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PERFORMANCE OF A TUBE BUNDLE FLOW STRAIGHTENER ON VELOCITY PROFILE ASYMMETRY REDUCTION IN A WIND TUNNEL FACILITY

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Abstract. Wind tunnels are equipment designed to establish flows under controlled and monitored conditions, promoting a known velocity profile. In this sense, a wind tunnel is installed with the aim of producing air flows for testing flow meters for flare gas applications. In this work, a unidirectional Laser Doppler Velocimetry is applied to measure velocity profiles in a wind tunnel with and without a flow straightener (FS) to evaluate the effects of the device in the development of the velocity field. The installation of the FS is performed at two distinct locations, 36 diameters (36D) upstream and 28 diameters (26D) downstream to the measurement section. Measurements are carried out at a Reynolds number of 2.4×10^5 in a position 36D downstream to the entrance of the wind tunnel. Asymmetry calculation is defined in this paper as the mean of the relative difference of axisymmetric measurement points relative to the tube's centerline. For each position of the FS, the velocity profile is measured three times to allow the evaluation of the repeatability of the flow velocity field. Results show that the placement of the FS downstream to the measurement section decrease the asymmetry of the flow velocity field from 5.4% to 1.9%, whilst placing the device upstream to the meter have turned the velocity profile even more asymmetric, increasing the asymmetry from 5.4% to 12%. This highlights the importance of evaluating the device positioning effect on the development of velocity profile.

Keywords: flow straightener, velocity profile asymmetry, wind tunnel, laser Doppler velocimetry

1. INTRODUCTION

Industries very often require flow rate measurement in operation, transport, or discharge lines of fluids. On the other hand, some flow measurement devices are sensible to the velocity field of the approaching flow. Additionally, there might be some spatial limitation in the plant, which constrains the mounting of a required straight tube section upstream from the flow meter in order to have a fully developed flow at the measurement section. A good solution to such spatial limitation is the installation of a flow straightener (FS) in the pipeline, which is a device that mitigates or removes swirl in the flow ISO 5167 (2003).

Flare stacks are safety devices often applied in oil rigs for the purpose of overpressure relief and emergency breaks. Hence, the gas flow meter applied to the device has requirements concerning this type of operation, such as: i) Being a non-intrusive meter; ii) has usually a set allowed measurement uncertainty. In this context, one of the main technologies for this application is the transit-time ultrasonic flowmeter, which are not intrusive flowmeters, but should operate under turbulent and fully developed flow conditions - symmetrical, therefore. However, the available space in oil rigs is usually restricted and many times do not allow the presence of the required straight tube length in order to have a fully developed velocity profile in the approaching flow. Thus, a flow profile factor, also called K-factor, is applied to the flow rate calculation. The K-factor is often calculated at the hand of numerical simulations. On the other side, those simulations are sensible to the inserted entrance and boundary conditions, as well as the turbulence model employed. For this reason, experimental testing is desired to validate simulation entrances and framework. In this sense, a wind tunnel is installed at the Flow lab of Research Group for Oil and Gas Flow and Measurement (NEMOG, in Portuguese), at Universidade Federal of Espírito Santo (UFES). The aim of this test bench is the evaluation of flare gas flowmeters.

Wind tunnel is an equipment designed to establish flows under controlled and monitored conditions, promoting a known velocity profile. Although flare operations do not allow the installation of obstructive devices in the flow line, a flow straightener may be applied to develop the flow in research facilities. On the other hand, one must check if the FS is

well positioned, installed, and performing its function properly. This guides the research carried out in this paper, which is the evaluation of the influence of a flow straightener on velocity profile asymmetry reduction in a wind tunnel.

2. LITERATURE REVIEW

2.1 Velocity flow field in circular pipes

The velocity profile changes as the flow advances in the longitudinal direction downstream from the pipe entrance, tube fittings (curves, bends, elbows) or fluid machines. When it reaches a sufficiently long straight tube section, the shear stresses of the flow are equalized, and the velocity distribution no longer changes. Hence, to achieve a fully developed state, a certain entry length is required (Fox et al., 2006; Hinze, 1959). Also, tube fittings, such as curves and bends, induce secondary and swirl flows (Martins, 2012). Thus, after curves it is also needed straight tube length in order to have a fully developed flow velocity field. In turbulent flows, the main velocity profile becomes fully developed within 25 to 40 diameters (Fox et al., 2006). On the other hand, swirl disturbances may remain up to eighty diameters downstream to a tube fitting (American Gas Association, 2007; Martins, 2012).

