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UNCERTAINTY EVALUATION AND EXPERIMENTAL ANALYSIS FOR A WIND TUNNEL AS REFERENCE TO GAS FLARE FLOW MEASUREMENT

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Abstract. *The wind tunnel of the Laboratory of Flow Machines at Federal University of Espirito Santo (UFES) is dedicated to the establishment of a turbulent and fully developed velocity profile. Its configuration provides experimental support in the evaluation of flare gas flow measurement technologies. As a reference flow meter, there is a standardized Pitot tube. In order to statistically define the behavior of the velocity profile inside the wind tunnel, experiments were carried out with the Pitot tube in several configurations. The experimental procedure is based in recommendations for Pitot installations in accordance to the standard ISO 3966 (2008), thus, aiming to enable a critic evaluation about the reliability of Pitot tube as the reference flow meter of this wind tunnel. The results indicate that the uncertainty of the measurement system is above the indicated by the standard, and the installation of a flow rectifier reduces the variability of the measurements and increase the symmetry of the velocity profile. Finally, it is proposed an experimental scenario that provides less variability of the measurement system using the Pitot Tube.*

Keywords: *Wind tunnel, Pitot tube, Flow measurement, Uncertainty.*

1. INTRODUCTION

Since the publication of Portaria Conjunta ANP/INMETRO nº 1 (2000), oil and gas industry in Brazil has been subjected to strict regulations about hydrocarbon flow measurement. The most recent update to this document is Resolução Conjunta ANP/INMETRO nº 1 (2013), that establishes conditions and proceedings for operational and fiscal metering that flow measurement systems must present, besides defining calibration frequency and uncertainty class of the measurement systems. In this context, researches for improvements in measurement systems have grown because of the high capital values and taxes involved in such process.

The Laboratory of Flow Machines at Federal University of Espirito Santo (UFES) provided experimental support in flow measurement technologies. Among its facilities, there is an open circuit wind tunnel dedicated to evaluate the performance of flare gas flow meters. The ultrasonic technology is the most used for this application because it presents advantages such as: i) operation in a wide flow range (typically more than 50:1), ii) tolerate wet gas, iii) no moving part and iv) non-intrusive installation.

For validation of the wind tunnel flow, the tests carried out by commercial flow meters are compared to a standardized Pitot tube. It is important to know the flow behavior in the wind tunnel, since commercial meters as the ultrasonic technology assume, a priori, an operation under a turbulent and fully developed flow.

The spread of application pitometry techniques for flow measurement encouraged research related to the application of the meter. Thus, a correction of the measured punctual velocities by Pitot Tube near to the inner wall of the duct were formulated by Raju et al. (1997). In his work, Klopfensteim (1998) argued that it is essential to determine the minimum and maximum speed ranges of the meter to obtain reliable readings. In addition, Pesarini et. al (2002) proposed a flow measurement methodology in the wind tunnel experiments aiming to achieve a deviation lower than established by the norm "IRAM standard 19004".

Questions related to hydrodynamic similarity of gas flare flow and wind tunnel flow are described in Salgado and Ramos (2009) and Martins and Ramos (2011).

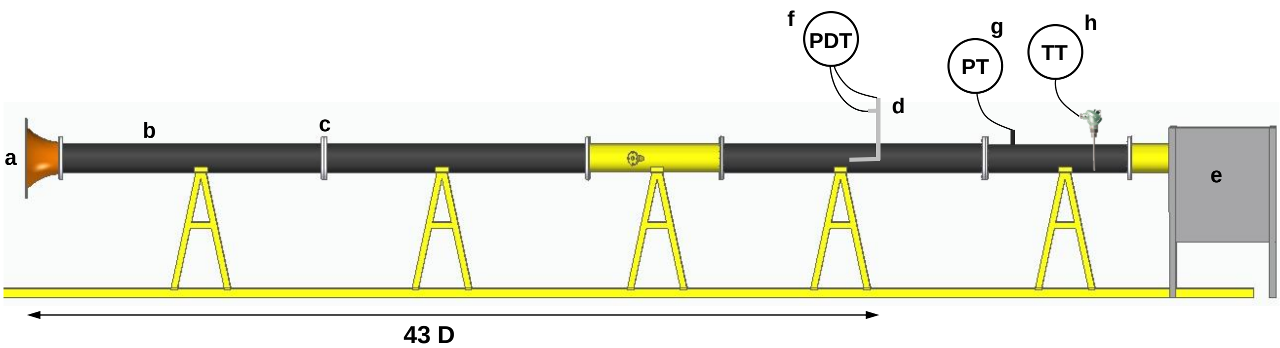
The aim of the paper is to analyze experimentally the velocity profile in wind tunnel using a standardized Pitot tube in order to better understand the behavior of the flow and establishes the uncertainties involved at several flow levels. Besides, the installation effect of a flow conditioner is evaluated.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 Experimental aparatus: Wind tunnel description

