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WIND TUNNEL VALIDATION AS REFERENCE FOR EVALUATION OF FLARE GAS FLOW METERS BY LASER DOPPLER VELOCIMETRY TECHNIQUE

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Abstract. A low-pressure wind tunnel has been designed and constructed at NEMOG - UFES aiming to analyze the performance of flare gas flow measurement technologies, under critical operational circumstances. Due to hydrodynamic similarity, wind tunnel results can be extended to offshore flare gaseous flow, considering Reynolds number range. This paper presents the validation of such test facility by Laser Doppler Velocimetry technique to examine the experimental velocity profile for Reynolds number up to 6.8×10^5 . Analysis shows that, in the chosen test section, turbulent flow is not fully developed yet. Nevertheless, the experimental profile factor is in a good agreement with the analytical one, with maximum deviation of 0.5%.

Keywords: Wind tunnel, Laser Doppler Velocimetry (LDV), law of wall, installation effects.

1. INTRODUCTION

Performance evaluation of flow measurement devices requires a trustful experimental test facility, with well-known geometrical aspects, calibrated instrumentation and traceability of fluid dynamic behavior. Geometrical aspects are related to proper construction and assembly of the test facility. For the second aspect, it is necessary to select adequate instrumentation and to perform a periodical verification of its performance. Lastly, for single phase flows, fluid dynamic traceability is the evaluation of its chemical composition and respective thermodynamic behavior, as well as turbulent characteristics of the flow.

Fluid dynamic characterization can be done theoretically and experimentally. In theoretical approach, Computational Fluid Dynamic (CFD) methods have been largely applied for engineering applications. As experimental methods, classical techniques are based on Bernoulli equation, such as Pitot tube and hot-wire anemometer. The latest techniques, as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV), present strong signal processing and digital filters, and highest advantage of being non-intrusive techniques.

On the other hand, flow meters performance is relevant for flare gas applications. 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. Due to the strategic role of natural gas production, in Brazil hydrocarbon flow measurement is ruled by Resolução Conjunta ANP/INMETRO N°1 (2013), which requires an accurate report of volume of gas burned in flare gas processes.

In this context, ultrasonic flow meter (USFM) are the preferred technology in flare gas flow measurement worldwide (Matson et al. 2010) because of its 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. Most USFMs require turbulent and fully developed flow assumptions, although offshore installations generally do not have sufficient straight pipe length to achieve this condition, due to curves and valves that disturb the flow. This assumption affects the flow measurement uncertainty, which is a matter for legal metrology field.

In this context, the Research Group for Oil and Gas Flow and Measurement (NEMOG, in Portuguese) provides experimental support in study of fluid dynamics and flow measurement for hydrocarbon industry. Among its facilities, there is a closed-circuit wind tunnel is designed to evaluate the performance of flare gas flow meters in high carbon dioxide (CO₂) concentration under installation effects. In order to characterize the flow profile in the measurement section of transit-time USFM meter, a one-dimension LDV system is installed in NEMOG's wind tunnel as reference device to experimental studying of flow turbulence effects.

The aim of this paper is to experimentally validate the velocity profile behavior in NEMOG's wind tunnel using LDV technique, comparing to a reference velocity profile (De Chant, 2005) for turbulent and fully developed flow and using law of wall approach. Furthermore, the installation effect of a flow straightener is examined.

2. LITERATURE REVIEW

2.1 Transit time ultrasonic flow measurement

Flow measurement process by ultrasonic technology is based on time measurement of ultrasonic pulse packets transmitted and received by ultrasonic piezoelectric transducers. The ultrasonic transit time technique requires at least one pair of transducers. Figure 1 shows a single path USFM sketch.

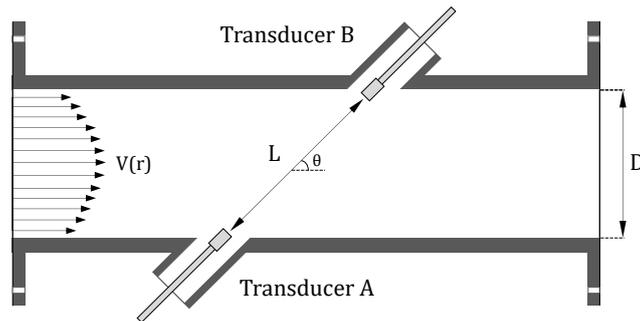


Figure 1 - Schematic illustration of a single path transit time ultrasonic flow meter

The mathematical expression involving the parameters of interest for ultrasonic flow meter technology by transit time principle results in a linear algebraic system composed by two equations and two unknown variables: velocity of ultrasonic propagation on acoustical path v_{AP} [m/s] and sound speed c [m/s]. The equations consider the measured transit time of ultrasonic pulses (t_{AB} [s] and t_{BA} [s]) and pipe geometric parameters: internal diameter D [m] and the acute angle between the ultrasonic path and the longitudinal pipe axis θ [°]. Solving this system leads to two important expressions for ultrasonic flow metering: c (Eq. 1) and v_{AP} (Eq. 2).