There is no universal relationship between the stresses field and the mean velocity field. Thus, turbulent fluid mechanics studies are compelled to rely in experimental data (Fox et al., 2006). The $1/n^{\text{th}}$ power-law velocity profile has still been applied as a representative approximation for flow distribution in circular pipes. This work proposes that velocity function is given as Equation (1), which represents half of the symmetric velocity profile of the pipe, with r ranging from 0 to R .

$$\frac{u(r)}{u_{max}} = \left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \quad (1)$$

Where $u(r)$ is the local mean velocity longitudinal component, u_{max} is the maximum mean velocity longitudinal component along the diameter, R is the pipe radius, r is the distance from the center axis towards the pipe's wall.

The Power-law exponent $1/n$ is an empirical function of the Reynolds number Re and pipe roughness. In 1933, Nikuradse has performed velocity profile measurements for a certain Reynolds number range, varying from 4×10^3 to 3.2×10^6 . Hence, by empirical observation, the author indicates that $1/6$ is a good fit for $Re = 4 \times 10^3$, $1/7$ is to be applied for a Reynolds number range from $Re = 1 \times 10^4$ to $Re = 1 \times 10^5$ and the exponent increases to $1/10$ at $Re = 3.2 \times 10^6$.

Lawrence De Chant (2005) has shown that the power-law is not only a viable empirical relationship for turbulent mean velocity profiles, but the analytical solution of a nonlinear boundary value problem based on large Reynolds number asymptotic closures. In his work, he also obtains another velocity profile for fully developed turbulent flow that is in good agreement with the power-law. The velocity profile proposed by De Chant is presented in Equation (2). It represents half of the symmetric velocity profile of the pipe, with r ranging from 0 to R .

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

2.2 Flow conditioners

A flow straightener is a device which removes or significantly reduces swirl in the flow. In other words, the device accelerates the development of the flow, shortening the required straight tube length upstream from the section of interest, for example, the location of a flow meter.

Although flow straighteners are not standardized, some examples of flow conditioners and flow straighteners are given in ISO 5167 (2003), for example, tube bundle flow straighteners, the AMCA straightener and the Étoile straightener. On the other hand, it is not intended that the descriptions of flow straighteners and flow conditioners given in this standard should limit the use of other designs which have been tested and proved to provide required changes in the flow.

2.3 Laser Doppler Velocimetry

Laser Doppler Velocimeter (LDV) is very reliable and high data rate acquisition flow velocity measurement (Damacena et al., 2020). The device is said to be a particle-based velocity meter, that is, tracking particles are needed to perform the readings (Tropea et al., 2007). In fact, the device measures the velocity of particles spread in the flow. If the size and composition of the particles are chosen properly, one can assume that the velocity of the portion of fluid volume surrounding the particle is the same as its velocity (Tropea et al., 2007; Zhang, 2010).

The Doppler effect is a shift in the observed frequency (or wavelength) perceived by the receiver in the presence of relative motion concerning to a light source (Sears et al., 1984).

The Doppler effect happens twice in laser Doppler velocimetry measurements. 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 (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, in which two laser beams are emitted from the LDV's head through a converging lens. Under those circumstances, the pair of beams cross each other in the converging lens focal length forming a measurement volume, where the velocity measurement takes place. Thus, the LDV is a single point velocity measurement. To obtain a velocity profile in a duct, for example, the measurement volume must be moved across the tube's diameter with the use of a traverse system to gather distinct points velocity readings.

Each pair of laser beams can obtain one velocity component of the flow. Thus, to obtain a two component or three component velocity field, one must employ two and three pairs of laser beams, respectively.

3. METHODOLOGY

This section describes the experimental setup and methodology applied to perform the measurements.

3.1 Experimental Setup

The wind tunnel is mounted by several segments of polypropylene tubes, with an internal diameter of 11.5 inches (290 mm). The tubes are coupled by male-female flange type connections to guarantee continuity of the internal surface. It can assume both close and open circuit configurations. When mounted in a close circuit, the air is recirculated through a curve connecting the lower and upper branches. On the other hand, in open circuit configuration, the curve is replaced by a bell-mouth type nozzle. The wind tunnel is powered by an OTAM RA 1000 centrifugal blower, controlled by a Siemens variable speed drive. The flow rate can range from 0 to 12000 Nm³/h. A plenum box is installed between the lower branch and the fluid machine aiming to mitigate swirl promoted by the centrifugal blower. The facility has temperature and pressure sensors and is controlled remotely (automated) by LabView[®] supervisory system. A Laser Doppler Velocimetry system (LDV) is installed in the lower branch of the tunnel, 36 diameters (36 D) downstream from the entrance, which correspond to approximately 10.5 m. Figure 1 shows the wind tunnel as well as the LDV test section location. Also, both flow straightener positioning locations tested in this paper are depicted in Figure 1.

