NUMERICAL AND EXPERIMENTAL STUDY OF THE GENERATION OF ATMOSPHERIC BOUNDARY LAYER PROFILE IN WIND TUNNEL

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Abstract. *Atmospheric wind tunnels are widely used in studies related to pollution dispersion, structural behavior in civil engineering, architectural aerodynamics and other applications. Atmospheric boundary layer (ABL) flows are specifically generated in wind tunnels to reproduce real wind profile conditions, and facilities for performing such experimental simulations are generally known as ''boundary layer wind tunnels (BLWT)''. In BLWT, a considerable thick boundary layer velocity profile and turbulence levels are produced to simulate an atmospheric boundary layer. The method to create the desired atmospheric features consists in adding appropriate devices at the entrance of the test section, such as grids, barriers, fences, spires and cubical roughness elements, in order to develop and increase the boundary layer height along certain wind tunnel length. This paper presents the design, experimental tests and computational simulation of different ABL configurations, which will be used in the atmospheric wind tunnel of the Brazilian National Institute of Metrology, Quality and Technology (Inmetro). Computational simulations, in OpenFOAM software, will be performed to compare the experimental data with numerical results and to evaluate the optimal spires set configurations to such wind tunnel. Several ABL simulations methods are available in literature. The method considered in this study is the Irwin Method. This scheme consists of a set of empirical formulae for spires design, which is related to the type of terrain (such as oceanic, hills, urban, among others) and is driven basically by two characteristics: the thickness of the boundary layer and the wind profile power law exponent. These formulae consider an uniform velocity profile at the wind tunnel inlet. Nevertheless, the Inmetro's atmospheric wind tunnel produces non-uniform velocities profiles at some mean velocities ranges, and so, the numerical and experimental studies also will be performed with the aim of evaluating the efficiency of this method when applied to non uniform velocity profile.*

Keywords*: Atmospheric boundary layer, wind tunnel, spires, experimental study, numerical simulation*

1. INTRODUCTION

The atmospheric boundary layer (ABL) is the lowest part of the troposphere where the winds, temperature and humidity are strongly influenced by the earth surface (Hartmann, 1994). The ABL is a result of interactions between the atmosphere and the surface below it (land or water) and it responds to a forcing with time scale of one hour or less (Arya, 1988). These forces include friction, evaporation and transpiration, heat transfer, pollutant emissions and modification of the atmospheric flow due the changes on the topography (Stull, 1988). The height of ABL varies between tens of meters to a few kilometers, and it depends on the heating or cooling rate emission of the floor, the intensity of the winds, topographical features, vertical large scale movements, heat advection and humidity, among other factors (Arya, 1988).

On the earth surface there are obstacles that work as ground aerodynamic roughness, and thus interfering on the free stream above it. These obstacles can be structures created by man, like buildings, or natural obstacles, such as trees and mountains. The disturbance intensity caused by each type of terrain can modify the atmospheric boundary layer thickness. This thickness is defined as the position (height) at which the atmospheric wind flow is no longer affected by the aerodynamic roughness. Above this height the wind speed variation with the vertical position is considered negligible, and the mean velocity profile is taken as uniform.

On studies concerning to atmospheric environments, the atmospheric wind tunnel is extremely important. These studies are related to industrial aerodynamics, meteorology, dispersion of pollutants, civil engineering structures among others. These wind tunnels, known as "boundary layer wind tunnels (BLWT)'', have appropriate devices to be added at the entrance of the test section in order to create the desired boundary layer.

The main objective of this paper is to provide directions to fulfill the challenges of adaptation of atmospheric wind tunnel for environmental studies in the Laboratory of Characterization of Fluid Flow Dynamics that belongs to Brazilian National Institute of Metrology, Quality and Technology – Inmetro.

2. LITERATURE REVIEW

Previously, most wind tunnels were constructed for aeronautical purposes and exhibited short test sections. The first boundary layer tunnel was built in 1965 by Prof. Davenport, in University of Western Ontario, Canada. The atmospheric boundary layer development was generated by a wide roughness floor.

