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TECHNICAL ASPECTS RELATED TO LASER DOPPLER VELOCIMETRY TECHNIQUE IN GAS FLOW

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Abstract. *Laser Doppler Velocimetry (LDV) system is a very applicable non-intrusive technology for measurement of single-point velocity. It is presented a review of important aspects of installation, proceedings and data treatment for LDV measurements. A methodology for using LDV technique on wind tunnel flow is detailed.*

Keywords: *Laser Doppler Velocimetry (LDV), Wind Tunnel, Turbulence, Gas flow*

1. INTRODUCTION

Flow measurement of the hydrocarbon industry in Brazil is regulated by Resolução Conjunta ANP/INMETRO N°1 (ANP/INMETRO 2013), for example in flare gas applications. In order to establish technical parameters for such task, the Research Group for Oil & Gas Flow and Measurement (NEMOG, in Portuguese) has designed and built a wind tunnel with hydrodynamic similarity to flare gas flow. The aim of this facility is to investigate the performance of flare gas flow meters. Flare gas operations present typical characteristics of: i) wide flow rate variations, ii) large tubing diameter, iii) wet gas with variable molecular composition and iv) low pressure flow.

NEMOG's closed-circuit wind tunnel is equipped with temperature and pressure sensors, a Pitot tube as reference flow meter for operation in closed-loop control, possibility of inert gas injection and gas concentration meter. The wind tunnel assembly is adaptable for different arrangements. Besides, the test facility presents a Laser Doppler Velocimetry system (LDV) as reference device for characterization of turbulent characteristics of internal flow.

Laser Doppler Velocimetry is an optical and non-intrusive velocity measurement technique that usually implies in high data rate and reliable results. Although its applicability is inherent scientific, once its mounting and setup are complex, LDV results can be applied towards industrial applications as reference to either calibration or validation of others meters, for example. LDV principle is based on the velocity measurement of seeding particles spread in the flow. Once the adequate size and composition of tracing particles is chosen, it is expected that the particles closely follow the flow changes and its velocity is assumed to be the velocity of the flow on the measurement volume.

A Laser Doppler Velocimeter is not a simple "plug and play" equipment. In practice, the installation and operation of an LDV system require caution in many aspects related to its assembly and results analysis, as well. Hence, the aim of this paper is to review some aspects about the operation of LDV system, highlighting some problems in LDV installation and to present some available solutions.

2. BASIC ASPECTS ON LASER DOPPLER VELOCIMETRY TECHNIQUE

2.1 Principle of operation

Laser Doppler Velocimetry applies the Doppler effect to measure the velocity of small particles spread within the flow. What is actually being measured is particles' velocities. However, with the adequate selection of the particle composition and size, it is reasonable to assume the velocity of the portion of fluid volume surrounding the particle is equal to the velocity of the particle.

Relative motion between a light source and a receiver promotes a shift in the observed frequency (or wavelength) perceived by the receiver. In regard to the application in flow velocity measurements, the Doppler effect happens twice. There is a first Doppler shift between a stationary light source (LDV head) and a moving receiver (seeding particle). Then, there is another Doppler shift between the moving light source (which now becomes the particle) and the stationary receiver (processor photodetector). As a result, through a direct comparison between the frequency emitted by the stationary source and the frequency perceived by the stationary receiver, one component of the particle velocity can be found.

However, the shifted frequency received is extremely high and cannot be measured by conventional devices (Zhang 2010). Therefore, the technology applies a dual-beam configuration, which intersects two light beams in a certain region of space, defining the measurement volume, represented in Figure Figure 1.

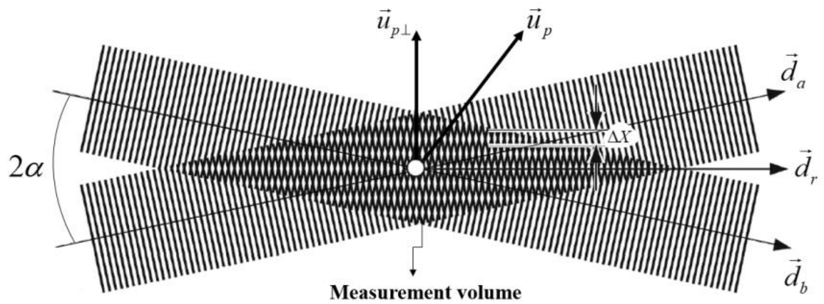


Figure 1. Laser beams sketch (Adapted from Zhang 2010)

Where $\vec{d}_a$ and $\vec{d}_b$ are the directions of the first and second laser beams, respectively; $\vec{d}_r$ is the direction of the receiver; α is the half intersection angle between the pair of beams; and $\vec{u}_p$ is the velocity vector of the seeding particle and $\vec{u}_{p\perp}$ is the perpendicular component of the velocity vector.

As a result, accounting for the interference of the laser lights in the measurement volume, the beat frequency, commonly called Doppler frequency, is many times lower than light frequency. Consequently, the Doppler frequency of the light scattered by the particle while passing through the measurement volume can be measured (Tropea et al. 2007; Zhang 2010). It is related to the velocity component perpendicular to the bisector of the pair of laser beams. Also, as indicated in Equation 1, the correlation depends only on geometric and physical properties. Therefore, the Doppler frequency is linearly proportional to the perpendicular component $\vec{u}_{p\perp}$.

$$\vec{u}_{p\perp} = \frac{\lambda_o}{2\sin\alpha} \cdot f_D \qquad (1)$$

Where λ_o is the stationary light source wavelength and f_D is the Doppler frequency.

An alternative way to describe the Doppler frequency is called Fringe Model. The interference between the pair of beams creates constructive and destructive fringes in the measurement volume. As a result, The movement of the particle across the alternating fringes in the measurement volume yields in a modulated scattering frequency f_D, the Doppler frequency (Tropea et al. 2007; Zhang 2010). The property of the system referred as fringe spacing (ΔX) is determined by the light source wavelength and the angle between the beams, that is $\Delta X = \lambda_o / 2\sin\alpha$. One can notice the fringe pattern in Figure 1.