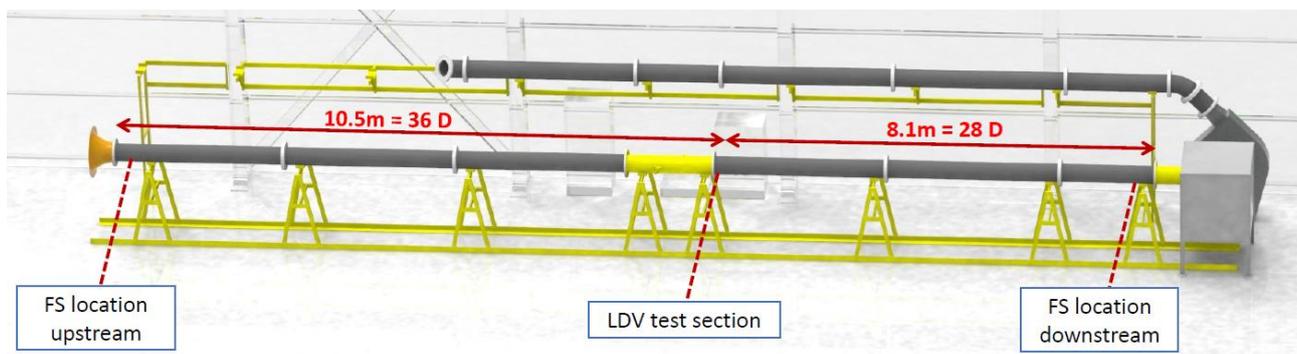


Figure 1. Wind tunnel sketch.

Tube bundle flow straighteners consist of a bundle of parallel and tangential tubes fixed together and held rigidly in the pipe. They are easy to build in a laboratory environment. For this reason, this type of FS has been chosen to be built and tested in this work for asymmetry reduction in the velocity profile.

The tube bundle flow straightener is mounted by twenty-one 2 inches aluminum tubes and fourteen 1-inch aluminum tubes, therefore, the bundle is not completely symmetrical. At the same time, the device has a longitudinal length of one diameter. Figure 2 presents the flow straightener installed in the wind tunnel pipe.

The flow straightener is fixed to the wind tunnel wall by three screws. The fixation is such to ensure that the various tubes are parallel to each other and to the pipe axis so the straightener itself will not introduce swirl to the flow, as described as an installation requirement in ISO 5167 (2003).



Figure 2. Flow straightener installed in the pipe.

3.2 Measurement methodology

A TSI Inc. unidirectional laser Doppler velocimetry system is applied to measure the velocity profiles presented in this paper. For this reason, only the axial velocity component is measured in these experiments. Laser Doppler Velocimeter (LDV) is a single point velocity meter, thus, a *Velmet Inc.* positioning traverse coupled with an VEXTA step motor is linked to the LDV software to move the LDV's measurement volume throughout the cross-section diameter of the tube to gather the full velocity profile for each testing configuration.

LDV is a particle-based velocity measurement technique, therefore, liquid atomized particles of *Bis(2-ethylhexyl)Sebacate* were used as seed particles for the readings. This atomization fluid is mentioned in Tropea et al. (2007) to be applied in air flow applications. Also, *TSI Inc.* six-jet atomizer model 9306 is employed to obtain the atomized particles with diameters of the order of $6 \mu\text{m}$. One can refer to the work of Tropea et al. (2007) for more information about the atomizer and atomizing fluid applied, which are detailed in his work. The LDV system hardware is presented in Figure 3, depicting the wind tunnel cross section, the Laser power-sight module, the FSA processor and the computer with the LDV software (Folwsizer64).

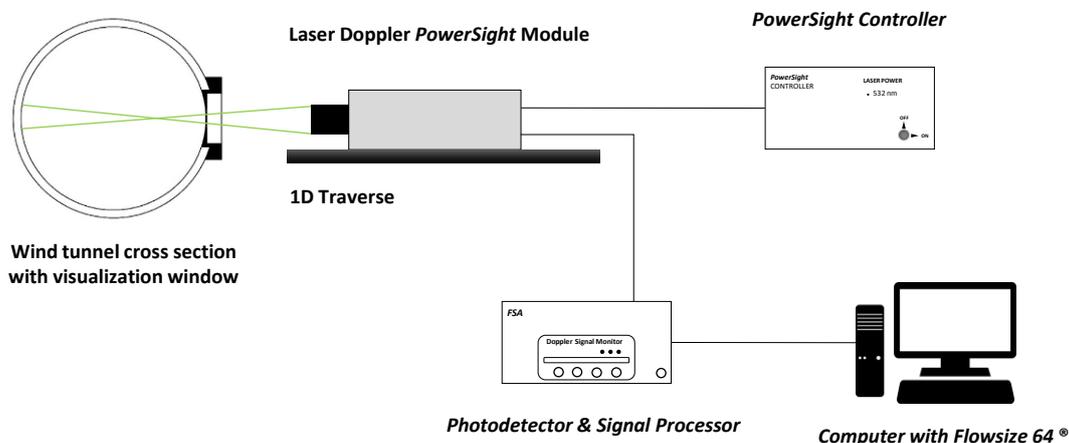


Figure 3. LDV system hardware. (Source: Franco, 2020).

