23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

DEVELOPMENT OF AN OPEN-CIRCUIT LOW-SPEED WIND TUNNEL

Ronaldo Menezes dos Santos Jr
André Luiz Amarante Mesquita
Department of Mechanical Engineering – Federal University of Pará A
Rua Augusto Corrêa, n. 1, CEP 66075-110, Belém, Pará, Brazil
ronaldo.santos@itec.ufpa.br
andream@ufpa.br

Miriam Lys Gemaque
Department of Mechanical Engineering – Federal University of Pará – UFPA
Rua Augusto Corrêa, n. 1, CEP 66075-110, Belém, Pará, Brazil
lysgmak@hotmail.com

Abstract. *Alternative systems of power generation has become increasingly intense in Brazil, and generation using wind power arouses great interest due to the good existing wind potential in coastal regions of the country. As part of the research in this area in the Amazon, Professors and Researchers at the Federal University of Pará and other research centers have developed mathematical tools for optimal aerodynamic design of wind turbines with and without diffuser, which have been well accepted in the scientific community. Despite these professionals to develop scientific work of international significance, their laboratories do not have adequate apparatus and instrumentation for testing dedicated to the development of research and wind systems technologies. Thus, in this work it was performed the design and fabrication of a blower open-circuit low-speed wind tunnel with 600 x 600 mm² test section, contraction ratio equal to 9 and maximum speed in the test section of 30 m/s. The resulting tunnel showed to have a good flow quality in its test section with a well-developed and flat speed profile along both vertical and horizontal directions.*

Keywords: *Wind Tunnel, Low-Speed, Open-Circuit*

1. INTRODUCTION

The pursuit of new energy sources and the impacts caused by traditional forms of electricity generation have led to demand for cleaner energy sources that complement the energy matrix. The increase in consumption and the growing economic and environmental pressures have justified the use of alternative sources such as wind energy. In this context, Professors and Researchers at the Federal University of Pará have been developing mathematical tools for optimum aerodynamic design of wind turbines with and without diffuser. Despite these professionals to develop scientific works of international importance, their laboratories do not have adequate equipment and instrumentation for testing dedicated to the development of research and wind systems technologies. Therefore, it is necessary to develop suitable conditions, such as a wind tunnel and measuring instruments.

Wind tunnels are powerful facilities which reproduce an air flow in a controlled manner (continuous or intermittent), with low turbulence (desirable for wind turbine testing), which will interact with the model located at the test section. According to Barlow *et al.* (1999) it is possible to classify the wind tunnel based on the air speed in the test section (Subsonic, transonic, Supersonic and Hypersonic), test section configuration (Open or Closed) and the type of circuit (closed circuit and open circuit). Moreover, there are two settings for open circuit wind tunnels, depending on whether the fan is at the air inlet (Blower Tunnel) or at the air outlet (Sucker Tunnel). It is extremely important to classify the wind tunnel before starting the project, since this classification defines features and application of the project.

The wind tunnel is of fundamental importance as it allows advancing the current knowledge of physical phenomena involved and the assurance of models used for the wind turbine project. Thus, this work aims to design and build a an open-circuit low-speed wind tunnel, designed for the insertion of instrumentation aimed at measuring flow parameters, in order to assemble a laboratory infrastructure capable of producing testing of small wind turbine models, capable of operating with good aerodynamic efficiency when placed at low wind speed characteristics found on the Atlantic coast of Brazil.

2. WIND TUNNEL COMPONENTS

2.1 Test Section

The test section design totally depends on the requirements of each experiment being performed in the wind tunnel, which include the dimensions of the tested model, operating rate and the desired flow quality. The flow velocity obtained and the dimension of the test section determine the maximum size of the model to be tested and the maximum Reynolds number obtained (Barlow *et al.*, 1999).

The test section shape depends on the wind tunnel application. For tunnels in which the tested models are mounted inside the test section, the section size and shape are generally prepared in order to minimize the interference from the wall to a model of predetermined dimensions. For civil and industrial applications, most of the time, the square section test chamber is recommended. Rectangular section of test chambers are recommended and very popular, especially in aeronautical applications (Mehta, 1977).

