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FLOW OVER STATIC SMOOTH CIRCULAR CYLINDER IN WIND TUNNEL

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Abstract. *The current study investigates the flow characteristics over a static smooth circular cylinder at varying Reynolds numbers. Flows over circular cylinders are well-studied and understood in fluid dynamics, making them crucial for validating experimental procedures, calibration of measuring equipment and computational codes, and gaining knowledge about the process. This study aims to determine the pressure coefficients of the flows over the cylinder at different Reynolds numbers, and to assess the validity of the wind tunnel, and pressure sensors used for the research. The results indicate that the pressure sensors delivered expected outcomes for the pressure coefficient.*

Keywords: *Wind tunnel, Cylinders, Pressure, Experimental.*

1. INTRODUCTION

The wind tunnel is a tool for studying the aerodynamic phenomena of bodies immersed in a flow. They are also widely used for validating surveys that use CFD. The main objective of this equipment is the simulation of the effects of flow on solid bodies for scientific study, contributing to the determination of several parameters in projects of many equipment, structures, among others. Among the various ways of measuring aerodynamic loads in the wind tunnel, there is the aerodynamic balance, which is considered quite complete and widely used. (Soares; Neto and Silva, 2019).

Francis H. Wenham, in 1871, was the first researcher to create a wind tunnel and use it for experiments, and since its creation, over 150 years ago from the date of this work, they are considered important tools for aerodynamic study and research. (Souza Junior; Ferreira and Leta, 2012).

NASA (National Aeronautics and Space Administration) divides wind tunnels into two large groups, depending on the environment in which the fluid enters the tunnel, open return wind tunnels and closed return wind tunnels, with subgroups for each type. The wind tunnel used to carry out this work is classified as an open return wind tunnel, subsonic sucker type.

This wind tunnel is classified and characterized by Barlow (1999) as equipment widely used for instructional and research purposes of fundamental phenomena. In addition, it is also considered a low-cost tunnel that occupies a small physical space, making it a more accessible equipment.

The constructive elements of this equipment are divided into 4 main parts, contraction (where the screen and honeycomb and the high pressure and low-pressure outlets are installed), test section (place where the body to be studied is positioned), diffuser, and propulsion system (Queiroga and Viana, 2021), which can be seen in Figure 1.

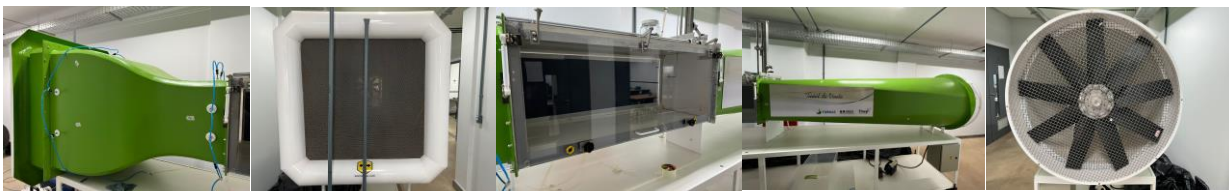

Figure 1. Section of the wind tunnel (contraction, honeycomb, test section, diffuser and thruster)

The wind tunnel used in the development of this work operates at velocities between 5.0 m/s and 30 m/s, which is considered subsonic. Furthermore, the fluid that is used in the flow promoted by the tunnel (through the exhaust) is the atmospheric air itself, therefore it is an open return wind tunnel of the suction type.

The other equipment that makes up the wind tunnel are the pressure modules and the aerodynamic scale. The aerodynamic balance used does not interfere with the flow as it is located outside the tunnel, behind the test section. According to Égea and Coimbra, (2017), the determination of forces for the external model is performed through mechanical elements, and is more applied in subsonic wind tunnels. After determining the forces, it is through a computational interface that all information about the effects of flow on the test model is acquired (Smith et al., 2009). It is noteworthy that the pressure data also follow the same pattern.

Static pressure is measured through a small hole drilled in the surface of the cylinder, which is connected to a manometer or pressure transducer. (Miranda, 2019). In the case of the presented work, the pressure tap is connected to the pressure module of the tunnel itself.