Several research labs lacked the resources to build long tunnels and attempts were made to reproduce some of the features of the atmospheric boundary layer with completely artificial methods. Slip flow can be generated by cross bars with different spacing (Owen, Zienkiewicz, 1957) or by a bent screen (Elder, 1957), and these techniques have been used to reproduce the average wind velocity profile using the power law model. These artificial methods described by Lawson (1968), represented only the mean velocity profiles and were unable to reproduce the turbulence characteristics.

In the early 60's, Jensen (1963) and Frank (1963) showed that, covering a considerable length in wind tunnel floor with a suitable roughness material, is possible to reproduce an appropriate scale structure of the natural wind. This device corresponds to the main turbulence source in the atmosphere at lower altitudes. Afterwards, Cermak (1975) had built a weather tunnel at Colorado State University, United States, capable of reproduce thermally stratified boundary layers. However, the natural growth of the boundary layer is relatively slow, depending on the bottom roughness. Thus, it is necessary some artificial devices, such as spires, rods and barriers to increase the thickness of the boundary layer and achieve higher scales (Irwin, 1980; Cook, 1990).

Another technique, which began in 1971 (Schon, Mery, 1971), intend to reproduce the structure of the natural wind by aerodynamic means, through air jets launched in the bottom of the tunnel, perpendicular to the wind generated. However, the most widely technique consists in employing roughness elements in wind tunnel entrance, in order to reproduce the atmospheric boundary layer on few meters afterwards. In the work of Guimarães, et al., (1999), it was decided that three types of geometrical elements would be considered for the development of the boundary layer required. According to Counihan (1969) and Guimarães et al. (1999), grid, elliptic wedge generators, cylindrical rods and rectangular bars were used in this work, as show in Fig. 1.
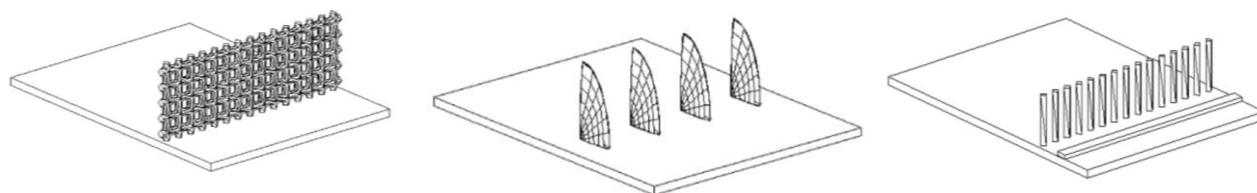

Figure 1. Grid, elliptic wedge generators and rods (Guimarães, et al., 1999)

3. EXPERIMENTAL APPARATUS AND PROCEDURES

3.1 Wind tunnel description

The Inmetro's atmospheric wind tunnel was made of wood sheets, with metal frames and transparent polycarbonate windows for optical access and visualization, as show in Fig. 2. It is an open-circuit tunnel of low speed and high turbulence intensity level. It has 10 m in length and square test section (1 m^2). The flow velocity is controlled by a frequency inverter which turns a 9 kW fan, reaching a maximum mean velocity about 10 m/s. Before entering in the test section, the air crosses a diffuser (ratio 1:2), a set of screens and a honeycomb (Farias, et al., 2014).

Figure 2. The atmospheric wind tunnel of Inmetro

3.2 Measurement Instruments

3.2.1 Hot-Wire Anemometry

In this study, the hot wire anemometry was used. The hot-wire anemometry is an intrusive technique used to measure flow parameters such as turbulent intensity and averaged velocity by sensing the changes in heat transfer from a small, electrically heated sensor exposed to the fluid motion (Goldstein, 1996). There are two categories for hot-wire anemometers, i.e., single and x-probe. Single wire probes, where the wire is oriented normal to the mean flow direction, are used to measure the velocity component in the mean flow direction. The crossed wire probes or x-probes, consisting of two wires arranged in an x-configuration, are employed to measure both stream-wise and cross-flow velocity components simultaneously (Manshadi, 2011).