The wind tunnel consists of a set of plastic polypropylene tubes, interconnected by flanges, presenting internal diameter of 182 mm (Ø = 8 "). Considering aspirated operation of the wind tunnel, internal pressures is slightly below the atmospheric pressure. Flow velocity is controlled by a frequency inverter that controls a 1200 rpm blower, reaching a maximum mean velocity about 40 m/s ($Re = 4.5 \cdot 10^5$). The basic scheme of such wind tunnel is illustrated in Figure 1.

A bell mouth (Figure 2) nozzle, fiberglass made, is installed upstream to the wind tunnel, in order to direct airflow and reduce pressure drop at the inlet velocity profile.



LEGEND

a – Bell mouth nozzle
b – Polypropylene tubes
c – Flanged connections
d – Pitot tube
e – Plenum and Blower
f – Differential pressure transmiter
g – Static pressure transmiter
h – Temperature transmiter

Figure 1 - Wind tunnel basic scheme

Figure 2 - Bell mouth fiberglass nozzle installed at the wind tunnel

A flow conditioner, PVC made, is shown in Figure 3. It can be installed upstream to wind tunnel, just after the bell mouth nozzle, or downstream, before plenum.

Figure 3 - Flow conditioner

Considering typical off-shore flare gas operational conditions, according to Salgado and Ramos (2009), it matches similarity between the internal flow promoted by the wind tunnel and typical flare gas flow. So, experimental results in the wind tunnel can be applied to the study of flare gas flow meters, considering same Reynolds number. Strength signal level indicate that both scenarios reaches the appropriate coupling transducer-flow, as well.

2.2 Measurement instruments

This study use a Pitot tube L-shaped type, constructed from co-axial tubing. The inner tube conducts the total pressure from the total pressure port whereas the outer tube provides a path from the static pressure tap to the static or reference pressure port. Thus, it can evaluate the velocity and fluid flow from the differential pressure reading applied to Bernoulli's equation.

The wind tunnel is equipped with a Pitot tube Kimo ITMP 120 (FT Pitot type L PT) as a reference meter, whose dimensions and installation are in accordance to the standard ISO 3966 (2008). The Pitot tube is located along the cross section through an automated system composed of pulleys coupled to a stepper motor. Thus, one can make the local readings of velocity, allowing the velocity profile mapping after diameter scan.

As instrumentation, it has a differential pressure transmitter connected to the Pitot tube pressure ports, plus a static pressure transmitter and a temperature transmitter.

The wind tunnel is equipped with a data acquisition and control system based in NI Labview platform. The supervisory system allows to set the blower speed and make the acquisition speed of internal flow, temperature and pressure inside the wind tunnel.

2.3 Experimental procedure

The main premise for the accomplishment of the experiments is the adherence to the requirements of installation and operation of Pitot tube according to ISO 3966 (2008).

That standard establishes the discharge coefficient of standardized Pitot tubes approximately to 1 (one), since the operational limits specified have been respected. Such limits are referred to a minimum speed (corresponding by a minimum Reynolds number of $Re_{min} = 200$) to a maximum speed limited by a maximum Mach number $Ma = 0.25$. Considering such limits, atmospheric air flow and the mean internal diameter of the pipe (Ø = 182 mm), Pitot tube can be used in a range from 0.02 m/s to 85.00 m/s.

