Field Experience of Ultrasonic Flow Meter Use in CO_2-Rich Applications

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1 INTRODUCTION

Ultrasonic gas flow meters have gained a wide acceptance in the field of natural gas exploration, transport, storage and distribution as well as in the process industry. There is one major segment, which could not be addressed so far with this technology – high attenuating gases like Carbon Dioxide.

On the other hand exploration of less conventional natural gas sources will lead to more diverse operating conditions and compositions for natural gas measurement. One significant change compared to traditional sources is the increased level of CO_2 in the gas. While standard applications deal with levels well below 5 mole percent, this amount may be as high as 20 mole percent, or even higher at some installations.

Re-injection of CO_2 into declining oilfields will require accurate and reliable flow measurement. Such applications contain up to 60% CO_2 and require an accuracy level comparable to custody transfer for natural gas. While the flow measurement is currently being done primarily using Δp devices, such as orifice meters, it would be a significant improvement to use ultrasonic meters with their increased functionality, larger turn-down ratio reduced maintenance, and diagnostic capabilities. Applications such as CCS (Carbon capture and storage) with CO_2 concentrations near 100% are even feasible today.

Table 1 gives a short summary of various applications and the typical amount of carbon dioxide in the gas stream.

Application type	CO_2 Content	Other components	Pressure	Accuracy requirements
Natural gas, low CO_2	<5%	CH_4, N_2, higher HC	150 to 2250 psig	Custody transfer
Natural gas, high CO_2	5% to 20%	CH_4, N_2, higher HC	150 to 2250 psig	Custody transfer
Re-injection	Up to 60%	CH_4	700 to 1480 psig	Allocation
Carbon capture & storage	Nearly 100%	no	150 to 2250 psig	Allocation

Table 1: Typical CO_2 content in different applications

Such applications are handled by orifices today, although many users would prefer to use ultrasonic meters due to there benefits of the technology. Unfortunately high carbon dioxide content usually causes serious problems for ultrasonic flow meters because its attenuation of ultrasonic signals is extremely high compared to that of other gases. That is why ultrasonic flow meter manufacturers must state the maximum amount of CO_2 allowed in the gas stream at which the meter will still function within specifications.

The main purpose of this paper is to show how today's advanced ultrasonic flow meters can handle such high amounts of CO_2. Based on a systematic study of the attenuation of ultrasound in CO_2-rich mixtures, an application model for ultrasonic flow meters was developed at the manufacturer's facility. This model created an estimation of the applicability of ultrasonic flow meters under different operating conditions and indicated a requirement for special meter design considerations. Operational limits regarding path length, pressure and frequency where determined by laboratory examinations and an optimized meter design is concluded.

Field experiments on a typical re-injection application with a CO_2 concentration near 60% showed the successful operation of an ultrasonic flow meter and are presented in this paper.

2 PHYSICAL BACKGROUND OF ULTRASONIC SIGNAL ATTENUATION

Carbon dioxide is well known for the significant attenuation it causes to ultrasonic sound waves. Table 2 shows the attenuation coefficients and the signal losses (absorption at atmospheric pressure) of methane and carbon dioxide as compared to dry air. The attenuation coefficient is defined by the Lambert-Beer-Law:

(1) $$p = p_0 \exp(-\alpha l)$$

- p - acoustic pressure at distance l
- p_0 - initial acoustic pressure at source
- α - attenuation coefficient

Operating frequency	Dry air		Methane		Carbon dioxide	
	α [m^{-1}]	dB cm^{-1}	α [m^{-1}]	dB cm^{-1}	α [m^{-1}]	dB cm^{-1}
80 kHz	0,09	0	5,3	-10,4	33,5	-25,3
135 kHz	0,26	0	9,9	-13,5	39,9	-31
208 kHz	0,62	0	12,3	-15,2	42,6	-33,3

Table 2: Comparison of attenuation coefficients gases at typical operational USM frequencies and loss of acoustic pressure per length due to attenuation compared to dry air

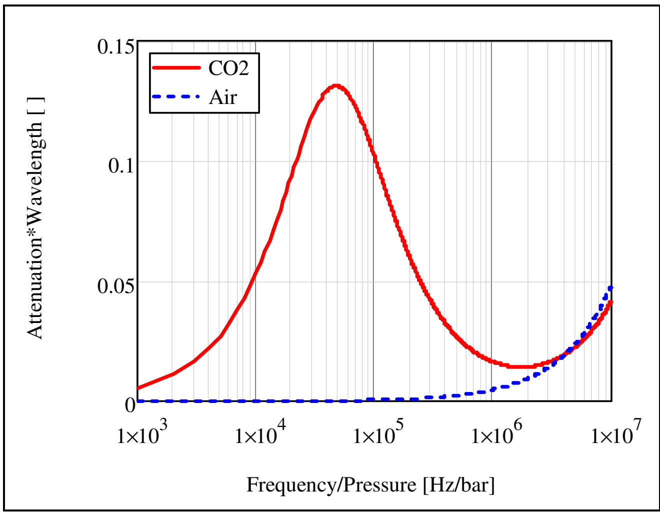
These numbers show that carbon dioxide is one of the most difficult gases to measure with ultrasonic gas flow meters. To develop the successful application of USMs in CO_2-rich atmospheres, the basics behind the attenuation and all other influences on performance must be understood. The acoustic absorption by gases can be divided into two main contributions:

- classical absorption
- thermal relaxation phenomena.

The classical absorption is based on the viscosity and the thermal conductivity of the gas. This attenuation increases with the square of the frequency. Since the difference between various gases is quite small, this classical absorption can not reflect the enormous differences in the behaviour between carbon dioxide and other gases.

Attenuation based on thermal relaxation processes reflects the fact that energy is exchanged between molecular vibrations and translations. A maximum of normalised attenuation can be found depending on frequency (see Figure1a). The frequency position and the strength of this maximum attenuation are typical for the gas or gas mixture to be measured. If this maximum is located within the range of the operating frequency of ultrasonic transducers, there may be a strong influence on the performance of the ultrasonic flow meter.