According to Mehta (1977), **the test section length should be 0.5 to 3 times its hydraulic diameter**. This design criterion is considered due to the flow in the contraction outlet, in general, needs a distance of 0.5 times the hydraulic diameter of the test chamber so that non-uniformities in the flow are reduced to an acceptable level. This requirement establishes the minimum length of the test section. On the other hand test section with lengths greater than 3 times the hydraulic diameter results in unnecessary increase of the boundary layer thickness along this section, which may result in detachment of the boundary layer at the exit of the test section (Mehta, 1977).

2.2 Contraction Section

The contraction is an integral part of practically all wind tunnel projects. It is usually installed upstream of the test section and has great influence on the flow quality. The two main purposes of this section are: (i) reducing the variations of both average speed and its fluctuations over time, for a given cross-section. This is due to the fact that the total pressure through the contraction remains constant. (ii) Increasing the average flow velocity from the settling chamber, thereby the flow straightener elements (honeycomb and screen) may be installed in a low speed region reducing pressure loss and, consequently, the wind tunnel power factor. Consequently, a smaller amount is required of screens in stabilizing section, further reducing the pressure loss (Bell and Mehta, 1988).

The most important parameter to achieve these two effects is the contraction ratio (c), defined as the ratio between the input and output contraction area. The choice of contraction ration value is influenced by the space available, flow quality and cost. **Contraction ratio between 6 and 10 were found as being most suitable for most low speed wind tunnel** (Pankhurst and Bradshaw, 1964; Mehta and Bradshaw, 1979; Bell and Mehta, 1988). The upper limit of c is generally limited by the maximum length of the contraction or the maximum acceptable distance between the center line of the tunnel and the floor (Bell and Mehta, 1988).

The contraction shape is another very important parameter and many methodologies for determining the contraction wall profile have been developed. Among them, the 5th order polynomial developed by Bell and Mehta (1988) has been widely used in many wind tunnel projects by the fact that there is no present flow separation in both the center line and in the corners of the contraction, satisfies the minimum requirements for the number of Reynolds and provides excellent uniformity in the flow.

According to Mehta and Bradshaw (1979), it is always possible to avoid flow separation increasing sufficiently the contraction length, since it has a reasonable wall shape. The flow uniformity in the contraction outlet improves as the length increases. This is related to the fact that the radius of curvature decreases with increasing length. Bell and Mehta (1988) state that for the profile created from the 5th order polynomial, **flow separation occurs when the ratio L/Hi (length/height of contraction) is equal to 0.667**. **In addition, also detachment of the boundary layer occurs when the contraction is too long (L/Hi values greater than 1.79)**. This flow separation occurs due to adverse pressure gradient region near the contraction exit. Whether the contraction is too short, then detachment of the boundary layer also tends to occur, but this time, near the contraction entrance (Bell and Mehta, 1988).

2.3 Settling Chamber

The settling chamber, located between the diffuser outlet and the contraction inlet (open circuit type) is the wind tunnel component that has the largest cross-sectional area. This component has the greatest influence on the flow quality obtained in the test section due to the high local drop pressure generated by the honeycomb and screens. Due to its larger area, the speed in the settling chamber is the smallest along the wind tunnel, which makes it important to place such straightener elements in this section, since their contribution to the overall pressure loss is minimized. This section is very important for the wind tunnel project as it smoothes out irregularities caused by the fan and minimizes inconsistencies generated in the diffuser expansion (Lindgren and Johansson, 2002). When the flow requirements are of low quality, this section is a simple duct of constant section, which connects the diffuser outlet to the contraction inlet. However, when high quality flow is desired, the straightener flow devices are installed to improve flow uniformity and reduce turbulence levels at the contraction inlet. The most commonly used devices are screens and honeycomb (Hernández *et al*., 2013).

The screens are usually made of metal woven wires into the form of square or rectangular meshes, and installed generally in the settling chamber to increase the flow uniformity and reduce turbulence levels. The screen makes the flow velocity profile more uniform, imposing a static pressure loss proportional to the speed square. Thereby reduces the boundary layer thickness and increases its ability to withstand a certain pressure gradient. The flow quality is based on the blockage created by the screen, thus the wire diameter and the screen mesh are important parameters. These two parameters can be related by the porosity (β), defined as the ratio of the projected open area and the total area of the screen.