All measurements are carried out at a Reynolds number of 2.4×10^5 . Moreover, all experimental velocity profiles presented in this paper are composed of sixty-five data points equally distributed throughout the measurement cross-section diameter, distanced by 5 mm. In each position, data acquisition is performed for sixty seconds. Data processing is performed by an FSA 8500 processor by *TSI Inc.* The data is then exported to a dual processor computer and processed in MATLAB®.

3.3 Velocity profile analysis

The velocity profile is measured three times for each testing configuration of the flow straightener positioning. That is, the velocity profile is obtained three times for the same flow conditions. Under those circumstances, one can compare the velocity readings deviation point by point to check for repeatability. That way, the measurement methodology can be validated.

In order to verify the errors of different experiments with the same flow conditions, the velocity readings are compared in terms of relative deviation, presented in Equation (1).

$$D_{relji} = \frac{u_{RUNi} - u_{RUN1}}{u_{RUN1}} \times 100 \quad (1)$$

Where D_{relji} is the relative deviation between readings in a point j along the diameter, that is, $j=1,2, \dots, 65$; u_{RUN1} is the first reading; and u_{RUNi} is the second and third readings for that measurement point ($i = 2, 3$). For the purpose of numerical continuity, runs 5 and 6 are compared to run 4, which regard the same flow conditions. The following runs apply the same logic for comparison.

The maximum and minimum relative differences represent the upper and lower limits of the variations between the velocity profiles. It is chosen to apply the median as opposite as the mean value to represent the overall difference between runs, because the former is more robust in the presence of outliers.

Equation (3) calculates the standard deviation between readings for a single measurement point, out of the 65 composing the velocity profile. Hence, a statistical analysis is needed to verify the repeatability of the measurements. Because the velocity gradient is larger close to the pipe walls, the velocity profile is divided in three parts when calculating the statistics of the relative deviation. Figure 4 depicts the division for the relative deviation analysis.

The first part of the velocity profile encompasses the region in which $-1 < y/R < -0.7$, according referential presented in Figure 4. Similarly, the second part comprise the region in which $-0.7 < y/R < 0.7$. Likewise, the third part of the velocity profile embody the region in which $0.7 < y/R < 1$.

The deviations are evaluated in terms of maximum, minimum and median. The latter is chosen as the central tendency as opposed to the use of the mean because the median is more robust in the presence of outliers. The statistical quantities are then evaluated according to the criteria: The first one is the consistency of the median of relative deviations in the same region of corresponding velocity profiles. That is, in a certain region (I, II or III), the median of the relative deviations should be around the same magnitude between experiments. The second criterium is that the maximum relative deviation should be no higher than 10%.

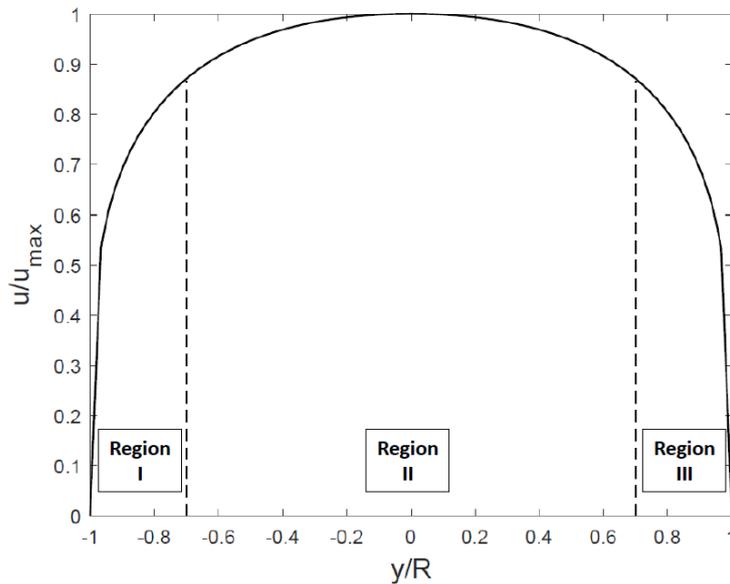


Figure 4. Zones for velocity profile analysis.

