ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

EXPERIMENTAL STUDY OF THE AIRFLOW AT THE EXIT OF THE TEST SECTION OF A LOW SPEED WIND TUNNEL

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Abstract. Wind tunnel testing is the most popular method to investigate the effects of wind on large structures, such as high-rise buildings, long-span bridges, and tall towers. It is a well-established discipline in Wind Engineering and it is applied for a wide range of studies. Despite the increasing performance in the past decades, CFD has not succeeded in replacing the wind tunnel. In order to ensure accurate and reliable measurement data, the airflow in a wind tunnel test section must meet high standards. Good flow quality demands a certain degree of spatial uniformity and temporal steadiness of velocity and pressure. This paper presents the evaluation of the characteristics in the exit section of an open-loop low-speed wind tunnel. For this purpose a hot wire anemometer and a Pitot tube were implemented for the measurements of mean velocity and velocity fluctuations. Experimental results are presented in form of velocity profiles and turbulence intensities. Results of measurements in the tunnel showed an uniform velocity field and low turbulence intensities.
Keywords: *Wind tunnel, Pitot tube, velocity profile, HWA, turbulent intensity.*

1. INTRODUCTION

According to Baker (2007), although the creation of the first wind tunnel precedes the arrival of the aircraft, the development of the wind tunnel was driven by the aircraft industry in the period from 1900 to 1960, when it was seen essentially as a research tool. Between 1960 and 1980, it has become a reliable and robust tool for industrial and commercial projects.

The wind tunnel, in addition to being an important reference in aerodynamics and aeronautical research, can also be applied in simulations that engineers and architects need to predict the development of their projects such as building resistance to the winds, behavior of motor vehicles, and to allow the measurement and mapping of displacement and dispersion of pollutants at the atmosphere.

According to Mehta and Bradshaw (1979), it is not easy to establish design rules for wind tunnels, because there is a great variety of needs and configurations of components in a wind tunnel and its parts. However Winkler et al (2007) suggested that an optimal design of a wind tunnel should allow modular structures, with quick disassembling, and implementation of additional screens when necessary. The pressure losses must be properly calculated for fan specification.

Currently, General Motors (GM) has one of the largest world wind tunnels, located in Detroit, U.S., applied to full-scale automotive industry. This tunnel is equipped with a closed-loop system to assess the aerodynamic performance, the directional stability and the thermal comfort in passenger and medium-sized cars (Kingsley, 2007). Once experimental tests are expensive and complex, Kim et.al (2006) proposed a numerical wind tunnel.

The indoor air pollutant dispersion and possible cross-unit contamination in residential buildings was investigated by Liu et al. (2008), using a boundary layer wind tunnel representing a 10-story residential building. The assessment of ventilation in buildings was studied by some researchers (Bady et. al., 2011, Karava et. al., 2011). Several other researches were performed using wind tunnels: analysis of the development of secondary instabilities in compressible swept airfoil boundary layers (Li et al., 2010), study of exhaust gas dispersion from road vehicles (Kandaa et al., 2006a,b), analysis of the characteristics of the flow in wind turbines (Yu et. al., 2011) and evaluation of the effect of long-term flights in birds (Jenni-Eiermann et al., 2009).

Currently, there is a demand for the reduction of the fuel consumption of buses and commercial passenger cars. Carregari (2006) used a wind tunnel to analyze the behavior of the flow around a scale model of a bus in order to develop a new concept in design.

The objectives of the present paper are to experimentally characterize the airflow at the exit of the test section of a low-speed wind tunnel and to evaluate the influence of screens on the turbulent intensity. The wind tunnel was evaluated with and without screens between diffusers. Pitot tubes and hot wire anemometers (HWA) with constant temperature were used to measure the parameters.

2. EXPERIMENTAL SETUP

The wind tunnel used in this work has a total length of 2990 mm. with 790 mm in the test section, 795 mm in contraction and 1095 mm in the chamber stagnation. It consists mainly of a blower, screens, and diffuser, stagnation, contraction, and tests sections. A schematic representation is shown in Fig. 1.

