Investigation of precision sound velocity measurement methods as reference for ultrasonic gas flow meters

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***Abstract*— Ultrasonic gas flow meters for volumetric flow rate fiscal metering of natural gas (USMs) may possibly also be used for mass and energy flow rate measurement, partially based on velocity of sound (VOS) measurement. To establish the accuracy of the VOS measurements given by the USM, and for traceability purposes, an independent and high-accuracy VOS measurement cell may be used as reference. To include relevant effects of dispersion, the cell should preferably work in the operational frequency range of USMs, e.g. 100-200 kHz, with natural gas under high pressure.**

Three different transient methods are investigated, aiming to realize a VOS measurement cell, and they are seen to have several common experimental uncertainty sources. In the present work, a two-distance method is discussed in more detail as an example, and some results from measurements in an insulated chamber with air at 1 atm and ca. 25 °C are presented.

The relative expanded measurement uncertainty was estimated according to ISO guidelines to 282 ppm (95 % conf. level). One major source of measurement uncertainty was experienced to be small convection currents in the chamber. Without these, the expanded uncertainty would have been about 162 ppm. Such convection effects are expected to be strongly reduced in a properly designed measurement cell.

The VOS measurement results were compared with predictions from a VOS model for standard air, including dispersion [J. Acoust. Soc. Amer. 93 (5), pp. 2510-2516, 1993], resulting in a mean deviation of -18 ppm with a two standard deviation spread in the data of 190 ppm over the temperature range.

I. Introduction

Ultrasonic gas flow meters (USM) are currently employed to measure gas volumetric flow rate in fiscal gas metering. As the USM gives a measurement of the velocity of sound (VOS) in addition to the volumetric flow rate, it may offer a potential for gas density and energy measurement [1].

Recent developments have proposed methods for calculation of the mass and energy content of the gas from the measured VOS, pressure and temperature [1]. If using the USM as an energy or mass flow meter, the uncertainty in the VOS output from the USM should be evaluated against an independent, accurate and documented method. No such reference method exists today, raising the need for a precision VOS measurement cell for natural gases.

A feasibility study for realizing such a cell has been carried out [2]. The literature on the field appears to be extensive, but none of the identified measurement methods could directly meet the specifications given below. VOS measurement cells with extreme accuracy are available in the audio frequency range, for which uncertainties down to 1 ppm have been reported. Less work was however identified at a sufficient accuracy level in the frequency range 100-200 kHz. A more recent literature study was carried out in 2004 [3], still not revealing any directly applicable cell method. The most promising methods needed development, or alternatively, a new method should be devised.

Tentative technical cell specifications have been pointed out [2], and the absolute VOS measurement uncertainty should not exceed $\pm$(0.05 – 0.1) m/s (100 – 200 ppm) at a 95 % confidence level. The operational parameters are those of the USMs, a pressure range of, say, 0 – 250 barg, a temperature range of 0 – 60 °C, and the frequency range 100 – 200 kHz.

Three transient methods are being investigated [2], [4], [5] as part of the work to realize a precision VOS cell. They are seen to have several similarities, as being transit time based, cancelling out system delay, and the same time detection method may be applied.

One of these methods is presented and used in this paper, as a preliminary method, mainly due to moving parts which is regarded to be a disadvantage in a practical measurement cell. However, the method is flexible and well suited for investigating common experimental aspects and uncertainty sources that also are relevant for the two other candidate methods.

II. Theory

A. The two-distance VOS measurement method

The two-distance VOS measurement method (2DM) is described in e.g. [6], [7], and the principle is shown in Fig. 1. In [7] the method was applied on water, and an experimental accuracy of about 205 ppm was achieved. The measurement principle is as follows (cf. Fig. 1): a pulse (1) is transmitted in the gas over the distance L_1, and the total transit time t_1 is measured. The transducer separation is changed by ΔL, and the process is repeated at L_2 to obtain the transit time, t_2, from the second pulse (2).

The model in Fig. 2 illustrates the system time delay components, and according to this, the following expression represents the measurements at distances L_1 and L_2

$$t_i = t_T^{eltr} + t_{i,plane}^{gas} + t_i^{corr} + t_R^{eltr}, \quad i = 1, 2, \qquad (1)$$

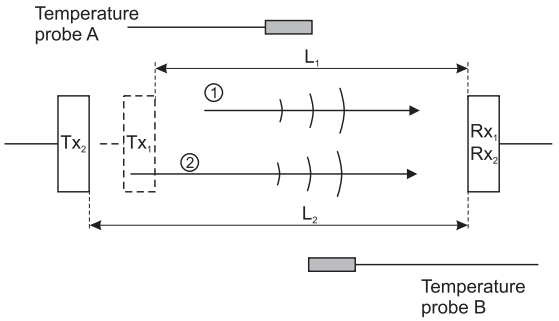

Fig. 1. Principle sketch of the two-distance method. $\mathrm{Tx}_{1,2}$ denotes the transmitted pulse at respective distance 1 and 2, and $\mathrm{Rx}_{1,2}$ denotes the received pulse at respective distance 1 and 2.

