practice to set the un-normalised total limits for gas chromatograph analysis to ± 2%.

Analysis Results - Range Limits. If the gas composition is known to be relatively stable then limits for the ranges of individual component measurements or calculated physical properties can be set.

Calibration. Regular calibration of process gas chromatographs provides a method of updating response factors for small changes in local conditions. However, for most process gas chromatographs detector response is constant over a long time period. Perhaps the most significant feature of regular calibration is that it gives a performance check, i.e. a comparison of current performance with a known standard against the last good calibration with that standard. Limits are set on response factor and retention time deviation, and changes outside these indicate a significant change in the performance of the analytical unit.

4.2 Uncertainties in Gas Chromatograph Analysis

It is outside the scope of the current paper to discuss the uncertainties associated with on line gas chromatograph analysis, and a fuller discussion can be found elsewhere [5, 6]. Briefly, the principal causes of uncertainty in process gas chromatographs measurement are the following. First are uncertainties in the calibration gas concentrations. Next are uncertainties due to variation in instrument response, i.e. repeatability of the process gas chromatographs. Third are bias errors caused by non-linearity of detector response. Fourth are uncertainties associated with the values used in the calculation of physical properties, such as density. At best, with no bias errors and a top quality approved calibration gas, this can give a density uncertainty of 0.05%. However, when bias errors are introduced and/or poor quality calibration gases are used, errors of 0.3% or greater are possible.

5 ACCURACY OF SPEED OF SOUND MEASUREMENT BY ULTRASONIC METERS

The "dry calibration" of ultrasonic meters is accomplished by making precision measurements of the meter geometry and transducer delay times. The transducer delay times are determined by measurements taken in a test cell filled with a known gas (nitrogen) at known temperature and pressure. The speed of sound of nitrogen is thus known to within 0.1%. When the complete ultrasonic meter is later assembled, a final check is done by filling the meter with nitrogen. Measured speeds of sound on all chords must agree within 0.1%, which takes into account the uncertainty in the geometry (chord length) and transit time measurements.

For a flowing gas, there may be additional effects due to the inability of simple ray theory to fully describe the complex interaction of the ultrasonic pressure wave with the flow. (For a more complete explanation, see AGA 9 [2], Appendix C.) This phenomenon is evident by looking at how the velocity of sound values vary from inner to outer paths. In the data presented later in this paper, using four-path meters, it was found that at the highest flow velocities (28 m/s), the four individual speed of sound readings fell within a range of 0.1% of the average. At lower velocities this figure dropped to 0.05%. It therefore seems reasonable to bound these errors in flowing gas to about 0.1%.

Overall then, the uncertainty in the speed of sound measured by a multi-path ultrasonic meter from these three kinds of errors is estimated to be $\pm\sqrt{(0.1^2 + 0.1^2 + 0.1^2)} = \pm 0.17\%$.

6 USE OF THE AGA 8 EQUATIONS.

If the gas composition, pressure, and temperature are known, then both the gas density and the Speed of Sound can be calculated from the gas equation of state. The accepted standard equation of state for lean natural gases is the current revision of AGA Report No 8 [7], using the Detail Characterization Method (complete gas composition).

This equation is valid for lean natural gas mixtures over a wide range of conditions.

In principle, the gas chromatographic technique for the determination of density should be as effective as that using a fully calibrated and traceable densitometer, given that the measurements of pressure, temperature, and the gas composition are made to a sufficiently high standard.

6.1 AGA 8 Accuracy - Lean Natural Gases

The accuracy of the AGA 8 equation of state depends on the composition of the natural gas and on the temperature and pressure at the metering conditions. The targeted uncertainties (at two standard deviations) for the AGA 8 equation of state in terms of temperature and pressure are:

Table 1

Region	Temperature Range	Absolute Pressure Range	Uncertainty in Density
1	-8 to 62°C	0 to 120 bar	0.1%
2	-60 to 120°C	0 to 170 bar	0.3%
3	-130 to 200°C	0 to 700 bar	0.5%
4	-130 to 200°C	0 to 1400 bar	1.0%

The AGA 8 equation is claimed to meet these expected or targeted uncertainties for gas mixtures having a *normal range* of compositions, see below, within Region 1, and in parts of Regions 2, 3, and 4. For the *expanded range* of compositions given in the following Table, the uncertainties are expected to be higher.