Carbon dioxide is one of the model gases used to study this type of attenuation, and therefore a lot of literature can be found to describe its behaviour. From that data, a theoretical model of the attenuation in CO_2 can be developed. Figure 1b shows the attenuation coefficient and the normalized attenuation coefficient for CO_2 at room temperature.



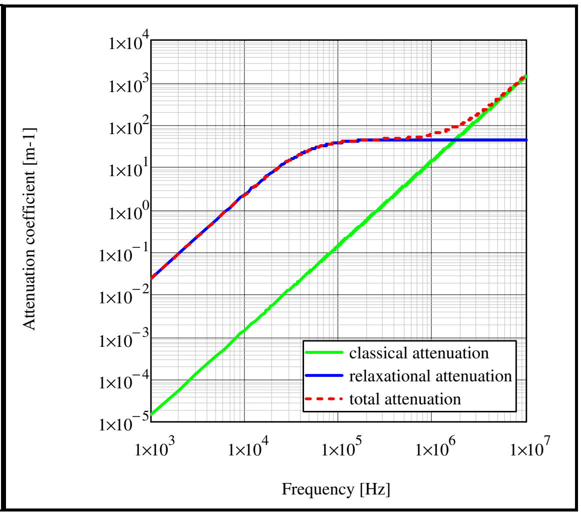


Figure 1a: Normalised attenuation coefficient for CO2

Figure 1b: Attenuation coefficient for CO2

The relaxation frequency of CO_2 can be found at about 50 kHz and has an extremely high attenuation coefficient compared to other gases. The thermal relaxation dominates the attenuation in the kHz-range, and this leads to the difficulties exhibited in the application of ultrasonic flow meters in carbon dioxide. Classical absorption will contribute significantly at frequencies above 1 MHz.

While pure gases are quite well understood from a theoretical point of view, the influence of additional gas species in a mixture is rather complicated to describe. Different relaxation interactions between the various molecules will lead to an effective relaxation frequency different from that of the pure gas, and will influence the relaxation strength. Unfortunately, this influence depends on the kind of gas and the concentration in the mixture.

So far, only attenuation has been addressed. In addition, two other affects need to be taken into account. First, gas composition and pressure will change the density of the gas. This leads to a change of the acoustic coupling efficiency of the ultrasonic wave from the transducer into the gas. Higher pressure will result in better coupling and therefor lead to higher signal strength.

Second, there is an influence of the actual speed of sound on the beam characteristic transmitted from the transducer. The beam width characteristic is dependent on the speed of sound. Reduced speed of sound, compared to dry air, will sharpen the beam and concentrate more sound energy into a smaller area. Affects of temperature on the speed of sound, or dispersion from relaxation processes, have to be considered here also.

Both affects can be described easily and are incorporated into an application model.

3 GENERAL CONCLUSIONS FOR ULTRASONIC METER DESIGN FOR CO_2 RICH STREAMS

Looking at formula (1) it can be seen that some general conclusions can be made with respect to meter design. The values, which can be influenced to generate sufficient signal quality at the receiver, are:

- Initial acoustic pressure coupled into the gas
- Transducer frequency
- Measuring path length

First, the acoustic pressure can be increased by a higher driving voltage at the transducer. Unfortunately this voltage might be limited by explosion proof design requirements of the meter installation, or by the breakdown voltage of the piezoceramics. As such this option is only a possibility in special cases.

Second, the design of the transducer itself can raise the acoustic sound pressure level (SPL). This is inherent in modern design principle compared with traditional design utilizing an epoxy matching layer.

Nevertheless, a matching layer could further increase the acoustic coupling. Such a layer is made of epoxy resins using hollow glass spheres, and its thickness is dependent on the working frequency of the ultrasonic sensor. Unfortunately this matching layer could exhibit some drawbacks like a pressure or temperature dependency, and also lowers the SPL. Therefore, the acoustic matching layer should be left out if it is possible to achieve sufficient vibration amplitudes at the sound emitting surface.

A stacked piezoelectric transducer in the form of a resonance converter is a viable alternative. A metallic spring-mass-system is used to increase the amplitude at resonance (see Figure 2a). By utilizing numerical optimization of mechanical and electrical parameters, it is possible to produce sensors which exhibit:

- sufficient bandwidth for short signals with a very high amplitude (SPL)
- a maximum acoustic efficiency (efficiency converting electrical energy into sound energy).

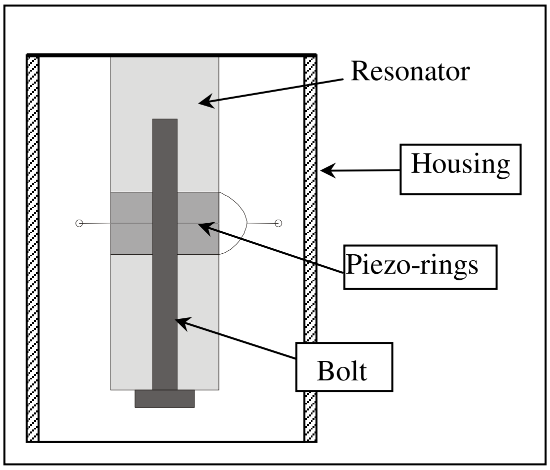


Figure 2a: Schematic diagram

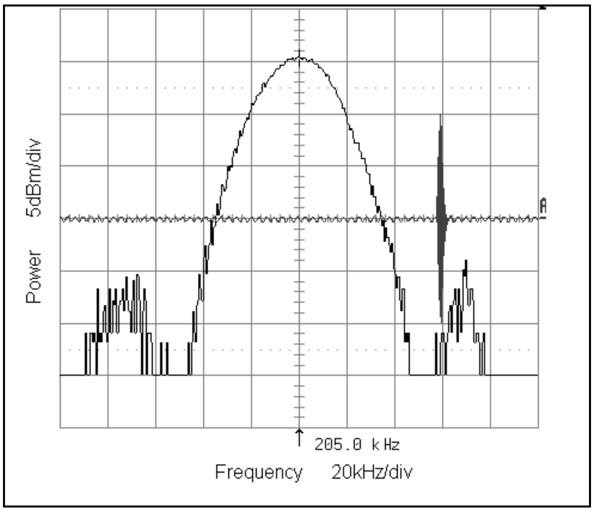


Figure 2b: Acoustic spectrum of the sound signal

Figure 2: Stacked ultrasonic transducer

This sensor concept is characterized by pure tone resonance mode and a well-defined working range (see Figure 2b). There are several advantages:

- the electric energy is efficiently transformed into acoustic energy,
- the transducer is hermetically sealed and has a full metal housing,
- the bandwidth allows relatively short pulse signals.