The standard ISO 3966 (2008) specifies that the measurement straight tube section should be a length of upstream conduit between the beginning of the working section and any significant upstream irregularity of, at least, 20 internal diameters (20D) of a circular cross-section. Similarly, there should be, at least, 5 diameters (5D) of a circular cross-section between the measuring cross-section and any significant downstream irregularity. Among others, a remarkable recommendation is related to the measurement of the local velocities should be done in, at least, two mutually perpendicular diameters. In order to meet this requirement, two planes were defined for the Pitot tube diameter, corresponding to a horizontal measurement plane (0°) and vertical measurement plane (90°). Figure 4 shows the measurement planes disposition.

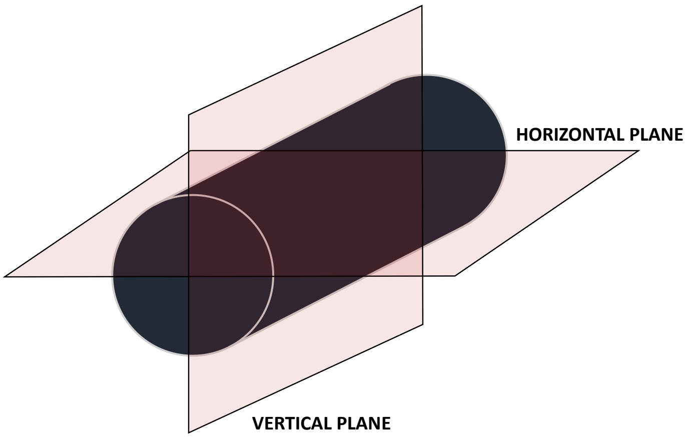


Figure 4 - Measurement planes

The present study choose the Log Chebyshev estimation method for determination of the measurement positions. Such approach assumes a logarithmic behavior of velocity distribution in the outermost elements of the section and polynomial in the other elements. It is adopted four measuring positions per radius, according to ISO 3966 (2008), as specified in Table 1.

Table 1 - Measuring positions by Log Chebyshev method

Point	**P1**	**P2**	**P3**	**P4**
y/R	0.14	0.20	0.38	0.67

With the aim of analyze asymmetries in velocity profile systematic aleatory errors tend to cancel in the two halves of the course, scanning in full diameters are proceed, instead of just radius.

In order to reduce the flow swirl, the influence of a tube-type flow rectifier (or flow conditioner) on the velocity profile is evaluated. This accessory has been evaluated in two mounting positions: after the nozzle mouth bell and before the plenum. Differential pressure measurements were performed at each Pitot tube position, by a time period of 40 seconds, at data acquisition rate of 10 Hz. Three set-up blower rotation levels are imposed: 500 rpm, 860 rpm and 1100 rpm. Pitot tube measuring cross-section is positioned at 43 internal diameters (43D) from the inlet of the wind tunnel (bell mouth). Table 2 shows the test matrix for variation of the parameters studied.

Table 2 - Pitot tube test matrix

Flow conditioner position	**500 rpm**		**860 rpm**		**1100 rpm**	
	Horizontal	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**
No flow conditioner	NFC_A0_500	NFC_A90_500	NFC_A0_860	NFC_A90_860	NFC_A0_1100	NFC_A90_1100
Upstream	FCU_A0_500	FCU_A90_500	FCU_A0_860	FCU_A90_860	FCU_A0_1100	FCU_A90_1100
Downstream	FCD_A0_500	FCD_A90_500	FCD_A0_860	FCD_A90_860	FCD_A0_1100	FCD_A90_1100

3. EXPERIMENTAL RESULTS ANALYSIS

The general relationship between the velocity of the air stream and the differential pressures caused by the air moving over the Pitot tube is given in Eq. 1:

$$v = \alpha \cdot (1 - \varepsilon) \cdot \sqrt{\frac{2 \cdot \Delta p_d}{\rho}} \qquad (1)$$

Where: α is the calibration factor for Pitot tube, $(1 - \varepsilon)$ is compressibility correction factor, Δp_d corresponds to the differential pressure measured and ρ is the density of the fluid. The installation and operation complies with the standard, $\varepsilon = 0$ and $\alpha = 1$ (ISO 3966, 2008).