Table 2

	Normal Composition Range		Expanded Composition Range	
Component	Lower limit (mole%)	Upper limit (mole%)	Lower limit (mole%)	Upper limit (mole%)
Methane	45	100	0	100
Nitrogen	0	50	0	100
Carbon dioxide	0	30	0	100
Ethane	0	10	0	100
Propane	0	4	0	12
Butanes	0	1	0	6
Pentanes	0	0.3	0	4
Hexane's plus	0	0.2	0	dew point

7 THE APPLICABILITY OF AGA 8 TO RICH NATURAL GASES.

The application of the AGA 8 equation to rich natural gases (approximately 60% methane with the balance being heavier hydrocarbons), as encountered in gas condensate fields in the North Sea, has only recently been tested.

The UK National Engineering Laboratory (NEL) has been involved in a Joint Industry Project to investigate the applicability of the AGA 8 equation to rich natural gas mixtures. A measurement program was launched, firstly, to determine the magnitude of the differences between AGA 8 and reference-quality density data for ten natural gas mixtures in the range 80 to 180 bar and 40 to 80°C; and secondly, to provide reference-quality density data for subsequent refinements to the AGA 8 equation. The reference-quality data were obtained using NEL's primary standard densitometer.

The evidence from this major research program has established that:

- calculated densities for mixtures with compositions in the *expanded range* are better than expected.
- the maximum differences between measured and calculated densities occur for those mixtures with component compositions above, or close to, the upper limit of the *expanded range* of compositions; and
- the upper composition limit for carbon dioxide (30%) for *normal range* application is much too high.

8 CALCULATION OF THE SPEED OF SOUND.

The Speed of Sound of the gas mixture can be calculated by an extension of the equations given in the AGA 8 standard.

The necessary equations are detailed in a GRI report [8], which uses essentially the same equation of state as found in the 1985 version of the AGA 8 standard. These equations should be upgraded to be consistent with the latest (1994) edition of AGA 8. Also, the equations require a knowledge of Cp, the ideal specific heat of the gas at constant pressure.

All calculated values of Speed of Sound in this paper were derived using the implementation of the AGA 8 equations by Daniel Measurement and Control for use on their systems. Similar calculations are available as PC based programs from various sources, e.g. the AGA 8 package from NEL, which supplies a complete range of calculated properties, including Speed of Sound, and is supplied in Excel compatible form.

8.1 Uncertainty of the calculated Speed of Sound

The uncertainty in the calculated Speed of Sound depends upon:

- the uncertainty inherent in the equation of state calculations.
- the uncertainty in line pressure and temperature
- the uncertainties in the measured gas composition

The accuracy of the AGA 8 equation of state depends on the gas composition, pressure and temperature. The equations are less accurate at high gas density (lower temperatures and higher pressures), and with richer gases, or gases containing relatively large amounts of CO_2.

The accuracy of the Speed of Sound calculation (Daniel implementation) has been quantified by comparing the calculated values with experimental data published by NIST [9], which has a stated accuracy of ± 0.05% on measured Speed of Sound values.

The NIST data uses 4 natural gas mixtures, 2 of which (Gulf Coast and Amarillo) are lean gases within the *normal* range of AGA 8. The third mixture used (Statoil Dry gas) is only slightly outside the *normal* range (ethane = 13%), and is included in the results below as a *normal* gas. The final mixture is Statoil Statvordgass, which is a richer gas in the AGA 8 *expanded* range.

For lean natural gas above 0°C and below 130 bar, the agreement (95% limit) between calculation and measurement was found to be ± 0.07%.

The results for a wider range of conditions are summarised in Table 3.