It should be noted that the measured frequency is independent of the receiver position. Also, particles with the same velocity magnitude generate the same Doppler signal. Therefore, an additional step is usually performed to resolve the particle's direction. It is shifted the frequency of one of the light beams with the use of a Bragg cell, in order to obtain directional sensitivity. More about such process can be observed in the work of Zhang (2010) and Tropea et al. (2007).

It is worth to mention that one pair of laser beams is capable to measure only one specific component of the particles' velocity. Under those circumstances, it can be added a second velocity component by adding another pair of laser beams perpendicular to the crossing plane of the first pair. The second pair is required to operate in a different wavelength than the first pair of beams. Similarly, a third pair of beams can be added. However, in order the have linearly independent vector components the third pair correspond to a non-orthogonal component, which is later suffer coordinate transformation (Zhang 2010).

2.2 Velocity Bias

Most commercial Laser Doppler Velocimetry systems operate in individual realization mode. In this type of data acquisition, the processor samples a velocity data whenever a particle crosses the measurement volume. That is, the sampling rate is conditional to the particle arrival rate. Consequently, the data is not equally spaced in time, as in alternative single-point velocity measurement technologies, for example Pitot tube.

The ensemble average resulted from this type of data acquisition is biased to a higher value, this is called velocity bias. It is due to the fact that more fluid volume with higher velocities than the average passes through the measurement volume per unit of time than fluid volume with lower velocities than the average. Under those circumstances, more seeding particles with high velocities will cross the measurement volume. As a result, there will be more samples of high velocity data than low velocity data.

The most applicable ways to eliminate or mitigate velocity bias are: i) weighting factor correction method and ii) even-time sampling method.

Even-time sampling is a method of data acquisition in which particles' velocities are sampled in an equally spaced period of time. Using this feature, the sampling is now random and there is no need for velocity bias correction. The user selects a sampling data rate in which the first available particle data will be recorded and the next data recorded will happen only after the set time interval. However, for the data sample to be collected as close as possible to the set time interval, the sampling data rate must be many times lower than the available processor data rate in individual realization mode. Consequently, the sampling data rate depends on the processor data rate (TSI Incorporated, 2017). Therefore, even-time sampling is not appropriate to be used on non-homogeneous seeding conditions, because the processor data rate varies significantly.

The other correction methods are grouped in a category of weighting correction. Let (u,v,w) be components of a velocity vector. It was proposed that, given some assumptions, there is a weighting factor assigned to each instantaneous velocity value that rectifies the count disparity between fast and slow particles (Buchhave et al. 1979; Hoesel and Rodi 1977; Mclaughlin and Tiederman 1973; Rodriguez et al. 2018). The general formulations for mean velocity and mean square fluctuating velocity is given by Equations 3 and 4, respectively.

$$\bar{u}_{true} = \frac{\sum_{i=1}^{N} u_i g_i}{\sum_{i=1}^{N} g_i} \qquad (2) \qquad\qquad [\bar{u}'_{true}]^2 = \frac{\sum_{i=1}^{N} (u_i - \bar{u}_{true})^2 g_i}{\sum_{i=1}^{N} g_i} \qquad (3)$$

Where $\bar{u}_{true}$ is the true mean value of the flow velocity in a certain location, u_i is the instantaneous value of the measured velocity and g_i is the velocity bias correction weighting factor (Rodriguez et al. 2018).

The first correction was proposed by Mclaughlin and Tiederman (1973). It is called "inverse velocity weighting", in which the instantaneous velocities are weighted by the inverse of its magnitude, with the weighting factor $g_i = 1/|u_i|$. It attributes lower weights to higher velocities and higher weights to lower velocities. The method is valid given some assumptions: i) that seeding particles are uniformly distributed, ii) turbulence intensity is relatively low, iii) the measurement volume is a sphere (Hoesel and Rodi 1977; Rodriguez et al. 2018). However, those seeding assumptions are not met in near-wall regions of the flow, once the turbulence intensity in this region is significantly high, as well as large velocity gradient. Also, other methods make less assumptions regarding the measurement volume shape.

Following the studies at the time, Hoesel and Rodi (1977) and William K. George (1976) proposed the "transit time method" (also referred as "residence time method") for flows with uniformly distributed particles. This method uses the time in which the Doppler signal is generated by each particle as the weighting factor, that is $g_i = \Delta t_i$. Once the residence time is inversely proportional to the instantaneous velocity, lower weights will be attributed to the faster particles. Besides having a uniformly seeded flow, it is assumed sufficiently large number of samples. This method was later enhanced by Buchhave et al. (1979) in his work.

The "interarrival time method" was another method presented by Hoesel and Rodi (1977), which uses the time elapsed between two doppler signals as the weighting factor, that is $g_i = \Delta t_i^*$. This method was developed theoretically at the time. It was then accessed experimentally by further works (Gould and Loseke 1993; Johnson et al. 1984).

A new technique was recently proposed by Rodrigues et al. (2018), where a combination of the interarrival time and the transit time techniques is applied to correct velocity bias in flows with non-homogeneous seeding conditions. Once transit time technique requires homogeneous seeding conditions and interarrival time does not correct velocity bias, but correct burst random errors. Their correction method, called "Interarrival-Time and Transit-Time weighting (ITTT)", is an interesting prospect to access bias correction in the regions close to surfaces in the flow. The weighting factor in this case is expressed as $g_i = \Delta t_i \, . \, \Delta t_i^*$.