The experimental velocity profile is evaluated on the following requirements: uncertainty based on variability of measurements, asymmetry and proximity to a theoretical reference velocity profile. The chosen theoretical reference velocity profile is the analytical model for fully developed flow, as presented by De Chant (2005), as Eq. 2:

$$v(y) = v_{máx} \cdot \left\{ sen\left[\frac{\pi}{2} \cdot \left(\frac{y}{R} \right)^{\frac{1}{2}} \right] \right\}^{\frac{1}{2}} \tag{2}$$

3.1 Statistic analysis

The uncertainty components may grouped into two types. Type A involves all components whose uncertainty may be calculated from a series of observations, generally applying statistical methods. Type B groups represent the components whose uncertainty must be evaluated using available information about the respective component because it is not possible, or it is hard to be statistically evaluated. For a type A uncertainty, the standard uncertainty u_A of the component is defined as equal to one standard deviation of the series of observations. The standard uncertainty u_B must be evaluated taking into account the information available. The standard uncertainty is obtained by the Eq. 3 (ISO GUM, 2008).

$$u_s = \sqrt{u_A^2 + u_B^2} \tag{3}$$

When performing data readings, an important question to be made is: How far from that measurement value can the true value of the actual measurand be? Or, statistically speaking: What is the probability that the true value of the actual measurand is in a U interval around the value of the measurement performed?

The expanded uncertainty for the value of U, is associated to the chosen probability. Generally, to obtain the expanded uncertainty the standard uncertainty of the measurand is multiplied by a factor called the coverage factor, ie:

$$U = k \cdot u_s \tag{4}$$

Taking a normally random distribution variable as a reference, the relationship between the probability and the respective factor is given in Table 3.

Table 3 - Coverage fator

Confidence level p [%]	Coverage factor k
68.27	1
90	1.645
95	1.96
95.45	2
99	2.576
99.73	3

Applying ISO 3966 (2008), the evaluation of Pitot tube uncertainty in this work is performed with a 95% confidence level.

3.2 Velocity profile asymmetry analysis

For the asymmetry analysis of the experimental velocity profile, local velocities (by Pitot tube measurements) were dimensionless by the maximum velocity on cross section. Then, the difference between the velocities at the symmetrical measuring points, with respect to the center of the cross-section of the duct, was calculated using Eq. 5:

$$\Delta v_i = \frac{v_i - v_{p-i+1}}{v_{máx}} \tag{5}$$

Where Δv is the magnitude of the asymmetry (as a percentage of the maximum velocity in the measurement cross-section). v_{max} is the maximum measured velocity between the measurement points and the number of measurement positions p in the cross section of the duct. Subscript i refers to the point of measurement at which asymmetry is evaluated. The subscript $(p + 1 - i)$ corresponds to the measuring point symmetrical to point i.

4. RESULTS AND DISCUSSION

The Chauvenet rejection criterion, according to Taylor (1997), determines the magnitude of the deviation of a particular reading. If the deviation is greater than the Chauvenet rejection limit, the reading should be rejected.

Figure 5 and Figure 6 shows, respectively, the dimensionless velocity profile on reference cross-section of the wind tunnel, on both: vertical and horizontal planes. It is observed that, in all experiments, the velocity profile diverges from De Chant's velocity profile, mainly when the punctual velocity readings approach to pipe wall.

As can be observed in Figure 5 (a), (b) and (c), the shape of the experimental velocity profile in vertical scan plane are similar, regardless of whether or not the flow conditioner is present, for all blower speeds.

However, as can be seen in Figure 6, the shape of the velocity profile in horizontal plane diverge themselves bellow the pipe's axis. In this region, the Pitot tube is most inserted (meter steam obstruction reaching between 2.1% and 3.9% of the flow are) and the experimental velocity profiles with the flow conditioner upstream had lower punctual velocity readings.

Before pipe's axis, with Pitot obstruction among 0.3% and 2.1%, the shape of the velocity profile, with flow conditioner upstream and downstream, are conformable. In same region, but without flow conditioner presence readings reaches higher velocities levels.