Table 3

Gas Composition	Temperature	Pressure	Uncertainty in calculated SOS (95% limit)
Normal	> 0°C	< 100 bar	0.07%
"	"	100 to 130 bar	0.16%
"	-23°C to 0°C	< 100 bar	0.13%
"	"	100 to 130 bar	0.64%
Statoil Statvordgass*	25°C to 75°C	< 60 bar	0.11%
"	"	60 to 105 bar	0.90%

* The Statoil Statvordgass composition is:

methane	74.348%
ethane	12.005%
propane	8.251%
normal butane	3.026%
normal pentane	0.575%
normal hexane	0.230%
nitrogen	0.537%
carbon dioxide	1.028%

Similarly, the uncertainties due to measurement of gas composition, pressure and temperature have been estimated numerically by observing the effect on the calculated Speed of Sound, independently varying each parameter. If we postulate uncertainties of 0.3°C and 0.2 bar in the measurement of pressure and temperature (maximum allowed by NPD requirements for fiscal systems) and feed these into the Speed of Sound calculations, the added uncertainty in Speed of Sound is roughly 0.07%.

Similarly, the uncertainties in composition from a typical gas analysis system results in an added error of roughly ± 0.05%.

In summary then, the overall uncertainty (95% confidence limit) in **calculated** (AGA 8) Speed of Sound, for a *normal* gas below 100 bar and above 0°C, is:

from NIST measurement:	0.05%
from equation of state:	0.07%
from P and T:	0.07%
from gas analysis:	0.05%
Total (square root rule) =	**0.12%**

For richer gases, lower temperatures or higher pressures, the uncertainty will be greater, as indicated above.

9 AN INTEGRATED CONFIGURABLE SYSTEM

Refer to the system shown in Figure 1. This is an integrated system for volume, mass and energy flow with additional checking, in the sense that the three main components provide two independent measures of both Speed of Sound and density. They can therefore cross-check one another, as well as provide an extra level of redundancy. However it is also configurable in the sense that various components can be switched off, or even omitted entirely to give reduced cost for suitable applications.

It is worth noting that the Speed of Sound is used as a correction to the densitometer measurement, and therefore in this system, the densitometer accuracy can be increased by using the live Speed of Sound measurement from the ultrasonic meter (backed up by the gas chromatograph).

Possible reduced configurations are:

1) USM +GC (no densitometer):
Still provides volume, mass and energy measurement with cross checking on Speed of Sound.

2) USM + densitometer (no GC):
Provides volume and mass flow. The 'fall back' for energy would be to enter a fixed gas composition, or fixed heating value.

3) USM only.
This is suitable for certain kinds of systems, and can be useful if the gas composition is well known and does not vary significantly from week to week.

10 EXPERIMENTAL DATA COMPARING SPEED OF SOUND AND DENSITY

In order to investigate the degree of agreement that can be expected in normal operation, between the dual measurements of Speed of Sound and density, data has been collected from flow calibration tests of Daniel 4-path ultrasonic meters with nominal sizes of 6", 8", 10" and 12". In each case the data covers flow velocity ranges of approximately 2 to 28 m/sec, using typical lean natural gases, pressure ranges of roughly 30 to 50 bar. The 8" meter data was obtained during approval tests at the Gaz de France facility at Alfortville, Paris. The remaining data were obtained during flow calibrations carried out at the British Gas flow test and calibration facility at Bishop Auckland, UK. The gas chromatograph at Bishop Auckland was a Danalyzer, that at Alfortville was by another manufacturer. The authors gratefully acknowledge the help and co-operation received at both of these sites.

10.1 Speed of Sound

The preceding sections show that the expected uncertainties (2 standard deviations) in Speed of Sound are:

USM measurement	± 0.17%	
Calculated (AGA 8)	± 0.12%	(lean gas, P < 100bar)

In actual practice, using lean natural gas below 100 bar, we would therefore hope to find that 95% of readings agree within about 0.21% (about 0.8 m/sec).

The actual data for the 4 meter sizes is summarised in what follows. Each figure shows trended values covering 2 to 3 hours.