3.4 Asymmetry analysis

Asymmetry calculation is defined in this paper as the mean of the relative difference of axisymmetric measurement points relative to the tube's centerline, as given in Equation (2).

$$A_i(\%) = \frac{|u(i) - u(\text{length}(u) + 1 - i)|}{u(i)} \times 100 \quad (2)$$

Where i ranges from the first index of the velocity vector to the index immediately prior to the symmetry axis. That is $i = 1, 2, 3, (\dots)$, $\text{length}(u)/2$ (rounding to the lowest integer).

The velocity profile asymmetry is then characterized by the mean of the of the calculated relative differences for each measurement point, as follows in Equation (3).

$$AS = \sum_{i=1}^n \frac{A_i}{n} \quad (3)$$

Where AS is the asymmetry qualifier (mean asymmetry); n is half of the number measurement points, once the relative difference is calculated between two axisymmetric points concerning the pipe's centerline. Moreover, the maximum asymmetry is also evaluated as a secondary asymmetry qualifier.

4. RESULTS

The results are given for each of experimental setup configurations: i) No flow straightener; ii) Flow straightener downstream to the measurement section (before the plenum box); iii) Flow straightener upstream to the measurement section (after the bell mouth nozzle); and iv) Flow straightener upstream to the measurement section (after the bell mouth nozzle), but rotated 180°. The evaluation in 'iv' was performed taking into consideration that the FS used here is not symmetrical. Besides, the results obtained in configuration 'iii' do not represent the expected behavior for a flow passing through a flow straightener.

4.1 No flow straightener

The experimental velocity profile for the first configuration, which is without flow straightener, is shown in Figure 5. The results are compared against De Chant's (2005) velocity profile for fully developed turbulent flow, for reference. Three velocity profile readings are taken to evaluate repeatability of results.

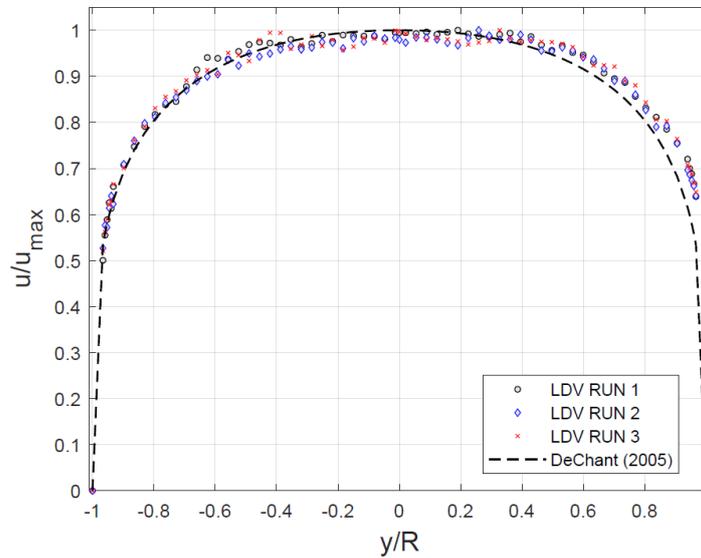


Figure 5. Velocity profiles for a setup without flow straightener.

Figure 5 shows three velocity profiles almost overlapping one another. On the other hand, an additional evaluation is required to check repeatability of results. As discussed in Section 3.3, the repeated velocity profiles are compared in this work by relative deviation. For that, the velocity profile is divided into 3 regions, which have different characteristics between each other. Relative deviation is applied to quantify a percentage of difference between one run and another. For that, the first run is used as the reference run whilst it is compared to the second and third runs, point by point, according to Eq. (1). The relative deviations are given in statistics of minimum, maximum and median when compared to the first run. The results are shown in Table 1.

Table 1. Relative difference of velocity profiles in Runs 2 and 3 compared to Run 1.

Radial Position	Minimum		Maximum		Median	
	Run 2	Run 3	Run 2	Run 3	Run 2	Run 3
$-1 < r/R < -0.7$	0.42	0.19	5.53	3.50	1.76	1.22
$-0.7 < r/R < 0.7$	0.02	0.07	4.13	4.30	0.92	1.36
$0.7 < r/R < 1$	0.20	0.16	3.01	2.34	1.08	1.11

The maximum difference between data in distinct runs for all regions of the flow is 5.53%, whilst the minimum difference is as low as 0.02%. The maximum median difference is around 1.76%. Such statistics point out repeatable results for velocity profiles without a flow straightener in the experimental setup. One can notice that for each metric, the maximum relative differences are found in the position close to the wall ($-1 < r/R < -0.7$).