A set of transducers with different operating frequencies, but identical installation dimensions, are presented in Figure 3.

Figure 3: Ultrasonic transducer with different operating frequencies (80 kHz, 135 kHz, 208 kHz)

The absorption coefficient of the gas to be measured must be considered by having ultrasonic transducers with various operating frequencies available to be installed into the same meter body. Based on Figure 1a, it is obvious the optimum operating frequency pressure ratio should be below 50 kHz/bar for CO_2. That means operating frequencies of less than 50 kHz at atmospheric pressure. Unfortunately, such transducers would be relatively large and not suitable for typical pipeline sizes less than 16 inch.

If a short path length is considered as a requirement for measuring high attenuating gases, only direct path layouts should be used. The influence of doubling the path length is shown in Figure 4 which plots signal strength as a function of path length. Assuming a direct path length of 6 inches (150 mm), it can be seen that the measured signal strength is above the noise level for this path length. If, however, the path length is doubled to 12 inches (300 mm,) the signal strength is below the noise level.

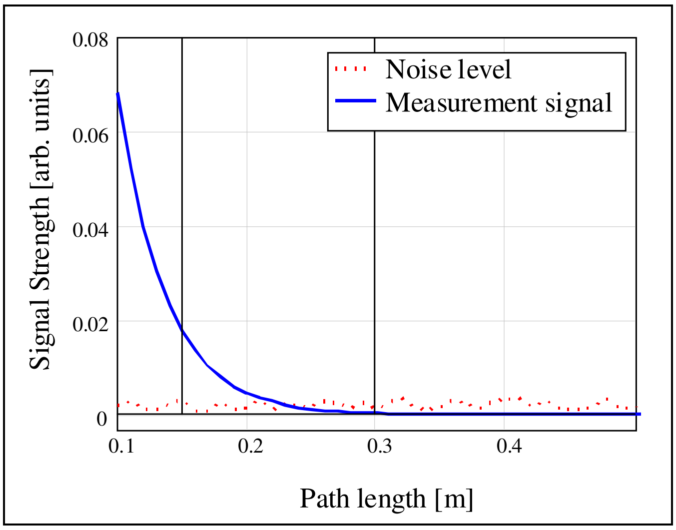


Figure 4: Influence of path length on signal strength

Based on the knowledge of the transducer design and meter performance parameters, as well as the attenuation characteristics of the gas or gas mixture under consideration, an application model can be set up. Such a model will allow prediction of a maximum measuring path length for operation of the meter within acceptable specifications and accuracy.

4 LABORATORY VERIFICATION OF THE ATTENUATION CHARACTERISTICS OF CO_2-RICH GASES

The primary consideration in the application model is the attenuation characteristics of the gas or gas mixture. While these values are known for some pure gases, the parameters can not be found for special mixtures. To extend the knowledge on this topic, a special measurement system was developed. Measurements were carried out in a special pressure chamber equipped with a moveable mount (see Figures 5 and 6) equipped with transducers of different operating frequencies.

The tested transducers were 80 kHz, 135 kHz and 208 kHz standard probes as used in a FLOWSIC600 ultrasonic gas flow meter. The distance between the transducers can be varied between 0 and 10.2 inches (260 mm) from outside of the chamber. The gas within the test chamber can be mixed for a maximum of three different gas components. The gas composition is defined by mixing rules based on partial pressures corrected for real gas affects. Pressure and temperature are measured during the tests. While pressure is a significant parameter for the measurement target, temperature is measured for check purposes (stability of the gas atmosphere) only.