3. LDV INSTALLATION

3.1 Basic LDV assembly

A Laser Doppler Velocimetry system is usually composed by a transmitting unit, a receiving unit and a processing unit (Zhang 2010; Tropea et al. 2007). In the transmitting unit one can usually find: i) Laser light source; ii) beam splitters, that split the generated laser beam in two; iii) Bragg cell, which shifts the frequency of one of each pair of beams in order to resolve velocity direction; iv) LDV head, which includes a converging lens that compels the pair of beams to cross each other.

The receiving unit captures the light scattered by the tracing particles and transmit it to the processor through a fiber optic cable. There are different assembly configurations for the positioning of the receiving optics: i) Forward scattering, in which the receiving optics is placed in the opposite side of the measurement volume to the transmitting optics; ii) Backward scattering, in which the light receiver is placed within the transmitting unit, i.e., the same lens that transmit the pair or pairs of beams is going to receive the scattered light; iii) Side scattering, in which the light detector is placed at a certain angle to the transmitting optics direction.

The receiving unit can be placed at any angle. Tropea et al. (2007) indicated that the intensity of the scattered light from the tracer particles is usually much stronger when the receiving unit is placed in forward scattering mode. However, when the receiving unit is not integrated with the transmitting unit there is a time demanding process to align the receiving optics with the measurement volume whenever the it is repositioned (Zhang 2010).

The processing unit is usually associated with photomultiplier tubes and an electronic assembly for signal processing. Also, the system bears a computer for data acquisition and control.

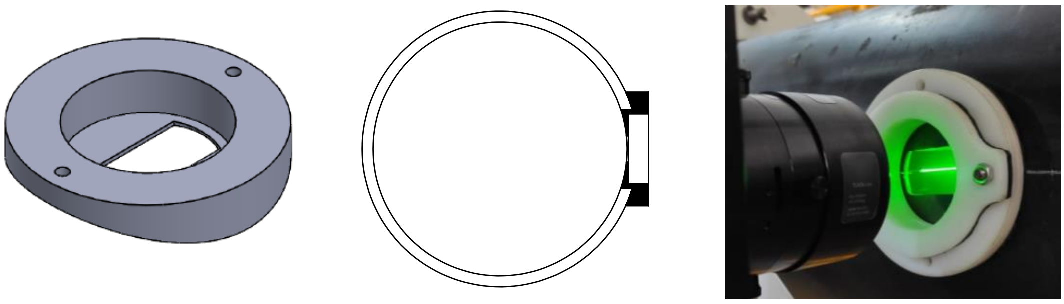
3.2 Optical effects and measurement on circular pipes

Being a non-intrusive device, Laser Doppler Velocimetry requires a transparent area to allow the transmission and propagation of the light beam emitted by the Laser unit through the tubing wall. Also, the receiving optics must be able to detect the measurement volume accurately. Measurement in circular pipe becomes a challenging operation for LDV, because of several optical aberration effects, such as diffraction, scattering and fringe distortion, that occurs in the medium between the LDV head and the flow (Zhang 2010). Some installation methods have been used in LDV applications to mitigate optical effects when performing experimental readings in curved surfaces.

The first method involves the cut of the external surface of the transparent pipe, manufacturing it in a way to turn it flat and the light beams undergo only a one-time refraction on a curved surface (Zhang 2010).

Another method widely used involves matching the refractive index (Durst et al. 1995; Zhang 2010). It is usually applied a fluid matching the pipe wall refractive index. In this method, it is used a rectangular tank filled with the same fluid evolving the tubing so the receiving optics signals can be enhanced and, therefore, increasing the measurement quality. However, the laser beams still suffer from a two-time refraction on the curved interfaces (Zhang 2010). Also, it is not always possible to apply a fluid in the experiment that matches the refraction index of the pipe wall, especially in gaseous flows, as occurs in wind tunnels.

In this context, a third alternative is here presented to meet the light transmission and minimize flow interference requirements. It is designed a nylon made holder to support a flat glass, forming a window in which the light beams pass through a flat surface in the pipe's wall. The element's surface fits the internal curvature of wind tunnel tubing, as showed in Figure Figure 2. It presents an orifice in which allows the installation of a removable flat glass visor. Under these circumstances, both internal and external surface of the transmitting optics through the pipe wall are flat. This setup is only possible in large tubes, because when the internal diameter is sufficiently large, the flat slit provokes minimum interference in the flow field. Also, the slit must be large enough so the receiving optics can capture the light scattered in the measurement volume. Another attribute of the holder is that the glass visor can be easily replaced, even during an experiment. This feature eliminates the blurring effects, due to seeding fluid oleic characteristics that result in loss of transparence of the glass. More about this is discussed at Section 3.5.



(a) (b) (c)

Figure 2. Window design for this project: (a) Isometric view; (b) Fit to the internal curvature; (c) Picture of the prototype

3.3 Seeding particles

Particles selection depends on the type of flow under study. This paper is focused on the application of LDV system on gas flows. Therefore, the discussion is limited to this particular case. However, examples of tracer particles for liquid flows can be found along the available literature (Tropea et al. 2007; Zhang 2010).

When selecting seeding particles to a gas flow, the following characteristics must be meet (Tropea et al. 2007; Zhang 2010):

i) Particles must be inert to the flow composition or facility material;
ii) Particles must be resilient over the travel time to the measurement volume;
iii) Particles must reliably follow flow fluctuations;

iv) Particles must scatter enough light to produce a signal suitable for the receiving optics;
v) A sufficient number of particles must be present to produce good data rate.

The two first aspects mentioned are correlated because if a particle is injected in the flow and a chemical reaction happens, it can deteriorate and not be able to reach the measurement volume, although it may meet other requirements. In this case, the tracer does not present enough resilience. Such aspect will be further approached in Section 3.4, when examining particle's injection. Also, particle's material must not harm the facility plant or operators.