Thus, it is not noticeable the influence of the blower speed on experimental velocity profile shape. On all tests configurations, it is observed that the shape of the velocity profile with presence of flow conditioner downstream is closer to the velocity profile with no conditioner.

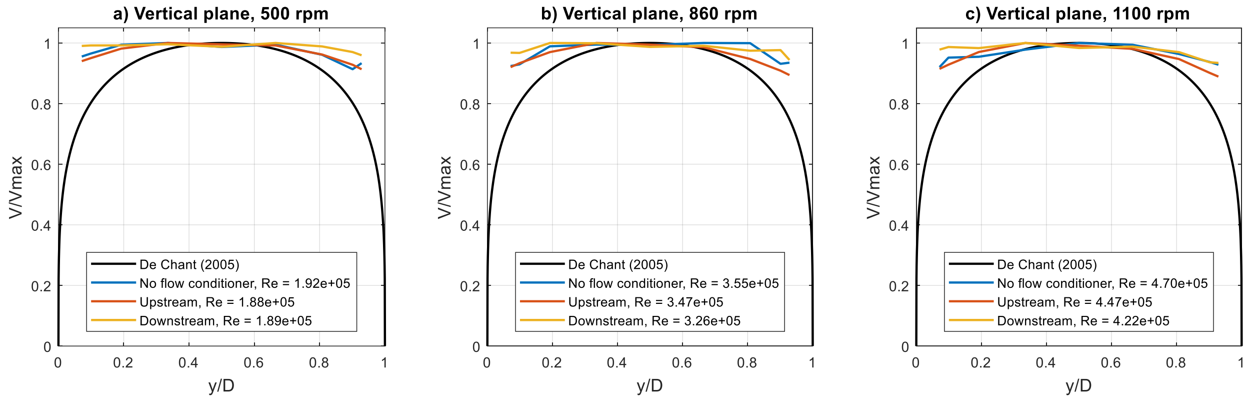


Figure 5 - Experimental velocity profile on the vertical plane

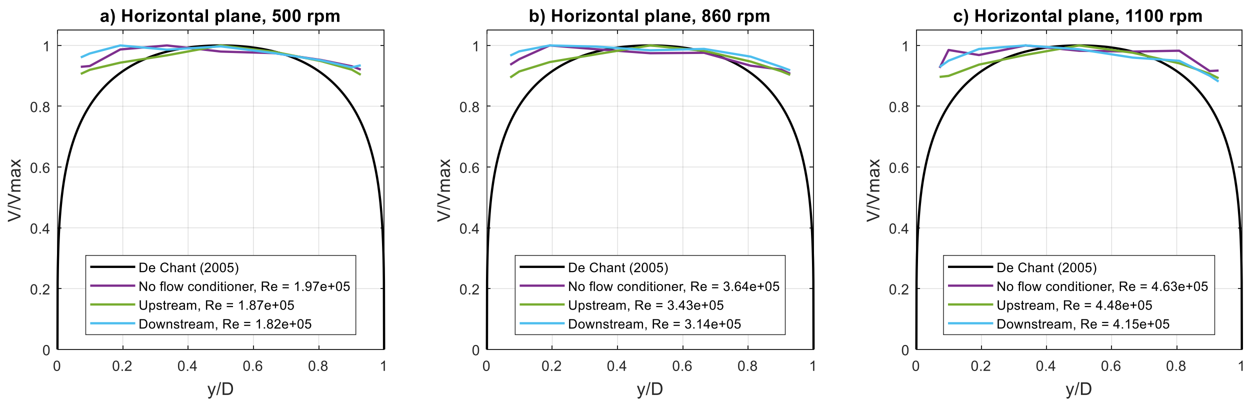


Figure 6 - Experimental velocity profile on the horizontal plane

Figure 7 and Figure 8 show the influence of measurement plan and the installation of the flow conditioner on uncertainty of Pitot tube local readings.