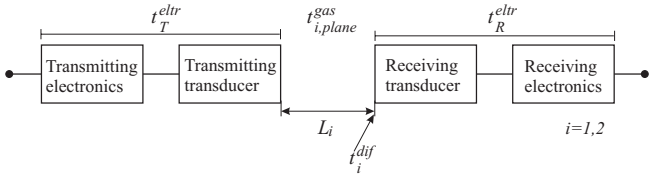

Fig. 2. A model of the transit time measurement with the two-distance method. Subscript *i* denotes the measurement at respective distances 1 and 2. t_i^{dif} is the diffraction time advance due to departure from plane wave propagation.

where t_i denotes the total measured transit time and t_T^{eltr} is the time delay in the transmitting electronics, cables and transmitting transducer. $t_{i,plane}^{gas} = L_i/c$ denotes the plane wave pulse time-of-flight in the gas, and t_i^{corr} accounts for non-ideal effects such as non-plane wave propagation, i. e. diffraction phase shift, t_i^{dif}, and other possible contributions. t_R^{eltr} is the time delay in the receiving transducer, cables and receiving electronics. Note that the time delays in the transmitting and receiving circuits are assumed to be constant throughout the measurements at distances L_1 and L_2 (i.e. not affected by temperature).

By rewriting (1) and subtracting t_1 from t_2 we obtain

$$t_2 - t_1 = t_{2,plane}^{gas} - t_{1,plane}^{gas} + t_2^{corr} - t_1^{corr}. \qquad (2)$$

Now, by introducing $\Delta L \equiv L_2 - L_1$, $\Delta t \equiv t_2 - t_1$ and $t^{corr} \equiv t_2^{corr} - t_1^{corr}$, the VOS, c, may be obtained as

$$c = \frac{\Delta L}{\Delta t - t^{corr}}. \qquad (3)$$

B. A VOS model for standard air

A model for VOS in air given in [8] was chosen for comparison due to its extensive empirical support [9], [10, Table II]. A virial equation of state, including first and second virial coefficients was used to develop a pressure dependent model for VOS in standard air. Model input parameters are temperature, pressure, humidity and CO_2 concentration. As an example, at standard temperature and pressure (0 °C and 101 325 Pa) the model predicts a VOS of: $c_0 = 331.46$ m/s $\pm$ 300 ppm [8] at a 95 % conf. level, where subscript '0' denotes the zero frequency limit.

The following relation was used to account for dispersion in the medium [8], [11]

$$\frac{1}{c_0} - \frac{1}{c_\phi} = \sum_r \frac{\alpha_r}{2\pi f_r}, \qquad (4)$$

where c_ϕ is the VOS at a specific frequency and α_r and f_r are the attenuation coefficient and relaxation frequency respectively for each relaxation process. The dominating processes in air are due to nitrogen and oxygen, hence, the model was confined to accounting for these. From (4), the dispersion, $\Delta c \equiv c_\phi - c_0$, in the experiments described here was typically 0.15 m/s ($\sim$ 435 ppm), and thus significant.

Although this is a well known dispersion model, little empirical data have been found that may validate the model in the relevant frequency range [8], [11]. The dispersion model uncertainty, $u(\Delta c)$, is thus not determined, but may contribute to the overall model uncertainty. The uncertainty contribution from this dispersion model is therefore omitted, hence, the overall model uncertainty is taken to be 300 ppm [8] (95 % conf. level; see above).

III. Experimental

A. Measurement system

A functional diagram of the experimental setup is outlined in Fig. 3, and some relevant measurement settings are given in Table I. The transducer separation was adjusted with a linear *Ealing 53-8116/5* positioning stage with a length resolution of 5 μm.

The temperature was acquired from a probe A (T_A), seated just below the acoustic path, and from probe B (T_B), located right below the chamber ceiling. The calibrated, combined temperature uncertainty of the *ASL F250* thermometer and the probes was 13 mK (95 % conf. level).