Measurements by LDV technology are based on measuring the velocity of particles scattered in the flow. Therefore, in order to characterize flow velocity, the selection of proper seeding particles is required. In order to assume that particles' velocities in the measurement volume represent the velocity of the fluid, particles must follow flow dynamics and fluctuations accurately. Otherwise, the measurement process simply represents the velocity of a body being carried out in the flow.

Zhang (2010) simplified particle motion equations, assuming that particle's motion is only influenced by the drag force and the force of added mass. As a result, the Equation (4) calculates the relaxation time. This equation can be used as a parameter for the capability of a particle with a selected composition to follow fluctuations in the flow. It is a constant involving both fluid and particle properties.

$$\tau = \frac{\rho_p d_p^2}{18\mu} \tag{4}$$

Where ρ_p is the particle's material density, d_p is the particle's diameter and μ is the fluid viscosity. Similar equation is presented by Tropea et al. (2007).

Obviously, fluid properties, such as viscosity and density, are unconventional to be modified because there is usually a motivation for this choice. Thus, is desirable to minimize the particles' density to lessen the relaxation time. However, for gas flows, the density ratio between particle material and fluid is always too high. Hence, to improve particles' traceability, it is expected the use of the smallest particle's diameter available.

For LDV technology in gas flows, tracer particles are usually in liquid state rather than solid state, once it is possible to produce very small particles using one of the available particles generating techniques. The most common is atomization, which is the technique used in current paper. Another method available is fog machines, which applies the principle of condensation to produce the required particles. Although it is a useful method, fog machine particles usually depend on the fog fluid applied and can be very irregular in size and delivery rate. (Tropea et al. 2007).

Atomizers may be expensive, but they present a simple principle of operation and are available in many configurations and sizes. Compressed air is used to break down a liquid drained from a reservoir. The manner in which that happens depends on the atomizer configuration. Also, the rate of produced tracers is usually regulable. This characteristic is very useful, because one can adjust the rate of particle production according to the pipe diameter and flow rate.

3.4 Particle injection placement

The injection position of seeding particles in LDV applications is relevant to define the experimental setup. At least, two "trade-off" concepts should to be considered.

The first concept is particles' resilience, from the moment of production and injection in the flow to the moment they reach the measurement volume. The resilience depends on the travel path. The longer the path travelled by a particle, more adversity it faces in a turbulent flow. Its resilience is inherent dependent their composition and size, as well as pressure, temperature and turbulence level.

The second concept is the distribution of particles in the tubing cross-section. It is desirable the particles to be homogeneously distributed within the flow, once data acquisition is dependent on particle arrival in the measurement volume. Thus, it is demanded a search for an adequate particles' distribution throughout the diameter. A satisfactory distribution of the particles in the cross-section area is better achieved as the travel path increases, for the turbulence itself promotes such distribution.

It is noteworthy the fact that in closed-circuit configuration usually there is recirculation of tracer particles within the flow, which contributes for particle distribution and also indicate particle resilience. Thus, the injection placement becomes particularly relevant in open-circuit configuration and high velocity flows.

3.5 Pipe wall blurring

Tracing particles can cause a decrease in measurement quality due to optical influence on reception signal. Even if the experiment remains unchanged (flow rate, setup, and particle injection), it is noticeable in many cases that data rate decreases with time, characterizing a trade-off between the number of tracing particles and reception signal quality.

Data rate is one of the performance indicators in LDV readings. The user seeks to achieve the highest data rate possible without depreciating others indicators, such as signal efficiency. Data rate varies according to the particle arrival rate in the measurement volume, and thus its expected variations on its value, especially in the near-wall region. However, even though it is expected some fluctuations on the data rate, it is noticeable a progressive decrease in its average with time.

If the flow and the number of particles remains unchanged but data rate drops, that may be an indicator of loss on signal quality. This effect can be associated with blurring and, consequently, loss of transparency on the pipe visor, due to fasten of particle fluid on its internal surface. Consequently, less signal is perceived or considered valid. This phenomenon is acknowledged in gas flows and even in liquid flows (Han et al. 2014).

The blurring is a function of many factors, such as particle injection rate, piping diameter, flow rate and flow temperature. Comparing two flows with the same particle injection rate and same flow rate, the receiving signal quality will decrease faster in the flow with the smaller piping diameter. Therefore, the treatment of this problem will be specific to each experiment according to the parameters mentioned.

Hence, in many operations, the measurement section has to be disassembled and reassembled for the purpose of cleaning the wall. The solution for the visualization area (window) raised in this paper allows easy removal of the visor for cleaning, and thus one can change the visor during the experiment. Furthermore, it is recommended to have available many visor glasses for easy replacement in order to speed up the process. Figure 3 is a sketch that depicts the transparency decrease in a seeded flow.

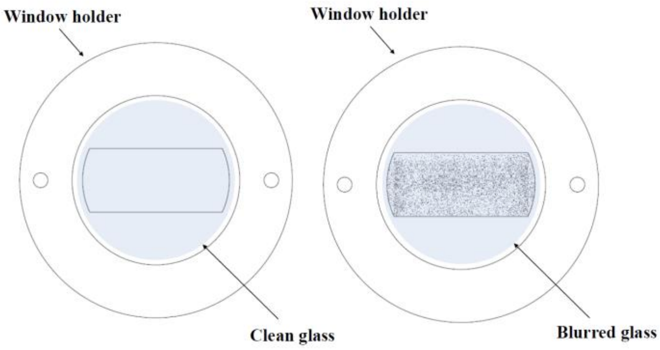


Figure 3. Sketch of aspect of the glass after exposure to a certain seeded flow

4. DATA TREATMENT: CASE STUDY

The experiment described below aims for detailing important steps in order to evaluate velocity distribution by LDV technique, especially in pipe tubes and gas flows.