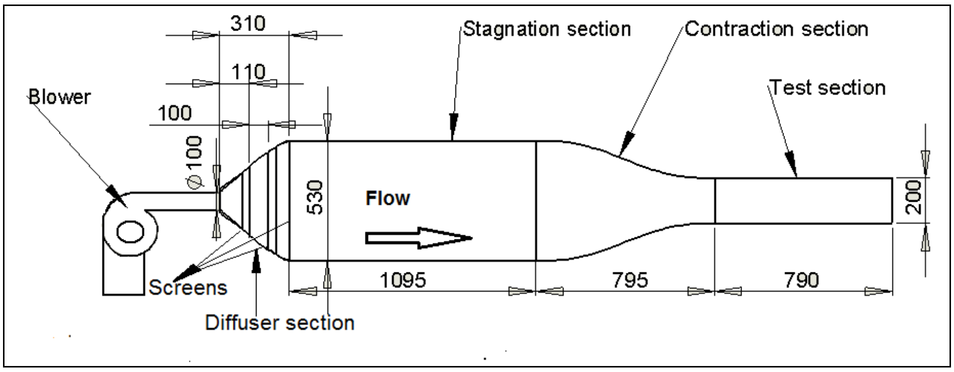


Figure 1. Schematics of the low-speed wind tunnel

The screens placed between the diffusers are made of steel, with 1 mm width, as seen in Fig. 2.

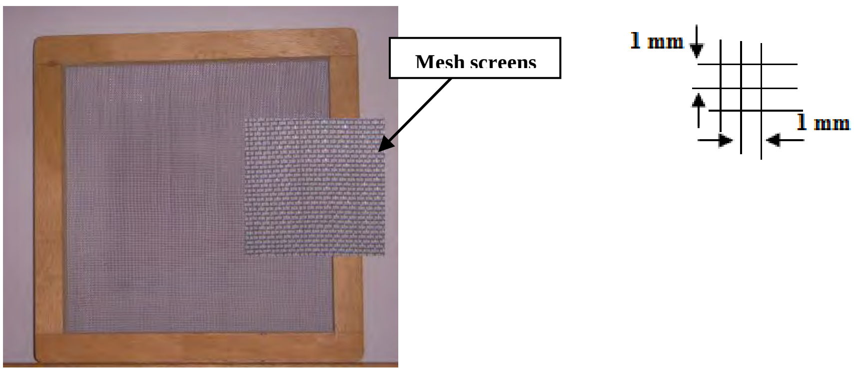


Figure 2. Mesh screens

In the experimental tests, the dynamic pressure was measured using a Prandtl type Pitot tube connected to a differential pressure manometer liquid column, and the turbulent intensities and its fluctuations were measured using HWA.

The measurements were carried out using ISO 3966:2008 standard recommendations for the distribution of the velocity points in the cross section of the test section. Six horizontal and verticals lines were considered to determine 36 experimental points for the measurement of the dynamic pressure (Fig. 3).

