



25<sup>th</sup> ABCM International Congress of Mechanical Engineering  
October 20-25, 2019, Uberlândia, MG, Brazil

**COB-2019-1838**

## **ESTABLISHMENT OF A REFERENCE STATE FOR EVALUATION OF ATTENUATING EFFECTS IN GAS FLOW MEASUREMENT BY ULTRASONIC TECHNOLOGY**

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**Abstract.** *It is well known in literature that carbon dioxide strongly attenuates waves generated by ultrasonic gas flowmeters. This study proposes an experimental evaluation to establish a reference state, in order to analyze such attenuating effects of high concentration of CO<sub>2</sub>. The aim is to evaluate the behavior, as well as the performance of flowmeter devices submitted to several mixtures of atmospheric air and carbon dioxide. Results show that carbon dioxide alters significantly the measured speed of sound and, concomitantly, the flow measurement performance. In order to surpass such effects, transducer approximation technique shows to be a viable alternative.*

**Keywords:** *Flow measurement, Attenuation, Sound speed, Ultrasonic technology, Carbon dioxide.*

### **1. INTRODUCTION**

Flare gas systems are applied to vent and burn off hydrocarbons gases under routine gas purge and emergency conditions, such as an unexpected compressor shutdown. Ultrasonic flowmeters are often a viable technology choice, due to the typical characteristics of the flow in off-shore gas flare tubing, such as low pressure (1atm approximately.), high rangeability (2000:1, approximately), presence of impurities in gas stream, indication for no-obstructive flow measurement process.

In this way, ultrasonic flow meters (USFM) presents some advantages such as: i) operation in a wide flow range (typically more than 50:1), ii) tolerate wet gas, iii) no moving parts and iv) non-intrusive installation). It is the technology most used for flare gas application, counting thousands of units installed worldwide in process plants and refineries (Matson, Sui, & Nguyen, 2010).

On the other hand, carbon dioxide gas (CO<sub>2</sub>) is the component in natural gas that most affects the USFM performance, by its attenuating effects (Helden, Ehrlich, Dietz, & Tan, 2009). CO<sub>2</sub> concentration in flare gas systems may reach about 95% (Matson, Sui, & Nguyen, 2010).

Due to the strategic role of natural gas production, flow measurement performance is governed by environmental and legal laws. In Brazil, Resolução Conjunta ANP / INMETRO No. 1 (2013) governs the measurement of hydrocarbon flow. It establishes conditions and procedures for the operational and fiscal measurement under which flow measurement systems will be installed, in addition to defining the calibration frequency and uncertainty class. Due to the high capital values, the taxes involved, as well as the environmental issues involved in such processes, have increased the search for improvements in metering systems, for example in flare gas application.

According to AGA Report No. 9 (2007), high concentration of CO<sub>2</sub> in gas can cause high signal attenuation in ultrasonic flow measurement.

So, the technological challenge is to define the performance of ultrasonic flowmeters of diverse configurations of hardware and software, in order to guide the selection and acquisition processes of USFM.

High variation in flow velocity, typical of gas flaring operations, also alters ultrasonic signal performance (Matson, Sui, & Nguyen, 2010). However, before assessing the velocity profile and CO<sub>2</sub> absorption on the performance of the ultrasonic flowmeter, it is essential to establish a reference state for further analysis. This reference state, mounted in a dry calibration arrangement, is applied in the zero flow condition.

Regarding the various attenuating effects that occur in the ultrasonic flow measurement process, this work aims to characterize the attenuation of the ultrasonic pulse due to the chemical composition of the gas in flue gas operating flow meters. Sound velocity sensitivity and transducer approximation in various air and carbon dioxide mixtures are also evaluated.

In this context, this work proposes and tests a reference state, easy to reproduce worldwide, for use in the field.

