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Experimental study on low-frequency sound propagation in dispersed water-air pipe flow

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Abstract. *The acoustic properties of two-phase flow are a topic of interest in gas transportation in the petroleum industry. A low-frequency acoustic sound wave is used to determine the speed of sound and single-phase air velocity in pipe flow. However, those cannot be obtained using classical methods of signal processing (coherence and cross spectrum) due to the high noise produced by turbulent flow and the pumping equipment. Therefore, cross correlation and a time-frequency analysis are promising to determine the time delay between acoustic signals captured experimentally for a four microphone array, hence, determining the sound speed and flow velocity. Later, based on this information, relevant quantities related to of water dispersed-air flow are measured and the effect of the liquid volumetric fraction on sound speed and signal attenuation are investigated. The goal is to deliver a robust experimental methodology for multiphase flow metering.*

Keywords: *waves, dispersed flow, water-air flow, sound propagation, signal analysis.*

1. INTRODUCTION

In the petroleum industry, the presence of gas and liquid in pipe flow can significantly reduce sound speed. Thus, flow meters that operate using acoustic technology such as ultrasonic and Long wavelength flow meters can be affected under two-phase flow conditions into the pipe. Hence, acoustical measurements as a sound speed and attenuation in gas-liquid flow become relevant to the multiphase flow measurement study.
The sound speed is highly dependent on the pressure and temperature in gas-liquid mixtures (Kieffer, 1977). The sound velocity in water and air is 1440 m/s and 340 m/s, respectively; however, under two-phase conditions in pipe flow, for example, air-water pipe flow, the sound velocity falls to values of 20 m/s as a function of the gas fraction into the gas-liquid mixture (Kieffer, 1977; Nguyen *et al.*, 1981; Gudmundsson *et al.*, 1992). This reduction occurs because, in gas-liquid pipe flow, the mixture has the liquid density and the gas's compressibility. Hence, even for small gas fractions, the sound speed reduces more than 100 m/s and can affect the performance of flow meters used in the petroleum industry. Kieffer (1977) analyzed the effects of high pressure, temperatures, and volumetric gas fractions varying from 10% to 90% in air-water pipe flow into the sound speed, using fundamental multiphase flow concepts the classical theory of acoustics. The author analyzes those effects based on the following hypotheses: there is no slip between the phase; the air is an ideal gas; the liquid has a constant bulk modulus, and that the wavelength of any sound wave which travels into the gas-liquid mixture is greater than the characteristic length of the Kolmogorov's scales. The results showed that the gas-liquid mixture's pressure increase, there is an increase in the sound velocity into the mixture. On the other hand, as the gas volumetric fraction increase, there is a further decrease in the sound speed into the mixture, even with shallow gas volumetric fractions (10%), and reaches a minimum at 50% of the volumetric fraction of the gas phase. For the more

significant gas volumetric fractions (80%), the sound speed approaches the air's sound speed, even for pressures of 500 bar (Gudmundsson *et al.*, 1992). Gudmundsson *et al.* (1992) develops an experimental work measuring the gasliquid mixture velocity based on the propagation of a pressure pulse in an air-water mixture with volumetric gas fraction ranging from 10% to 85%. The technique consists of the measured time-of-flight of the sound waves into the two-phase flow. The pressure pulse is detected using sensitive pressure transducers (or microphones) located at a determined distance upstream and downstream of the sound generator. Hence, it is possible to determine the sound speed and the mixture velocity for a determined time-of-flight and the sensors' distances. This method shows very accurate measurements with the high mixture velocities and a larger distance of the pressure transducers. However, the technique's accuracy decreases with 50% of the volumetric gas phase into the mixture. Based on this brief literature review, most of the studies related to gas-liquid mixtures' acoustics are very limited, principally, with volumetric gas fractions in the range of 85% to 99%. This study aims to determine the effects of the water drops on the sound speed and attenuation of the sound waves in this two-phase flow regime. Hence this study experimental study is composed of two stages: I) development of an experimental setup which allows determining the sound speed and flows velocity of a turbulent dry-airflow in pipe flow using low-frequency sound (<2000 Hz), II) Extensive experimental analysis of dry-air to the two-phase flows, injecting finely dispersed water drops and analyzing those particles' effects into the sound propagation in two-phase flows.