First shown is data from the 8" meter in Figure 3, comparing the **average** Speed of Sound over the 4 paths with the AGA 8 calculated value.

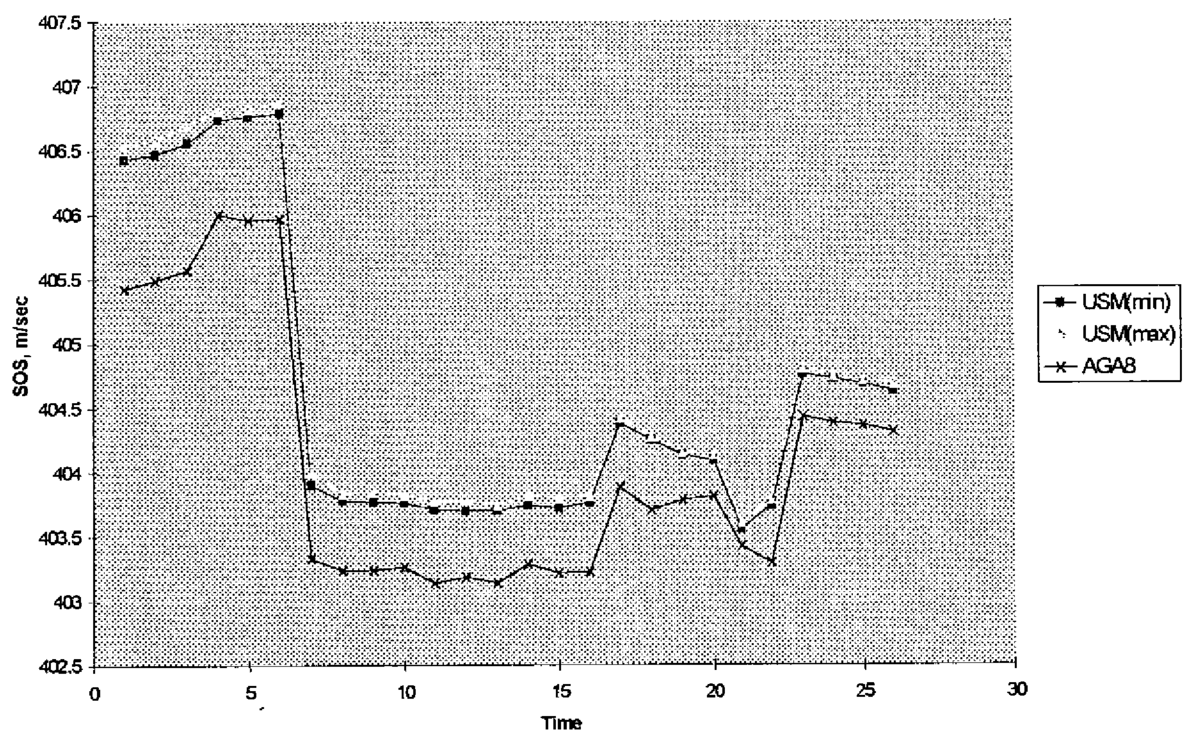

Figure 3 - 8" meter. Measured vs. calculated SOS

At each measurement point, ten successive values of the ultrasonic meter Speed of Sound were logged. The two curves which show the minimum and maximum values from each of these sets demonstrate a repeatability in the SOS measurements of better than 0.03%.

Figures 4 through 6 show the AGA 8 <u>calculated</u> Speed of Sound trended against the individual Speed of Sound readings from the four paths. Note that in each case the agreement on all chords is roughly as expected, but that the agreement on the two central paths (chords B and C) is significantly better than on the outer paths (chords A and D).