## 2. PROBLEM DESCRIPTION

### 2.1 ULTRASONIC FLOW METER FUNDAMENTALS

The flow measurement process by ultrasonic technology is based on the transit time measurement of the ultrasonic pulses, which are transmitted and received by the ultrasonic transducers. Figure 1 shows the basic USFM installation, mounted in a zero flow condition (dry calibration arrangement).

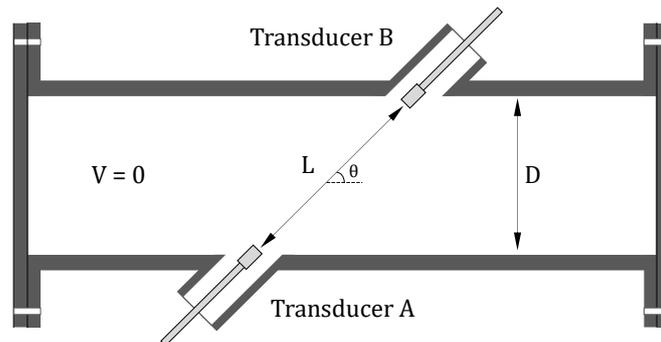


Figure 1 - Schematic illustration of a single path in ultrasonic transit time flow meter in a dry-calibration arrangement

The mathematical expression involving the parameters of interest in the ultrasonic flow meter technology by transit time, results in a linear algebraic system, composed by two equations and two unknown variables, that considers pipe geometric parameters ( $D$  and  $\theta$ ) and the transit time of ultrasonic pulses ( $t_{AB}$  and  $t_{BA}$ ). The solution of such equation leads to two important expressions on ultrasonic flow metering: measured sound speed  $c$ , given by Equation [1], and flow velocity  $v$ , calculated by Equation [2].

$$c = \frac{D}{2 \cdot \sin \theta} \left( \frac{1}{t_{AB}} + \frac{1}{t_{BA}} \right) \quad [1]$$

$$v = \frac{D}{\sin(2\theta)} \left( \frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) \quad [2]$$

Where  $t_{AB}$  and  $t_{BA}$  are measured transit time downstream and upstream, respectively.  $D$  is pipe diameter,  $\theta$  is the acute angle between the ultrasonic path and the axis of pipe section.  $L$  is the acoustic path length.

On the other hand, the speed of sound (SOS) is a thermodynamic property. Therefore, it is a function of temperature, pressure and chemical composition and independent of flow velocity measurement. For this reason, and observing Eq. 1 and Eq. 2, experimental SOS readings can be monitored in USFM applications and used as a diagnostic performance parameter of USFM as compared to thermodynamic SOS. This operating performance of the flowmeter is reliable as the measured SOS depends on the same flow parameters.

### 2.2 ATTENUATION OF ULTRASONIC WAVES IN GAS

The absorption of acoustic signal in ultrasonic frequency by  $\text{CO}_2$  has been studied since last century. Abello (1928) measured the intensity of acoustic pressure it exerted against a torsion vane and found that there was a nearly logarithmic decrease in the intensity with an increase in  $\text{CO}_2$  concentration. Curtis (1934) applied a similar experiment to measure absorption coefficients in ultrasonic frequency range in air and carbon dioxide mixtures and found an absorption coefficient not described by classical absorption theory. Kittel (1947) made a literature review in absorption modeling in gas media with thermal relaxation effects.

Dain & Lueptow (2001) described a model that predicts the attenuation from vibrational relaxation in gas mixtures. In order to validate this model, Ejakov, Phillips, Dain, Lueptow, & Visser (2003) measured the attenuation coefficient using a pulse technique for several gases, including carbon dioxide/nitrogen.

Despite industrial requirement and relevance, there are just few studies about  $\text{CO}_2$  attenuating effects applied to current engineering challenges, like on flare gas transit time ultrasonic flow metering. Helden et al. (2009) and Vermeulen, Drenthen, Hollander, Lanoux, & Groningen (2013) evaluated some transducers frequencies to the absorption promoted

by carbon dioxide, inside a pressure vessel, in mixtures of N<sub>2</sub>+CO<sub>2</sub>. Barros & Ramos (2016) examined a 100 kHz transducer in wind tunnel experiments and proposed a methodology to manage with CO<sub>2</sub> attenuation effects, based on a fault count technique.