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

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

Where t_{AB} [s] and t_{BA} [s] are the measured transit time on downstream and upstream direction, respectively, and L [m] is the acoustical path length.

The velocity of an ultrasonic wave propagation on the acoustic path v_{AP} can be related to flow velocity considering the relation of velocity component variation on acoustical path and average velocity along pipe's cross section. Flow pattern effect on USFM is predicted by American Gas Association Report (AGA) No. 9 (American Gas Association, 2007), referring to it as profile factor or k factor. The k factor is expressed as Eq. (3).

$$k = \frac{\bar{v}}{v_{AP}} \quad (3)$$

Once the velocity profile $v(r)$ is known, the profile factor is obtained as Eq. (3), using the area of cross section A [m²] and the acoustical path length L [m].

$$k = \frac{\frac{1}{A} \int_A v(r) \cdot dA}{\frac{1}{L} \int_L v(r) \cdot dL} \quad (4)$$

Obtained the profile factor, flow rate Q [m³/s] measured by USFM is calculated as Eq. (5). A profile factor of one ($k = 1$) means uniform flow and so, velocity profile measured along acoustic path is equal to the actual mean velocity. In internal flow, the velocity profile is not uniform due to wall shear stress as well as velocity's gradients, inducing turbulent flow characteristics. Besides, the velocity profile is generally not fully developed due to installation effects. That is the reason why the knowledge of velocity profile is so important in USFM applications

$$Q = k \cdot v_{USFM} \cdot A \quad (5)$$

AGA 9 (American Gas Association, 2007) proposes to consider turbulent and fully developed flow and suggest using the semi empirical velocity profile as proposed by Nikuradse (1966). Such profile is a semi-empirical power function, based on experimental data for smooth pipes, as Eq. (6).

$$v = v_{max} \left(\frac{r}{R} \right)^{\frac{1}{n}} \quad (6)$$

Where v_{max} [m/s] is maximum velocity measured, which for a fully turbulent velocity profile is located on the pipe's axis, R [m] is the cross-section radius and r [m] is a radial position. The constant n represents the empirical exponent from Nikuradse's velocity profile, derived from experimental data. It is calculated as Eq. (7).

$$n = 2 \cdot \log \left(\frac{Re}{n} \right) + 0.8 \quad (7)$$

Considering profile factor definition in Eq. (4), the analytical k factor, as proposed by AGA 9 is predicted as Eq. (8).

$$k_{AGA9} = \frac{2n}{2n+1} \quad (8)$$

The knowledge of flow profile in fully developed conditions is well defined over a wide range of Reynolds numbers. However, in industrial applications, this condition is not generally achieved due to the presence of curves, valves and short straight tubes length upstream/downstream from the metering section. In those cases, assuming fully developed condition in k factor leads to flow metering error. Thus, installation effects must be deeply analyzed.

2.2 Installation effects

Manufactures of ultrasonic flow meters generally recommend installation of the meter with, at least, 20 straight tube diameters (20D) upstream and 10 straight tube diameters downstream (10D) to the metering section (GE Sensing, 2013). Still, it is not rare to find industrial plants that do not meet the recommended dimensions. Furthermore, flow metering process by USFM is very sensitive to velocity profile, since manufactures assume operation under a turbulent and fully developed velocity profile and short tube dimensions from curves, bends and valves result in flow disturbance, as illustrated in Figure 2.

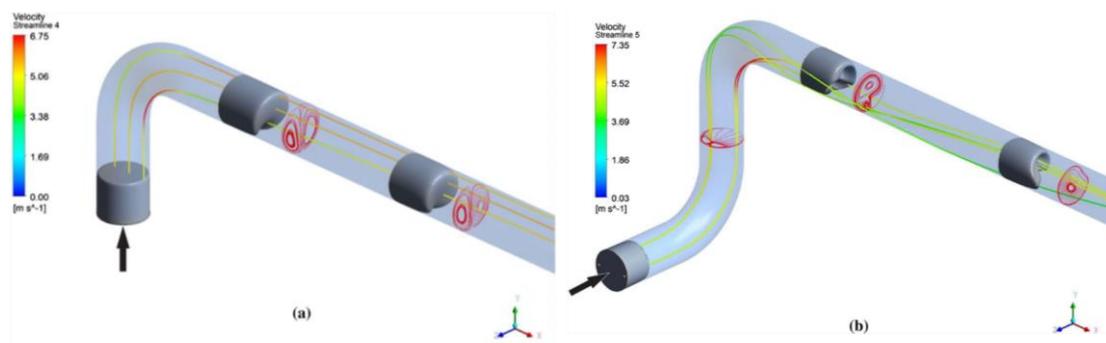


Figure 2 - Examples of profile disturbances downstream to single-elbow and a double elbow-configurations in flare gas flow conditions (Martins et al. 2020)