2. ACOUSTICAL BASED FLOW METERS

Multiphase flow metering by a non intrusive methods are a great goal and interest of the petroleum and gas industry. Ultrasonic flow meters were developed to this purpose, and it offers great advantages behind classical intrusive methods of flow metering (Andrade *et al.*, 2020). Among the main advantages are the high measuring range, high tolerance to humid gases, no mechanical and intrusive parts and, a lower intrusive installation (Raine *et al.*, 2015; Andrade *et al.*, 2020). The working principle of the ultrasonic flow meters is the measured transit time between two transducers located at the pipe wall (Schneider and Peters, 2003; Gorny *et al.*, 2013; Raine *et al.*, 2015; Andrade *et al.*, 2020). Then, the transit time are determined through the cross correlation method, and later, correlated with the sound speed and flow velocity. However, in the presence of water drops or any two phase flow pattern, the ultrasound waves can be completely attenuated causing several error measurements to the two-phase flow (Andrade *et al.*, 2020; Nguyen *et al.*, 1981).
In the works of Gorny *et al.* (2012), Gorny *et al.* (2013) and Potzick and Robertson (1984) are presented an alternative to the ultrasonic flow meters based on the use of long-wavelength acoustic paths, $i.e.$, acoustic waves with frequencies below of 2000 Hz. This type of acoustical flow meter averages the spatial non-uniformities of the axial velocity over the entire cross section in a manner insensitive to flow distortions (Gorny *et al.*, 2012). In addition, the long-wavelength acoustic waves can be present certain immunity to the presence of particles or liquid drops that can be present in to the flow, also, low attenuation along their direction of propagation can improve flow determinations applicable to the flare and continuous emissions monitoring systems (Gorny *et al.*, 2012; Potzick and Robertson, 1984). The working principle of this type of flow meter, is on the propagation of plane waves along the axial direction of the pipe flow, hence, the plane waves are recording with a microphone array (figure 1), upstream and downstream of a loudspeaker positioned in the pipe. Hence, The recorded signals are correlated, providing the time delay between them, later, the flow velocity and the sound speed, based on the equation system given in Eqs. (1) and (2), respectively (Gorny *et al.*, 2012, 2013):

$$C = \frac{1}{2}\Big(\frac{d_{0,1}}{t_{down}} + \frac{d_{2,3}}{t_{ups}}\Big) \tag{1}$$

$$V = \frac{1}{2}\Big(\frac{d_{2,3}}{t_{ups}} - \frac{d_{0,1}}{t_{down}}\Big) \tag{2}$$

where $d_{0,1}$, $d_{2,3}$, t_{ups}, t_{down}, C and V are the distance between the microphones 0-1 and 2-3, the time delay upstream and downstream of the loudspeaker, the sound speed and the flow velocity, respectively. All the definitions of the long-wavelegth are based on figure (1) and the works of Gorny *et al.* (2012), Gorny *et al.* (2013) and Potzick and Robertson (1984).

3. EXPERIMENTAL APPARATUS AND TEST MATRIX

The experimental apparatus consists of a 4,50 m pipe with 0,5 m of internal diameter. The pipe is open at one end and connected to a turbofan at the other, the latter providing a wide range of air velocities varying from near zero to 30 m/s. There is a BS-305ST loudspeaker with 80 RMS of power and 108 dB of sensitivity, positioned at the pipe's middle as can be seen in figure 1 and figure 2. There is a TL-500 amplifier with 90 W RMS of output power. The turbofan is controlled manually using a frequency inverter. Then the flow velocity can be varied over a range previously described. The experiment is carried out as follows: (i) the turbofan is turned on and then it is selected a specific velocity, (ii) the loudspeaker is turned on with the swept sine function with five seconds of duration and frequency ranging from 800 to 1200 Hz, (iii) the data acquisition is done generating a text file registering the time interval and signal amplitude in Pa for each microphone and the procedure is repeated for the entire operational range. All the used equipment is presented in more detail in table (1).
The water is pumped through 36W pump through a cooper pipe, the water is constrained in a nozzle designed to provide water dispersion under a wide range of flow conditions, as can be seen in figure 2. The drop diameters can be roughly controlled through the nozzle diameter and we adopted: 0,6 mm, 0,8 mm and 1 mm (figure 2B) respectively. Therefore, for the two-phase experiments, the procedure previously described with the single phase air flow is repeated with a constant water mass flow rate for the entire range of air velocity.
The experimental test matrix is presented in the form of a classical flow map of the superficial velocities, based on Taitel and Dukler (1976), presented in figure 3, for three different nozzles and water volumetric fraction ranging from 1% to 13%.