4.1 Measurement facility

The experimental facility is located at Research Group for Oil & Gas Flow and Measurement (NEMOG, in Portuguese), in Federal University of Espirito Santo (UFES). The wind tunnel can operate in closed or open-circuit. This adaptative setup is possible because the wind tunnel is assembled by a set of polypropylene tubes coupled by male-female flange type. In closed-circuit, internal flow is recirculated. On the other hand, the open-circuit mounting replaces the curve part by a bell shape inlet nozzle. The facility is powered by an OTAM RA1000 centrifugal blower, with aspiration in the inferior branch and return in the superior branch. A plenum box is placed between the blower aspiration and the inferior branch, in order to mitigate swirl effects. Blower rotation, data acquisition and all the experiment control are executed by a supervisory system in LabVIEW® platform, except for LDV data acquisition and control that have a dedicated system.

The LDV positioning present an upstream length of 36.5D and a downstream length of 27.5D. The full wind tunnel design is represented in Figure 4.

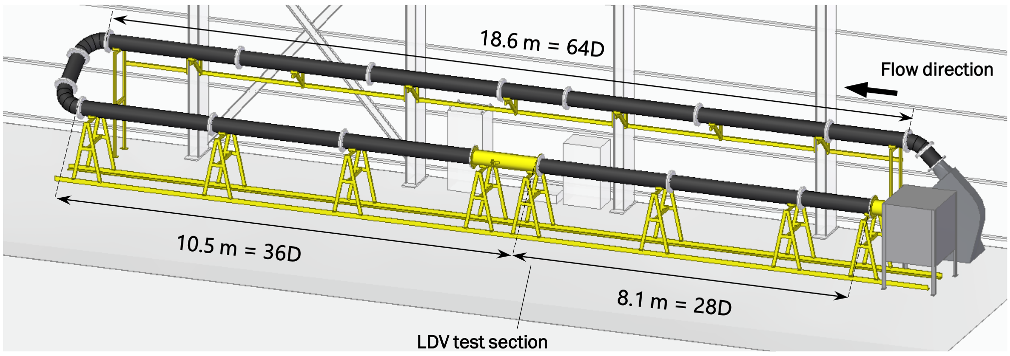


Figure 4. Wind tunnel for flow measurement tests facility

4.2 Laser Doppler Velocimetry System assembly

The experiments were performed using a commercial one-dimension (1D) Laser Doppler Velocimetry system, by TSI Inc. The system presents a laser unit and its controller, an external signal processor, and a computer baring the system's software. Besides acquiring and recording the data from the processor, the software also controls the 1D traverse system applied to move the probe volume throughout the diameter in the measurement cross-section.

The transmitting optics consist in a dual pumped solid-state laser, generating a 532 nm laser beam that is later split into two beams by a Bragg cell that also shifts one of the beams frequencies, ensuring bidirectional velocity measurement capability. The two beams develop through transmitting optics and parallelly reach the LDV head. The LDV head bear a focal lens, which focus both laser beams to cross each other and constitute the measurement volume. Some further information about the meter applied in this case study is presented in Table 1.

Table 1 - LDV Characteristics

Wavelength [mm]	532
Focal Length [mm]	362.60
Beam Separation [mm]	50
Measurement volume length [mm]	3.30
Measurement volume diameter [mm]	0.23
Fringe Spacing [um]	3.76
Fringe Number	62

The receiving optics are placed in backscattered configuration, which means that the LDV head also receive the signal rather than just delivering it. The light signal is collected, collimated and transported through a multi-modal optical fiber to the signal processing unit.

This unit containing both the transmitter and receiver optics is called Laser Doppler Power Sight Unit, which is mounted on a traverse system. The traverse control is integrated in LDV software (in the present case Flowsizer 64®), so the velocity profile scanning can be automated by setting up a measurement matrix. The user can than select which points of the cross-section diameter will be measured and select a cut off parameter to end the measurement in the point, which may be by elapsed time or scattering centers maximum count. All the LDV system setup is presented in Figure 5.

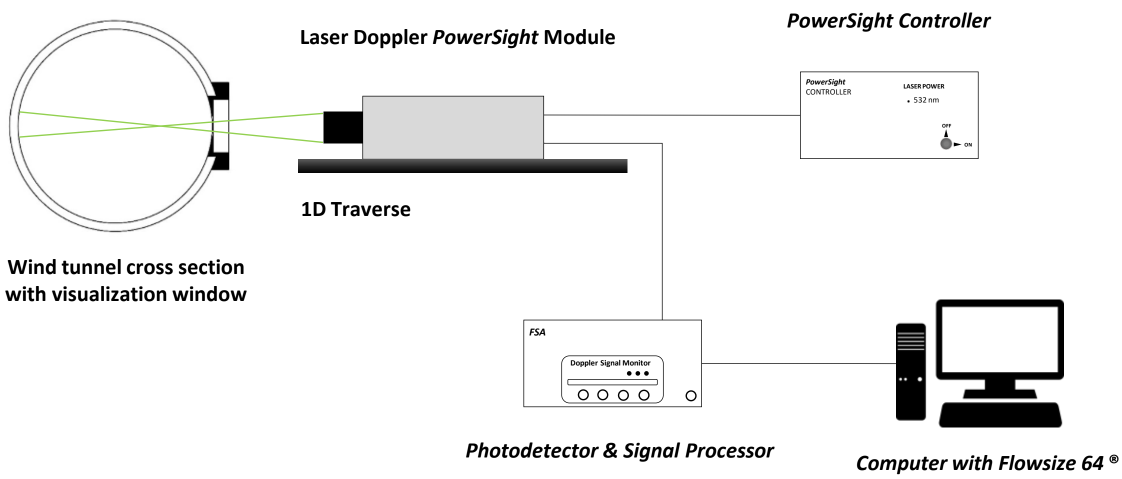


Figure 5. LDV system's assembly

4.3 Methodology

4.3.1 Seeding particles

An atomizer is used as particle generation technique. The six-jet atomizer model 9306 by TSI is driven by compressed air to produce the tracer particles. It is built in a way that the user can activate up to 6 independent jets that produce the number of particles adequate in the experiment. The choice, regarding to the number of jets, depend on the data acquisition rate desired, once the data rate is given by the particle arrival rate in the measurement volume. It is important to realize that incrementing the number of activated jets increases consumption of atomization fluid.