All authors cited argue that the approximation of transducers improves USFM readings, as they increase signal strength. Therefore, it is an alternative for high CO<sub>2</sub> applications. With current diagnostic capabilities, USFM can be used in CO<sub>2</sub>-rich applications (Helden et al., 2009).

Due to wave propagation, the harmonic acoustic pressure  $p$  decreases proportional to the distance  $L$ , from the emitter to receptor, according to exponential relation, Equation [3].

$$p = p_0 \cdot e^{-\alpha L} \quad [3]$$

Where  $p_0$  is the amplitude of the acoustic pressure at the emitter and  $\alpha$  is the attenuation coefficient.

Attenuation of acoustic pressure results from energy transfer mechanisms of the acoustic wave into other forms of energy. It can be understood as ultrasonic wave weakening caused by absorption and diffusion processes (Gudra, 2008).

In absence of any external perturbation, the internal degrees of freedom are in equilibrium, and the attenuation is only due to classical effects (viscosity, heat conduction, diffusion). Energy exchange facility between the external energy and the rotational-translational energy of molecules by means of thermal equilibrium adjustment is related to ultrasonic wave frequency (Rogers, 1934), a phenomenon known as thermal relaxation. When there is an external perturbation, like emission of ultrasonic wave, thermal relaxation losses arise from the incomplete establishment of thermal equilibrium in a system (Kittel, 1947).

The voltage produced in the receiving transducer, by the sound wave, is proportional to the acoustic pressure (Ejakov et al., 2003). Thus, the attenuation can be found by the slope of the logarithm of the voltage amplitude plotted as function of path length of the transducers, as described by some authors (Ejakov et al., 2003; Petculescu, Hall, Fraenzle, Phillips, & Lueptow, 2006). In addition, it is necessary to correct diffraction effects of the sound wave by Pinkerton (1949) relation, given by Equation [4].

$$A(z) = A_0 e^{-\alpha x} \left\{ \sin \left[ \frac{1}{2} k \left( \{L^2 + R^2\}^{1/2} - L \right) \right] \right\} \quad [4]$$

Where  $A_0$  is the amplitude at the emitter,  $k$  the wave number ( $k = 2\pi/\lambda$ ).

The attenuation coefficient is calculated by Equation [5].

$$\alpha = \alpha_c + \alpha_{rm} \quad [5]$$

Where  $\alpha_c$  [1/m] is the classic attenuation coefficient that arises from transport phenomena (viscosity, heat conduction and diffusion). The coefficient  $\alpha_{rm}$  [1/m] is called thermal relaxation attenuation, is due to molecular internal degrees of freedom, a phenomenon called relaxation process.

Classic attenuation is well understood phenomenon and can be predicted. The classic attenuation coefficient is calculated by Stokes-Kirchoff equation (Kittel, 1947), Equation[6].

$$\alpha_c = \frac{\omega^2}{2\rho_0 c^3} \left[ \frac{4}{3} \mu + (\gamma - 1) \cdot \frac{k}{c_p} \right] \quad [6]$$

Where  $\omega$  [rad/s] is angular frequency,  $\rho_0$  [kg/m<sup>3</sup>] gas density,  $c$  [m/s] sound speed,  $\mu$  [Pa.s] kinematic viscosity,  $\gamma$  heat capacity factor,  $\kappa$  [W/m<sup>2</sup>.K] thermal conductivity and  $c_p$  [J/kg.K] specific heat at constant pressure.