ISSN 2176-5480

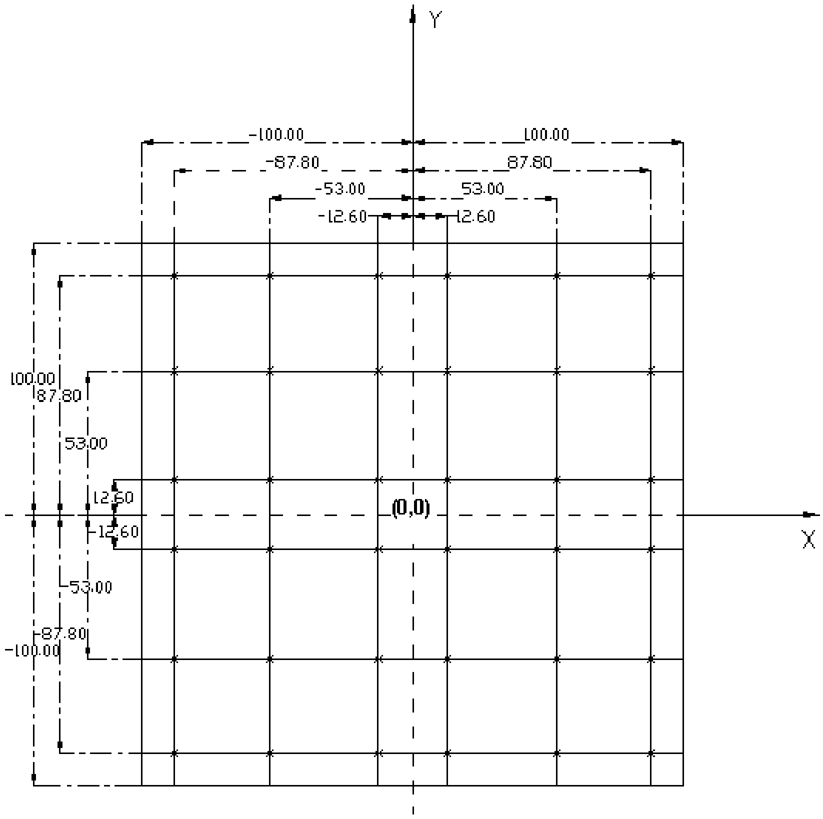


Figure 3. Distribution of the measurement points

Figure 4 shows a photo of the Pitot sensor positioned at the exit test section.

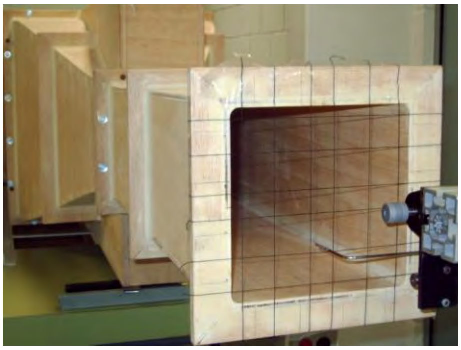


Figure 4. Pitot tube positioning

2.1 Experimental tests with the Prandtl type Pitot tube

During the tests, ambient temperature and atmospheric pressure were monitored in order to maintain a temperature range between 17ºC and 20ºC in order to remain near ambient conditions in all tests. This precaution was taken because preliminary tests indicated that temperatures below 17ºC and above 20ºC could cause significant variations in the dynamic pressure and flow velocity.

The frequency blower was gradually increased between 1800 and 3200 rpm, with regular intervals of 100 rpm. For each frequency, the Pitot tube was placed at each point defined in Fig. 3. The measurements were repeated 3 times, in order to reduce the uncertainties.

Preliminary tests indicated that a time interval of five minutes was required for the airflow to achieve steady state conditions after a flow disturbance. Therefore, this time interval was used to perform the measurements after each change of the position of the Pitot tube and the blower frequency.

2.2 Formulation for calculating the speed of airflow through the dynamic pressure

The relationship between the airflow velocity and pressure obtained with a Pitot tube is defined by Eq. 1 (Klopfenstein, 1998).

$$V = 44{,}72136\sqrt{\frac{\Delta P \cdot f}{\rho}} \tag{1}$$

Where:
V = Air velocity (m/s).
Δ P = Dynamic pressure (kPa).
f = correction factor for the slope of the differential pressure manometer.
ρ = air density (kg/m^3).

The air was considered as an ideal gas.