In order to find appropriate values of porosity screens, Mehta and Bradshaw (1979) conducted a series of experiments using several screens with different porosities, in which concluded that screens with very low porosity ($\beta \approx 0.3$) produce large fluctuations in flow. For low porosity ($0.3<\beta<0.57$), the screens also produce instabilities resulting from random streamlines coalescence which supposedly set to form longitudinal vortexes, persisting throughout the contraction. They concluded then that to be effective in reducing the turbulence, **a screen must have a porosity in the range 0.58 to 0.8**.

Screens are not very efficient to remove swirls and lateral velocity variations. Thus, honeycombs are used to solve this problem. It is a passage of ducts, laid along the axis of main air stream to minimize the lateral velocity components caused by swirling motion in the air flow during settling chamber entry. Many researchers have conducted studies to investigate the optimal setting, aspect ratio and effect of the honeycomb in the flow conditions. Loehrke and Nagib (1976) conducted some tests using a honeycomb made of plastic straws and found that fluctuations in the cross-flow components were inhibited depending on the honeycomb cells length. According to Mehta (1977), to obtain the maximum benefit from the honeycombs, the **length/diameter cells ratio should be around 7-10**. The cross sections of honeycomb cells are not critical and they are chosen according to availability. However, to suppress the turbulence the use of small cells is advisable. Kulkarni *et al*. (2011) conducted some numerical simulations to honeycombs of different shapes, in which it was observed that the **turbulence intensity decay rate is high up to a distance of around eight times the cell diameter** and there onwards the turbulence intensity decay rate has a much lesser effect. Using shorter honeycombs with length-to-diameter ratio less than eight should not be preferred because of the initial high turbulence intensity decay rate. Therefore, this ratio is considered as optimum for the honeycomb structures in wind tunnels.

2.4 Diffuser

The flow behavior through diffusers depends on its area ratio (A), the diffuser angle (2θ), its cross section shape and walls contour. Other parameters such as flow conditions at the diffuser entrance and exit and the boundary layer control elements, also influence the diffuser performance. Any combination of these parameters makes the flow passing throughout the diffuser difficult to predict in detail. This problem is further complicated when there is occasionally the presence of boundary layer separation caused by adverse pressure gradients present in the diffuser. These characteristics make the diffuser one of the least understood flow devices (Barlow *et al*., 1999).

Many problems that occur in wind tunnels are caused by inappropriate diffusers designs. These problems are more evident in large tunnels with high Reynolds numbers, where the boundary layer separation occurs suddenly for diffusers angles greater than 8°. The problem of flow separation is caused by the sudden change in the wall curvature at the diffuser inlet. This abrupt change is related to a strong decrease in pressure followed by a sharp increase of static pressure along the wall. The higher the Reynolds number and the higher the speed at a certain distance from the wall, more the boundary layer will be affected due to this change in wall contour. However, in order to keep the space requirements and the cost as low as possible, most wind tunnels have large diffuser angles, known as wide-angle diffusers. Also, most diffusers, especially those with area ratio larger than 3, have rectangular or square cross section. This is because rectangular diffusers are much easier and cheaper to build than circular (Kramer and Gerhardt, 1984).

One of the most popular means of preventing separation in wide-angle diffusers is by introducing screens of perforated metal or, more usually, woven wire gauze. Screens remove the direct effects of the boundary layer growth and flow separation. Other boundary layer control methods include splitter system, suction slots, trapped vortex and vanes, and their use is preferred with diffusers in very severe geometries ($A> 5$, $2\theta> 50$ °) (Mehta and Bradshaw, 1979). A clear evidence of the effect of these methods on the flow quality can be observed in the study performed by Calautit *et al*. (2014), in which a diffuser with 3 horizontal splitting plates with 0.25 m spacing and 3 vertical splitting plates with 0.17 m spacing were installed inside the diffuser. The effect of the splitting plate was investigated by CFD simulations and they showed that without the splitting plate, the flow separation occurred at the downstream part of the diffuser. The separation was reduced significantly following the integration of the splitting plate. This was evident from the uniformity of the flow field at the diffuser exit which showed that velocity variation was reduced from 30% to 5%.