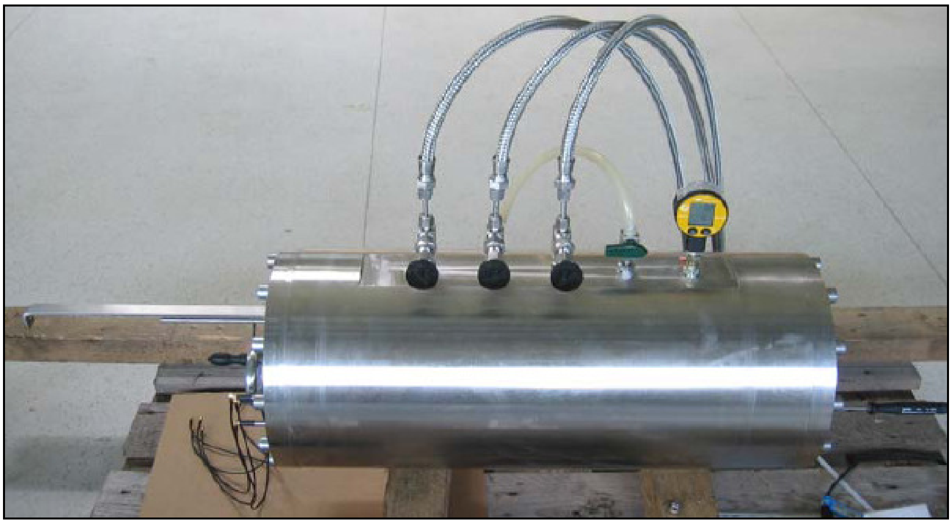


Figure 5: High pressure chamber – outside view

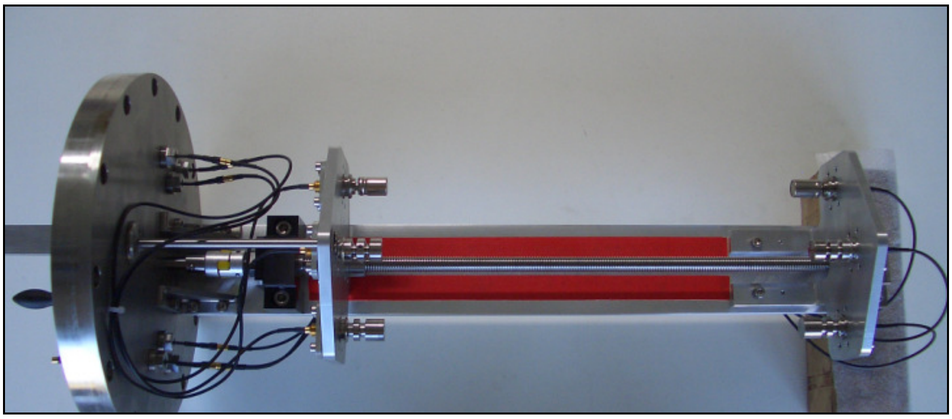


Figure 6: High pressure chamber – inside view

Various gas mixtures were evaluated using this chamber. First, pure CO_2 was measured to confirm the theory. Afterwards different mixtures of CO_2, CH_4 and N_2 where used in the measurement tests. Table 3 gives the nominal and actual composition of the mixtures. Mixture 2 is a typical re-injection gas and mixture 3 simulates a natural gas with increased CO_2 content.

Mixture	**CO_2**		**CH_4**		**N_2**		**Balance**	
	Nominal	Actual	Nominal	Actual	Nominal	Actual	Nominal	Actual
1	100	99.9					0	0.1
2	60	59.4	40	40.3			0	0.3
3	12.5	13.1	85	84.8	2.5	2	0	0.1

Table 3: Nominal and actual composition of the mixtures

The attenuation coefficients measured for pure CO_2 are plotted and compared with theoretical values shown in Figure 7. There was very good correlation between the theory and the actual measurements.

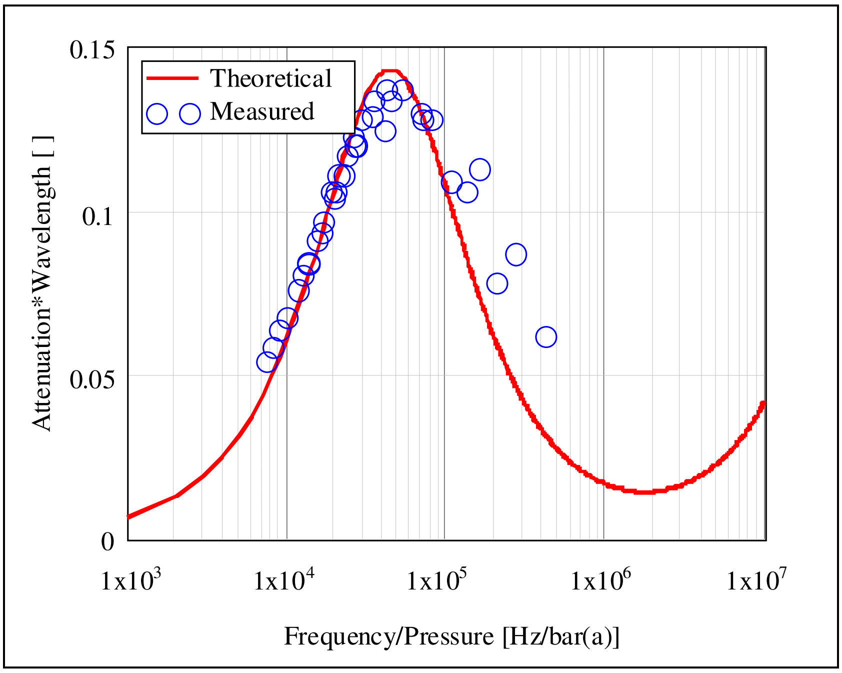


Figure 7: Measurements and theory for normalised attenuation coefficient in Carbon Dioxide

The measured attenuation coefficients (shown as blue circles in Figure 7) were used to establish a model of the frequency dependent attenuation as an input for the application model.

5 APPLICATION MODEL FOR AN ULTRASONIC GAS FLOW METER

The application model should result in the ability to predict the maximum working path length depending on operating conditions (e.g. pressure, temperature, gas composition), and meter parameters (e.g. operating frequency) based on easy to measure meter characteristics. Besides attenuation, the affect of pressure on the acoustic coupling and speed of sound related acoustic beam width of the transducer, have to be considered. Gas parameters, such as viscosity and thermal conductivity, which are necessary for calculation, can be found in the literature [1] or can be calculated for gas mixtures [2, 3].

The receiver sensitivity parameter AGC (automatic gain control) of an ultrasonic meter is a measurement value inversely proportional to the acoustic pressure at the receiving transducer, and therefore directly linked to the signal attenuation on the acoustic path. This parameter is meter design specific, due to different path layouts, transducers and electronics design used by the various meter manufacturers. Therefore, each manufacturer will have different pre-defined values to estimate the quality of the measurement.

In this test, the FLOWSIC600 by SICK (Figure 8) was evaluated. This meter uses direct path layout, advanced transducer technology with no epoxy matching layers, low noise receiver electronics, and appropriate signal processing. Acceptable operation of the meter is ensured up to an AGC level of 93 dB.

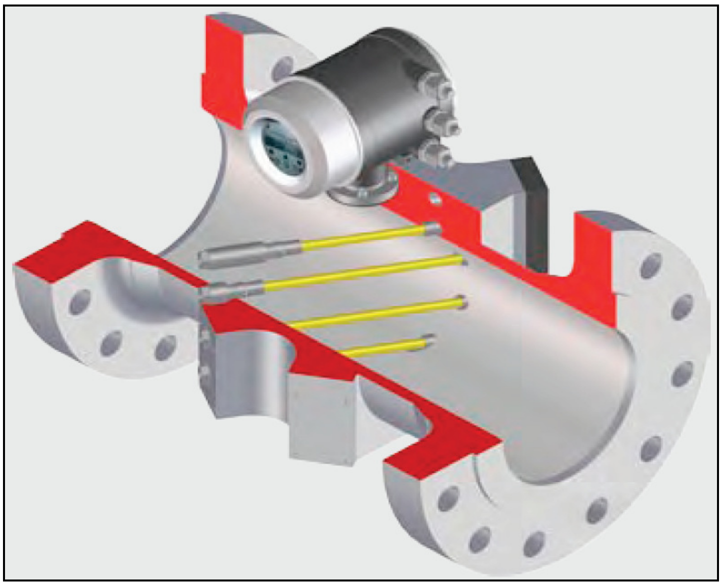


Figure 8: Path Layout for the 4 Path Meter

The model reference point for the acoustic signal strength is the behaviour in ambient air. Driving voltage is limited in design to allow for operation in an explosion proof (hazardous gas) installation. Attenuation, speed of sound and, gas pressure is well known. Transducer characteristics, e.g. AGC levels for the different path lengths, are proven by standard procedures in each meter. The pressure and speed of sound for the gas in the specific application is used to calculate changes in sound pressure due to the operating conditions compared to ambient air.