Table 1: Technical specifications of the sensing system used in this study.

Item	Manufacturer	Model	Range	Uncertainty
$M_{0,1,2,3}$	GRAS sound and vibration	40PH	Freq:10-20kHz Dyn.Range:32A-135 dB	±2 dB
BS	BS 305ST	–	$0 - 108dB$	–
FT1	Contech	CTH-FT1	$0 - 935,5Kg/hr$	±1% L
B_1	Injetronic	V10/4	$4 - 10\ L/hr$	–
EH	Endress Hauser	PDM75	$-3to3\ kPa$	$\pm 3\ kPa$
$T_{1,2}$	Contech	PT100	$0 - 100\ ^oC$	$\pm 0,3\ FE$

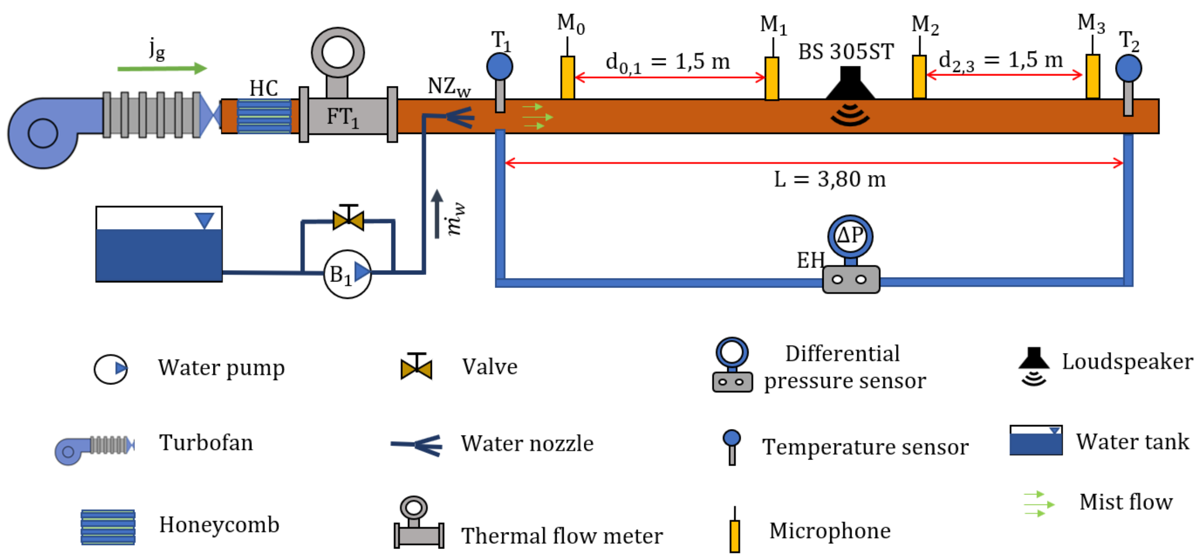

Figure 1: Schematic diagram of the experimental apparatus.