A good way to emphasize the relaxation effects on acoustic attenuation is to represent normalized attenuation  $\alpha\lambda$ , where  $\lambda$  [m] is the wavelength. The thermal relaxation attenuation coefficient  $\alpha_{rm}$  is estimated by empirical model, Equation [7] (Vermeulen et al., 2013).

$$\alpha_{rm} \lambda = 2 \cdot [\alpha\lambda]_{max} \cdot \frac{\frac{f}{f_{rm}}}{1 - \left( \frac{f}{f_{rm}} \right)^2} \quad [7]$$

Where  $f$  [Hz] is the transducer nominal operational frequency,  $f_{rm}$  [Hz] the maximum thermal relaxation frequency of attenuation and  $\alpha\lambda_{max}$  is the maximum attenuation coefficient per wavelength.

### 3. METHODOLOGY

#### 3.1 MODEL

The measurement model assumed here is based in Matson et. al (2010) model, as shown in Figure 2. Taking advantage of piezoelectric properties, voltage at  $V_A$  level is applied to Transducer A, which produces acoustic waves at ultrasonic frequency in a gaseous medium (mixtures of  $CO_2$  and air in the present case). Transducer B receives those ultrasonic waves, generating voltage at  $V_B$  level. Both transducers operate alternating as transmitter and receiver of ultrasonic waves.

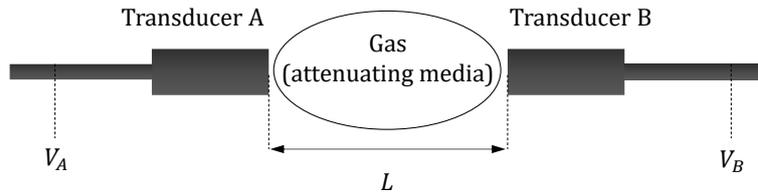


Figure 2 - Measurement model

An oscilloscope is connected to transducers connections in USFM. So, both emitted and received signals can be recorded.

In this model, the ratio between signal amplitude received and emitted relation is given by Equation [8].

$$\frac{A}{A_0} \propto e^{-\alpha L} \quad [8]$$

For current application, transducer separation distance and gas mixture composition are changed.

#### 3.2 EXPERIMENTAL DESCRIPTION

The experimental set up is shown in Figure 3.

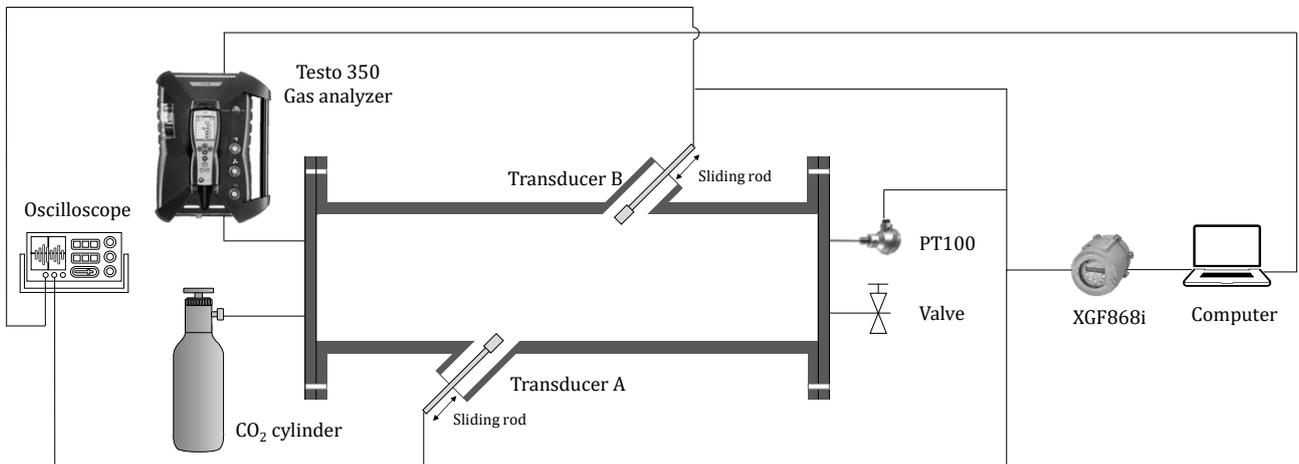


Figure 3 - Experimental apparatus: dry calibration set up, showing transducers in reference position.