3. WIND TUNNEL DIMENSIONING

3.1 Specifications

The wind tunnel configuration chosen in this work is a blower open-circuit tunnel. This configuration was chosen due to the characteristics of the tests to be performed. Knowing the dimensions of the test section cross section, speed and contraction ratio desired, the other components can be sized. The choice of these parameters for this project originated in the evaluation of the room space available for the tunnel installation. The wind tunnel shall be installed in the Turbomachinery Laboratory of the Federal University of Pará, which has a total length of 12 m available. However, it was established that the total length of the wind tunnel must not be more than 9 m, including all its components. Thus, three test sections were evaluated (1.0 x 1.0 m², 0.60 x 0.80 m² and 0.60 x 0.60 m²) for contraction ratio values between 6 to 10, as stablished in Section 2.2, to obtain the best combination that meets to the design requirements. Based on the values obtained, the 1.0 x 1.0 m² test section was discarded because its total length exceeded the upper limit for all contraction values. By comparing the remaining two sections, it was concluded that the best section would be 0.60 x 0.60 m². This is due to the fact that although the 0.60 x 0.80 m² section is within the established total length limit, this criterion is achieved only for contraction ratio smaller than 8. Considering that the greater the contraction ratio, the better the flow quality obtained in the test section, it is concluded then that the section which best meets the design requirements, using the largest contraction ratio possible, is the 0.60 x 0.60 m² section with contraction ratio equal to 9 and total length of 8.25 m. Moreover, the desired speed on the test section is equal to 30 m/s, a value which is widely used in low speed wind tunnel.

3.2 Dimensions of the wind tunnel components

As the input data has been established, it is possible to dimension the other components. Since the test section cross-sectional area has been set, its length can be calculated. It was then decided by the length equal to 3 times the hydraulic diameter of the test section, which is in accordance with the criterion defined in Section 2.1. The length of the test section is therefore equal to 1.8 m.

The contraction outlet cross-sectional area is equal to the area of the test section, and since the contraction ratio is ratio of the inlet and outlet areas of the contraction, the contraction inlet area, which is equal to the area of the settling chamber, can be found.

The stabilizing section is square and therefore the contraction input is also square. Thus, its dimensions, height (H_i) and width (W_i) can be calculated by the square root of the contraction inlet area. The contraction length is calculated using the restrictions set by Mehta (1977), showed in Section 2.2. It was used then the ratio L/Hi as being equal to 1, resulting in a contraction length of 1.8 m.

Following the design recommendations already discussed, the screen should have a porosity greater than 0.6 and less than 0.8. Thus, among the screens commercially available, it has been chosen a galvanized steel screen with the wire diameter (d) equal to 0.45 and mesh (M) equal to 2.08 mm. The screen porosity is therefore equal to 0.61, which is in agreement with the reviewed literature. Two screens are installed in the settling chamber in order to improve the flow quality.

Aiming at low cost and ease of manufacture the honeycomb, plastic straws having an inner diameter of 10 mm and thickness of 0.05 mm were used. Thus, it is possible to calculate the cell length, which is equal to 8 times the diameter of the cell. This value was found to be optimal for the length of the hive, as already presented in this paper. Therefore, the honeycomb has a length of 80 mm.

Finally, the total length of the settling chamber can be found. For this purpose, the expression developed by Mehta and Bradshaw (1979), which states that the distance between the screens should be 0.2 times the hydraulic diameter of the settling chamber has been used. As the configuration of the test section consists of two screens, a honeycomb (considered as a screen for this purpose) and an accommodation section, there are 3 free spaces among these components, leading to a settling chamber with an overall length of 1.16 m.

The diffuser was the last component to be dimensioned due to its dependence with the discharge area of the blower. Thus, it was chosen a diffuser to have an area ratio of approximately equal to 4, resulting in a diffuser angle equal to $2\theta = 42°$. The last parameter to be dimensioned is now the diffuser length, which can be calculated since the area ratio and the diffuser expansion angle are known. Table 1 summarizes all the dimensions of the wind tunnel components.