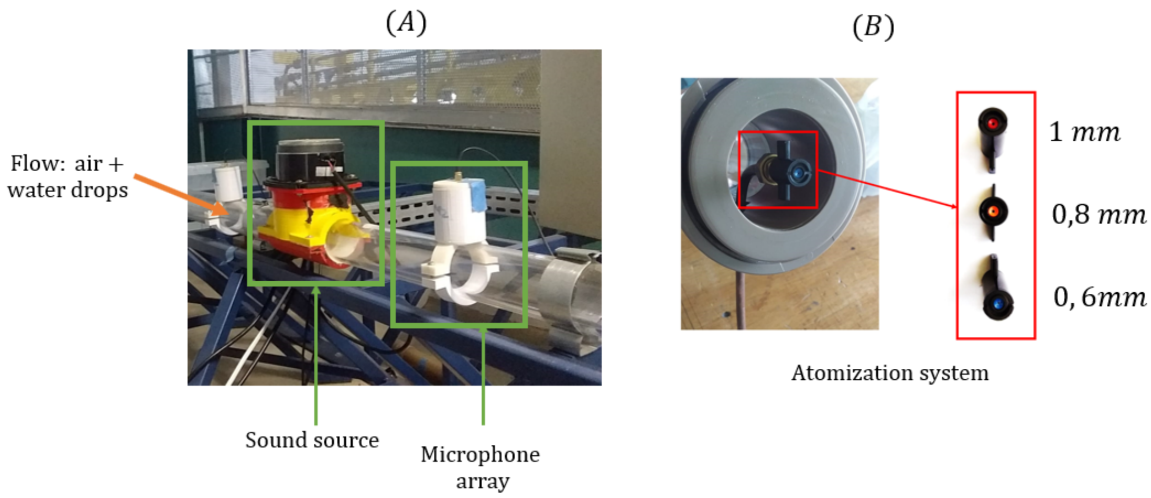

Figure 2: Experimental apparatus: A) sound source and microphone array; B) water injection system.

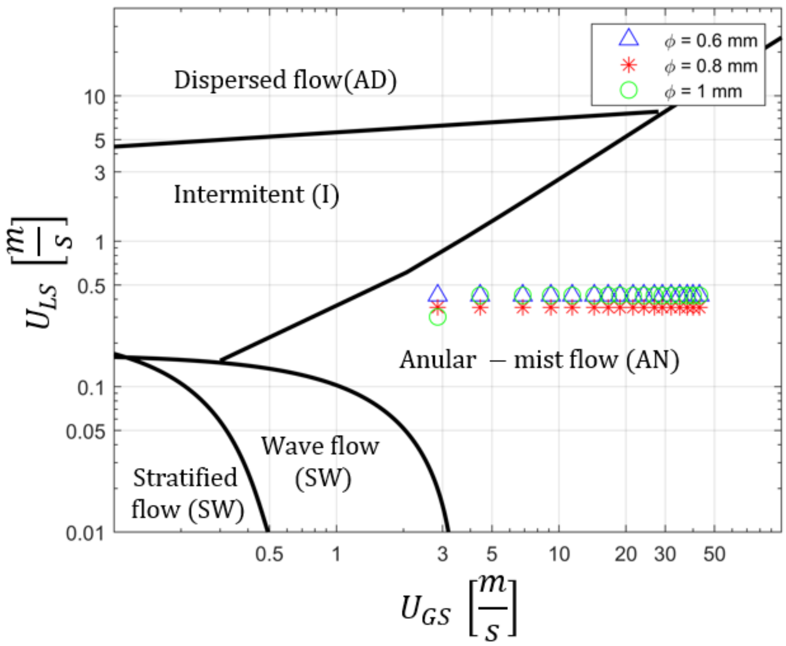

Figure 3: Experimental test matrix based on Taitel and Dukler (1976)

4. SIGNAL PROCESSING TECHNIQUES

Acoustic data of single-phase air and mist flow at different superficial velocities is recorded using a four-microphone array located at different positions of the pipe flow. The collected data is analyzed using classical methods as cross correlation in time domain (GCC) and Gabor transform in the time-frequency domain. As can be seen in the figure (4), those methods are used as a base of the signal processing and the time delay estimation of the acoustic signal. Hence, based on this information, relevant quantities related to of mist flow are measured and the effect of the liquid volumetric fraction on sound speed and signal attenuation are investigated. The goal is to deliver a robust experimental methodology for multiphase flow metering.