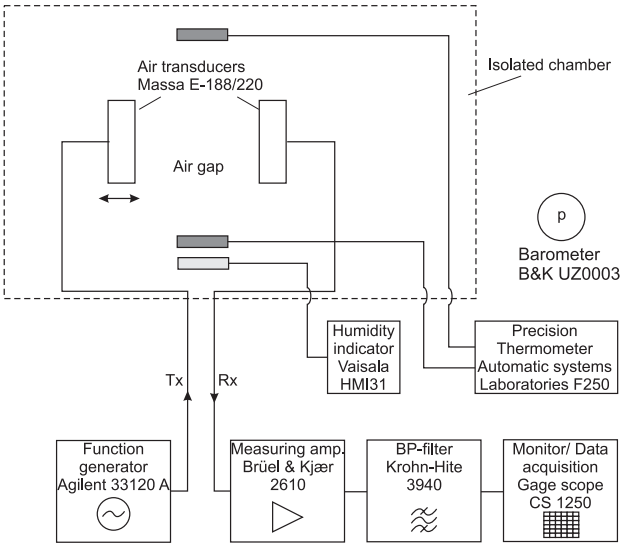

Fig. 3. Functional diagram of the experimental setup for the 2DM.

TABLE I

MEASUREMENT PARAMETERS.

Parameters	Value
Carrier frequency, f_0 [kHz]	218
Burst wave form	Sine
Peak amplitude [V]	3
Number of periods	50
Burst repetition rate [Hz]	80, 100
Sampling frequency [MHz]	5, 10
$L_1,\ L_2$ [cm]	28, 40

B. Environmental conditions

A stationary, low-noise air environment is crucial to achieve high measurement accuracy, and such conditions were attempted obtained by using an insulated chamber enclosing the transducers and positioning system. The walls and ceiling consisted of layered plastic and expanded polyester, covered with a wool carpet on top. The chamber made a closed volume with inner dimensions $52 \times 60 \times 127$ cm^3, well large enough to avoid interfering reflections.

Phase shifts detected as rapid changes in the transit times have been observed when either changes or high values in the temperature difference, $\Delta T \equiv |T_A - T_B|$ were present.[1] The phenomenon is experienced to come from medium convection currents, caused by heating from the *Ealing* stage. The problem was also reported in [12], where the same positioning stage was used. To reduce the problem, the stage was insulated and in off-mode until the positioning took place.

C. Data acquisition

Relevant measurement settings were acquired just before the data acquisition, whereas the averaged temperature $\overline{T}_1 \equiv (T_{A1}+T_{B1})/2$ was recorded simultaneously with the acoustic data acquisition in position one. The transmitter was then moved to position two, immediately followed by a second averaged temperature ($\overline{T}_2$) and data acquisition.

The transit time was determined for twenty signal traces, and then averaged to constitute a mean transit time. The zero crossing times in the stationary part of the mean transit time were then averaged to obtain Δt to be input in (3).

The transmitted and received burst pulses were recorded with a *GageScope CS1250* (PC-Oscilloscope), with 12 bits sampling resolution. Presumably due to internal PC noise, the effective number of sampling bits were less than 12. By inspecting the level of the short-circuited sampling noise and knowing the range, the effective number of bits could be estimated to 8.4.

D. Processing

The transit time was determined by zero crossing time detection, combined with linear interpolation between the samples around zero to achieve a sufficient time resolution. By using this method in the stationary part of the burst, the measurand is the phase VOS [13, p. 220] which is the VOS model output as well.

A statistical software [14] was employed to determine the achieved time resolution as a function of sampling frequency (f_s), number of bits, burst periods and generator frequency variation. It was found that $f_s = 5$ MHz, 8 bits, 100 zero crossings and a linear frequency variation of 1 % yielded a standard time uncertainty of 0.14 ns, which is insignificant compared to other quantities. By inspecting the transit time for each zero crossing through the burst, it was found that sampling frequencies exceeding 5 MHz had no impact on the span of the transit time variations.

A threshold was utilized for capturing the burst to determine zero crossings within. Due to medium absorption and long transducer risetime, the signal onset is typically embedded in noise. Consequently, the detected zero crossings of burst (1) may not necessarily correspond to those of burst (2). However, by limiting ΔL, the shape of burst (1) and (2) will be very similar, so by scaling the treshold to the burst amplitude, the zero crossings of the two bursts are likely to correspond.[2]

E. Corrections

The only identified contribution to the correction term, t^{corr}, in (3) was that of a diffraction correction. Williams' model [15] for diffraction correction was used to account for diffraction effects. Model assumptions are that the transmitter oscillates as a plane, circular piston source with a uniform radius, seated in an infinite rigid baffle. This may be a somewhat rude approximation, as the transducers used here probably are designed for fundamental radial mode oscillation [16], and also, the transmitter is not mounted in an infinite baffle.