The objective of the present work is to investigate the characteristics of pressure, drag and lift on a static smooth circular cylinder under several Reynolds numbers, determining their respective coefficients, aiming to validate the use of the wind tunnel for future experiments on different bodies, so that if the results obtained by the aerodynamic scale and/or pressure module are not true, it will be necessary to calibrate the equipment.

2. METHODOLOGY

The presented work was divided into two stages, both using the same cylinder, with the first stage referring to the execution of the experiments with the objective of obtaining the drag and lift coefficients in a static smooth circular cylinder, with the use of the aerodynamic balance. The second part is restricted to obtaining the pressure coefficient around the same cylinder, using the pressure tapping on the cylinder itself and the pressure module of the wind tunnel.

The velocities used in the experiments can be obtained directly by the "AeroAlcool" software, through the speed setpoint chosen by the operator, or indirectly, through the rotation controller of the tunnel fan motor. For the development of this work, it was preferred to obtain the flow velocity indirectly, aiming to reduce the velocity fluctuations generated when using the setpoint directly in the software. In addition, it is worth mentioning that the tunnel used to carry out the experiments works with velocities between 5.0 and 30 m/s, which represent a Reynolds number in the range of $2.54x10^4\ to\ 1.52x10^5$.

It is important to emphasize that tests were carried out with the dirty wind tunnel, and others carried out after cleaning the wind tunnel, also to verify the influence of dirt particles on the results and to determine a periodicity that the cleaning of the equipment should be carried out for the carrying out the tests.

The time of each test of the experiments aimed at obtaining the pressure coefficient was determined and defined from statistical analyzes of variance and sampling power for times from 30.0 to 180 seconds.

The instrument used to support the cylinder was the aerodynamic balance, which is positioned on the outside of the test section of the tunnel as can be seen in Figure 2, which does not generate any interference in the flow. This balance has an acquisition frequency of 3.0 Hz, which is considered low for the flow velocities studied, thus requiring a longer test time.

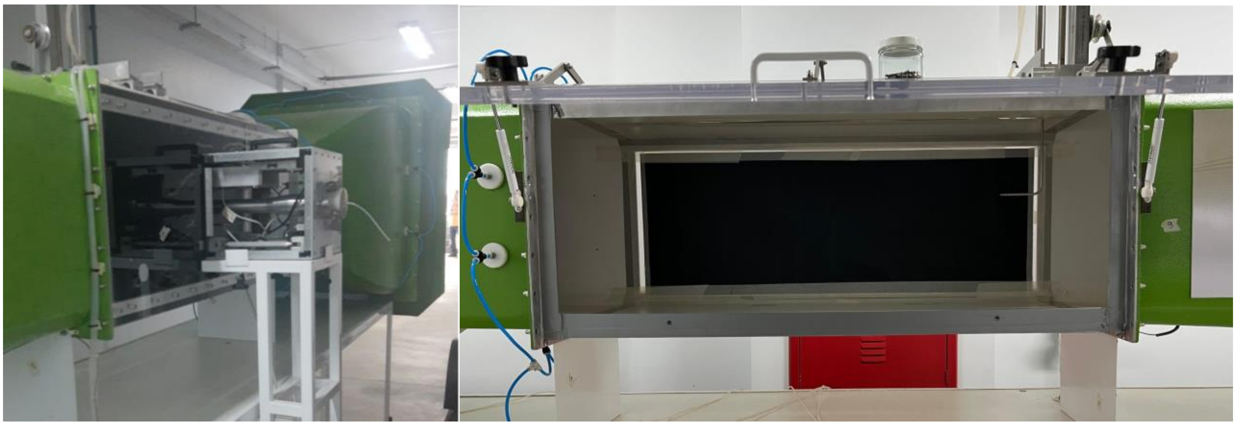

Figure 2. Outside air balance positioning and open and empty test section

2.1 Determination of test time

To determine the test time, tests were carried out in the wind tunnel using the cylinder at an angle of 0.0°, inside the test section, with times of 30 s, varying in 30 s, up to a maximum time of 180 s. Every 30.0s of the tests it is possible to obtain 180 points, therefore, in the time of 30.0s, 180 values of pressure difference were obtained and the time of 180 s with 1080 values. At the end of the experiments, the mean of each pressure difference obtained at each time was calculated and an analysis of variance was performed between these means to determine whether they could be considered equal. If they are considered equal, it means that any test time used in the next experiments will not influence the final result.