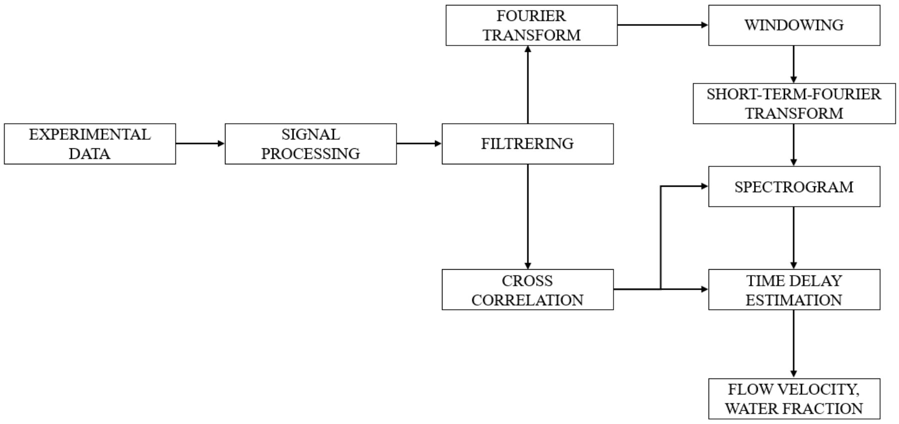

Figure 4: Block diagram of the signal processing being used in this work.

Based on figure (4), the signal processing process consist of a data recording from the microphones along the pipe flow, then a simply band-pass filter from 750 to 1250 Hz is applied to the recorded signal. Later, the signal is processed using two ways: (i) cross correlation: from which it is directly obtained the time delay and the flow velocity and (ii) using the Fourier transform and window process (Gabor transform), hence, the noise caused by the flow field is attenuated and again, the cross correlation were applied, providing the flow parameters to our problem. The cross correlation method and the time-frequency analysis (Gabor transform) are briefly described bellow.

4.1 Cross correlation

The principle of the use of cross-correlation in the flow metering were widely studied in ultrasonic flow meters (USFM) which it is non-intrusive, does not requires any information of the speed of sound into the fluid system and can be applied to single phase flows and in some cases, to multiphase flow systems (Schneider and Peters, 2003). The working principle of the cross-correlation USFM consist of a two signals received continuously by a transducers separated a distance L between them, hence, the position of the maximum GCC function is usually interpreted as the time that the ultrasonic pulse travels from the emissor to the receptor (Andrade *et al.*, 2020; Schneider and Peters, 2003; Raine *et al.*, 2015).
The Cross-correlation of a linear, time-invariant system and linear transmission characteristics depends on the existence of stationary and fully developed flow between the transducers used in the sensing flow process (Schneider and Peters, 2003; Marple Jr and Carey, 1989; Therrien, 1992). Hence, the cross-correlation $R_{x,y}$ of two recorded signals $x(t)$ and $y(t)$ is given in Eq. (3):

$$R_{x,y} = \frac{1}{T}\int_0^T x(t)y(t-\tau)dt \tag{3}$$

where T and τ is the samplig period and the lag between the signals. It is important to remark that the signal $y(t)$ is considered as a copy of $x(t)$ but shifted in time τ seconds (Marple Jr and Carey, 1989).

4.2 Time-frequency/Gabor transform

In music and audio applications, the signals are modeled using the classical Fourier transform, however, a sound signal is never periodic and can prove useful due to its ability to carry information about the source emitted (Franz Hlawatsch, 2013). The time-frequency analysis consist of the representation of a signal in the form of a time-frequency energy maps based on the Fourier analysis, usually called spectrogram (Marple Jr and Carey, 1989). Those maps satisfies the Parseval-Plancherel theorem which consist of an comparison of the energy content of a given signal in time domain and its Fourier representation in frequency domain, $i.e$, the energy content of the signal $x(t)$ must be the same of the transform signal $\hat{x}(t)$ (Marple Jr and Carey, 1989; Franz Hlawatsch, 2013).
The Gabor transform is a fundamental tool for signal analysis, and it is based on the Short-Term-Fourier transform described as follows in a simple way. Given a real signal $x(t)$, their classical Fourier transform $\hat{x}(f)$ in terms of the complex exponential function in frequency domain, as can be seen in Eq. (4):

$$\hat{x}(f) = \int x(t)e^{-j2\pi ft}dt \tag{4}$$

The Short-Term-Fourier transform (STFT) of a signal $x(t)$, is defined in terms of a Fourier transform and the window