As transmitter-receiver of sound waves, a flare gas ultrasonic flow meter model XGF868i is examined. It is a narrow-band piezoelectric transducer operating at 100 kHz. The transducers flanges are connected to valve's flange, mounted in 284 mm (12 inches) metallic spool, that is closed on both sides of the pipe. Thus, gas can be injected and it will be confined within the leak-free spool.

Temperature inside the spool is monitored by a PT100, so that temperature gradients within the gas can be detected. Room temperature and relative humidity are registered by a digital thermo-hygrometer. Room temperature is approximately 28°C in each case (between 26°C and 30°C), and 70% of relative humidity. Internal pressure is atmospheric pressure.

For attenuation evaluation, either acoustic pressure or frequency can be varied. Transducers are adjusted to a particular resonant frequency. Since the aim of this study is to evaluate carbon dioxide concentration effect on commercial flare gas ultrasonic flow meters, just gas composition and transducer distance are changed, in the current research.

The injection of CO<sub>2</sub> in the spool is made by opening a CO<sub>2</sub> cylinder valve (carbon dioxide purity is 99,99%). During the injection, a purge valve is open to avoid increasing gas pressure inside the spool. So, atmospheric pressure is kept during the experiments.

After adjusting the carbon dioxide content to the desired value, the mixture is allowed to stand for 20 minutes, to reach equilibrium. Gas composition is monitored by Testo 350 gas analyzer.

The arrangement allows changes in transducers positions inside the spool, by moving transducer stem. Transducer positions are adjusted by holding one transducer and moving the other half the desired distance. Distances are set by a micrometer. Now the position is adjusted to the total distance and the fixed transducer is moved. The desired positions are marked on transducer stem, so that the transducers can be moved to the desired distance without need to open the spool. Transducers are positioned in the so-called far field zone.

Table 1 details transducers separations as a function of the reference distance.

Table 1 - Experimental configurations of transducer approximation

Test code	% Reference distance	Path length [mm]	Axial length [mm]
Ref.	100%	$L_{ref} = 401,6$	284,0
1	80%	$L_1 = 321,3$	227,2
2	60%	$L_2 = 241,0$	170,4
3	50%	$L_3 = 200,8$	142,0
4	40%	$L_4 = 160,7$	113,6

For each position of the ultrasonic transducers, the amplitude of both transmitted and received signal is measured using an isolated oscilloscope. Speed of sound, traveling time, flow velocity and technical performance parameters are recorded using the flowmeter data acquisition system.

## 4. RESULTS

### 4.1 CARBON DIOXIDE EFFECT ON SOUND SPEED MEASUREMENT

Acoustic absorption promoted by carbon dioxide leads to attenuation of the ultrasonic signal emitted by ultrasonic transducers. For this reason, there must be failure events in the flow measurement process that can be monitored by diagnostic parameters. Assessing the effect of carbon dioxide on sound velocity measurement, ultrasonic transducers are in the position recommended by the technical specifications (facing the inner wall of the tube, as a reference position).

Figure 4 shows measured speed of sound and the estimated speed of sound, according to AGA Report No. 10 (2002) – AGA 10, that consider mixtures of dry air (79% N<sub>2</sub> + 21% O<sub>2</sub>) and carbon dioxide. Mean values of speed of sound is obtained from 180 readings of stable CO<sub>2</sub> levels. Differences between measured and estimated speed of sound,  $SOS_{Measured}$  versus  $SOS_{AGA10}$ , are calculated in Equation [9].

$$\Delta C = \frac{|SOS_{Measured} - SOS_{AGA10}|}{SOS_{AGA10}} \times 100\% \quad [9]$$

USFM is sensitive to high CO<sub>2</sub> levels. Regarding sound velocity measurement, the rated 100 kHz transducer can perform sound velocity measurements with a difference between 0.1% and 1.9% compared to the AGA 10 reference sound velocity up to 100%. CO<sub>2</sub>

Considering technical specifications and legal requirements, tests with high carbon dioxide levels are considered validated.