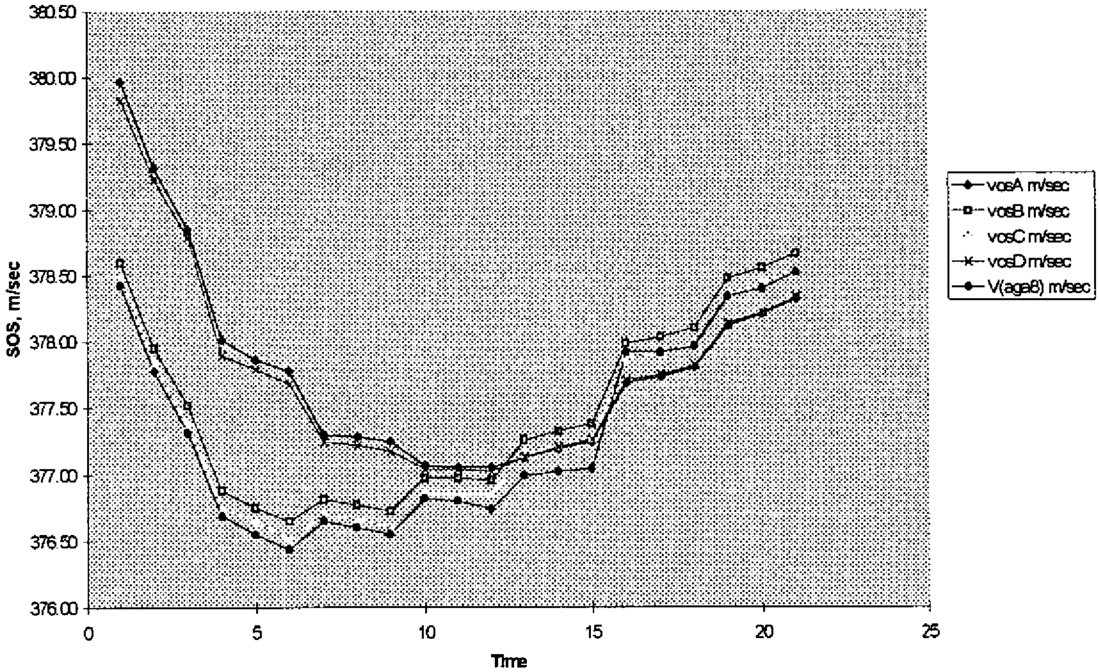

Figure 4 -Six-inch meter. Measured Speed of Sound on four chords vs. AGA 8 calculation