$g(t)$:

$$STFT_x^g = \int x(t^{'})g^*(t^{'} - t)e^{-j2\pi ft^{'}}dt \tag{5}$$

while x is a function of time t, its short-time Fourier transform $STFT_x^g$ is a function of time t and of frequency f. We note that the transformation x $\rightarrow STFT_x^g$ is linear and depends on the chosen window g. The window $g(t)$ is an even function with positive real values, concentrated around time 0 where it is maximum. Its Fourier transform is generally concentrated around the zero frequency where it is maximum (Therrien, 1992; Marple Jr and Carey, 1989).
There are a variety of expressions for the windows that can be chosen in order to attenuate several sharp peaks in the Fourier transform (Marple Jr and Carey, 1989), however, for the particular case of the Gabor transform or STFT applications, a Gauss window will be used due to its facility and equivalent expression for the time and frequency domain:

$$g(t) = \frac{f}{2\pi}e^{\left(-\frac{\sigma f^2(\tau-t)^2}{2}\right)} \tag{6}$$

where f, τ and σ corresponds to the frequency component, the center of the window and the standard deviation ($\sigma = 0,5$).

5. RESULTS

A linear swept sine function were used as acoustic signal, with frequency range varying from $800Hz$ to $1200\ Hz$ and duration of 5 seconds, then, for a velocity range from $0\ m/s$ to $40\ m/s$ are calculated the STFT for each case and each microphone in the experiment. The results are presented for a few cases, in figure (5). It is important to remark that only a few cases for single phase flow are presented here, because the limitation of the content.

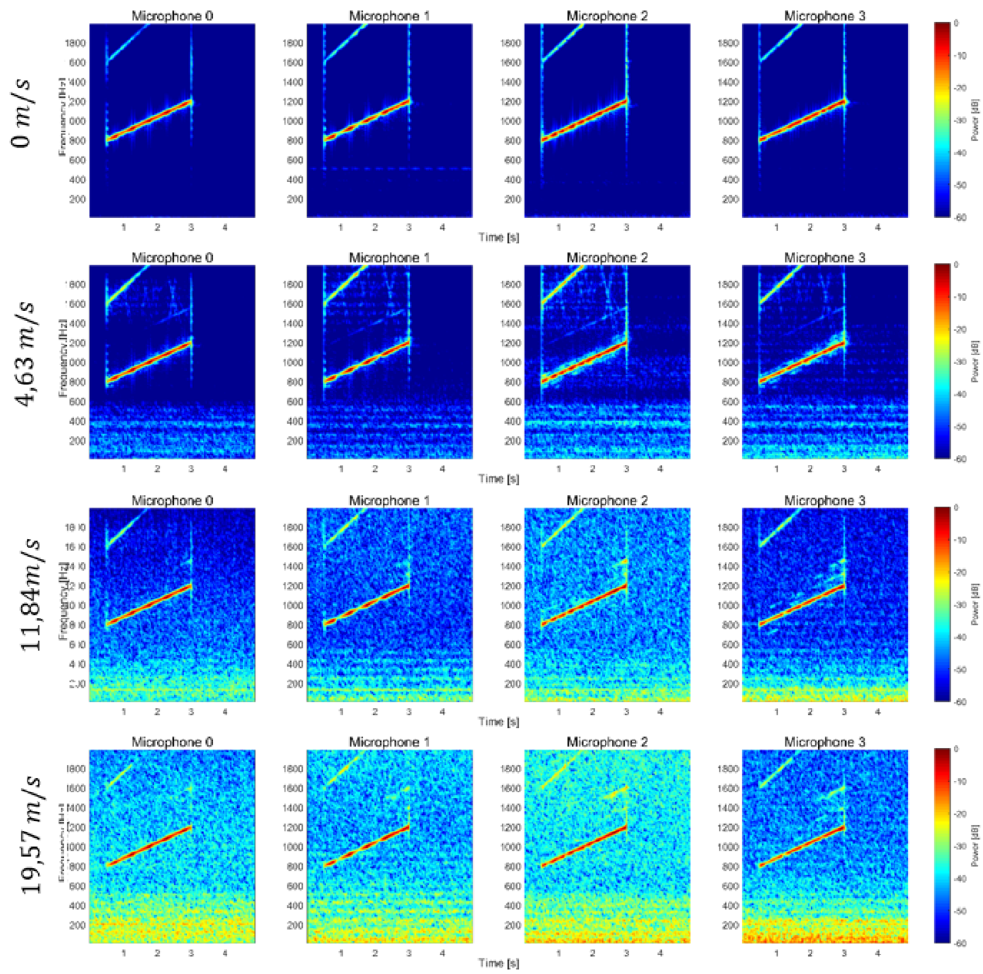

Figure 5: Spectrogram of the recorded signals for different velocities of the flow.