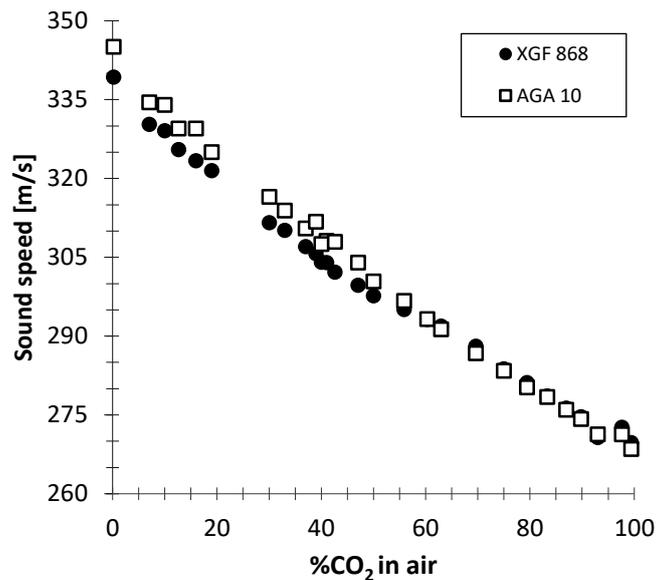


Figure 4 - Comparison between measured sound speed and reference value AGA 10 with CO<sub>2</sub>

#### 4.2 TRANSDUCERS APPROXIMATION

Path length reduction is an alternative to improve performance of USFM. Figure 5 illustrate transducer approximation effect on sound speed variations calculated by Equation [9]. Especially at CO<sub>2</sub> levels above 70%, sound velocity variations decrease as transducers approach. It is also noteworthy that the differences between the sound velocity measured by USFM and the reference sound velocity by AGA10 increase with increasing carbon dioxide in the mixture.

Considering pure air, sound speed difference is between 0,6% and 0,9%. Minimum difference is reached in reference path length. For 15% of carbon dioxide level, differences are between 0,2% and 0,5%. For mixtures of air and carbon dioxide with 30% CO<sub>2</sub>, the differences are between 0,1% and 1,1%.

Below 50% of the carbon dioxide concentration in the air, the largest difference calculated by Equation [9] is 1.1%. Since legal requirements dictate that the flow measurement uncertainty should be less than 5%, this value corresponds to this restriction, considering that other sources of uncertainty are kept under control. For 100% CO<sub>2</sub>, differences are between 3,1% at  $L_{ref}= 401,6$  mm and 1,8% at  $L_4= 157,9$  mm.

For all five different path length evaluated, maximum  $\Delta c$  is achieved at 100% CO<sub>2</sub>. This is evidence of attenuating effects induced by high levels of CO<sub>2</sub> that affect USFM transit time and, consequently, ultrasonic flow measurement performance.