It is important to emphasize that the tests were carried out for each rotation that will be used later in the other experiments related to pressure, being 400, 600, 1000 and 1400 rpm, and that each rotation was analyzed separately, that is, the times of 30, 60, 90, 120, 150 and 180 s for 400 rpm, then for the others.

Through the tests it was determined that the time of 30 s could be used for the cylinder pressure experiments. In addition, a sampling power test was performed to determine the number of replicates necessary to obtain a 95% reliability for determining the test time, aiming at greater confidence and criteria in determining the time.

2.2 Velocity determination in the test time

The experiments carried out to determine the flow velocity were performed with a time of 30s per test, with the test section of the tunnel empty. With this, the pressure difference of the convergent section of the tunnel was obtained, making it possible to calculate the velocity V_2, by Bernoulli equation:

$$V_2 = \sqrt{\frac{2\Delta P}{\rho(1-\beta)}} \quad (1)$$

here $\boldsymbol{\beta}$ is a dimensionless value determined by the square of the areas of the entrance and exit sections of the convergent section of the wind tunnel, $\boldsymbol{\Delta P}$ is the average pressure difference between these two sections for a time of 30.0 s, obtained through the tests carried out in the wind tunnel, and finally $\boldsymbol{\rho}$ is the specific mass of the fluid, which in this case was atmospheric air. All quantities follow the international system of units (SI). The convergent section of the tunnel can be seen in Figure 3, so that the pressure difference obtained is through the points HP (High Pressure) in red, and LP (Low pressure) in blue. The areas used for the calculation refer to the location of high and low-pressure points.

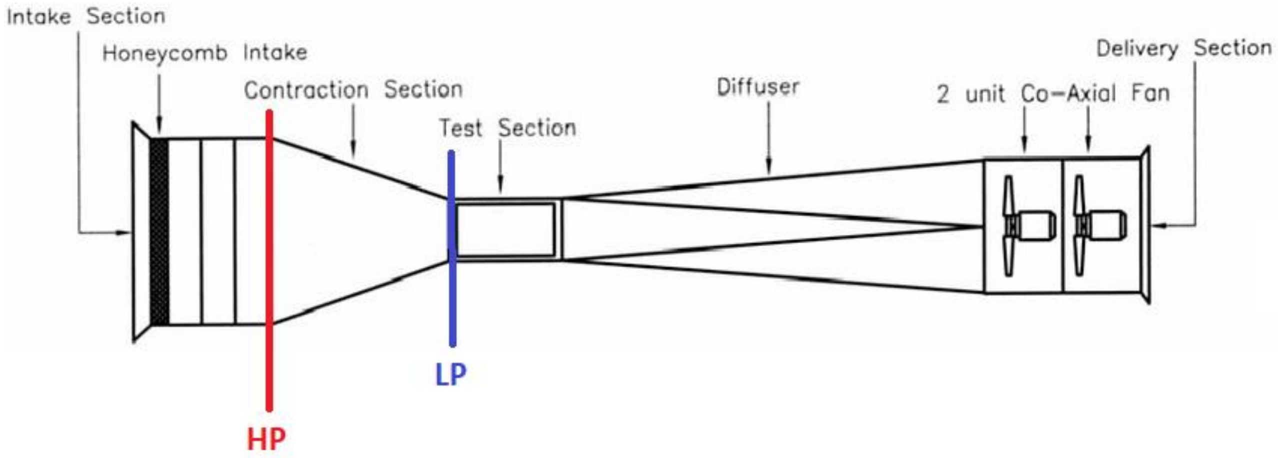

Figure 3. sections of the wind tunnel (contraction, honeycomb, test section, diffuser and thruster)

A time of 30.0 s per test was defined because the pressure difference between the sections did not have a large fluctuation, not generating a large variation in its average value, which was used in Eq. (1), so the same time as the tests carried out to obtain the pressure coefficient was defined for this experiment, which will be discussed later in this work.

The rotations used vary from 200 rpm to 1400 rpm, with a step of 100 rpm. With this, an average pressure difference was obtained for each rotation, which was later used to calculate the velocity.

The experiment to obtain the flow velocity was carried out the first time, right after cleaning the wind tunnel, and the second time after 2 months of tunnel use, to evaluate a possible interference of dirt in the velocity of the flow projected by the wind tunnel fan. tunnel.