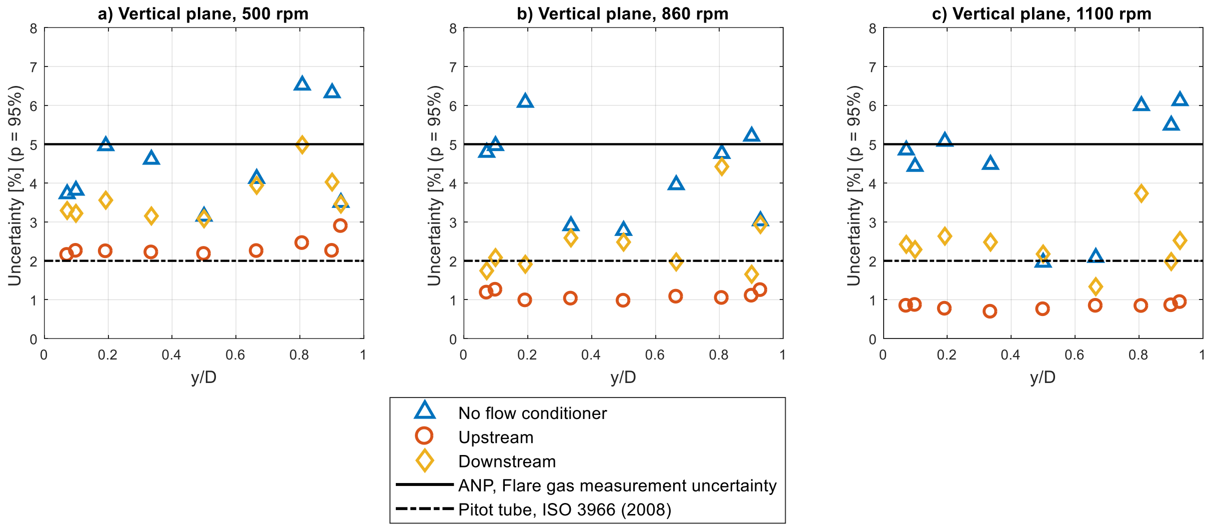


Figure 7 - Uncertainty of the local Pitot tube local velocities readings on the vertical plane

The measurement variabilities shown by the uncertainty in the experimental velocity profile at all blower speed (500 rpm, 860 rpm and 1100 rpm) were lower considering the installation of flow conditioner upstream to the reference cross section, in the vertical plane. Considering such configuration, it is achieved a maximum uncertain value with a 95% confidence level of 2.9% at 500 rpm, 1.3% at 860 rpm and 0.9% at 1100 rpm. With flow conditioner installed downstream, such values increased to, 5% at 500 rpm, 4.4% at 860 rpm and 3.7% at 1100 rpm. In the tests with no flow conditioner, maximum uncertainties were 6.5%, 6.1% and 6.1% respectively at a blower speed of 500 rpm, 860 rpm and 1100 rpm.