Using the measured frequency dependent attenuation model, the changes in sound pressure due to different attenuation characteristics can be modelled. Finally a maximum path length can be determined for the specific application. Figure 9 gives an example for the gas mixture 2, e.g. the re-injection type gas shown in Table 3. The maximum path length is plotted against the absolute pressure of the application.

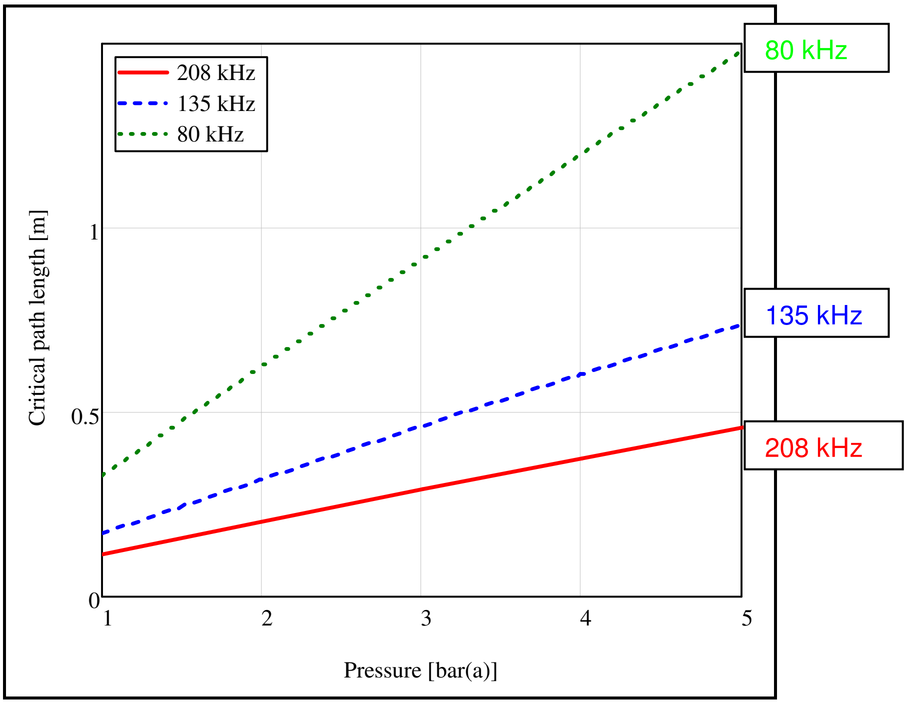


Figure 9: Critical length vs. Absolute Pressure in gas mixture 2 (60%CO_2+40%CH_4)

For a specific ultrasonic flow meter design, the critical path length can be translated into the maximum nominal pipe size for each transducer frequency. For each operating pressure a maximum nominal pipe size can then be calculated. Figure 10 shows correlation for a 4-path FLOWSIC600 ultrasonic gas flow meter. As an example, for 30 psig (2 bar(g)) operating pressure, and 80 kHz transducer frequency, a maximum nominal pipe size of 32-inch should result in acceptable meter operation and performance.

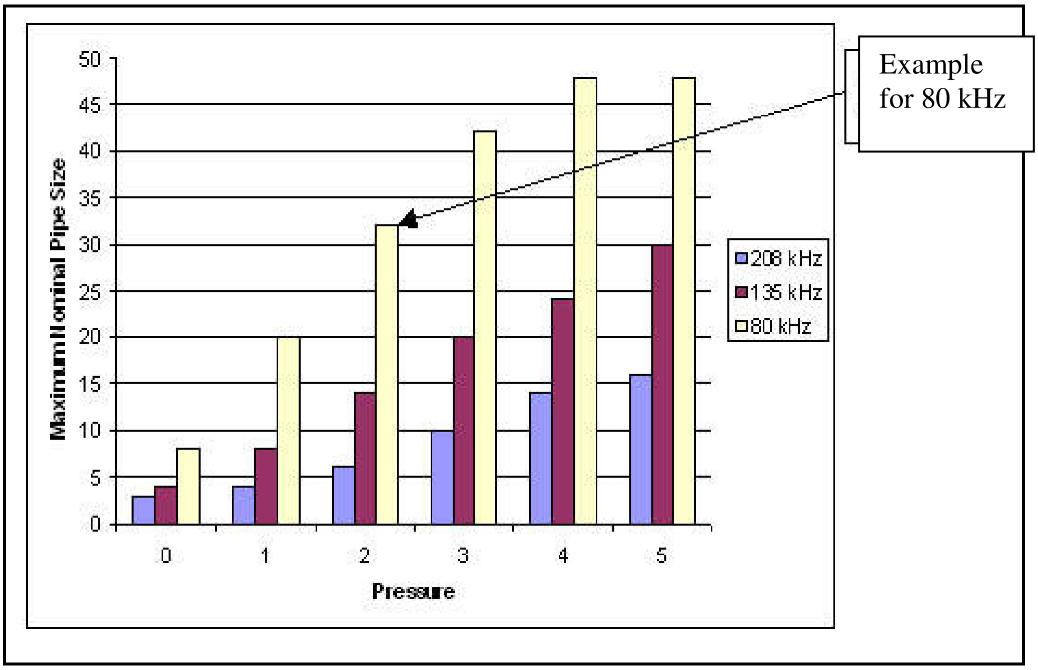


Figure 10: Application limits for a 4path meter in 60%CO_2, 40%CH_4 (mixture 2) type application

The model can be used to evaluate an application on a systematic basis with regard to the maximum possible meter size at the given application's operating conditions. For applications which do not fall within this criteria, potential solutions such as reduced path lengths by using protruding transducers, may need to be considered.