From the completion of the experiments of test time and speed within the test section, it was possible to proceed with the other experiments of this work.

2.3 Pressure coefficient

The cylinder used for the experiments to determine its pressure coefficient has only one pressure tap, located in the middle of its length. Therefore, it was necessary to rotate the cylinder for each test with angles ranging from 0 to 180°, and a step of 10° per test, totaling 19 tests lasting 30.0 s each. Each angle was measured using a protractor, which is positioned at the rear of the aerodynamic balance, and for this experiment, it was used only as a support for the cylinder and for orientation of the angle used. In Figure 4, the cylinder positioned in the test section and the balance protractor can be seen.

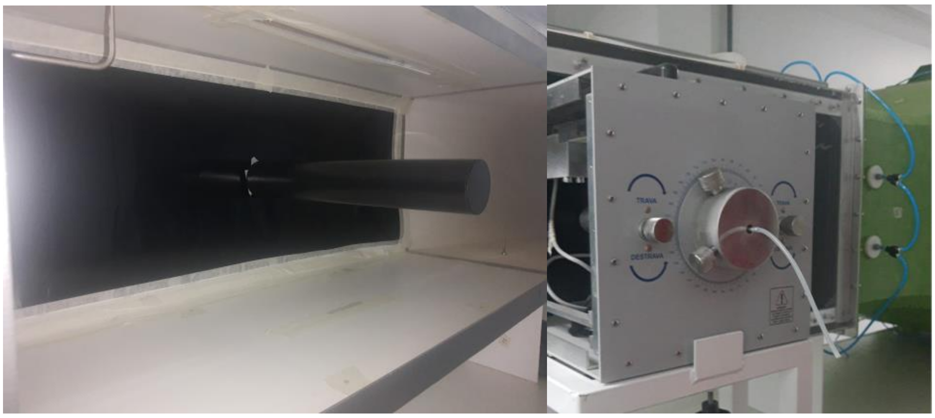

Figure 4. Cylinder positioned inside the test section and aerodynamic scale protractor outside the test section

For this experiment, the low-pressure intake of the tunnel's converging section was used, and the pressure intake of the cylinder itself to obtain the necessary pressure difference for the calculation of the pressure coefficient.

The velocity of each test was obtained as a function of the rotations of 400 rpm, 600 rpm, 1000 rpm and 1400 rpm, with 2 replicates for each rotation. the behavior of the cylinder pressure curve at different Reynolds numbers.

The calculation of the pressure coefficient was performed according to Eq. (2).

$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho {V_\infty}^2} \tag{2}$$

here: $\boldsymbol{P}$ is the pressure on the surface of the cylinder in θ°, $\boldsymbol{P}_\infty$ represents the dynamic pressure of the frontal stagnation point, $\boldsymbol{\rho}$ is the specific mass of the fluid and $\boldsymbol{V}_\infty$ represents the flow velocity, which for the case of this work is calculated from the pressure difference for each set speed.

The test time was defined through an analysis of variance, and the number of replicates necessary to obtain a 95% reliability was determined through the sampling power test. For this purpose, times from 30 s to 180 s were selected, with a variation of 30 s each, and a comparison was made between the means and variances of each time to assess the best time for each test.

The first experiment was carried out right after the complete cleaning of the wind tunnel and was repeated 2 months after the tunnel was cleaned in order to evaluate a possible interference of dirt in the results.

Remembering that all specific mass values used in the equations were used through what was provided by the "AeroAlcool" software, therefore, depending on the climatic conditions at the time of the experiment, there was a slight change in its value, but not much important to the point of altering the result if the same value were used for all tests.

3. RESULTS

For the determination test of the test time, several experiments were carried out with several rotations for different times using the test section of the tunnel containing the cylinder, in order to obtain the pressure difference between the high-pressure region of the converging section of the tunnel and cylinder pressure tapping. The mean values obtained for the pressure difference depending on each parameter used can be seen in Table 1.