Mickan et al. (1997) performed experiments comparing flow patterns downstream to several pipe geometries using Laser Doppler Velocimetry (LDV) technique, simulating a real gas industrial pipe facility. Aiming similar goal, Carlander

and Delsing (2000) examined flow rate measured by USFM under disturbed conditions and found an increase in standard deviation up to 100% in measured flow rate comparing to a reference condition. The authors compared measured flow rate in case of one and two elbows and found, experimentally, differences below 4%.

Transducer mounting angle also affects meter correction factor (Mori et al. 2006). Ruppel and Peters (2004) examined ultrasonic flow rate errors caused by flow patterns downstream single and double curves installation. They conclude that error shift is very sensitive to mounting angle and straight tube length for a range of Reynolds number from 1.5×10^5 to 3.0×10^5 .

Recently, computational numerical techniques, such as Computational Fluid Dynamics (CFD), are applied for installation effects evaluation. Zheng et al. (2013) perform three-dimensional flow patterns downstream to a single elbow water flow. The article claims that downstream distance from installations effects and mounting angle disturb velocity profile. Martins et al. (2020) examine deviations on profile factor induced by disturbed flow using atmospheric air via CFD methods. The authors found that for higher Reynolds numbers, higher is the relative deviation of profile correction factor comparing to fully developed reference flow.

Nowadays, legislation requirements brought out numerical simulations in flow metering market, indicating the appropriate profile factor taking consideration pipe's geometry and operational conditions.

3. METHODOLOGY

3.1 Flow facility

NEMOG's wind tunnel is designed to test flow meter technologies for flare gas applications at high flow rate and high carbon dioxide concentration. The test facility consists of a set of plastic polypropylene tubes, with different spool tube sections lengths, presenting internal diameter of 12 inches. The coupling between distinct tube sections is made by male-female (M&F) nylon flanges. This setup ensures interchangeability between straight section tubes and tube fittings (such as bends, curves, tees, valves). Figure 3 illustrates this test facility.

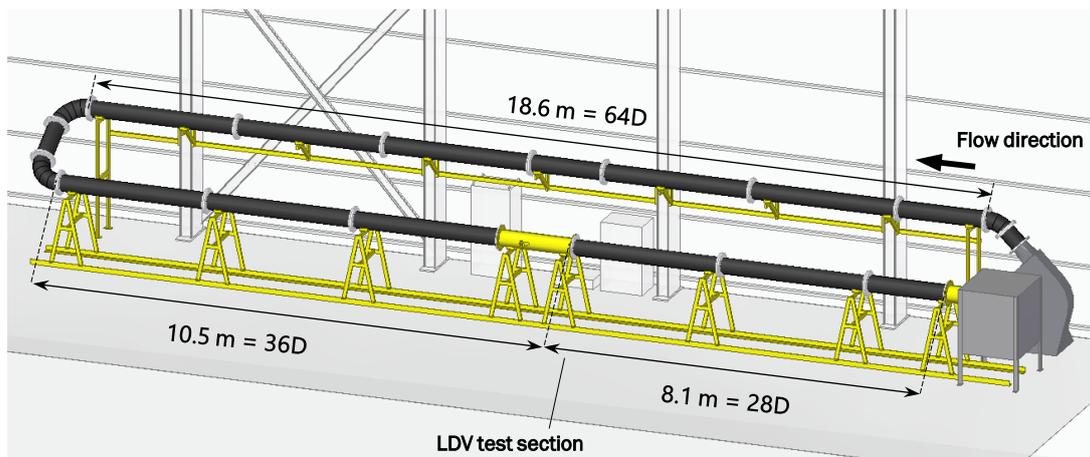


Figure 3 - Wind tunnel in closed-circuit configuration

Internal flow is promoted by a centrifugal blower model OTAM RA100, with aspiration in the lower horizontal segment and return in the upper horizontal segment. A plenum box is installed between the blower and the lower horizontal segment, aiming to reduce the swirl effect generated by the blower. Such phenomenon will be further analyzed in this paper.

The maximum total length of each upper and lower horizontal segment is 18 meters, which corresponds to straight length of 64D (internal diameters), approximately. In order to simulate different fluid flow conditions, two mounts configurations are possible.