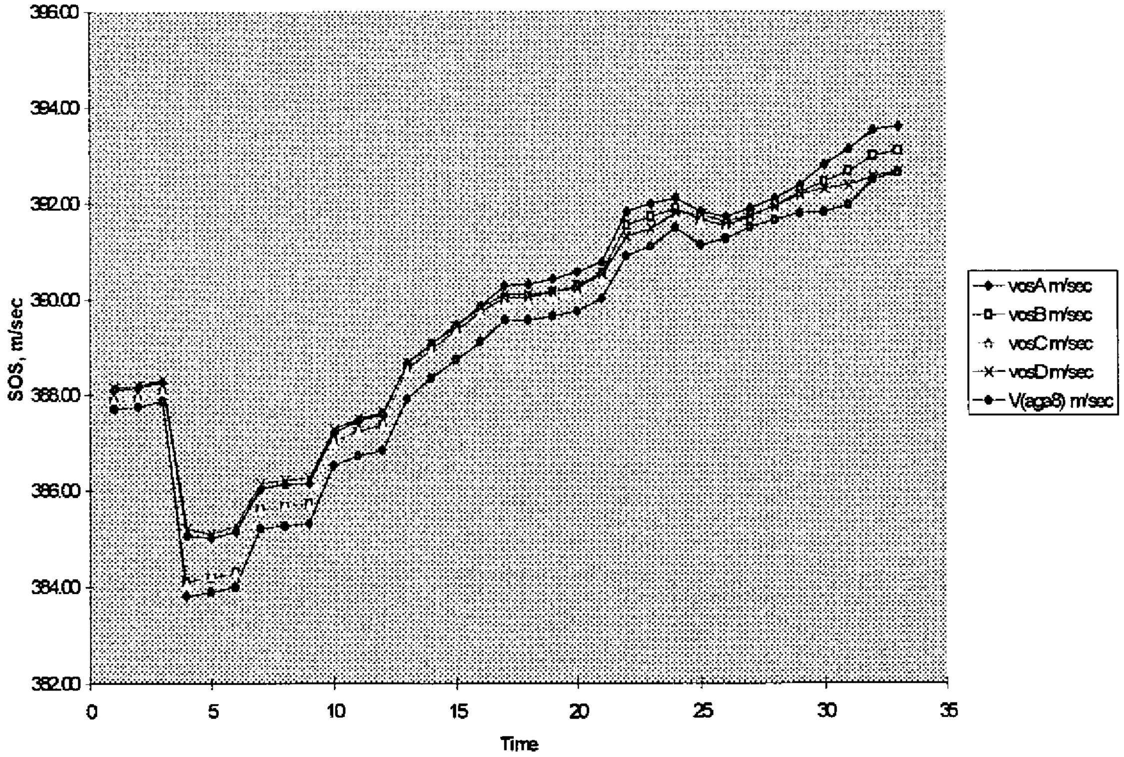

Figure 5 - Ten-inch meter. Measured Speed of Sound on four chords vs. AGA 8 calculation

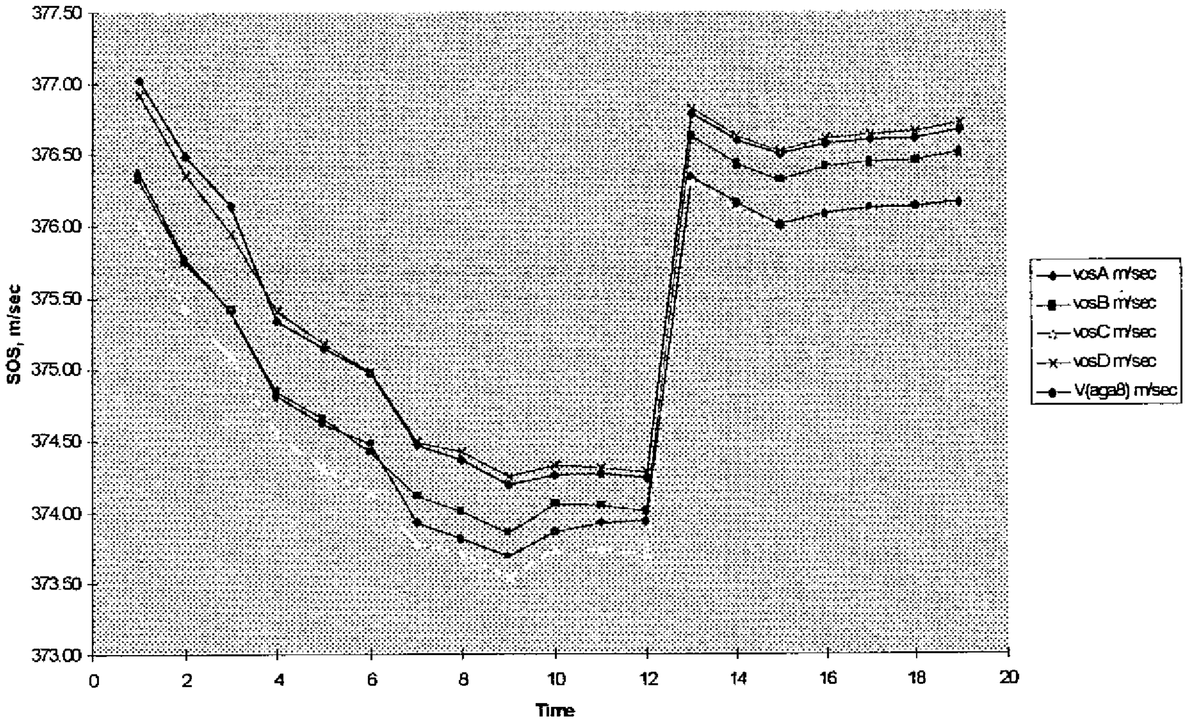

Figure 6 - Twelve-inch meter. Measured Speed of Sound on four chords vs. AGA 8 calculation

From the above results, it is clear that on a multi-path meter, absolute Speed of Sound comparison is best done using the central paths. As pointed our in our earlier discussion, this is due to the complex nature of wave propagation in the flowing medium, which seems to most greatly affect the outer chords.