Asymmetry is given according to the methodology presented in Section 3.4. The results are given in Table 2, where one can recognize that the mean asymmetry is in the order of 5.35%. Also, such asymmetry reaches up to 27.71% close to the wall for the flow without flow straightener. This result highlights the possibility of installing flow straighteners for asymmetry reduction.

Table 2. Asymmetry statistics for the flow without flow straightener.

Run	Mean [%]	Maximum [%]
1	5.17	27.71
2	5.40	21.62
3	5.49	24.53

4.2 Flow straightener downstream to the measurement section

The second configuration is placing the flow straightener downstream to the measurement section. Results for the velocity readings are shown in Figure 6. One can notice that the readings seem to slightly overlap De Chant's fully developed turbulent velocity profile. Also, on the right side of Figure 6 the experimental data seems to agree more with the reference velocity profile than in the previous setup configuration, without flow straightener. That can be notice comparing Figure 5 and Figure 6. As in the previous case, three velocity profiles are taken for the same experimental conditions.

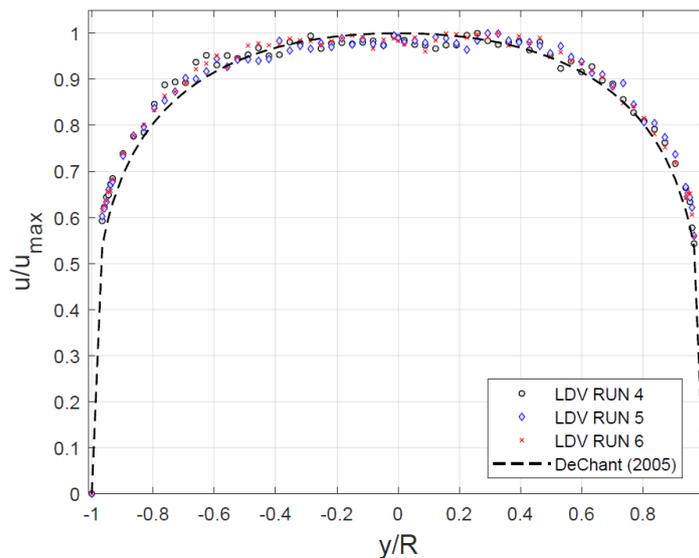


Figure 6. Velocity profiles for flow straightener downstream to the measurement section.

Figure 6 depicts three repeatable velocity profiles when the flow straightener is placed downstream to the measurement cross-section, immediately upstream from the plenum box. Applying the same coordinate system, the results for the relative deviation between runs are showed in Table 3.

Table 3. Relative difference of velocity profiles in Runs 5 and 6 compared to Run 4.

Radial Position	Minimum		Maximum		Median	
	Run 5	Run 6	Run 5	Run 6	Run 5	Run 6
$-1 < r/R < -0.7$	0.41	0.10	4.42	3.49	1.37	1.68
$-0.7 < r/R < 0.7$	0.02	0.13	4.63	3.38	1.15	1.12
$0.7 < r/R < 1$	0.35	0.13	6.98	4.60	1.11	1.50

In Table 3, one can notice a maximum relative difference of 6.98%, located in the radial position near the wall ($0.7 < r/R < 1$). On the other hand, the minimum relative difference is as low as 0.02%. Also, the median difference is less than 1.68%. Asymmetry is calculated and shown in Table 4.

Table 4. Asymmetry statistics for the setup with flow straightener downstream to the measurement section.

Run	Mean [%]	Maximum [%]
4	1.98	8.34
5	2.19	8.74
6	1.70	9.29

Mean asymmetry is in the order of 1.96%, whilst the maximum asymmetry calculated is up to 9.29%. The indices of asymmetry have shown to be lower than in the case where the flow straightener is not installed. There is at least a 59% reduction in the mean asymmetry and significant decrease in the maximum asymmetry as well.

4.3 Flow straightener upstream to the measurement section

The third setup configuration deals with the flow straightener mounted upstream from the measurement cross-section, immediately downstream to the entrance nozzle. The three velocity profiles for the same flow conditions are depicted in Figure 7.