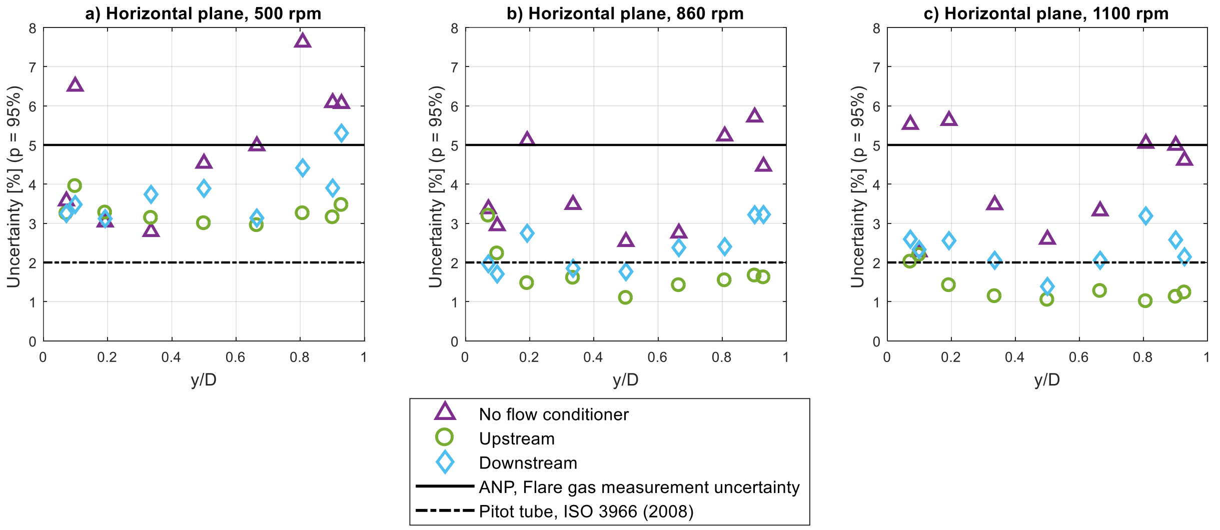


Figure 8 - Uncertainty of the local Pitot tube local velocities readings on the horizontal plane

In the tests carried out on the horizontal plane, the uncertainties with the installation of the flow conditioner were higher at 500 rpm, with a maximum uncertainty of 7.6% with no flow rectifier, 3.9% with it upstream and 5.3% downstream of the measurement cross section. At 860 rpm, these values were, respectively, 5.7%, 3.2% and 3.2 %. In 1100 rpm, the maximum blower speed of this study, the maximum uncertainties reached 5.6% with no flow conditioner, 0.9% with flow conditioner upstream and 3.2% with flow conditioner downstream.

Figure 9 and Figure 10 illustrate the asymmetry level in the reference cross section for the tests made on the vertical and horizontal plane.

The experimental velocity profile on the vertical plane at 500 rpm reaching higher asymmetry levels of 5.2% with no flow conditioner, 2.7% with flow conditioner upstream and 3.1% with it downstream. At 860 rpm, these values changed to, respectively, 1.1%, 2.6% and 2.6%. At 1100 rpm the maximum asymmetry magnitude obtained was 1.6% with no flow conditioner, 2.6% with it upstream and 5% downstream to the reference cross section.

Although maximum asymmetries magnitudes were higher without flow conditioner, as can be seen at Figure 9, the mean asymmetry levels were lower in this configuration, for blower rotations of 860 rpm and 1100 rpm. So, the flow conditioner does not seems to be really effective at vertical plane experiments.

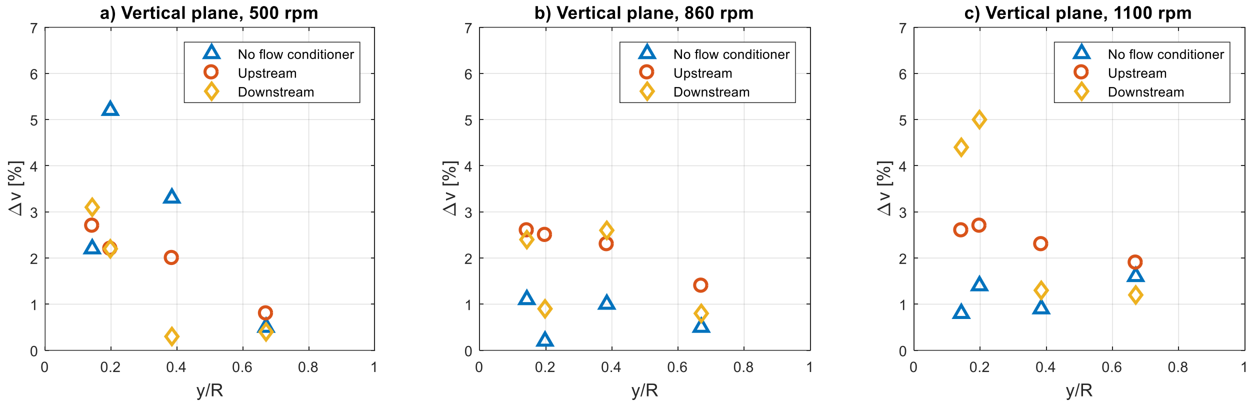


Figure 9 - Asymmetry magnitude on the vertical plane

Still, flow conditioner installed upstream to the measurement cross section was effective on the horizontal plane. In this experimental configuration, it was reached a maximum asymmetry amplitude of 1.1% at both 500 rpm and 860 rpm and 0.7% at 1100 rpm. The same values for the tests with flow conditioner downstream presence were 4.9% at 500 rpm, 5.2% at 860 rpm and 4.9% at 1100 rpm. Without presence of flow conditioner, maximum asymmetry levels were 3.5% at 500 rpm, 6.7% at 860 rpm and 6.9% at 1100 rpm.