According to [17], a disc-shaped transducer element can have an effective radius being 40 % smaller than the physical dimension. The effective source radius, a_{eff}, was thus estimated to increase the accuracy of the model input parameters. This was done by adapting the -3 dB angle, θ_{-3dB}, of the piston directivity to the measured directivity, and solving for the radius, resulting in $a_{eff} = 4.25$ mm.

Fig. 4 shows the calculated diffraction correction as a function of distance, for the parameters: VOS 345 m/s, source radius 4.25 mm and frequency 218 kHz. t_1^{corr} and t_2^{corr} are marked as a function of the respective distances L_1 and L_2. It is seen that for a pulse travelling a distance like L_1 and L_2, the calculated diffraction time shift becomes a significant portion of one period, nearly -85° in the example here. It is also evident from Fig. 4 that the diffraction correction, t^{corr}, which is the difference between t_2^{corr} and t_1^{corr} can be made relatively small [18] by choosing suitable values for L_1 and L_2. The value of t^{corr} was about 28 ns in the present experiments.

[1] Typical values of the temperature difference, ΔT, could be from 30 - 110 mK, with the highest temperature beneath the chamber cealing (T_B).

[2] At the given frequency and VOS, a possible mismatch of one period in Δt gives a perturbation in the VOS of about 4 m/s, which deviates a lot from the model value. The model was thus used to identify erroneous period detection that could arise from the treshold criterion.

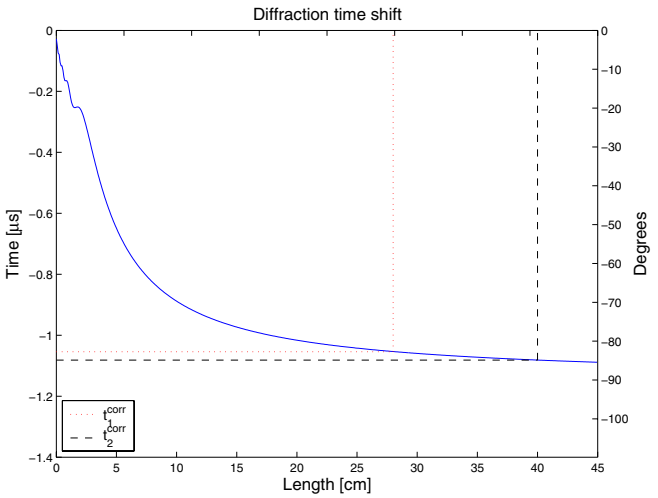

Fig. 4. Example of calculated diffraction time shift with Williams' model for a plane piston with a VOS of 345 m/s, source radius 4.25 mm and center frequency, f_0 = 218 kHz.

IV. Results

A. Sound velocity

The measurement results with estimated uncertainty (cf. Sec. IV-B), shown as vertical errorbars, are plotted as a function of temperature in Fig. 5, together with the model predictions. The mean and maximum deviation from the model is -18 ppm and -222 ppm respectively, with a two standard deviation spread of 190 ppm (95 % conf. level), over this temperature range. Hence, the measured VOS values are within the model uncertainty band.

It is stressed that the model uncertainty band possibly should be expanded due to the neglected dispersion model uncertainty, cf. Section II-B. Note also that the "bumps" in the model value / uncertainty band are due to varying air humidity.

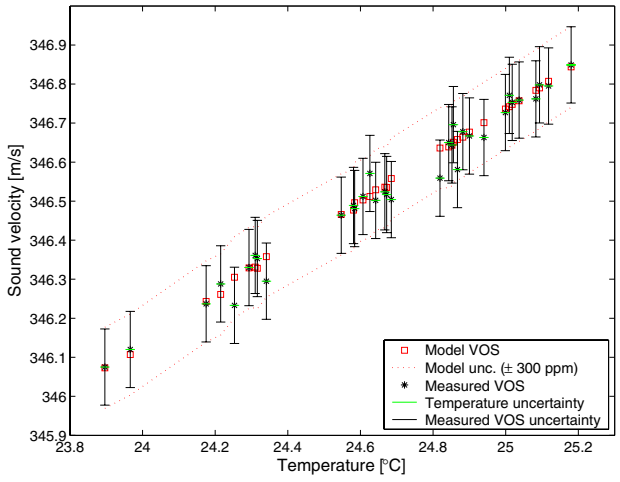

Fig. 5. VOS measurement results and model predictions. The vertical and horizontal errorbars illustrate the uncertainty in measured VOS and uncertainty in temperature respectively.