2.3 Normalized velocity

It was established a comparison of experimental results with standard conditions of atmospheric pressure and temperature (White F.M, 1979):

$$\left(\frac{\dot{m}\sqrt{T}}{P}\right) = \text{Constant} \tag{2}$$

Equation 2 can be applied to define a relationship between the standard conditions and the data obtained experimentally by Eq. 3.

$$\left(\frac{\rho V A\sqrt{T}}{P}\right)_{Experimental} = \left(\frac{\rho V A\sqrt{T}}{P}\right)_{Standard} \tag{3}$$

The standard normalized velocity is given as:

$$V_{Normalized} = \frac{Patm_{Standard}\left(\rho V\sqrt{T}\right)_{Experimental}}{Patm_{Experimental}\left(\rho\sqrt{T}\right)_{Standard}} \tag{4}$$

2.4 Turbulent intensity

For the tests with hot wire anemometers at constant temperature, it was used a probe with only one sensor element, reference code-Dantec 55P01, capable of measure one component of the velocity vector and its fluctuations (u'). Its characteristics are: 1.25 mm of length and diameter of 5 µm, thus having an aspect ratio of 250. This probe has one sensor element welded directly to the teeth and the bared ends. The entire length of the wire acts as a sensor to be fully exposed to the airflow.
The instantaneous velocity u is defined as:

$$u = \overline{U} + u' \tag{5}$$

Where $\overline{U}$ is the time averaged or mean velocity and u' is the velocity fluctuation. The mean velocity is defined by Eq. 6 (Wilcox, 2000):

$$\overline{U} = \frac{1}{T}\int_{t}^{t+T} u(t)\, dt \tag{6}$$

According to Ting et.al (2007), the relative turbulence intensity (it %) is typically defined as the root-mean-square of the stream-wise component of the velocity fluctuation, u‘, divided by the mean velocity of the flow, U. Usually it is

ISSN 2176-5480

represented as a percentage. In other words, the turbulence intensity represents the strength of the random fluctuations occurring over the duration of the flow (or intensity indicates the amplitude of the fluctuating components of velocity). It can be denoted by Eq. 7:

$$it\% = 100\frac{\sqrt{(u')^2}}{\overline{U}} \tag{7}$$

The positioning of the probe was at the midpoint of exit test section. This point is represented by the (0,0) coordinates, shown in Fig. 3. In the present paper, the velocity and its fluctuation were considered only in the airflow direction.

3. RESULTS

The tests were carried out with the blower operating at frequencies ranging between 1800 rpm and 3200 rpm, with an increment of 100 rpm. Pitot tubes were used to measure the dynamic pressure at the exit test section, in order to obtain the velocity profiles. HWA was used to obtain the velocity fluctuation at the midpoint of the exit test section.

All results presented and discussed here were based in the standard velocity, trying to minimize the eventual differences from changes in temperature and atmospheric pressure.

3.1 Tests with Pitot tube at the exit test section

Figures 5 to 7 show the velocity profiles at the exit test section coordinates Y = - 12.6 mm; - 53 mm, and – 87.8 mm, respectively, for blower frequencies of 1900 rpm, 2400 rpm, and 2900 rpm. The influence of screens between the diffusers was evaluated.

It is important to mention that, although the wall velocities were not measured, they were represented into the figures. It was assumed no slip condition at the wall (null velocity), in order to better represent graphically the velocity profile.

The velocity obtained in the tests in all cases show a typically turbulent profile. The differences obtained in symmetrical points were lower than 0.3 m/s, which do not significantly affect the velocity profile. The velocity uncertainties are presented in Tab. 1, determined according to the recommendations and procedures of standard ISO 3966:2008. It can be seen that the differences observed are close to the uncertainties.