Table 1. Table of parameters used for the test to determine the test time for pressure with a rotation of 400 rpm

	400 RPM (Re = 36489)			
Rep.	**1**	**2**	**3**	**4**
30s	28,24	27,23	28,81	30,20
60s	28,04	27,77	26,68	29,56
90s	27,98	25,75	29,19	28,84
120s	27,94	26,28	28,91	28,49
150s	27,98	27,33	26,94	28,16
180s	28,02	28,59	28,39	27,97

For the other rotations used in the experiments, the same pattern was obtained and the same analyzes were performed.

Through the simple arithmetic mean and the standard deviation between the means of each replica, it was possible to perform the analysis of variance in order to analyze whether the means between each time and each replica can be considered equal, making it possible to considerably reduce the test time.

For the statistical test, the null hypothesis was used considering the averages as equal, and the alternative hypothesis that not all are equal, with a significance level of 0.05, or 5.0%, bringing a reliability of 95%. One test was performed for each rotation. For each rotation tested, the time factor was considered in 6 levels, in the values indicated in Table 1. The result obtained through the analysis of variance for the rotation of 400 rpm shows that all means of each time are considered equal. This result can be verified at the P-value greater than the significance of 0.05, thus resulting in the rejection of the alternative hypothesis, as can be seen in Table 2.

Table 2. Variance Analysis for 400 rpm rotation

Source	**LD**	**SQ Seq**	**Contribution**	**SQ (Aj.)**	**QM (Aj.)**	**F Value**	**P-Value**
TIME	5	2,394	10,16%	2,394	0,4787	0,41	0,837
Error	18	21,162	89,84%	21,162	1,1757		
Total	23	23,556	100,00%				

For the other rotations, the same result was obtained, that is, the alternative hypothesis was discarded, adopting the null hypothesis as true. The results for each rotation are shown in Table 3.

Table 3. Variance analysis for all rotations

Rot. (RPM)	**F Value**	**P-Value**
400	0,41	0,837
600	1,11	0,391
1000	0,31	0,902
1400	0,08	0,994

In this way, it is possible to conclude that the averages between the times from 30 to 180 s are considered equal, so for the experiments related to obtaining the pressure coefficient, it is possible to use 30 s as test time instead of some other longer time, bringing greater speed in obtaining results and carrying out the experiments as a whole.

Another test performed to reinforce this result is Tukey's, which was performed considering a 95% reliability index for the mean differences between the pressure difference values obtained for each test time. This test makes a comparison between pairs of factors, that is, between two times, combining all of them, and for the averages between the factors to be considered equal, their intervals must contain the point 0, as shown in Figure 5.

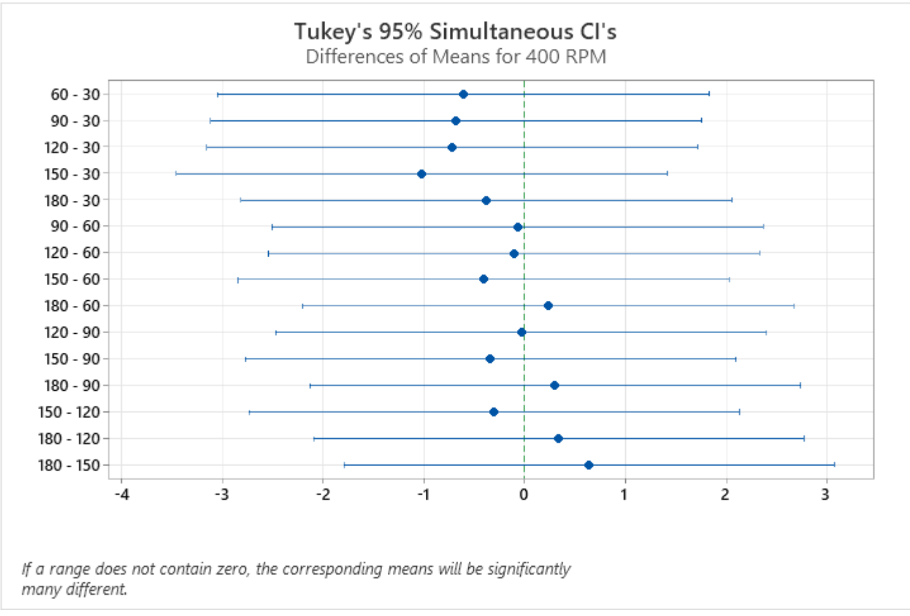

Figure 5. Tukey test for mid ranges at 400 rpm

For the other experiments, at other fan speeds, the same pattern is observed, all intervals between interactions pass through point 0, that is, all averages can be considered equal.