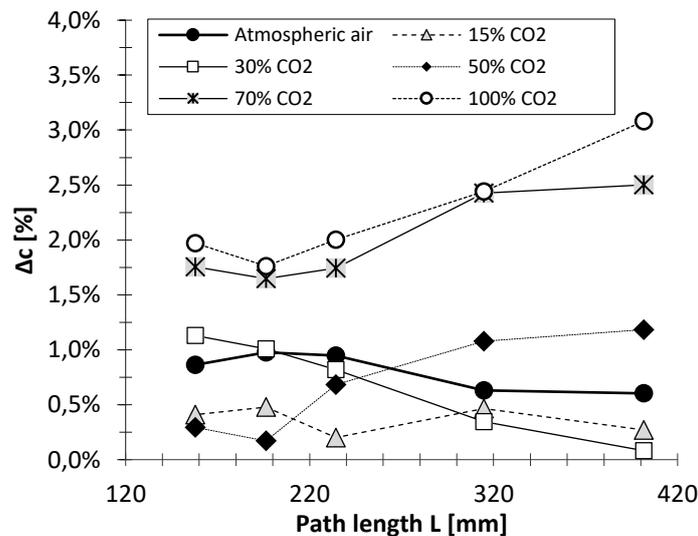


Figure 5 - Difference between USFM sound speed measured and reference sound speed, according to AGA10

For each acoustic path length, the peak to peak amplitude of the received signal voltage is measured by oscilloscope. Figure 5 shows the comparison of variations in signal amplitude with transducer approximation and CO<sub>2</sub> content in atmospheric air. Comparisons are made with the reference state, which ultrasonic transducers positioned close to the inner wall tube, operating in atmospheric air.

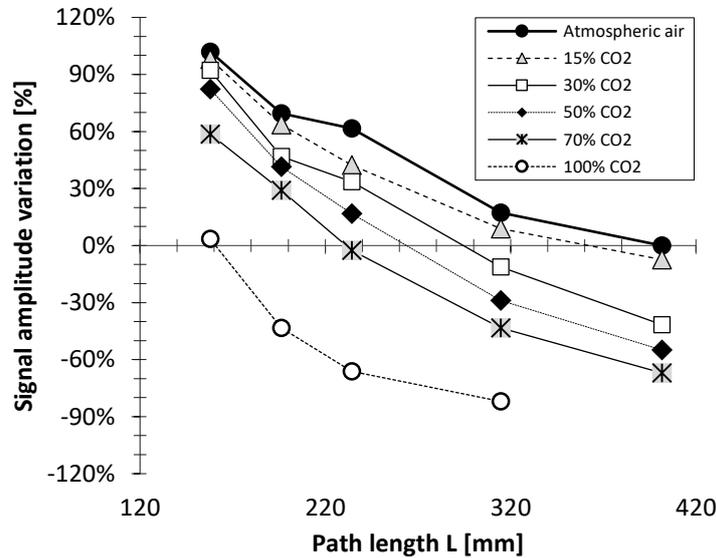


Figure 6 - Signal amplitude variation

For each air carbon dioxide level evaluated, the signal amplitude increases as the transducers approach. In atmospheric air, maximum signal variation is 156% at  $L_4 = 157,9$  mm.

Ultrasonic signal reduction is related to CO<sub>2</sub> increase. Therefore, when fixing the transducer separation, the signal variation is minimal in atmospheric air and maximum for 100% CO<sub>2</sub>. Pure carbon dioxide has such a strong attenuation that at the reference position of the transducers the received pulses were below our detection limit, so data could not be obtained in this case. However, as the transducers approach, the signal amplitude settles at -82% at  $L_1 = 314,6$  mm, indicating signal loss, and 3.4% at  $L_4 = 157,9$  mm, indicating signal increase.

### 4.3 ESTIMATION OF ATTENUATION

The attenuation coefficient determination applied the experimental and data analysis methodology proposed by Ejakov et al. (2003) and Petculescu et al. (2006).

The reference values for the attenuation measurement using USFM is the empirical model (Vermeulen et al., 2013) based on data for binary mixtures of N<sub>2</sub> and CO<sub>2</sub> (Ejakov et al., 2003; Liu, Wang, & Zhu, 2017). Results of the measured attenuating coefficient is illustrated in Figure 7 and detailed in Table 2.