Table 1. Dimensions of the wind tunnel components.

	Test Section	Contraction	Settling Chamber	Diffuser	Blower	**Total Length**
Cross Section	0,6 x 0,6 m²	-	1,80 x 1,80 m²	-	0,71 x 106 m²	
Length	1,8 m	1,8 m	1,16 m	1,20 m	2,30 m	**8,25 m**

3.3 Blower Selection

To select the ideal fan to the wind tunnel, it is necessary to know the required flow rate in the test section and the overall pressure drop of the wind wind tunnel. As the desired speed in the test section is 30 m/s and its cross section is 0.6 x 0.6 m², the wind tunnel has a volumetric flow rate required equal to approximately 38880 m³/h. Table 2 shows the pressure loss of each wind tunnel component, the total drop pressure, and the speed throughout each component.

As the tunnel flow rate and total pressure drop are known, the next step is to select the fan among those available in the market which can overcome this pressure drop and supply the required flow. The Vortex Software available for free from OTAM fans has been used to select the suitable fan. Among the many fans applicable to the project, the OTAM RLD 710 double inlet was chosen for meeting the project requirements, having a reasonable cost and not occupy too much space of the available room.

Table 2. Pressure loss and speed of each wind tunnel component.

COMPONENT	V_i [m/s]	K_i	$\Delta P_i = 0.5K_iV_i^2$ [Pa]
Discharge	30	1	553,5
Teste Section	30	0,0580	32,23
Contraction	16,67	0,0063	1,07
Settling Chamber	3,33	0,0106	0,07
Screens	3,33	0,2411	1,65
Honeycomb	3,33	0,0008	0,0016
Diffuser	14,3	0,7675	97,19
Damper	14,3	1,5	189,72
		TOTAL	685,72

4. WIND TUNNEL FABRICATION

The test section was constructed in a square section of 600 x 600 mm², which has three sides made from plywood of 15 mm thickness and a side made of acrylic, in order to enable the visualization of the interior section and facilitate observation of models and instruments that may be installed in the test section.

The contraction was built from the generation of its profile through the medium lines (Fig. 1a) obtained by the Bell and Mehta (1988) polynomial. With the profile completely generated (Fig. 1b), it is now possible to fabricate the contraction.

The procedure used to build the contraction is to extract the profile of one side from the Fig 1b, print it in full scale and then place the paper printed over the plywood sheets to draw the profile, in order to create a mold. This mold is than used to cut all the plywood sheets necessary to fabricate the contraction.

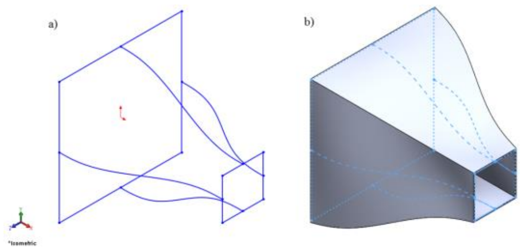

Figure 1. Medium lines (a) and contraction contour (b)

Due to the great flexibility required to follow the contraction contour, three layers of plywood of 5 mm thickness were used to construct contraction. To maintain the rigidity of the structure, each layer is fixed with screws.

The walls of the settling chamber were constructed with plywood sheets 15 mm thick, since flexibility is not needed in this section. This section is divided into three parts: module with screens, module with the honeycomb and a constant section to accommodate the flow before entering the contraction. The first module has two galvanized steel screens (Fig. 2a) fixed on supports made of square section steel bars 10 x 10 mm² welded (Fig. 2b), to promote greater rigidity to the screen and prevent them to vibrate due to the flow. To secure screens in the settling chamber, notches were made in the flanges where the flaps of the screens holders can be accommodated, not allowing any movement.