The power test was necessary to determine the number of replications necessary for this experiment to be considered reliable, that is, how many repetitions should be necessary for the results obtained to be considered true. This test was also performed individually for each rotation to more assertively determine the ideal number of replicates.

The result of one of the tests can be seen in Figure 6.

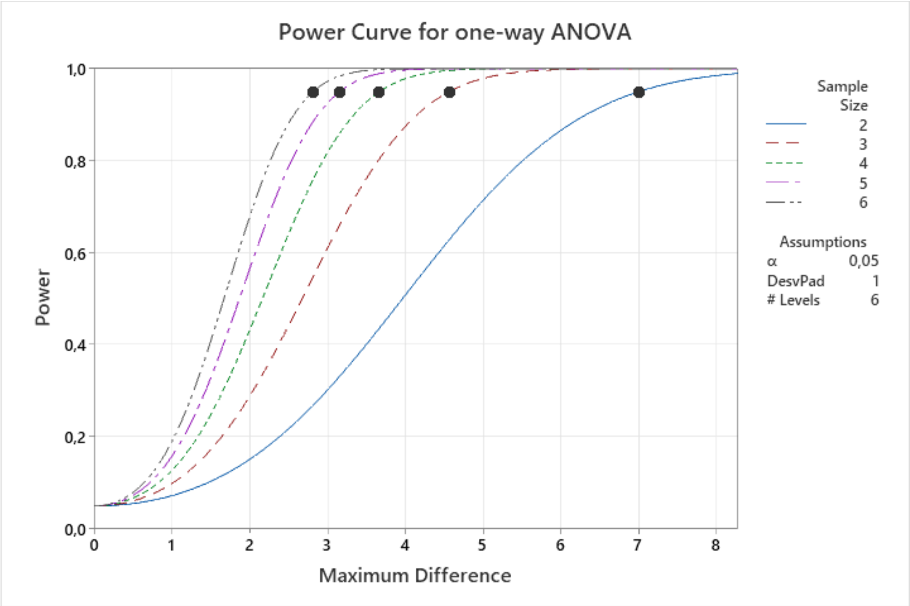

Figure 6. Power curve for 400 rpm

Through the graph it is concluded that 4 repetitions are an ideal value for this experiment, in which for 2 replicas it is possible to detect a maximum difference of 7.0 kPa between the averages. If only 3 replicates are performed, this perceived difference is between 4.0 kPa and 5.0 kPa, ideally 4 replicates, where the maximum perceived difference is very close if more repetitions are performed.

It is important to emphasize that the power test was performed using the standard deviation between the means for each time in each rotation and using the reliability set at 95%.

In the other tests for the other rotations, the same result was obtained, so 4 replicates were adopted as a standard for the experiment to determine the test time to obtain the pressure difference.

At the end of the part of determining the time used to carry out the experiments, the calculation of the flow velocity that would be used to obtain the pressure coefficient of the cylinder was performed. The experiment to determine the speed was also carried out right after cleaning the tunnel and also after 2 months of use, and its result can be seen in Figure 7.