The first one is the so-called “open circuit assembly”, in which a bell mouth nozzle is placed on the entrance and flow is aspirated. This mounting is adequate for establishing a symmetrical velocity profile. In “closed circuit assembly”, flow is recirculated by installing curves. This setup is important in evaluation of chemical composition effect in flow metering performance. In both configurations, internal pressure at test section is kept around atmospheric pressure and internal flow present hydrodynamic similarity with natural gas flow (Salgado, 2009; Silva, 2012). Thus, experiments performed in wind tunnel can be extended to the study of flare gas flow meters considering the same Reynolds number range.

The validation of wind tunnel flow profile is done experimentally by a Laser Doppler Velocimetry (LDV) system as reference meter in experimental study of turbulence. The LDV device is located just after USFM spool.

The wind tunnel is fully automated, controlled and monitored for flow, pressure, temperature and CO₂ concentration in a supervisory system in LabVIEW®. The LDV system presents its own dedicated computer and processing system.

3.2 LDV assembly

Laser Doppler Velocimetry (LDV) is an optical non-intrusive technique for characterization of velocity profile and turbulence. It usually implies in a high data rate and reliable results. Its principle of operation is based on the velocity measurement of seeding particles suspended in the flow. Once is chosen adequate particle size and proper fluid for tracing particles, it is expected that the particles closely follow the flow and its velocity is assumed to be the velocity of the flow on the measurement volume.

The LDV system consists in a transmission unit and its controller, a receiving unit in backscattered mode, a signal processor, a computer and a traverse system. It is mounted in the wind tunnel with approximately 36.5D straight tube length upstream and 27.5D of straight tube length downstream. Also, an atomizer is installed to produce the adequate seeding particles for the measurement. The particles are injected on the center of the tubing cross section, 36D upstream of the measurement location. The injection is done through an inserted pipe with a 45° cut on its tip facing the flow direction, according to Figure 4.

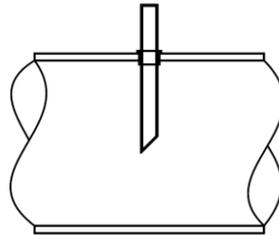


Figure 4 - Seeding particles injection

Being a non-intrusive measurement, LDV requires a transparent window to allow the transmission and propagation of the light beam emitted by the Laser unit through the pipe wall. This area must not interfere in fluid flow and should minimize disturbance in light transmission due to diffraction and other optical phenomena. The design of such window depends on characteristics of the test facility.

In this context, a special nylon holder is designed and manufactured. This element fits the internal curvature of the wind tunnel tube. The holder presents an orifice, allowing the installation of a flat borosilicate glass visor, as shown on Figure 5. Therefore, both the internal and external surface of the window are flat, which mitigates diffraction effects.

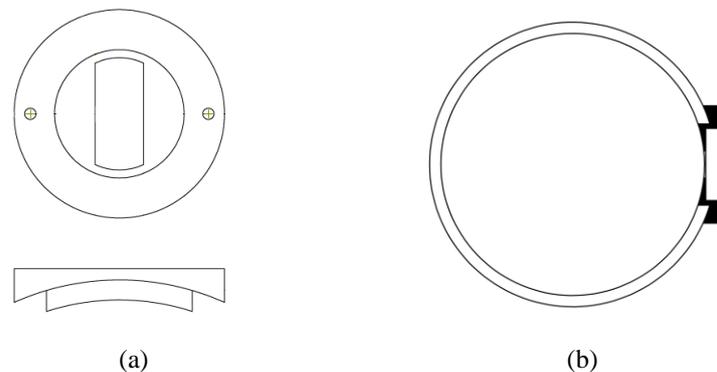


Figure 5 - Detail of transparent window holder: (a) Sketch, (b) Assembly in wind tunnel' wall

A special feature of the holder is that it allows the glass visor to be easily changed, when necessary, even during a high flow rate experiment. This is an attractive characteristic because the fluid for atomized particles presents oleic characteristics, resulting in loss of transparency of the visor as particles attach the surface.

3.3 Experimental procedure and data analysis

Considering configuration in closed circuit assembly, the flow is heated by friction and blower power, as well. This phenomenon occurs due to wind tunnel's high flow rate in a recirculated flow. As any variation in flow properties might cause deviations in flow turbulence, the main premise for the accomplishment of experiments with LDV is getting temperature steady state regime.

For validation of turbulent characteristics of wind tunnel, first the effect of Reynolds number on velocity profile is analyzed in closed-circuit assembly. Flow rate under test corresponds to Reynolds numbers of: i) $Re_1 = 2.3 \times 10^5$, ii) Re_2

= 4.8×10^5 and iii) $Re_3 = 6.3 \times 10^5$. In this setup, LDV test section present 36.5 D of straight tube upstream from the curve. Thus, it is expected some flow disturbances, with divergence from fully turbulent flow profile.