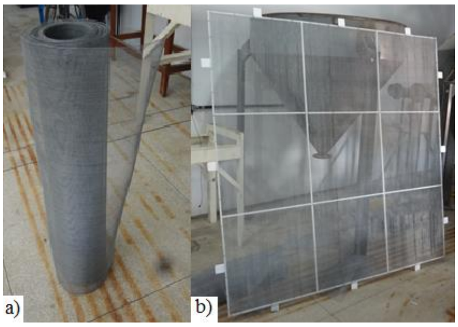

Figure 2. Galvanized steel screens (a) and screens fixed on the support (b)

Still in the settling chamber, the honeycomb was constructed with plastic straws of approximately 10 mm diameter and 80 mm in length. It was estimated that approximately 41000 cells would be required to fill the honeycomb. The straws were glued together with faster drying glue on supports made of steel plates (50.8 mm x 3175 mm x 1800 mm) welded together, similar to the screens supports. Figure 3 shows the honeycomb completely constructed. The rigidity of the honeycomb is much larger than screens thus justifying its position at the end of the settling chamber.

Figure 3. Honeycomb completely built

The diffuser was designed to have 2 horizontal splitting plates with 600 mm spacing and 2 vertical splitting plates with 600 mm spacing, technique similar to that used for Calautit *et al*. (2014) mentioned in Section 2.3. To maintain structural rigidity of the component, both the diffuser walls and its splitter clusters are constructed of plywood sheets of 15mm thickness. Figure 4 shows the diffuser built with the splitting plates.

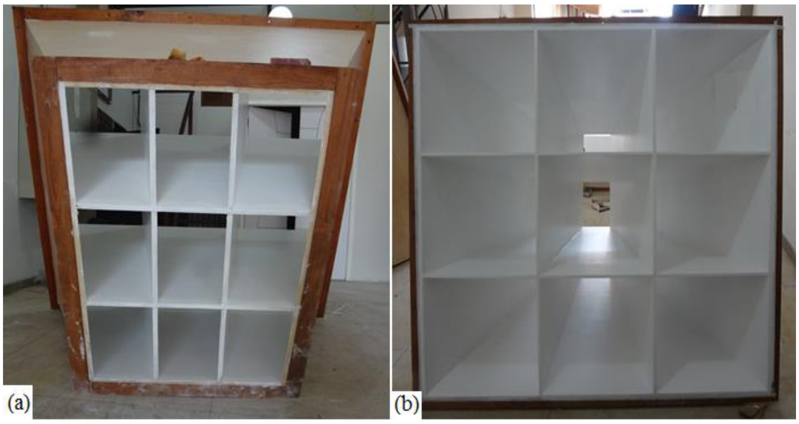

Figure 4. (a) Diffuser entry and (b) diffuser exit.

To attach a component to the other, flanges 2 cm thick and 5 cm height were constructed. Holes were made around the flange in which screws 25.4 mm diameter 177.8 mm in length, washers and nuts are used to connect the system components. In order to seal the internal environment from the external environment, to prevent flow leakage of the tunnel to the environment, 8 mm thick rubbers were glued between the flanges.

In order to prevent the fan vibration to be transmitted directly to the wind tunnel body, a tarpaulin 30 cm in length has been inserted. This device is important even though the vibration caused by the double-suction centrifugal blower is low. In addition, the blower was provided with six vibration damper arranged at the corners of the fan base reducing the vibration even more.

All wind tunnel components were reversed with laminate to provide a smoother outer surface and good aspect. In the inner tunnel walls, plaster was used subsequently sanded to remove imperfections from the wood surface, which would affect the flow within the tunnel. Finally, all components were painted with a special paint that provides a smoother surface which can be cleaned without ink to be removed. Figure 5 shows the tunnel completely built with the fan connected to it. The entire fabrication process lasted two months and the wind tunnel had a total cost of R$ 51,304.78, which can be considered low relative to the price of wind tunnels available on the market.