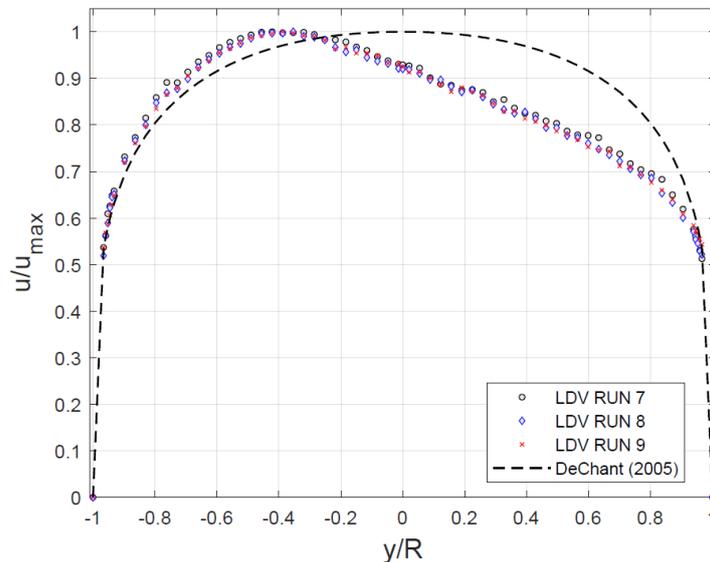


Figure 7. Velocity profiles for flow straightener upstream from the measurement section.

All three experimental velocity profiles seem to overlap each other. On the other hand, one can recognize a high level of asymmetry in the velocity profiles presented in Figure 7. The experimental velocity profile does not match the reference velocity profile for fully developed turbulent flow. That is, although the experimental velocity profile is repeatable, it is highly asymmetrical. Therefore, does not represent a fully developed velocity profile. In Table 5, it is presented a comparison between the three velocity profiles measured.

Table 5. Relative difference of velocity profiles in Runs 8 and 9 compared to Run 7.

Radial Position	Minimum		Maximum		Median	
	Run 8	Run 9	Run 8	Run 9	Run 8	Run 9
$-1 < r/R < -0.7$	0.03	0.01	2.13	2.62	0.60	1.34
$-0.7 < r/R < 0.7$	0.02	0.02	2.22	2.16	0.46	0.80
$0.7 < r/R < 1$	0.18	0.03	3.21	7.57	0.66	1.98

From Table 5, the maximum relative deviation between profiles is 7.57%, whilst the minimum relative deviation is 0.01. Also, the median deviation is as high as 1.98%. Table 6 presents the asymmetry results for the third mounting location for the flow straightener, immediately downstream to the entrance nozzle.

Table 6. Asymmetry statistics for the setup with flow straightener upstream to the measurement section.

Run	Mean [%]	Maximum [%]
7	12.13	19.58
8	12.21	19.69
9	11.79	19.70

Not only analyzing Figure 7, but also comparing the results presented in Table 6 with those presented in previous cases shown in

Table 2 and Table 4. One may recognize the increment in the asymmetry level for this third mounting location for the flow straightener. The results presented for the first case, where there was no flow straightener installed show a mean asymmetry of about 5% and the maximum values reaching up to 27.7%. In this case, the maximum asymmetry only reaches 19.70%. On the other hand, the mean asymmetry climbed to the order of 12%. If compared to the second case, the increment in asymmetry levels is even greater. The asymmetry levels had diminished in the previous case and increased to the current case. Mean asymmetry went from about 2% to around 12%.

4.4 Flow straightener upstream to the measurement section rotated 180°

The results presented in Section 4.3 were unexpected, where the asymmetry levels increased with the installation of the flow straightener upstream to the measurement section, which led to performing another set of velocity profile measurements. This fourth case preserves the mounting location of the flow straightener upstream to the measurement section but rotates it by 180 degrees in its longitudinal axis. The experimental velocity profiles are presented in Figure 8.

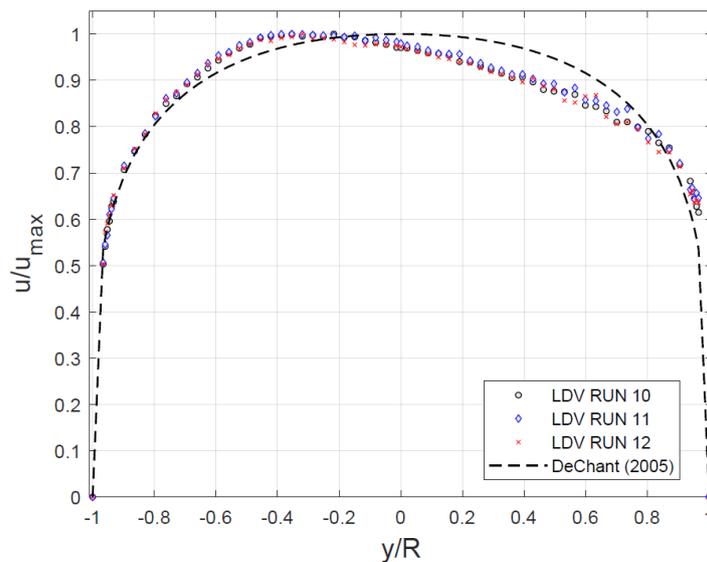


Figure 8. Velocity profiles for flow straightener upstream to the measurement section and rotated 180 degrees.