TABLE II
Experimental uncertainty budget.

Relative quantity	Value [ppm]
$u(\Delta L)/\Delta L$	43
$u(\Delta t)/\Delta t$	121
$u(t^{corr})/\Delta t$	58
Combined uncertainty, $u(c)/c$	141
Expanded uncertainty, $U(c)/c$ (conf. level 95 %)	282

B. Measurement uncertainty

The functional relationship in (3) states that $c = c(\Delta L, \Delta t, t^{corr})$. Although Δt and t^{corr} are correlated, they were for simplicity assumed to be uncorrelated, which is a worst case scenario. Hence, the uncertainty contributions $u(\Delta L)$, $u(\Delta t)$ and $u(t^{corr})$ were combined in a square-root-sum way [19, Eq. (10)].

Dominating uncertainty contributions in $u(\Delta L)$ were temperature expansion and tracking- and positioning accuracy of the positioning stage. Due to insufficient knowledge about the temperature expansion of the positioning stage, and that the measurement temperature was close to the reference temperature[3] stated in the *Ealing* manual, the temperature expansion effect was treated as an uncertainty contribution rather than being corrected for. Additional contributions to $u(\Delta L)$ were identified, but found to be of insignificant importance. $u(\Delta L)$ was estimated to 5 μm at a 67 % confidence level.

The two dominating uncertainty components in $u(\Delta t)$ were phase shift due to medium convection currents and non-linearity, with respective uncertainty contributions of about 28 ns and 9 ns (67 % conf. level). The combined uncertainty in $u(\Delta t)$ was estimated to 42 ns at a 67 % confidence level. If the convection currents could be avoided, then the relative, estimated uncertainty in $u(\Delta t)$ would presumably be reduced to 37 ppm (67 % conf. level)

The correction term uncertainty, $u(t^{corr})$, is difficult to evaluate (cf. Sec. III-E). It is expected that any departure from the plane piston diffraction model will be approximately equal for t_1^{corr} and t_2^{corr} well into the farfield. As $t^{corr} = t_2^{corr} - t_1^{corr}$, these deviations should thus be nearly cancelled out. $u(t^{corr})$ was estimated to 20 ns (67 % conf. level).

The expanded measurement uncertainty was estimated as recommended in [19] to 282 ppm (95 % conf. level). The experimental uncertainty budget is outlined in Table II.

V. Discussion and Conclusions

Table II shows that the experimental uncertainty is dominated by $u(\Delta t)$, for which the major contributor are medium convection currents. By avoiding the heating from the positioning stage and having a proper temperature control, the relative uncertainty in $u(\Delta t)$ would presumably be estimated to 37 ppm (67 % conf. level), and the expanded experimental uncertainty would be about 162 ppm. Obtaining this should be

[3]The temperature for which the performance figures of the positioning stage are stated.

practically feasible, and note that no moving parts are intended in the planned VOS cell.

The uncertainty contribution from nonlinear effects is also expected to be reduced in a well designed measurement cell facility. The *GageScope* used here put some restrictions on maximum number of signal traces that could be stored for averaging, and in addition, the measurement facility used here is not optimized for suppressing noise, like a properly designed measurement cell would. The transducer driving voltage is thus expected to be reduced in a measurement cell, yielding a linear system operation

The present work is considered to be preliminary in the sense that it aims to investigate important aspects and uncertainty sources relevant for the three methods [2], [4], [6], [7]. Particularly the uncertainty in transit time difference is affected e.g. by the time detection method and system stability, and these parameters are crucial also for the other two transient methods.

If both the convection currents and nonlinear effects could be reduced as outlined above, then the uncertainy in the time detection appears to be the least significant uncertainty contribution, with a relative, estimated uncertainty of only 14 ppm. This should indicate a fair potential for using this time detection method in one of the candidate cell methods, besides that the system stability should be sufficient.

A major challenge with the other two candidate methods is the diffraction correction, which will be much greater than here, and thus needs to be more carefully modelled than in the present case. A prototype measurement cell is now being deviced to test the potential of the two candidate methods on gases like e.g. argon and nitrogen.

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Steinar Vervik developed the transducer stages and measurement chamber as part of his Dr. Scient work [12].

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