Particles injection positioning in the experiment circuit was studied carefully. For this paper, the most adequate approach to the trade-off between particle resilience and particle distribution in the cross-section area was focusing in the distribution. The atomization fluid Bis (2-ethylhexyl) Sebacate produces particles with acceptable resilience so that the injection could be placed in the furthest upstream location possible. That is right after the curve, in the lower horizontal branch.

4.3.2 Positioning of the transmission and reception laser unit

A relevant aspect to the positioning, regarding to the measurement of velocity profiles, is the assurance that the scanning is performed along the diameter. It is mandatory to assure the horizontal and vertical alignment of the transmission unit and the tubing. If any deviation in alignment occur, the path being measured will not be a diameter but a chord.

Laser Doppler Velocimeter does not have a physical probe, instead the probe is formed in the crossing region of the pair of laser beams. Therefore, is necessary to precisely set the initial and final dimensional domain to be scanned.

Although the distance from the LDV head to the measurement volume is constant, some optical phenomena, like reflection and brightness from the glass visor or the from the wall, occur near regions extremely close to the surfaces (boundary layer region). In addition, it must be considered that the measurement volume is treated as a single point velocity measurement, but it presents its own intrinsic dimensions, as observed in Table 1

The procedure to positioning the Laser is performed in two steps. The first step is the positioning by visual observation, in which the operator, according to his experience and measurement methodology, places the measurement volume on the internal surface of the glass. The second step is burst signal monitoring and evaluation of the measurement performance indicators, such as data rate and signal efficiency. As a result, it is possible to set the least distant point from the surface that the measurement would begin.

4.3.3 Measurement matrix

As Laser Doppler Velocimetry is a single point velocity measurement, in order to scan a velocity distribution profile, it is required to move the measurement volume throughout the cross-section diameter, in order to get velocity readings for discrete points. As mentioned, it is applied an automated traverse to perform this operation.

It is necessary to define a matrix with the positioning of readings along the diameter to be measured by the system. The diameter is divided into 3 distinct regions to compose such matrix: i) Near Glass, ii) Core Flow and iii) Near Wall. In each of these areas, different settings are specified in the software. This is due to the fact that light scattering (reflection) happens near surfaces, but it may not have influence on the measurement for the core flow region. Also, more particles cross the measurement volume in the center of the flow than near the surface of the pipe. Moreover, there is a high velocity gradient close to the wall. Under those circumstances, it is necessary to refine the matrix position for these regions. On the other hand, in core flow section, the domain discretization does not have to be so severe. Hence, it is set a measurement matrix from the wall to the center of the flow. The spacing between two consecutive measured points near the surfaces started at a value of 0.25 mm, increasing to 0.5 mm, then to 1 mm. For the central area, 2 mm spacing is set.

For each element in the positioning matrix it is associated a group of settings in the software. The signal filters and processing methods are changed, in a way to maximize the performance indicators of the measurement. This is a standard procedure required due to the change of turbulent characteristics in the flow along the diameter, as well as optical phenomena.

4.3.4 Readings

After system calibration and positioning of the laser unit and after the selection of proper settings for the characteristics of the flow being analyzed, the measurement is initiated and the system scans automatically the diameter according to the defined position matrix, proceeding the acquisition of data. It is noteworthy that near the surfaces the adequate settings vary significantly between consecutive positions. Therefore, in the first 5 mm the measurement was performed without the automated feature of the traverse system.

As data rate changes depending on the segment of the cross-section being measured and because the data treatment is done on post-acquisition, it is chosen to cut off the run by elapsed time rather than particle count. So, the measurement in each position is performed for 15 seconds.

As mentioned above, different settings are required for different flow regions along diameter. Closer to surfaces, noise can be generated due to light scattering. Two important settings require a special selection regarding to these areas: i) laser power and ii) receiving unit power. The terms may differ according to each manufacturer, but the concept is similar. Laser power usually presents a spectrum in which the user can select according to the characteristics of the experiment. If the power of the laser unit is increased, the power of the receiving unit must decrease in order to avoid signal saturation. Also, noise filters levels might have to be changed.

4.4 Velocity Bias Correction

When choosing bias correction assessment, flow characteristics must to be taken into account. There are many techniques available. Each of them presents its own distinctiveness and restrictions to the physical phenomena happening in the flow, as described in Section 2.2. This paper proposes a combination of different techniques to access the velocity bias correction for velocity profiles measurements. Firstly, the flow is divided into the three regions, as described above.

Given that even time sampling is free of velocity bias, it can be used in the flow region where the requirements are met, that is the core flow region. However, as the particle arrival rate varies significantly near the surface, even time sampling method is not indicated. Thus, transit time weighting becomes more appropriate. For this reason, the center part of the flow is accessed by even time sampling and transit time weighting techniques, for comparison.

5. RESULTS

5.1 Repeatability

The first assessment is related to the repeatability of the readings. Measurement repeatability is defined as the closeness of agreement between measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions such as: i) same operators, ii) same measuring system, iii) same operating conditions and same location and iv) replicate measurements on the same or similar objects over a short period of time (J.C.G.M., 2008). Also, it is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement.

The expanded uncertainty is used as a numerical parameter for this evaluation. It provides an interval that encompass the distribution of values that could reasonably be attributed to the measurand (J.C.G.M., 2008). The expanded uncertainty U can be expressed a Eq. (5).

$$U = K_p \cdot y_{std} \tag{5}$$

Where: y_{std} is the standard deviation of the measurand, $\bar{y}$ is the measurand mean and K_P is the coverage factor for a certain confidence interval. Hence, the measurand Y can be expressed as $Y = \bar{y} \pm U$.