The effect of a flow straighter is also evaluated. In this case, a tube-type flow straighter is installed upstream to the plenum box, at approximately 20D downstream to LDV test section. This placement aims to mitigate the swirl effect induced by the blower.

Velocity profile results are examined in two approaches. One approach is comparing the experimental velocity profile in dimensionless form with the analytical velocity profile proposed by De Chant (2005), through Eq. (9).

$$u(r) = u_{\max} \left\{ \sin \left[\frac{\pi}{2} \left(\frac{r}{R} \right)^{\frac{1}{2}} \right] \right\}^{\frac{1}{2}} \quad (9)$$

Although American Gas Association Report (AGA) No. 9 employ the semi-empirical velocity profile proposed by Nikuradse (1966) in profile factor prediction, the analytical velocity profile proposed by De Chant (2005) present good agreement with its predecessor (Martins et al., 2020), with the advantage of its independence on Reynolds number.

The second approach is using law of wall theory for smooth pipes according to Hinze (1958).

4. RESULTS

4.1 Effect of Reynolds number on velocity profile

The first analysis is the verification of Reynolds number effect on velocity distribution. The velocity profile is measured by LDV technique at 155 discrete points along pipe's diameter.

Results are illustrated in Figure 6, for closed-circuit arrangement. In order to analyze the effect of Reynolds number, the velocity profiles are shown in their dimensionless form, being normalized in relation to the maximum measured velocity on each test. Each measuring point corresponds to the average from a large database, containing from 1×10^4 to 5×10^5 readings.

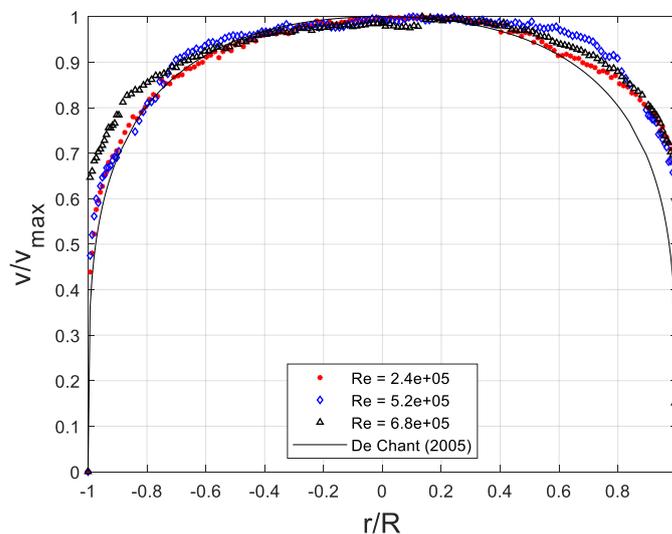


Figure 6 - Effect of Reynolds number on velocity profile

In the area at radial position r/R between -0.6 and $+0.6$, which corresponds to the core flow region, experimental points are very similar and almost coinciding with De Chant's velocity profile. Despite a relatively good visual agreement, in this region, relative deviation in relation to theoretical velocity profile are between 1.4% and -1.95% at Re_1 , between 1.0% and -2.0% at Re_2 and between 1.1% and -2.3% at Re_3 . However, it is noticeable divergences in velocity profile behavior in near wall region.

In the region of $-1 < r/R < -0.6$, experimental points at $Re_1 = 2.4 \times 10^5$ and $Re_2 = 5.2 \times 10^5$ are very close to theoretical velocity profile. Yet, in the same area, experimental velocities at $Re_3 = 6.8 \times 10^5$ in dimensionless form have higher dimensionless values. Considering Eq. (6) and Eq. (7), velocity profile becomes fuller as Reynolds number increases. This indicates a limitation in using De Chant's analytical velocity profile: it does not take account Reynolds number effect. Even so, De Chant's model is still a good reference in a qualitative analysis of the velocity profile and as well as its symmetry.

On the opposite wall region, between $+0.6 < r/R < 1$, experimental velocities data present almost the same behavior for the three Reynolds numbers under investigation, diverging from De Chant's velocity profile.

Using LDV readings and thermodynamic state by instrumentation data, Table 1 summarizes experimental parameters of the tests at three Reynolds numbers. It is important to emphasize that tests with LDV only begins after reaching temperature steady state regime.

For profile factor analysis, fully turbulent k factor as predicted by Eq. (8) is compared to experimental profile factor calculated applying Eq. (4). The quadrature of experimental velocity profile is done numerically by trapezoidal numerical integration rule. Differences between experimental profile factor and AGA 9 value considering turbulent fully developed flow is between 0.15% and -0.51%. It means that, considering k factor analysis, the velocity profile measured is near the fully developed.