The Table below shows the rms and maximum deviations between AGA 8 and USM observed, using the mean values of SOS on the central (B and C) chords for each meter (except the eight-inch, for which individual chord readings were not recorded).

Meter Size	rms deviation	Maximum Deviation
6"	0.04%	0.08%
10"	0.11%	0.15%
12"	0.04%	0.06%

This suggests that when using on-line cross-checking of Speed of Sound, a reasonable approach would be to set an alarm limit of about ± 0.3%.

10.2 Test Data - Density

The expected uncertainties (2 standard deviations) in density are:

Densitometer measurement: ± 0.3%
Calculated (AGA 8) density: ± 0.1% (*normal* gas, region 1)

In real operation, using lean natural gas, we would therefore expect the difference between the two derivations of density to fall within ± 0.33%. (95% limit).

Figures 7 and 8 show density data (densitometer v. AGA 8) from the tests of the eight-inch meter at Alfortville. The second figure shows the same data set as the first, expanded to show more detail.

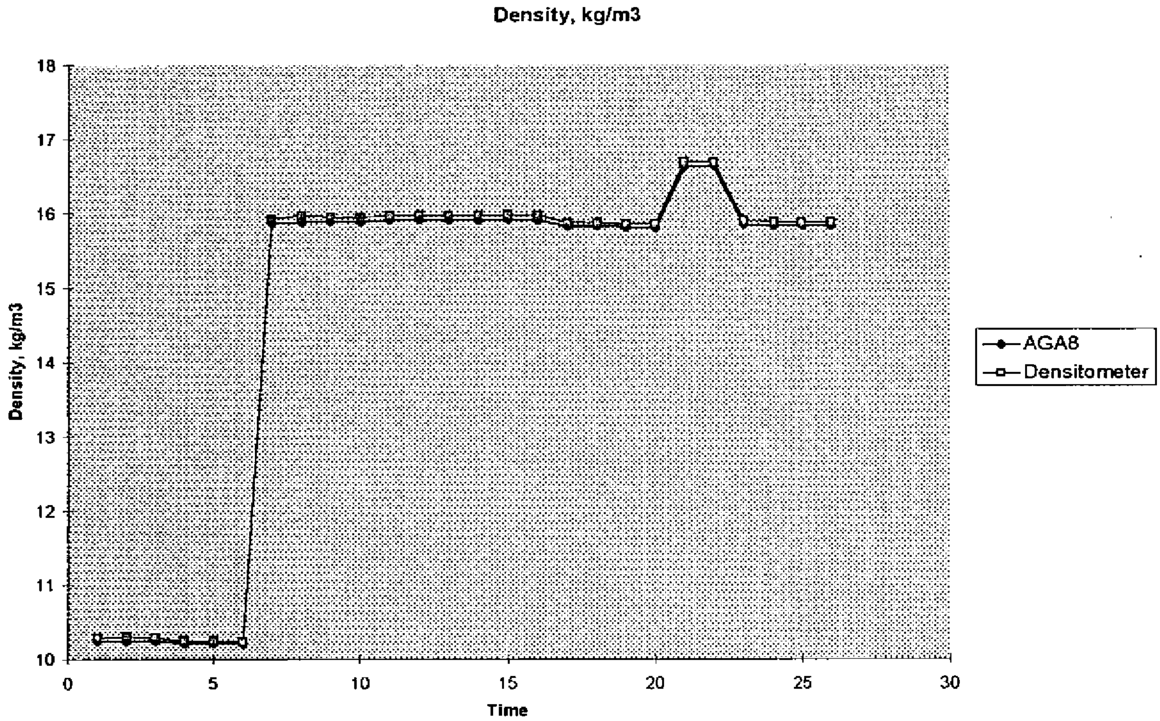

Figure 7 - Measured density vs. calculated density (AGA 8)