To evaluate repeatability, three readings were acquired for five distinct positions along the measurement cross-section. The relative expanded uncertainty U is calculated for the average of the three running tests using Eq. (5). It is defined a confidence level of 95%, resulting in a coverage factor K_P = 4.31 for 2 degrees of freedom. In each test run i, the average of the velocity reading v_i is compared to an error bar of the average velocity in each radial position and its uncertainty.

Table 2 shows the velocity mean value and its uncertainty. Also, Figure 6 depicts the distinct readings for each point with error bars.

Table 2 - Uncertainty assessment

(r/R)	v_1 [m/s]	v_2 [m/s]	v_3 [m/s]	U [m/s]
-0.93	10.32	10.30	10.33	0.07
0.66	13.31	13.28	13.36	0.17
0	14.78	14.79	14.76	0.07
0.66	13.35	13.34	13.31	0.11
0.93	10.31	10.30	10.32	0.05

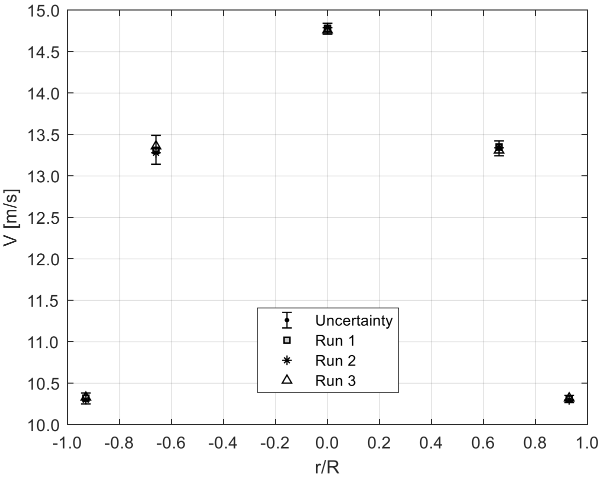


Figure 6. Repeatability evaluation

Figure 6 illustrates that, considering the readings v_1 with their expanded uncertainty with 95% confidence level, for all five points under evaluation measurements remain in the region $Y = \bar{y} \pm U$. Actually, for all radial positions at the three test runs, results are overlap. Thus, in terms of repeatability, experiments in NEMOG's wind tunnel in closed loop assembly with LDV are considered validated.

5.2 Reference velocity profile

The second part of the results analysis is the comparison between the experimental velocity profile and a reference velocity profile. Eq. (6) presents the analytical velocity profile for a fully developed turbulent flow (DE CHANT, 2005).

$$u(r) \sim \left\{ \sin\left[\frac{\pi}{2} \left(\frac{r}{R} \right)^{\frac{1}{2}} \right] \right\}^{\frac{1}{2}} \tag{6}$$

Figure 7 shows the experimental velocity profile and the reference velocity profile at a Reynolds number of $2.3\text{x}10^5$. The turbulence levels, illustrated in Figure 8, are higher near the pipe's wall than in the core flow region, as expected. This implies a higher uncertainty in those areas.

According to the reference axis of Figure 7, the window is located in *r/R* = -1 whilst the unaltered pipe wall is located in *r/R* = 1. In the region of r/R from -1 to -0.7 in this coordinate system, the highest relative error to the analytical curve fit is between 0.09% and 19.31%. Similarly, in the region of r/R from +0.7 to +1, the maximum and minimum relative errors are, respectively, 46.35% and 1.11%. The average relative error is 5.57% in the region near the window and 13.9% near the unaltered pipe wall region.

For the core flow region, which is defined from -0.7 < *r/R* < 0.7, the maximum relative error is 2.07% whilst its minimum value is approximately 0.01%. The average relative error for the core flow region is 0.83%.

The higher deviation in the statistical data next to $r/R = 1$ can be possibly justified by remaining influence of the curve on the measurement cross-section. Results from Figure 7 indicate that the experimental velocity is not fully turbulent yet.

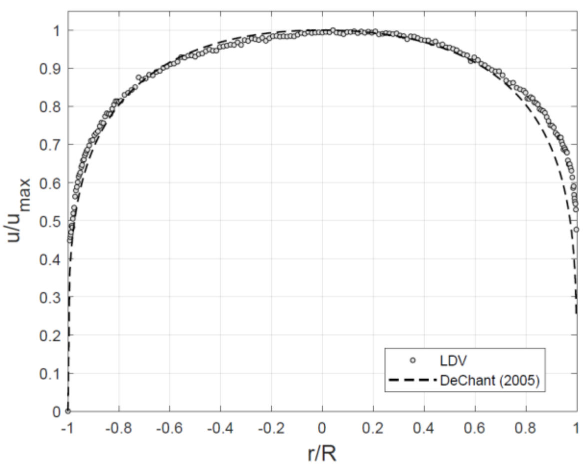


Figure 7. Velocity profile analysis

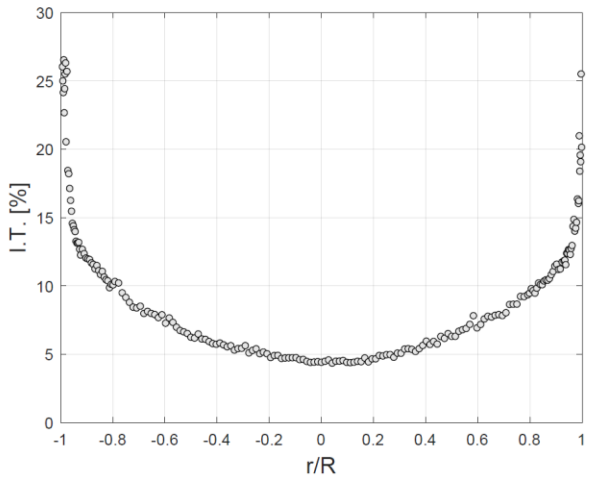


Figure 8. Turbulent Intensity [%]