It is important to point out that experimental profile factor only use the main velocity component, since the LDV system under test is a unidimensional device. The real k factor should use a three-dimensional velocity profile, accounting for all turbulent effects. However, as secondary velocity components might have small value, current analysis is a good estimation.

Average turbulent intensities are 7.7% at $Re_1 = 2.4 \times 10^5$, 7.2% at $Re_2 = 5.2 \times 10^5$ and 8.1% at $Re_3 = 6.8 \times 10^5$. From comparison between velocity profile points symmetrical in relation to the pipe's axis, asymmetry may be calculated. Main asymmetry are 4.7% at $Re_1 = 2.4 \times 10^5$, 5.0% at $Re_2 = 5.2 \times 10^5$ and 3.2% at $Re_3 = 6.8 \times 10^5$.

Also, one can calculate the asymmetry comparing readings from equidistant positions from the center point of the diameter, that is $r/R=0$. The asymmetry result indicates that the velocity profile is not turbulent fully developed yet, since it is expected null asymmetry in a fully developed turbulent velocity profile.

Table 1 - Main experimental parameters

Parameter	Q_{min}	Q_{int}	Q_{max}
Reynolds number	2.4×10^5	5.2×10^5	6.8×10^5
Flow rate [Nm ³ /h]	2,974.7	6,834.2	9,692.3
Temperature [°C]	25	40	80
Internal pressure [kPa]	101.3	100.5	100
Friction factor	0.01518	0.01313	0.01256
Average velocity [m/s]	12.7	30.8	49.6
k factor experimental	0.9406	0.9437	0.9520
k factor analytical	0.9421	0.9460	0.9472
k factor variation [%]	0.15	0.24	-0.51
Average turbulent intensity [%]	7.7	7.2	8.1
Average asymmetry [%]	4.7	5.0	3.2

4.2 Effect of flow straightener installation

Aiming the reduction of swirl effects induced by the blower, a tube type flow straightener is installed upstream from the plenum box. The flow straightener is designed according to Figure 7. This accessory is examined at the same blower rotation level of experiment Q_{min} .

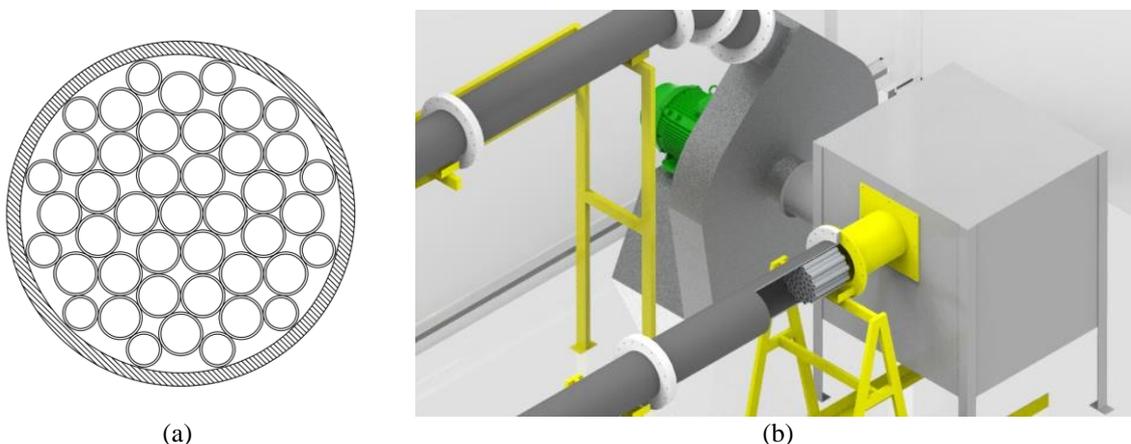


Figure 7 - Flow straightener: a) design and b) installation

Figure 8 compares the influence of flow straighter on velocity profile, comparing it with the analytical De Chant's (2005) profile.