As showed in Figure 8, the data points seem to almost overlap each other in the respective measurement points and the quantitative difference between runs is presented in Table 7.

Table 7. Relative difference of velocity profiles in Runs 12 and 13 compared to Run 11.

Radial Position	Minimum		Maximum		Median	
	Run 11	Run 12	Run 11	Run 12	Run 11	Run 12
$-1 < r/R < -0.7$	0.00	0.02	2.92	5.49	0.53	0.66
$-0.7 < r/R < 0.7$	0.01	0.01	1.13	2.76	0.45	0.62
$0.7 < r/R < 1$	0.30	0.13	4.27	4.34	1.85	1.42

The maximum relative difference is located near the wall ($-1 < r/R < -0.7$) and reaches 5.49%, whilst the minimum relative difference is 0.00%. Also, the median difference is no greater than 1.85%. Those statistics point to repeatable results, as in previous cases. Asymmetry statistics are presented in Table 8.

Table 8. Asymmetry statistics for the setup with flow straightener upstream to the measurement section rotated 180 degrees.

Run	Mean [%]	Maximum [%]
10	7.02	22.26
11	6.92	27.47
12	6.55	26.19

As in the previous case, the experimental velocity profile exhibits an asymmetrical shape. The shape of the velocity profile looks similar to the previous case, although slightly more symmetrical. Results in Table 8 agree to this conclusion, once the mean asymmetry has decreased from around 12% to the order of 7%. Also, the maximum asymmetry reaches 27.47%.

5. FINAL REMARKS

In this paper, a flow conditioner is evaluated at two mounting locations in a wind tunnel. Also, the experimental velocity profile is measured three times for each setup configuration, to evaluate the repeatability of results.

The first set of experiments have demonstrated precision in the measurement by the means of repeatability. With no flow straightener installed, the velocity readings have a maximum relative difference of 5.53% and a median difference up to 1.76%. Therefore, the measurement methodology is validated. Moreover, the asymmetry level is evaluated according to Section 3.4. The results point to a maximum asymmetry of the order of 27%, whilst the mean asymmetry is around 5.4%. Hence, a velocity profile measured without the flow straightener is in hand as a reference for comparison with the other three experimental setups.

A plenum box is usually installed in a wind tunnel facility to mitigate the swirl effects provoked by the fluid machine in the upstream line. On the other hand, there can be remaining swirl effects that the plenum box is not capable of attenuating. The first flow straightener mounting location studied is 28D downstream to the LDV test section, immediately upstream to the plenum box. This mounting setup aims to investigate a correction in the swirl effects induced by the fluid machine in the upstream line. Results for this setup have also shown repeatability of the measurement, reaching a maximum difference of 6.98% and a median difference of 1.68%. The insertion of a flow straightener downstream from the meter induced a 59% reduction in mean asymmetry level, which dropped from around 5% to approximately 2%.

The second installation location of the flow straightener is 36D upstream from the LDV test section. Once again, the velocity profile measurements have shown to be repeatable, presenting a maximum relative deviation between runs of 7.57%. In like manner, the median deviation is no greater than 1.98%. On the other hand, the asymmetry levels presented an unexpected behavior. In fact, instead of inducing a decrease in asymmetry with the installation of the flow straightener, the installation of the FS in such location has provoked an increase in the mean asymmetry level from 5.4% to 12%. Because the results showed a significant deviation from the expectations, another set of tests was performed with the flow straightener rotated by 180 degrees on its longitudinal axis. Although the asymmetry levels have decreased in comparison to the unrotated FS, such maneuver did not lead to a correction in the effects of the flow straightener in the flow when positioned upstream from the metering cross section. The asymmetry is about 6.8%, which is still slightly higher when compared to the velocity profile without the flow straightener. Thus, it can be concluded that the flow straightener evaluated in the wind tunnel is only effective when stalled downstream to the measurement section, before the plenum box.

A further study may clarify why the flow straightener has provoked such results when installed upstream to the meter. As there is a shift in the main velocity component of the flow, the quantity of motion may be transferred to the secondary velocity components, which were not measured because of the lack capability of the unidirectional meter. Thus, future

work might measure the secondary velocity components to master such behavior. The understanding of the results shows that flow straighteners must be tested to check for mitigation in flow asymmetry.

6. ACKNOWLEDGEMENTS

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