6 FIELD EXPERIENCE

Shown here is one of the first test installations, where the theory for using an ultrasonic meter for high CO_2 applications was demonstrated. This is a CO_2-reinjection project. The application utilizes a 4-path (8 inch) meter, operated at 928 psig (64 barg), 95 °F (35°C), and with a typical gas composition as shown in Table 4.

CO_2	CH_4	C_2H_6	C_3H_8	N_2
62.1	37	0.3	0.1	0.5

Table 4: Typical gas composition

The main goal of the installation was to demonstrate how an ultrasonic flow meter can handle high amounts of CO_2 and how the model can predict the performance of the meter in the application.

To prove the metering concept and the model, a standard 2plex 4+1 meter [4] was installed. This meter consists of a traditional 4-path custody transfer meter combined with an independent single path check meter (Figure 11). The 2plex meter is typically used for custody transfer applications.

It utilizes the traditional Westinghouse 4-path design, but incorporates a second, single path, center-line meter in the same body. Changes in operating conditions (e. g. a blocked flow conditioner or pipeline contamination) can be detected by the single path because it is very sensitive to profile changes. If this occurs, there will be a difference in reported volumes. Typically the 4 path meter continues to operate with virtually no impact on accuracy.

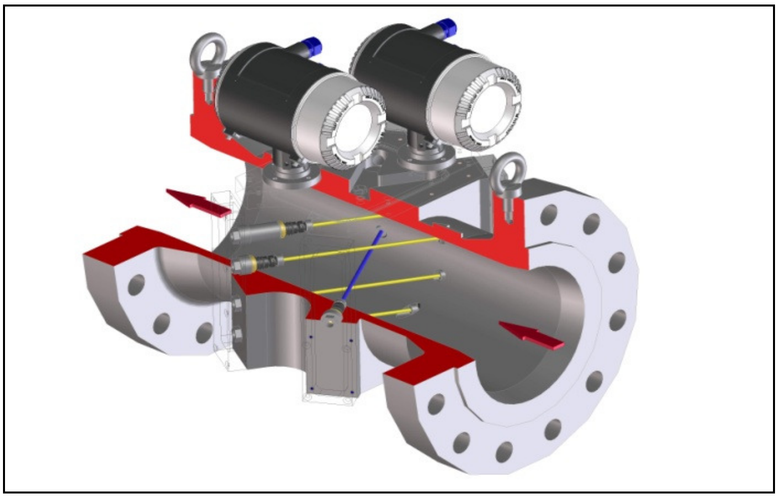


Figure 11: 2plex 4+1 Meter Design

For this special test case, the check system (single path) was equipped with a 135 kHz transducer pair, while all other paths of the main system (custody) operated with 208 kHz transducers. The data collected and presented in Section 4 of this paper predicted both frequencies should be suitable. AGC levels of about 25 dB for the 135 kHz transducers and 28 dB (outer paths) / 35db (inner paths) for the 208 kHz transducers where expected.

The meter was delivered without any high pressure calibration and installed as shown in the field (Figure 12) without a flow conditioner. The meter's flowrate was then compared with that of an existing orifice meter located upstream.

Figure 12: Test installation set up

Figure 13 shows a screen capture of the waveform signals detected on the 135 kHz system and Figure 14 the waveforms on the 208 kHz system outer path. Both systems run very stable and show signals with very acceptable SNR and AGC levels.

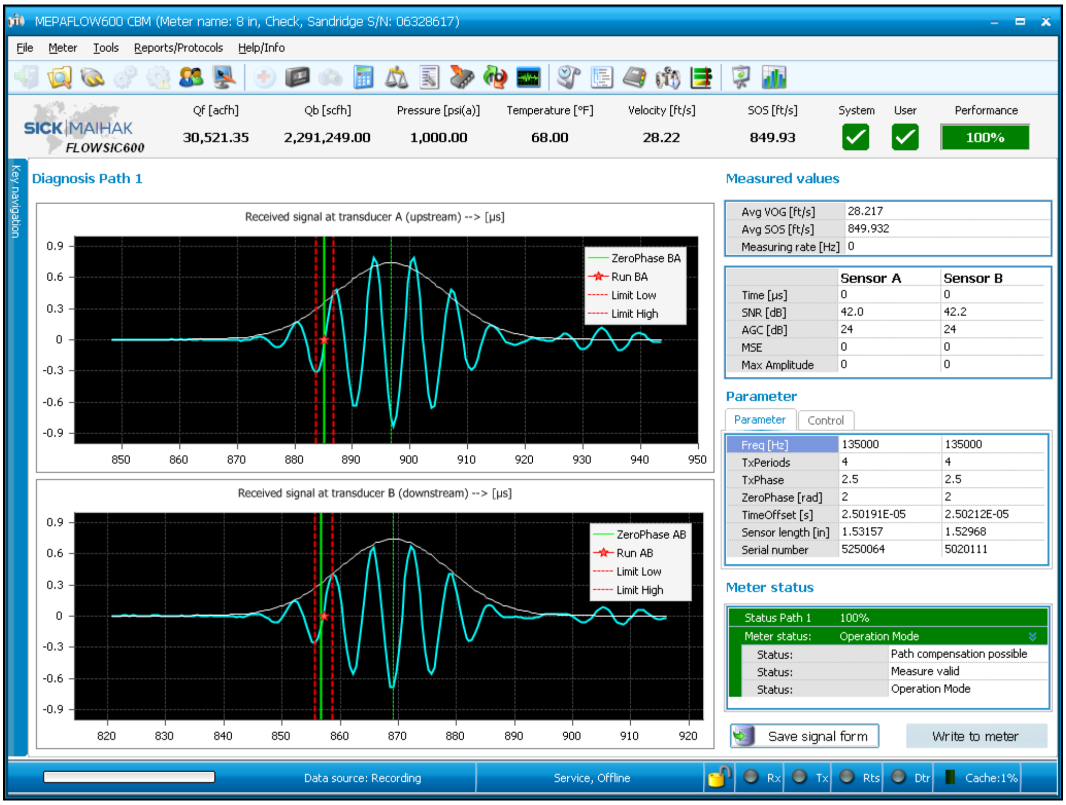


Figure 13: Waveforms for the 135 kHz single path meter

Figure 13 shows the average AGC of 24 dB (135 kHz) and Figure 14 shows an AGC of 28 dB/34 dB for the 208 kHz. Both are very close to the expected values. While both systems show stable operation, the signal of the 135 kHz transducer is 1.22 times higher compared to the inner path for the 208 kHz.