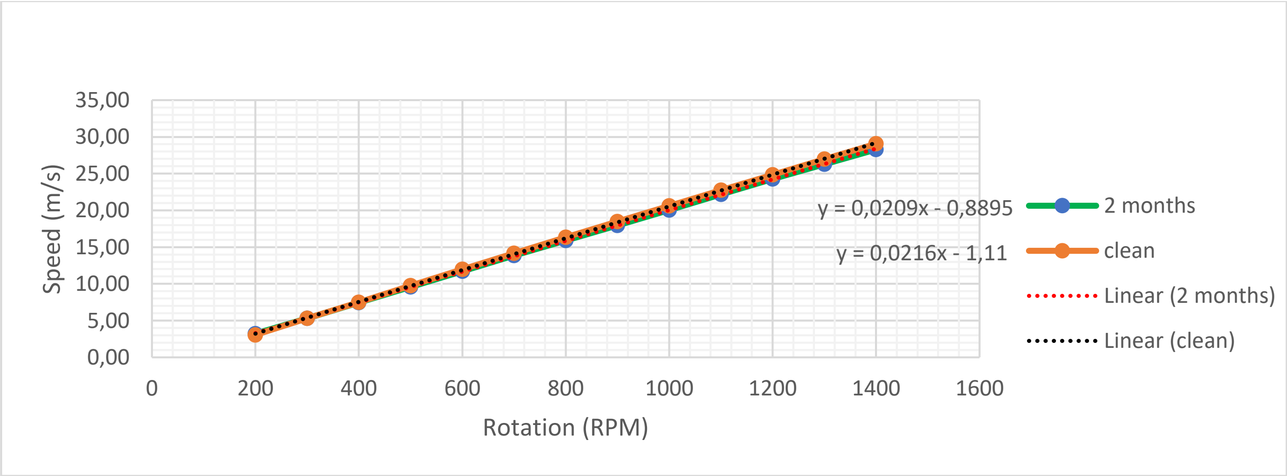

Figure 7. Velocity as a function of rotation with clean tunnel and after two months of use

Through the graph it can be seen that, after two months of use, there is a slight drop in the speed obtained, precisely because of the dirt in the tunnel hive. It is also possible to see this difference through the equation of each line in the graph.

Despite the little difference between the velocities obtained, it is interesting to carry out this test before each experiment involving flow velocity and that it is necessary to use it in some calculation, mainly in obtaining the drag, lift and pressure coefficients, because in their equations contain the square of the velocity, which generates a considerable difference during the calculations.

In the experiments to determine the cylinder pressure coefficient, the first test was carried out, with the wind tunnel clean, and the result obtained can be seen in figure 8.

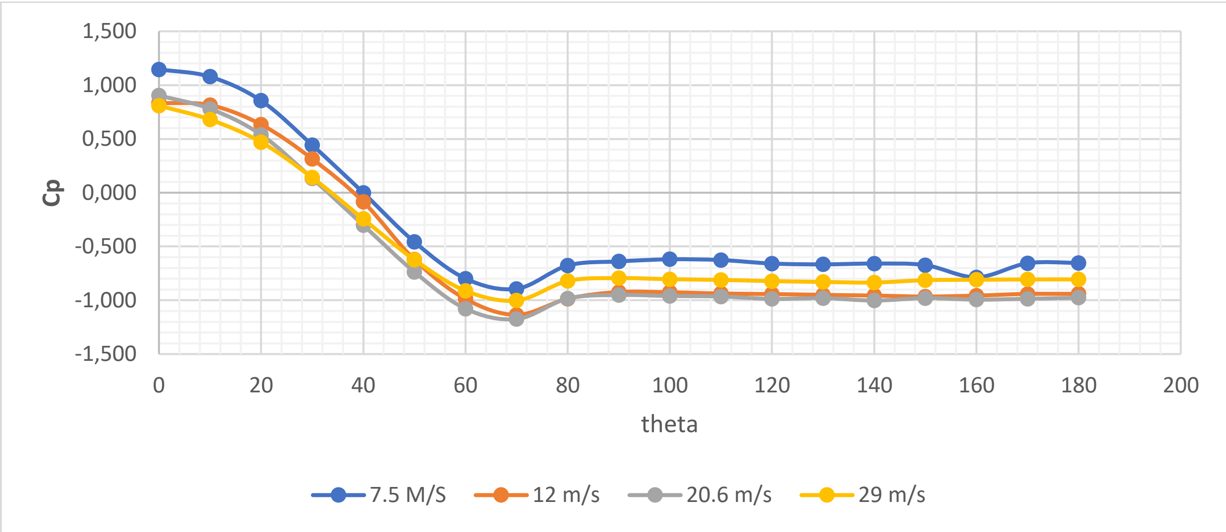

Figure 8. Pressure coefficient per Angle with clean wind tunnel

The speeds contained in the graph refer to the 4 rotations used in each experiment. It is possible to see that with the tunnel clean, for speeds at the ends (7.5 m/s and 29 m/s) the pressure curves are more distant from the others, which can characterize a small problem in the operation of the tunnel for these speed ranges. Furthermore, the part where the Cp becomes constant, which occurs from 80° for these speeds, it can be seen that they are greater than -1. Another important point to be observed is that at a speed of 7.5 m/s, referring to a rotation of 400 rpm, at angle 0° the Cp assumes a value greater than 1.0, and for the others this does not occur.