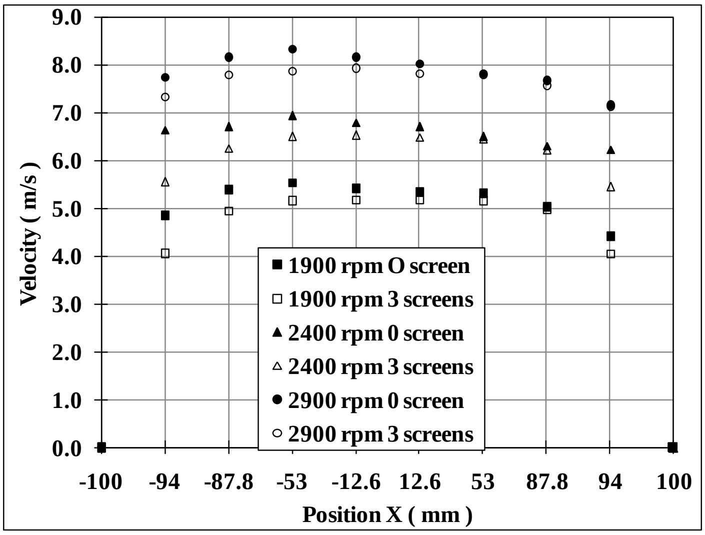


Figure 5. Velocity profile for Y= -12.6 mm, with 3 screens and without screens between the diffusers

Screens are usually used in wind tunnels to reduce the intensity and increase the uniformity of turbulent flows. Figures 5 to 7 compare the velocity profiles for the wind tunnel without screens and with 3 screens between the diffusers. When compared the results for the same frequency blower, it can be seen that the profiles obtained with the screens are more symmetric. Also, the screens increase the pressure losses of the airflow, causing a reduction of the velocity.

ISSN 2176-5480

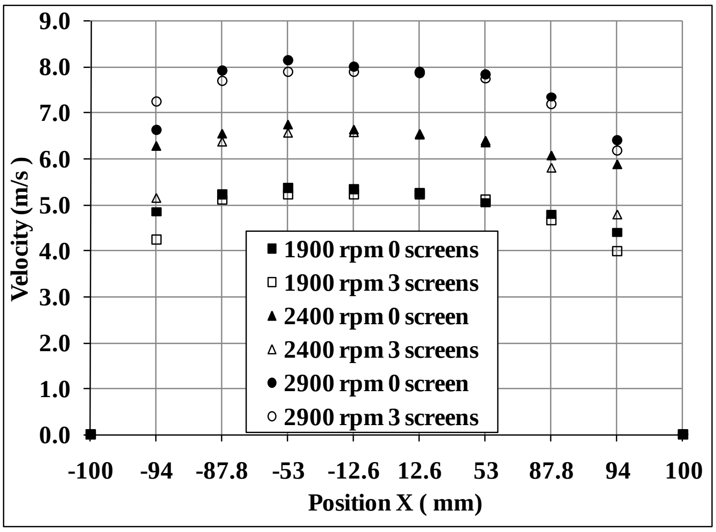


Figure 6. Velocity profile for Y= - 53 mm, with 3 screens and without screens between the diffusers

According to Fig.3 and the results presented in Fig.5 to 7, it can be noticed that the coordinate Y= -87.8 mm corresponds to the lowest velocity, and the coordinate Y= -12.6 mm to the highest value. This behavior can be explained by the proximity to the wall.