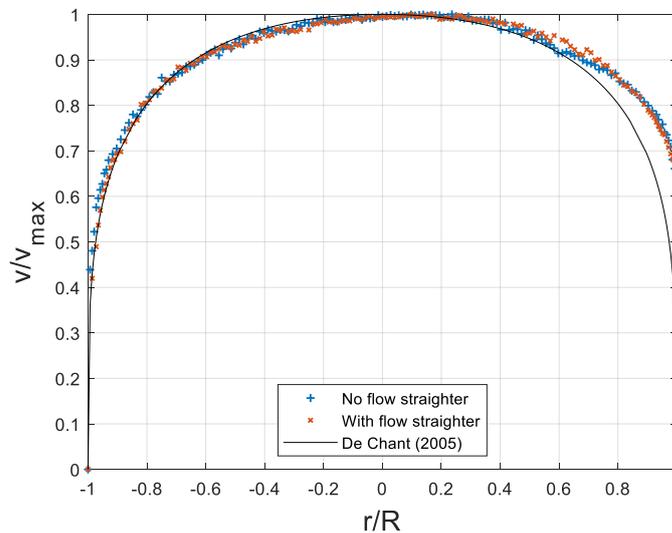


Figure 8 - Effect of flow straighter on velocity profile at Q_{\min}

It is noticeable that experimental points with and without flow straighter are almost coinciding for $-1 < r/R < 0.5$, following the behavior of analytical velocity profile. In the region of $0.5 < r/R < 0.8$, there is small differences on velocity profile induced by flow straighter installation, which needs another evaluation method besides dimensionless velocity profile.

Average turbulent intensity remains 7.7% even after installation of flow straighter, however main asymmetry level increased to 5.4%. After flow straighter installation, the profile factor decreased to 0.9352, representing a relative difference of 0.73%. Again, this profile factor results from a unidimensional experimental analysis. Reynolds number also changed with installation of flow straighter, decreasing to 2.3×10^5 . This reduction is due to pressure drop caused by this flow accessory installation.

Figure 9 presents the measured mean velocity as a function of normalized distance from the wall. The normalization of velocity and position is performed by the wall variables y_+ and u_+ , obtained through Eqs. (10) and Eq. (11).

$$y_+ = \frac{y(r) \cdot u_t}{\left(\frac{\mu}{\rho}\right)} \quad (10)$$

$$u_+ = \frac{u(r)}{u_t} \quad (11)$$

Where $y(r)$ [m] is the position from pipe's wall, $u(r)$ [m/s] is the measured velocity profile, u_t [m/s] is the friction velocity (also known as wall shear velocity), μ [kg/m.s] is dynamic viscosity and ρ [kg/m³] is the fluid's density. The friction velocity is calculated as Equation (12), using the wall shear stress, calculated through Eq. (13).

$$u_t = \sqrt{\frac{\tau_{wall}}{\rho}} \quad (12)$$

$$\tau_{wall} = \frac{f \cdot \rho \cdot \bar{u}}{8} \quad (13)$$

Where f [dimensionless] is the friction factor and \bar{u} [m/s] is the average of the main velocity component along pipe's cross section measured by LDV.

Experimental results are compared to the universal logarithmic velocity distribution for smooth pipes (Hinze, 1958) as Eq. (14), since pipe's roughness is very small (1.7 μm).

$$u_+ = 2.5 \log y_+ + 5.5 \quad (14)$$

Figure 9 analysis shows that experimental results do not completely adhere to the logarithmic behavior of the law of the wall. The first experimental point is located approximately at 1 mm from pipe wall and corresponds to a normalized $y_+ = 35$, for a Reynolds number of 2.4×10^5 . Thus, it is not possible to validate the velocity profile at the viscous sublayer region, since the transition zone from viscous sublayer begins at $y_+ = 7$. Maximum y_+ achieved is 5.1×10^3 .

Law of the wall analysis indicates that flow straightener installation does not induce significance improvement in neither flow asymmetry nor approaching the fully turbulent velocity profile shape. The asymmetry is more accentuated at y_+ below 1.0×10^3 .

On the other hand, such analysis indicates stable and repetitive readings, a desirable feature in wind tunnel operations.