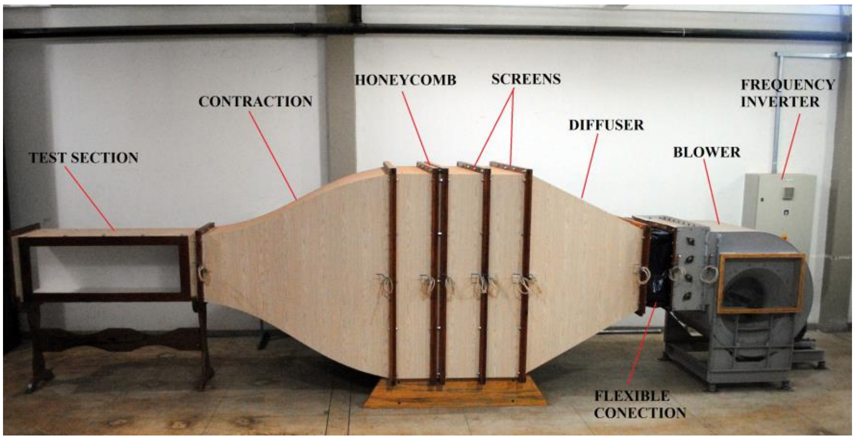

Figure 5. Wind tunnel

5. PROJECT COMMISSIONING

After the construction and assembly of the wind tunnel, the commissioning is necessary to ensure that all components are operating under the expected conditions. One way to confirm that the wind tunnel is operating in good condition, meeting the design conditions, is the evaluation of the velocity profile in the test section at different speed values. To assess the velocity profile in the test section, it is divided into two lines (horizontal and vertical) through the cross section center, which have been selected 25 points of interest within the mesh, as shown in Fig. 6a. The test was conducted for three different speeds, 5, 15 and 25 m/s to verify the velocity profile behavior with increasing flow velocity. To measure speed, a Pitot tube and a manometer KIMO MP 200, with pressure range of 0 to ± 500 Pa and accuracy of ± 1.5 Pa, were used as shown in Fig. 6b.

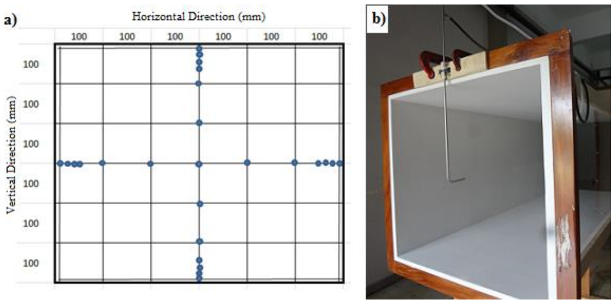

Figure 6. Test section mapping points

In each point of the mesh, for each of the three speeds evaluated in this experiment, 12 velocity values were measured. Thus, since there are a total of 25 measurement points in the mesh, 336 data points for each velocity are measured in an interval of 1 min between each point. Figure 7a shows velocity profiles in a vertical direction and Fig. 7b the velocity profiles in a horizontal direction for the three different speeds.

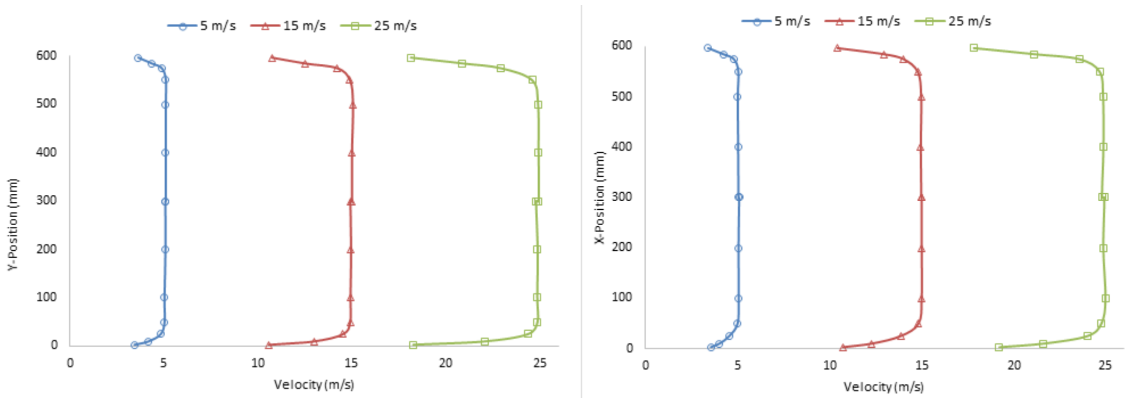

Figure 7. Velocity profiles in the (a) vertical and (b) horizontal directions

It is noticed from both Fig. 7a and Fig. 7b that the flow profile for the three speeds is well developed and flat along the vertical and horizontal positions in the test section, showing a good flow quality. It is also observed that as the speed increases, the effect of wall roughness increases and speed decreases near it.