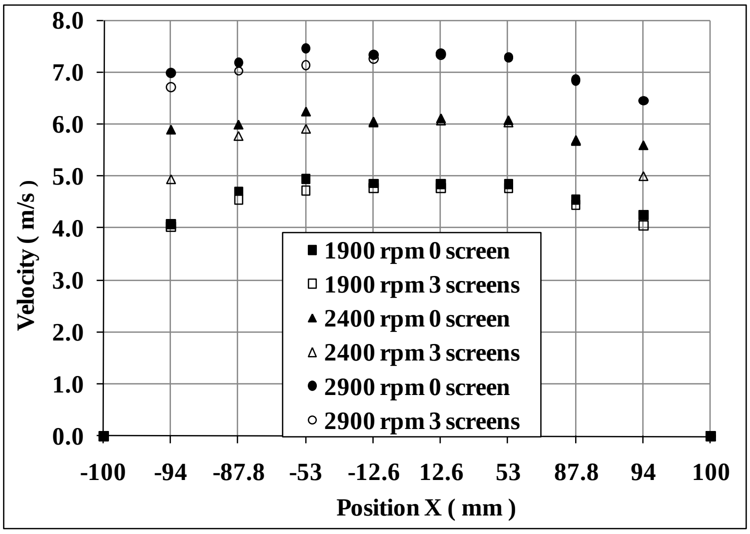


Figure 7. Velocity profile for Y= - 87.8 mm, with 3 screens and without screens between the diffusers

Tab. 1 shows the average velocities, flow rates and Reynolds numbers as a function of the blower frequency, and the corresponding uncertainties.

Table 1. Average velocities, flow rates and Reynolds numbers

	Without a screen			With a screen		
Blower frequency (rpm)	Average velocity (m/s) $^{\pm 0.11}$	Flow rate (m^3/s) $^{\pm 0.01}$	Re	Average velocity (m/s) $^{\pm 0.10}$	Flow rate (m^3/s) $^{\pm 0.01}$	Re
1900	5.17	0.21	6.8×10^{4}	4.99	0.20	6.6×10^{4}
2400	6.49	0.26	8.6×10^{4}	6.29	0.25	8.3×10^{4}
2900	7.86	0.31	1.04×10^{5}	7.60	0.30	1.0×10^{5}

ISSN 2176-5480

As expected by the similarity law, the average velocities increase linearly with the blower frequency. The relationship between these parameters is shown in Fig. 8.

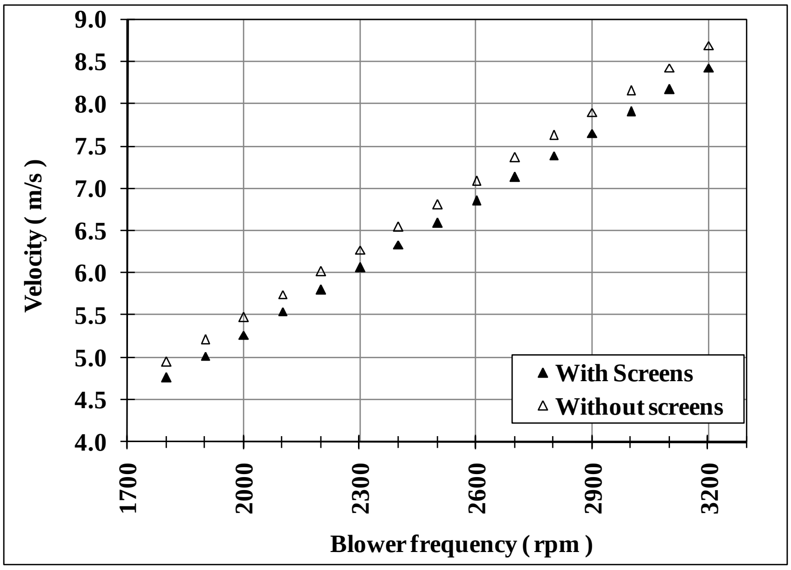
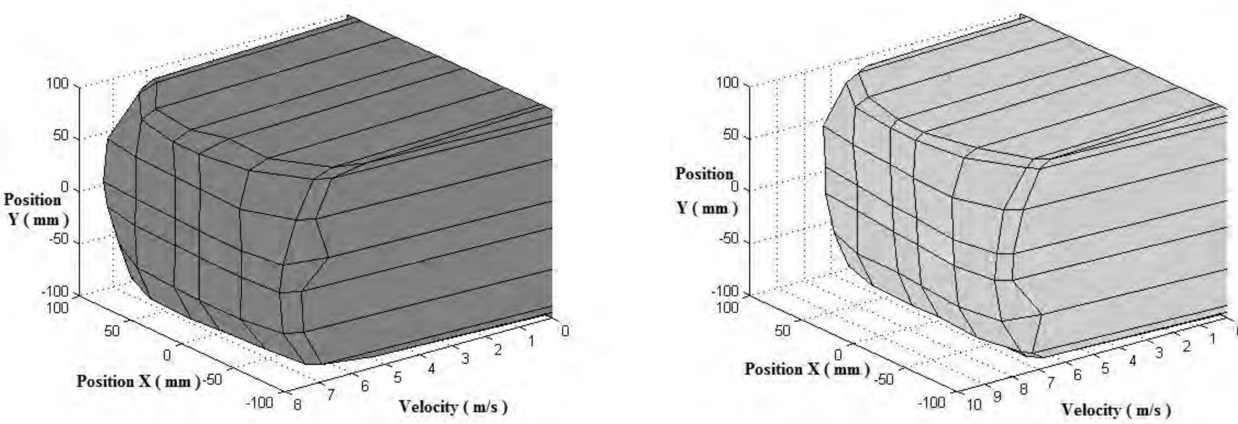