Based on figure (5), it is possible to see that when the flow velocity is increased, highly content of white noise of low frequency is recorded by the microphones of the experiment. However, with the help of a basic band-pass filter is possible to attenuate the noise outside of the swept sine signal, however, some of the information carried by it can be lose, hence, results in error calculations for the flow velocity and speed of sound. Finally, after the use of a band pass filter, and a cross correlation (section 4.1), and the Eqs (1) and (2), it will possible to obtain a flow velocity and the sound speed, as can be seen in figure (6).

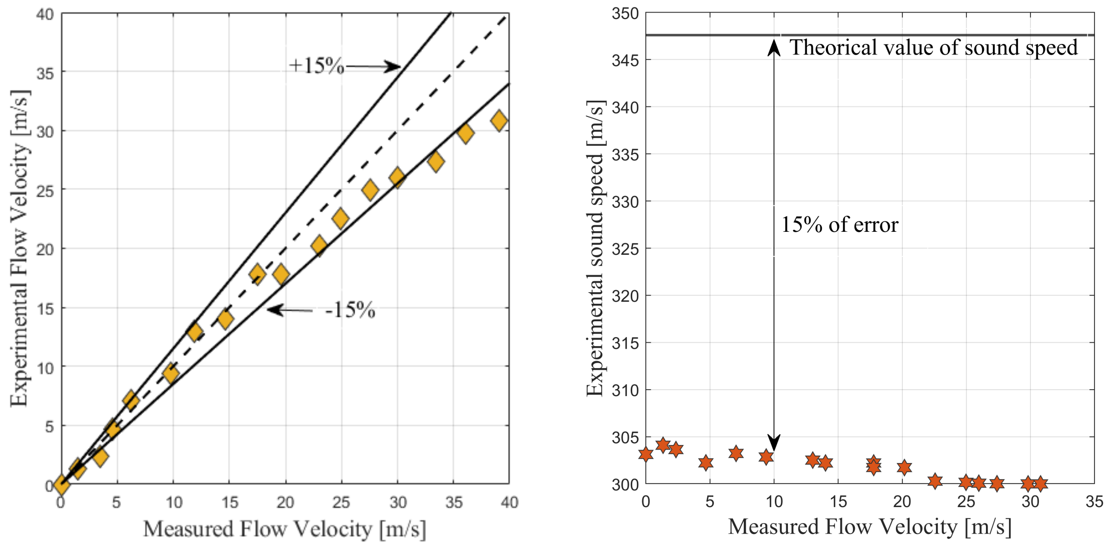

Figure 6: Comparison between the measured values and the experimental values: A) flow velocity. B) sound speed

From figure (6), it is possible to see that the previsions of the cross correlation technique for the flow velocity are in good agreement with the measured values using the thermal flow meter, however, the same does not happens with the sound speed, an 15% error is clearly notable when it compares with their theoretical value, obtained from Eq. (7). This suggest that the noise caused by the turbulent air flow causes several error calculations, even with the use of digital filters attenuating undesirable frequencies, it still remains in the filtered signal and propagating a lot of uncertain in our flow measurement system. In addition, it is still necessary to provide a methodology in order to estimate the experimental error and its propagation along the our signal processing method.

$$C_{Theor} = \sqrt{kRT} \quad (7)$$

where $k = 1,4$, $R = 287kJ/KgK$ and $T[C]$ are the adiabatic expansion coefficient, the ideal constant for gases, and the mean temperature of the test section.

6. CONCLUSIONS

The long-wavelength technique to measure gas flow velocity and sound speed are promising, but it is still very sensitive to external perturbations, which causes a higher uncertain propagation along the calculation method. On the other hand, it is necessary provide another model of calculation the flow velocity and the sound speed because the model used (Gorny *et al.*, 2012, 2013) does not include the effects of the white uncorrelated noise of the flow field, and some external vibrations present in the recorded signals.

The next steps are provide a methodology to the uncertain propagation, a combined signal processing methodologies to "cleaning" the recorded signals and analyze the sound propagation in horizontal mist-flow.

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