6. CONCLUSION

The main objective of this work was to develop a laboratory infrastructure for testing, mainly models of wind turbines through wind tunnel construction, since the researchers involved in this area of research at the Federal University of Pará, although they have extensive experience in numerical simulations in wind turbines, are lacking equipment for experimental study and evaluation of these turbines.

After the design of wind tunnel components, the construction of its components began. All wind tunnel components are made of plywood 15 mm thick, except that the contraction that was made with three layers of plywood of 5 mm thickness. The overall duration of construction stage was 2 months. Finally, the wind tunnel commissioning was carried out to ensure that all components of the tunnel were operating properly according to design requirements. One of the design requirements was to obtain a wind tunnel, which flow in the test section was as stable as possible. To confirm that this requirement was achieved, it was performed a mapping of the center lines in the horizontal and vertical positions, which was divided into 25 points. To check the behavior of the wind tunnel operating at various speeds, three speeds were evaluated (5, 15, 25 m/s). The results were very satisfactory, presenting a profile well developed in all tested velocities, confirming the quality of the wind tunnel constructed.

It was concluded that the available literature for wind tunnel design, although they are quite old (majority), are still very effective in wind tunnels project. The new wind tunnel acquired by the Federal University of Pará, especially the Turbomachinery Laboratory, has a total length of 8.25 m, with contraction ratio equal to 9 and area of the test section of 600 x 600 mm², operating in good condition with a maximum speed of 30 m / s in the test section.

7. ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the financial support from CNPQ (proc. no. 482.454/2013-0), without which this paper would be impossible.

8. REFERENCES

Barlow, J., Rae, W. and Pope, A., 1999. “Low Speed Wind Tunnel Testing”. John Wiley & Sons, NJ, United States of America, pp 105–122.

Bell, J. H. and Metha, R. D., 1988. “Contraction Design for Small Low-Speed Wind Tunnels”. NASACR-182747.

Calautit, J. K., Chaudhry, H. N., Hughes, B. R., Sim, L. F. A., 2014. “Validated design methodology for a closed-loop subsonic wind tunnel”. J. Wind Eng. Ind. Aerodyn. 125, pp 180–194.

Hernández, M. A. G., López, A. I. M., Jarzabek, A. A., Perales, J. M. P., Wu, Y., Xiaoxiao, S., 2013. “Design Methodology for a Quick and Low-Cost Wind Tunnel”. Wind Tunnel Designs and Their Diverse Engineering Applications, Dr. Noor Ahmed (Ed.), ISBN: 978-953-51-1047-7, InTech, DOI: 10.5772/54169.

Kramer, C. and Gehardt, H. J., 1984. “Wind Tunnels for Industrial Aerodynamics”. Journal of Wind Engineering and Industrial Aerodynamics, pp 225-264.

Kulkarni, V., Sahoo, N., and Chavan, S. D., 2011. “Simulation of honeycomb–screen combinations for turbulence management in a subsonic wind tunnel”. J. Wind Eng. Ind. Aerodyn. 99, pp 37–45.

Lindgren, B., Johansson, A. V., 2002. “Design and Evaluation of a Low-Speed Wind-Tunnel with Expanding Corners”. Technical Reports from Royal Institute of Technology, Department of Mechanics, SE-100 44 Stockholm, Sweden.

Loehrke, R.I. and Nagib, H.M., 1976. “Control of free stream turbulence by means of honeycombs: a balance between suppression and generation”. ASME J. Fluids Eng. 98, pp 342–353.

Mehta, R. D., 1977. “The Aerodynamic Design of Blower Tunnels with Wide-Angle Diffusers”. Prog. Aerospace Sci., Vol 18, No. 1, pp 59-120.

Mehta, R., and Bradshaw, P., 1979. “Technical notes: design rules for small low speed wind tunnels”. Aeronaut. J. R. Aeronaut. Soc., pp 443–449.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.