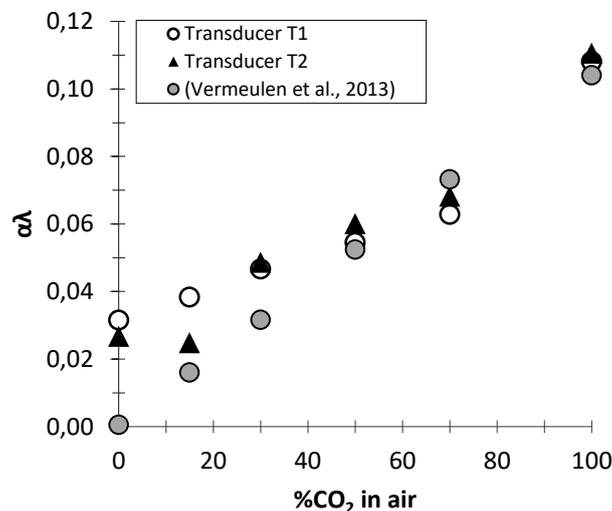


Figure 7 - Attenuation coefficient for several air + carbon dioxide mixtures

Table 2 - Comparison between the experimental attenuation coefficient and the empirical model

Gas	$\alpha_{T1}$	$\alpha_{T2}$	Empirical	$\Delta\alpha$ [%]
Air	0,032	0,027	0,0005	-5706%
85% air + 15% CO <sub>2</sub>	0,038	0,025	0,016	-96%
70% air + 30% CO <sub>2</sub>	0,047	0,049	0,032	-51%
50% air + 50% CO <sub>2</sub>	0,055	0,060	0,052	-9%
30% air + 70% CO <sub>2</sub>	0,063	0,068	0,073	11%
100% CO <sub>2</sub>	0,108	0,111	0,104	-5%

In Table 2, the attenuation coefficient measured for pure air is 5706% higher than the value estimated by empirical model for 100% N<sub>2</sub>. Although values of attenuation coefficient of dry air and N<sub>2</sub> have found to be similar (Bond, Chiang, & Fortunko, 1992), the empirical model applied in this study do not consider air humidity. The presence of air humidity has a strong influence in absorption of ultrasonic waves (Bass, Sutherland, Zuckerwar, Blackstock, & Hester, 1995).

The empirical model underestimates the attenuation coefficient up to 50% air + 50% CO<sub>2</sub>, especially for low CO<sub>2</sub> mixtures, where the empirical model considers only N<sub>2</sub> and CO<sub>2</sub>.

Above 50% of carbon dioxide level, experimental points are similar to empirical model, with differences between 11% and -9%.

## 5. FINAL REMARKS

Analysis of the results indicates that the attenuating effect of carbon dioxide affects USFM readings. The differences between the measured sound velocity and the estimated AGA10 sound velocity become larger, increasing the CO<sub>2</sub> concentration in the air, reaching a maximum difference of 3.1% in the position of the reference transducer. The transducer approach procedure proved to be viable to improve the performance of the USFM, as shown by the reduction in  $\Delta c$  and the increase in the received signal amplitude. Such a procedure has the advantage of not changing any of the apparatus components, only the positioning of the transducers, which are generally sliding in flare measurement applications.

The prediction attenuation effects measurement model does not consider transmission and reception efficiency factor, cable efficiency and diffraction effects. In addition, transducers were not modeled, and the effects of energy loss due to impedance differences in transducer components were not considered.

The empirical model cited, is limited to N<sub>2</sub> and CO<sub>2</sub> mixtures. The attenuation coefficient of N<sub>2</sub> is very similar to dry air attenuation coefficient, but humidity presence increases attenuation. So, higher differences in attenuating coefficient for low CO<sub>2</sub> content in air is expected. Even so, the experimental attenuation coefficient is consistent to the empirical model for CO<sub>2</sub> content, in air concentrations higher than 50%. Both empirical model and experimental evaluation of attenuation converges when carbon dioxide concentration is substantially higher than air concentration.

The results from this research establishes a reference state to evaluation of USFM performance in wind tunnel flow with high CO<sub>2</sub> levels. In future works, the attenuating effects in USFM with other frequencies besides 100 kHz will be evaluated in dry calibration.

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