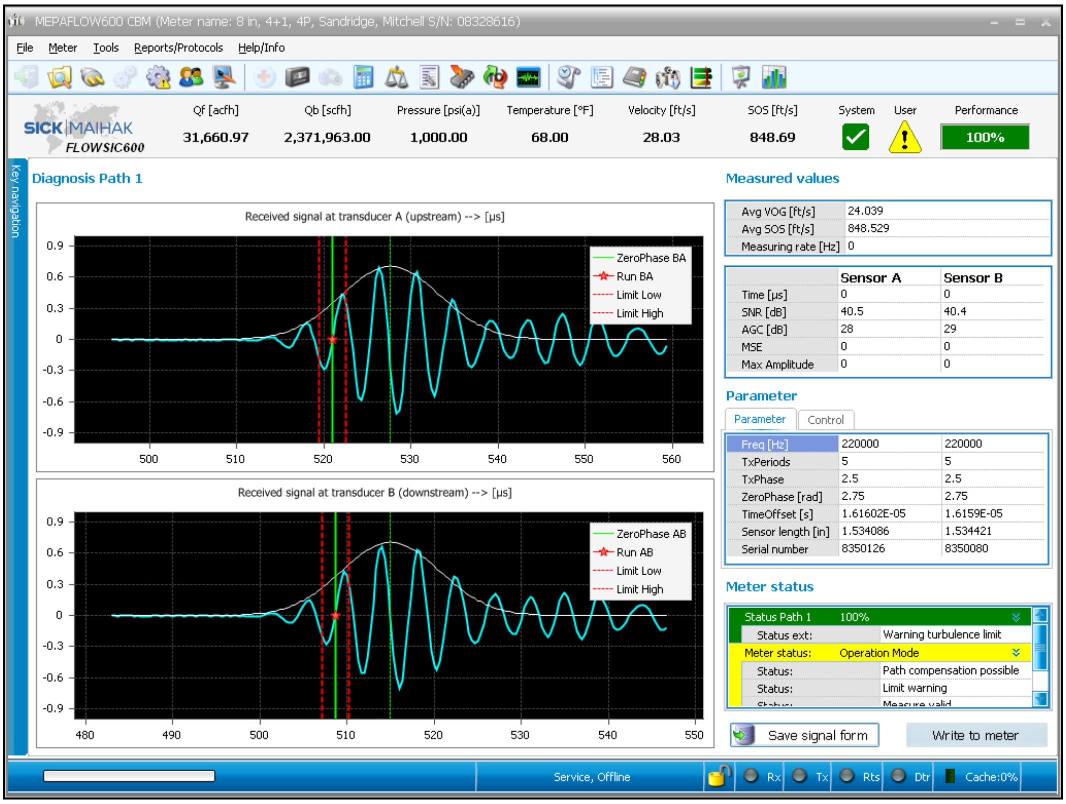


Figure 14: Waveforms for Path 1 (outer) for the 208 kHz 4 path meter

In this example both transducer frequencies worked very well. Depending upon the application (pressure, temperature and CO_2 percentage) the standard 208 kHz transducer frequency would be suitable for most typical applications.

Figure 15 shows a screen capture of all of the meter's diagnostics.