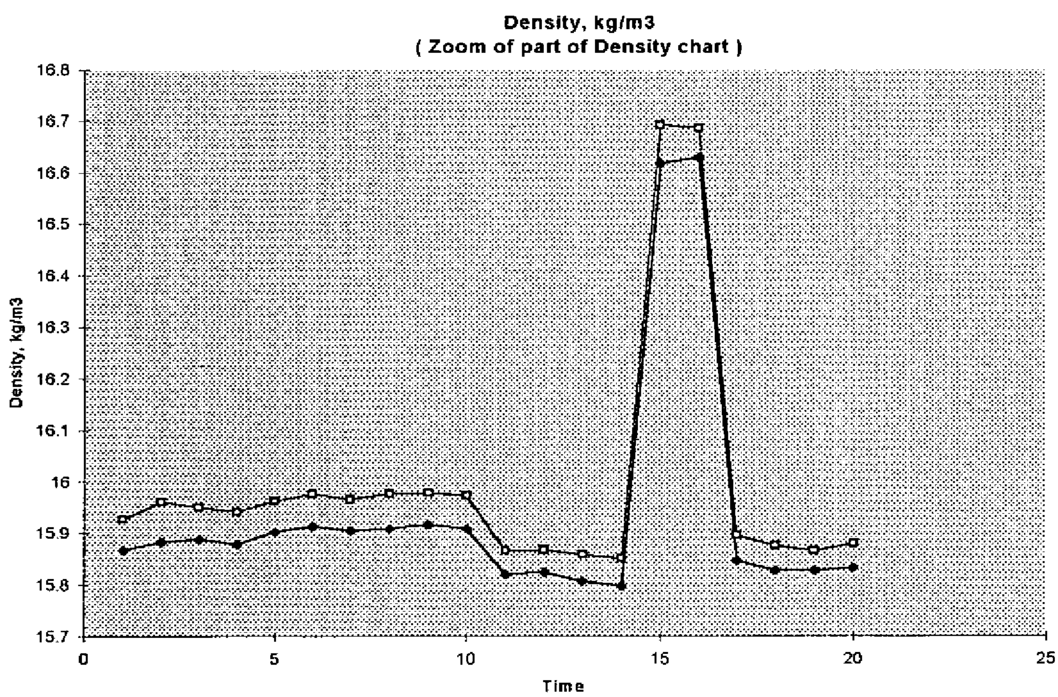

Figure 8 - Measured density vs. calculated density (AGA 8)

Once again, the two measurements track well, with a small systematic offset. The deviations between the two measurements range from 0.45% to 0.24%, slightly outside the theoretical predictions, but broadly as expected.

The result and theory both suggest that when using density as a health check, a reasonable limit for raising an initial warning alarm would be a difference of ± 0.9%. This may depend on the specific densitometer being used.

11 FIELD IMPLEMENTATION

What we have shown here is a method whereby three instruments can yield independent estimates of two key parameters, thereby permitting the user to detect a malfunction in any of the three. The calculations shown were all performed on a PC, which raises the question of how the method will be implemented in field operation. Must a PC, either standalone or as part of a supervisory system be present in order to perform the algorithms?

Fortunately, the next generation of panel-mounted flow computers will be capable of performing tasks such as this, which formerly required a standalone computer. One recent introduction incorporates a fast 32-bit processor, and is thus fully capable of performing the AGA 8 calculations, as well as interfacing to the ultrasonic meter, the gas chromatograph, and the gas densitometer.

12 CONCLUSION

The above results indicate that, in addition to the internal checks available within an ultrasonic meter, it is both practical and useful to incorporate both gas chromatographs and densitometers to give independent checks. Practical operational limits for initial warning alarms would appear to be about ± 0.3% deviation in Speed of Sound, and ± 0.9% in density.

13 REFERENCES

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