In general, pressure curves as a function of angle follow the pattern found in the literature (White, 2011), where a value close to 1.0 is assumed for the 0° angle, with the lowest pressure point being around 70° and a constant Cp from the angle of 80°.

A second graph was obtained in the same way, but after 2 months of using the tunnel, which can be seen in Figure 9.

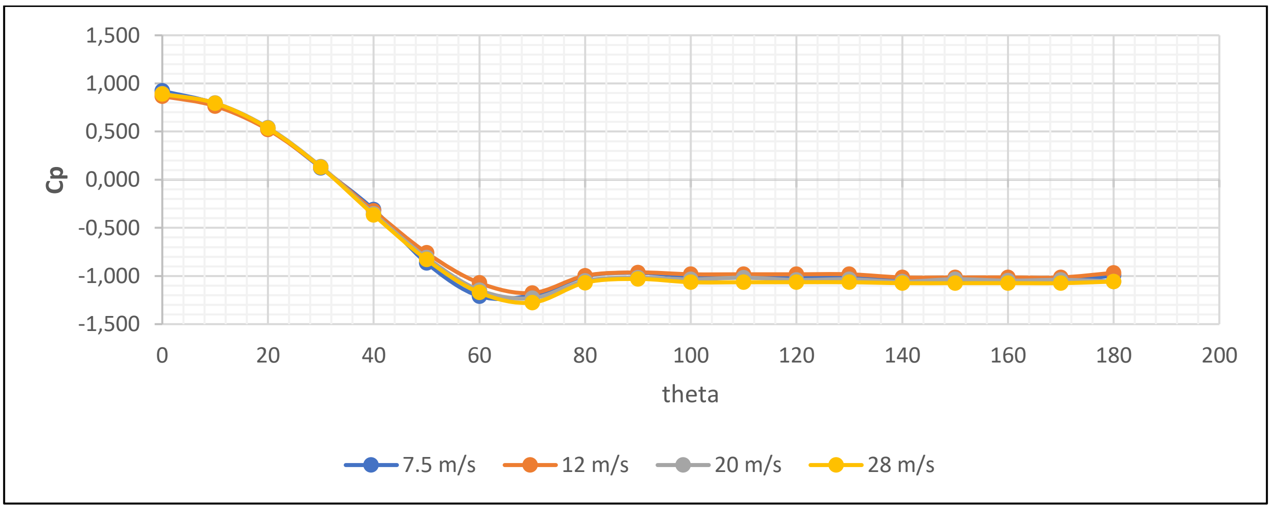

Figure 9. Pressure coefficient per Angle after 2 months of use

Through the graph it was possible to notice that for all speeds the pressure curves are superimposed, with no longer the difference noted for the speeds 7.5 m/s and 29 m/s in the previous graph. In this case, the same pattern was maintained, where at angle 0 a Cp close to 1 was obtained, at an angle of approximately 70° the lowest Cp value was obtained and from 80° onwards the Cp became constant at -1, as found in literature. (White, 2011).

It is noteworthy that the speed used in the experiment with the wind tunnel after 2 months of use was recalculated, so there is a slight difference between the speeds used to calculate the Cp in the first graph and in the second graph.

Thus, we can conclude that although there is a difference in speeds during the use of the clean tunnel and after 2 months of use, by recalculating the speed during the experiment it is possible to correct this problem. If the same velocity value used in the experiment with the clean tunnel were used, there would be a great difference between the results, because although the velocity does not change considerably during this time, when calculating the Cp there would be a notable difference in the value obtained.

4. CONCLUSIONS

From the obtained data, it can be concluded that the pressure module presented consistent results, through the calculation of the cylinder pressure coefficient, both with the clean wind tunnel and with 2 months of use. It was also noticed the importance of carrying out the experiment to determine the test time, which brought great agility in the execution time of each test. In addition, it was important to consistently analyze and define, through statistics, the number of replicates needed to validate the test time determination experiment for experiments involving pressure differences.

Another perceived factor, in relation to the Reynolds number, is the low or almost no influence on the calculation of the pressure coefficient for the speeds used, evaluating in the order of magnitude of 10^4, which was reached in the wind tunnel. It is important to note that this conclusion was made only for low Reynolds numbers.

5. ACKNOWLEDGMENT

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