5.3 Velocity Bias Correction

Figure 9 shows the relative difference between the velocity data without bias correction and the velocities values even time sampled, calculated as Eq. (7). Similarly, Figure 10 is a graphical comparison between the emssemble average and the transit-time corrected data, calculated through Eq. (8).

$$drel_1 = \frac{\overline{u}_E - \overline{u}_{ETS}}{\overline{u}_E} \tag{7}$$

$$drel_2 = \frac{\overline{u}_E - \overline{u}_{TTW}}{\overline{u}_E} \tag{8}$$

Where *drel₁* is the relative difference between the ensemble average and the even-time sampled data average, $drel_2$ is the relative difference between the ensemble average and the transit time weighted data average, $\overline{u}_E$ is the ensemble average without correction, $\overline{u}_{ETS}$ is the average of the even-time sampled data and $\overline{u}_{TTW}$ is the average of the transit-time weighted data. Note that it is not applied the relative difference absolute value for it is desirable to know if the corrected data is higher or lower than the enssemble average.

Results in Figure 9 for bias correction applying even-time sampling are unexpected, once biased results are expected to be higher than corrected results. That is, according to Eq. (7) and (8), no negative value is expected in Figure 9 and Figure 10. However, the majority of relative difference values between the results under even-time sampling and the ensemble average are significantly low. In the core flow region, as defined above, 100% of the absolute values of the relative differences are lower than 0.5%. The even-time sampling method cannot be used close to the wall. Therefore, no comment will be made regarding to such regions.

In Figure 10, results for bias correction applying transit time weighting are as expected in the core flow region. That is the ensemble average has a slight deviation to a higher value, resulting in positive values for the relative differences calculated through Eq. (8). This method is still criticized in recent papers for non-homogeneous particle arrival, such as close to the wall. That explain the higher difference for such region. However, the relative difference values in the core flow region between the results under transit time correction method and the ensemble average are significantly low. In the core flow region, as defined above, 100% of the absolute values of the relative differences are lower than 0.5%. Also, even close to the wall, the absolute values of the relative differences do not exceed 4%.

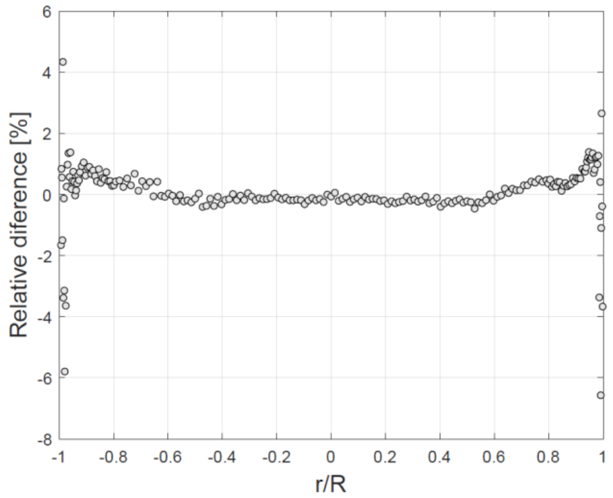


Figure 9 - Relative difference between uncorrected data (ensemble average) and even time sampled data average (*$drel_1$* – Eq. (7))

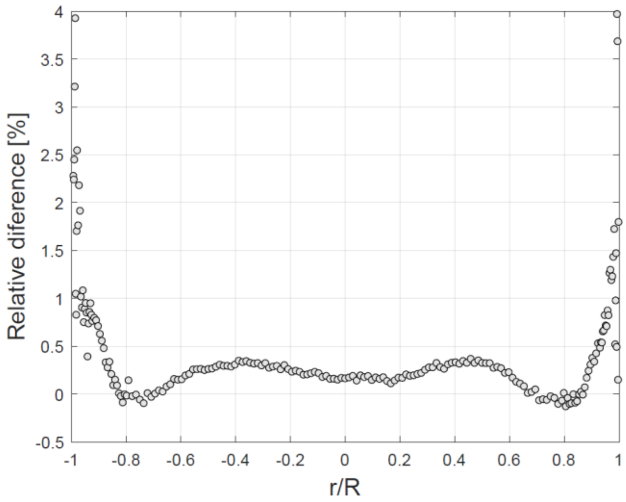


Figure 10 - Relative difference between uncorrected data (ensemble average) and transit time weighted data (*$drel_2$* – Eq. (8))

In the core flow region ($-0.7 < r/R < 0.7$), the results obtained under both correction methods agree with the confidence level of 95% previously defined in Section 5.1.

6. FINAL REMARKS

This paper discusses some aspects related to LDV installation in gas flow and about data treatment from LDV measurements.

The window designed to be installed in a 12 inches pipe has met the requirements, as it has as and advantage of possibility of cleaning the attached oil on the glass surface very efficiently in the experiment. Also, its format promotes minimum interference in tubing internal wall format, as shown in Figure 2, and, therefore, minimum internal flow disturbances.

Results from LDV are validated considering the repeatability analysis. In the velocity bias analysis, two methods are examined: even time sampled and transit time weighting. Results from both methods falls under the uncertainty range for the analyzed region of the flow ($-0.7 < r/R < 0.7$). Near the wall, transit time weighting shows an agreement with the expected behavior promoted by velocity bias, which is a slight deviation to a higher value when compared to the corrected mean value.

In future papers, it is expected a study of other methodologies to approach velocity bias correction in the near-wall region. The ITTT weighting correction method (Rodriguez et al. 2018) is an interesting prospect to such correction, due to the characteristics of the flow in the near wall region, including significant high turbulence level and high variability in data rate. Also, ITTT is the most recent developed technique in LDV data treatment at the present time.

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