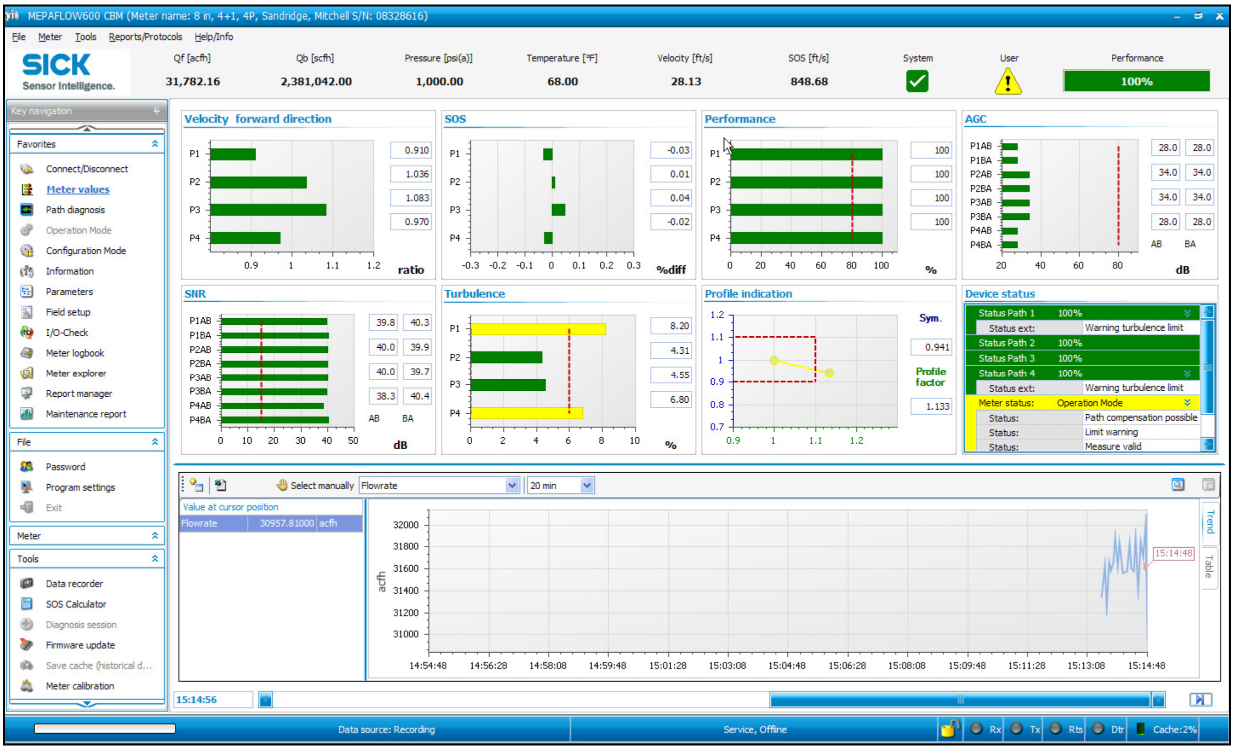


Figure 15: Diagnosis session 4 path meter

The Performance chart in Figure 15 shows 100% signal availability. The SNR and AGC levels are in a stable and normal range of operation. Speed of sound (SOS) differences between paths show no significant deviations. The Profile indication and Velocity ratio charts indicate a slightly asymmetric behaviour probably due to some residual swirl in the piping. The increased Turbulence value (above the normal) on the outer paths is most likely due to the orifice and the residual swirl upstream of the USM.

The comparison of the ultrasonic meter flow rate with that of the orifice meter (Figures 16 and 17) shows an excellent correlation between the two in spite of the fact that the ultrasonic meter was not even flow calibrated. The comparison between the orifice and the ultrasonic meter was within 0.2% during the test period (several weeks). This agreement was considered excellent.

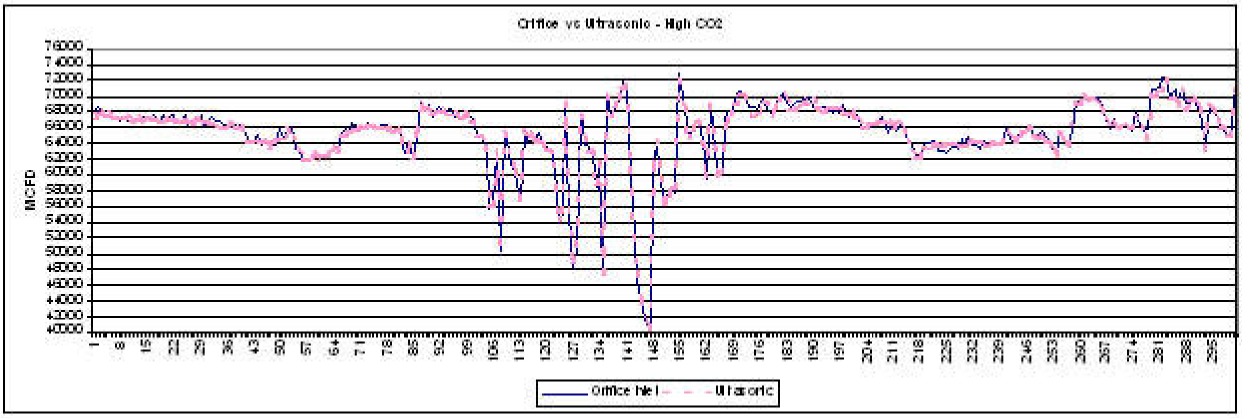


Figure 16: 5 day daily flow rate comparison of ultrasonic flow meter with orifice meter

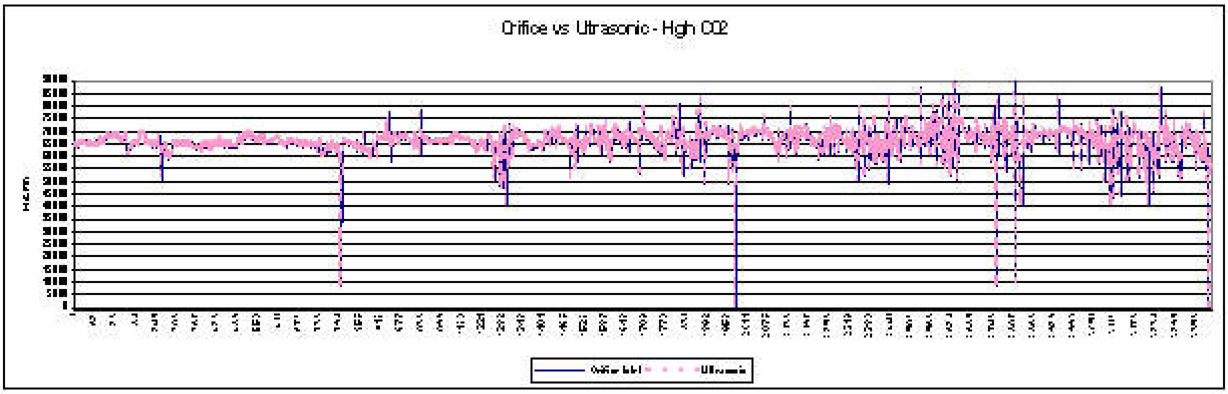


Figure 17: One month daily flow rate comparison of ultrasonic flow meter with orifice meter

7 CONCLUSION

Modern ultrasonic gas flow meters are capable of handling a broad range of metering applications with high CO_2 levels, and today even measurement of pure CO_2 is possible. Advanced ultrasonic transducer design, with high efficient acoustic energy coupling into the gas, are the basis for this capability. Choosing transducer frequencies suitable for the application and specific operating conditions will lead to successful installations. Since the received signal strength in high concentrations of CO_2 is more dependent on path length than in other gases, the use of reflection type path layout, or any other extension of the path length, is not recommended.

To ensure accurate operation, the meter design and specifics related to the application, will need to be thoroughly evaluated prior to selecting the meter. Knowledge of gas composition, pressure, temperature, and meter size (based upon flow rate requirements), will be the basis for an application model that can predict the performance of the meter in the field. The results predicted by the model will help to optimize the meter parameters and will give recommendations for the improvement of the installation design.

This paper confirms that the transducer's performance (AGC gain) in the field can be compared to that predicted from the laboratory test conditions. This correlation allows predicting other applications much more reliably.

With the added diagnostic capabilities of the ultrasonic flow meter, even difficult applications like custody transfer measurement of CO_2-rich natural gas, or CO_2 re-injection installations, are possible.

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