As shown in Figure 10, flow conditioner upstream were effective on all three blower speeds. However, it was not efficient when installed after the plenum, because mean asymmetry levels in this configuration were higher than with no flow conditioner installed.

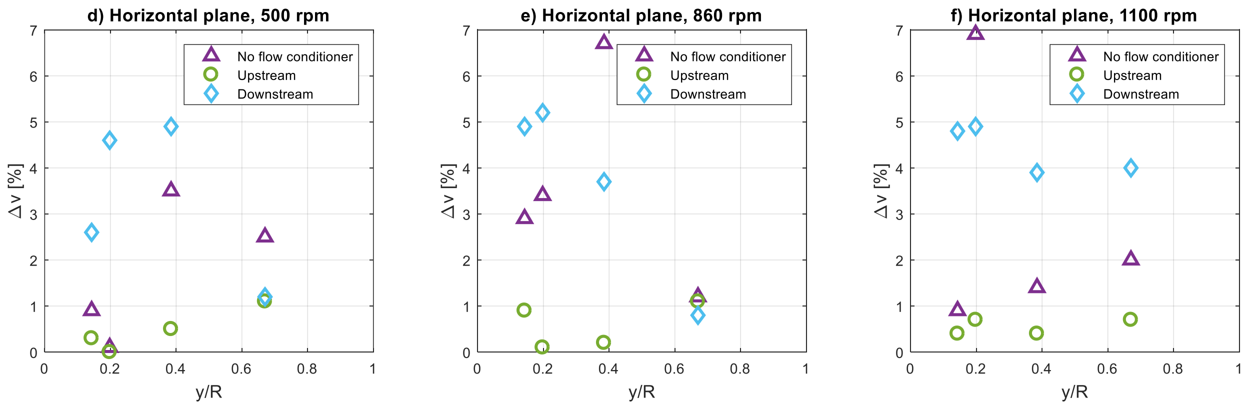


Figure 10 - Asymmetry magnitude on the horizontal plane

5. FINAL REMARKS

This analysis focuses on experimental studies using a standardized Pitot tube readings comparing to a theoretical analytical model for fully developed velocity profile, as proposed by De Chant (2005). Divergences are more relevant on the velocity profile closer to the pipe wall, than those at pipe axis region. In that location, hysteretic effects and Pitot tube stem obstruction can affect the experimental velocity profile. Also, it is observed effects related to boundary layer development and roughness of the inner pipe wall.

The experimental velocity profile measured by a standardized Pitot tube indicate that scanning in vertical measurement plane reach best uncertainties level, while horizontal plane scanning is best to reduce asymmetries.

The standard ISO 3966 (2008) states that uncertainty for Pitot tube, which dimensions and installation fits the standard, should be about 2% at 95% of confidence level. However, this value is hard to achieve in a laboratory experiment, probably due to electrical network interference and oscillations that frequently occurs at UFES. The application of tubing accessories to improve the flow seems to be a good tool, as shown by the uncertainty and asymmetry magnitude analysis. Pressure drop, associated to the installation of the flow conditioner, evidence the reduction of Reynolds number.

Results show that, in order to obtain a symmetrical velocity profile with less variability of Pitot tube local measurements, the best experimental configuration is the installation of the flow conditioner upstream to the reference cross section.

Although in some experiments uncertainties were higher than indicated by ISO 3966 (2008) for Pitot tube, on all tests with flow conditioner installed, the uncertainty levels of the local velocity readings were lower than established by ANP as maximum variability for flare gas flow measurement. Therefore, Pitot tube is suitable to be the reference flowmeter for this wind tunnel. Thus, this wind tunnel is capable to perform tests with commercial flowmeters.

In order to obtain more appropriate results, the present analysis reinforces the importance of performing tests with a flowmeter that have more reliability than a standardized Pitot tube used in this study, comparing the results with both flowmeters.

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