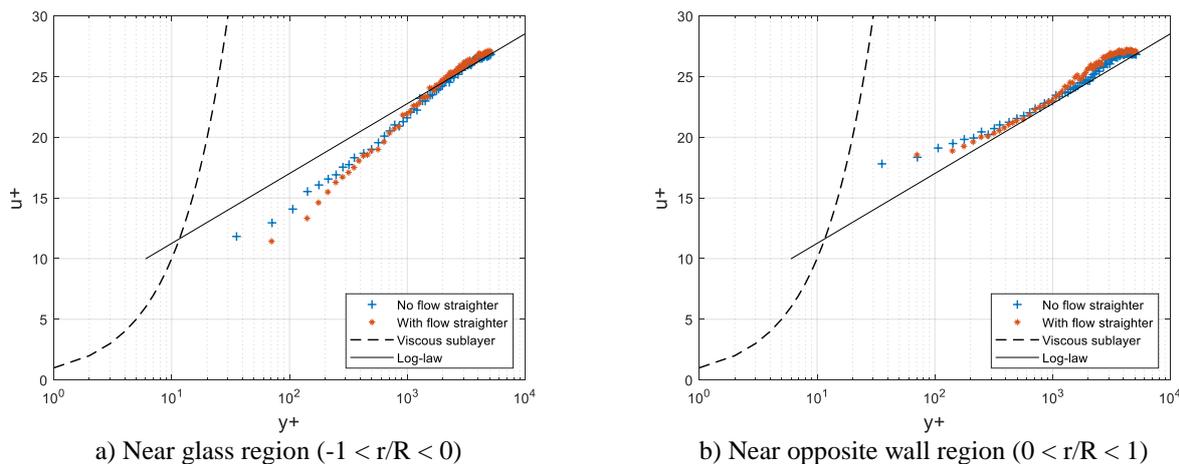


Figure 9 - Law of wall analysis of flow straightener installation

5. FINAL REMARKS

Measurement of the velocity profile using LDV made possible obtaining the experimental profile factor of NEMOG's wind tunnel in the measurement section. This is a very important result, once there are a few facilities around the world capable of test flare gas flow meters under critical circumstance, for instance the effect of attenuating gases and proximity of curves and bends.

Results shows that flow is not fully turbulent yet at none Reynolds number under evaluation. This is expected, since the upstream distance of LDV test section from curve is $36D$, far away from the $80D$ for a fully turbulent velocity profile (Martins et al., 2020). Flow straightener installation do not present significant improvement on experimental velocity profile.

An evaluation is then required to study the effect of the curve in the flow when compared to a suction from the atmosphere in open-circuit assembly. Furthermore, in future works the test procedure will be done in low velocities, trying to achieve the viscous sublayer in order to validate the methodology applied.

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7. REFERENCES

- American Gas Association. (2007). *AGA Report No. 9: Measurement of Gas by Multipath Ultrasonic Meters*. Washington, DC, U.S.A.
- ANP/INMETRO. (2013). *Resolução Conjunta Anp/Inmetro N° 1. Diário Oficial da União*, 1–34.
- Carlander, C., and Delsing, J. (2000). "Installation effects on an ultrasonic flow meter with implications for self diagnostics." *Flow Measurement and Instrumentation*, 11(2), 109–122.
- De Chant, L. J. (2005). "The venerable 1/7th power law turbulent velocity profile: A classical nonlinear boundary value problem solution and its relationship to stochastic processes." *Applied Mathematics and Computation*, 161(2), 463–

474.

- GE Sensing, “XGF868i Flare Gas Mass Flow Ultrasonic Transmitter,” no. April. p. 76, 2013.
- Hinze, J. O. (1958). *Turbulence: An introduction to its mechanism and theory*. McGraw-Hill.
- Martins, R. S., Andrade, J. R., and Ramos, R. (2020). “On the effect of the mounting angle on single-path transit-time ultrasonic flow measurement of flare gas: a numerical analysis.” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 42(1), 13.
- Matson, J., Sui, L., and Nguyen, T. (2010). “Ultrasonic Flare Gas Flow Meter Techniques for Extremes of High and Low Velocity Measurement and Experience with High CO₂ Concentration.” *North Sea Flow Measurement Workshop*, 1–23.
- Mickan, B., Wendt, G., Kramer, R., and Dopheide, D. (1997). “Systematic investigation of flow profiles in pipes and their effects on gas meter behaviour.” *Measurement*, 22(1–2), 1–14.
- Mori, M., Tezuka, K., and Takeda, Y. (2006). “Effects of Inner Surface Roughness and Asymmetric Pipe Flow on Accuracy of Profile Factor for Ultrasonic Flow Meter.” *Volume 2: Thermal Hydraulics*, ASME, 761–767.
- Nikuradse, J. (1966). *Laws of turbulent flow in smooth pipes*. (N. A. and S. Administration, ed.), NASA TT F-10, 359, Washington, U.S.A.
- Ruppel, C., and Peters, F. (2004). “Effects of upstream installations on the reading of an ultrasonic flowmeter.” *Flow Measurement and Instrumentation*, 15(3), 167–177.
- Salgado, A. R. R. (2009). “Perfect gas approach validation aiming estimation of thermophysical properties in flare flows considering operational data.” *Proceedings of the 20th International Congress of Mechanical Engineering – COBEM 2009*, ABCM, Gramado, 8.
- Silva, F. C. da. (2012). “Análise comparativa de medidor de vazão em flare por tecnologia ótica e pitometria utilizando túnel de vento.” Universidade Federal do Espírito Santo.
- Zheng, D., Zhang, P., Zhang, T., and Zhao, D. (2013). “A method based on a novel flow pattern model for the flow adaptability study of ultrasonic flowmeter.” *Flow Measurement and Instrumentation*, 29, 25–31.

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