Figure 8. Average velocity obtained experimentally with and without screens between diffusers

In order to allow a better visualization of the velocities in the test section, a 3-D velocity profile is shown in Fig. 9 for 2900 rpm, with three screens (Fig.9A) and without screens (Fig. 9B).



(A) (B)

Figure 9. (A) Velocity profile at 2900 rpm with 3 screens; (B) Velocity profile at 2900 rpm without screens between the diffusers

When the screens are not positioned between the diffusers, higher velocities are obtained in the exit test section of the tunnel.

3.2 Tests with a hot wire anemometer (HWA) at the exit test section

A comparison of instantaneous velocities U, obtained with a HWA is shown in Fig. 10. The probe was positioned at the midpoint of the exit test section. Tests were carried out with three screens and without screens between the diffusers, for blower frequencies of 1900; 2400 and 2900 rpm. The data acquisition time was 20 s. The acquisition frequency was of 10 MS (Mega Sample). Nevertheless, to a better visualization the range results are only presented for a 0.1 ms interval.

Figure 10 presents the velocity at the midpoint at the exit test section, while Fig. 8 presents the average velocity at the same section. Therefore, higher velocities were found in Fig. 10. y and turbulent intensity always been obtained with the mounting of the wind tunnel without diffusers between the screens for each frequency of the blower, Fig. 10.

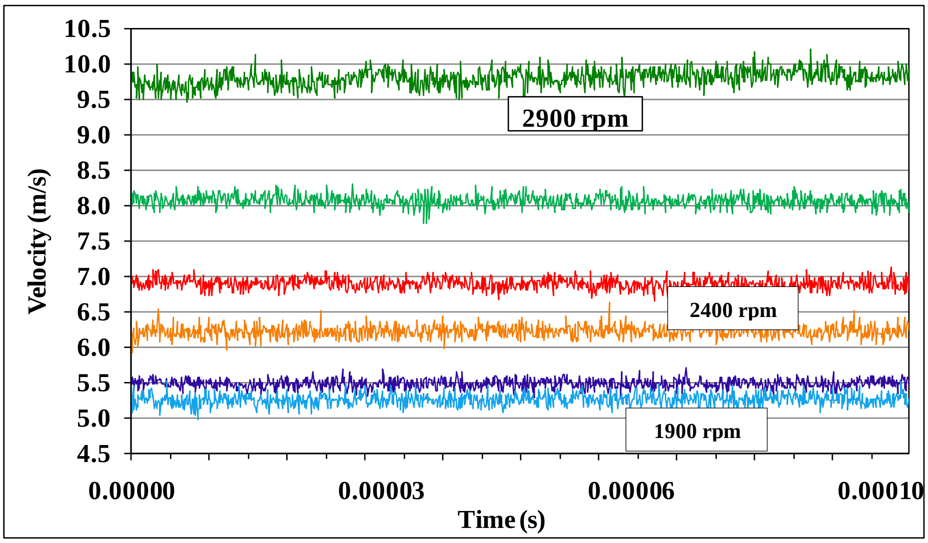


Figure10. Instantaneous velocity for the tunnel with and without screens

It can be highlighted that the higher velocity amplitudes were found for higher blower frequencies. Also, when the blower frequency was increased, the difference between instantaneous velocities obtained with and without screens was increased as well.

The values of turbulent intensities are shown in Fig. 11 for all frequencies tested. As expected the higher turbulence intensity is achieved without the screens for all blower frequencies. Moreover, it is not possible to determine a linear relationship between the turbulence intensity and the blower frequency. This behavior can be partially explained due the fact that the turbulence intensity was determined only by the measurement of one component of the velocity (U).

The turbulent intensity obtained for the tunnel without screens was 1.96% for 1900 rpm; 3.03% to 2400 rpm and 2.18%, for 2900 rpm, respectively. For the wind tunnel with three screens between the diffusers, the turbulent intensity obtained was 1.31% for 1900 rpm; 2.04% for 2400 rpm and 1.75% for 2900 rpm, respectively. The maximum uncertainty was ±0.01%.

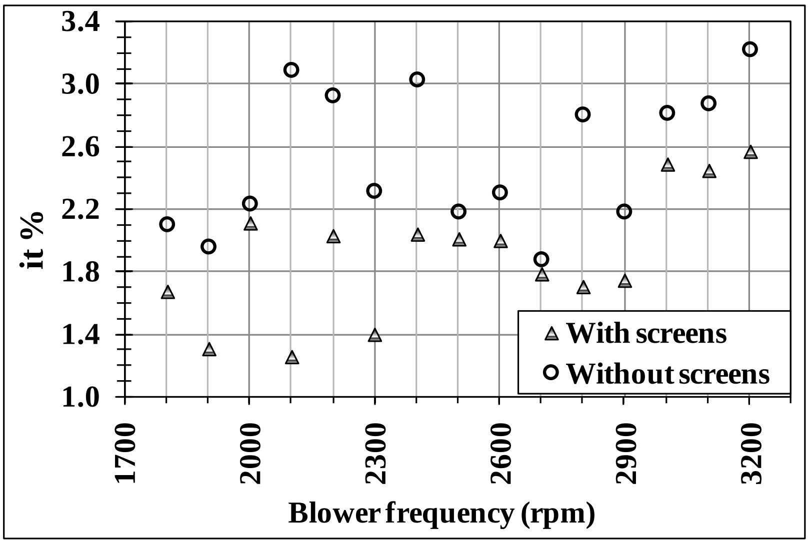


Figure 11. Comparison of the turbulence intensity for the tunnel with and without screens

4. CONCLUSIONS

In this work the fluid dynamic behavior in the exit test section of a low speed wind tunnel was studied. Two velocity measurement techniques were used. A Pitot tube was used to determine the velocity profile and a hot wire anemometer was used to measure the instantaneous velocity and its fluctuation. The behavior of the airflow was evaluated for the tunnel with and without screens between the diffusers. The blower frequency was varied from 1800 rpm to 3200 rpm with 100 rpm interval.

ISSN 2176-5480

The main conclusions of the work are:

- There is a linear relation between the blower frequency and the velocity at the exit test section of the wind tunnel;
- The higher velocity amplitudes were found for higher blower frequencies.
- The difference between instantaneous velocities obtained with and without screens was increased with the blower frequency.
- The results showed that tests with screens between the diffusers reduce the velocity without, however, significantly affect the velocity profile at the frequency range studied in comparison with tests without screens between the diffusers.

5. ACKNOWLEDGEMENTS

The authors are thankful to Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Centro Federal Center de Educação Tecnológica de Minas Gerais (CEFET-MG) and Pontifícia Universidade Católica de Minas Gerais (PUC Minas).

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