The correlation for instantaneous velocity determination by using the hot wire anemometry may be given by the King's law:

$$E = A + B.u^n \tag{1}$$

where: A and B are constants that will be determined by the correlation between the voltage (E [V]) measured and the calculated velocity (u [m/s]), or by a polynomial interpolation.

In the present work, the probe used was the single wire (55P11) with the software Streamware®, both from Dantec Dynamics. A Constant Temperature Anemometry (CTA) bridge was used to acquire the data, which were processed by the Mathematica® software. The Dantec Dynamics Hot Wire Calibrator was used before run measurements in each tunnel position. The number of samples for each point measured (y, vertical position) was 32768, under the sampling rate of 1 kHz.

3.3 Design Methodology for Spires

To reproduce an atmospheric boundary layer in Inmetros's wind tunnel, the Irwin method (Irwin, 1980) was applied. The technique of spires is widely employed and several different shapes of spires are in use (Irwin, 1980). The spires used in this work consist of triangular plates, made of wood and a metal sheet to help supporting them inside the wind tunnel.

All the spires were placed at the tunnel's entrance to get a develop boundary layer wind profile. This technique is commonly used to simulate boundary layers, because it promotes the formation of a velocity profile which shows good agreement with the power law profile and turbulent intensities similar to those observed in atmospheric boundary layers.

The design of the spires depends on the expected boundary layer thickness (δ), and on the expected shape of the average velocity profile, where this last is defined by the power-law exponent (Fig. 3), and described as:

$$\frac{U}{U_\delta} = \left(\frac{z}{\delta}\right)^\alpha \tag{2}$$

where U is the velocity at the height z, U_δ is the velocity at $z > \delta$, and α is the power law exponent.
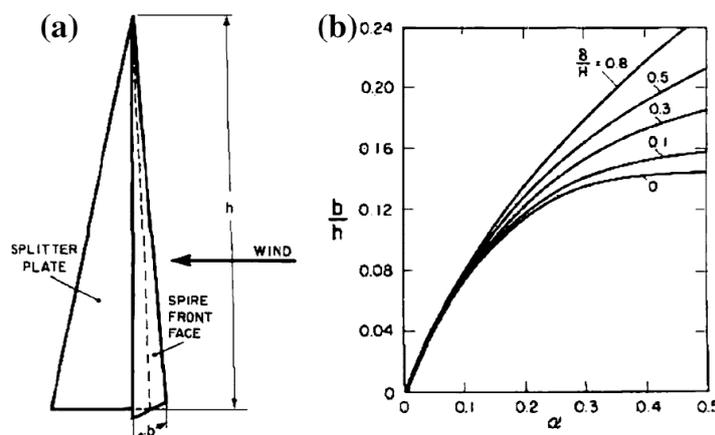

Figure 3. **(a)** A typical spire configuration and **(b)** Relation between the spire base-to-height ratio and velocity-profile exponent (Irwin, 1980)

The alpha exponent used on this paper has a value such that allows to represent the atmospheric boundary layer of a suburban environment, i.e., α is 0.28 and the respective boundary layer thickness is 500 mm (Parker, 1977). So, with these values it is possible to estimate the height (h) and base-length (b) of the spires, according to:

$$h = 1.39 \, \delta / \left(1 + \frac{\alpha}{2}\right) \tag{3}$$

$$\frac{b}{h} = 0.5 \left[\psi\left(\frac{H}{\delta}\right)/(1 + \psi)\right]\left(1 + \frac{\alpha}{2}\right) \tag{4}$$

where:

$$\psi = \beta \left\{[2/(1 + 2\alpha)] + \beta - \left[1.13\alpha/(1 + \alpha)(1 + \frac{\alpha}{2})\right]\right\}/(1 - \beta)^2 \tag{5}$$

$$\beta = \left(\frac{\delta}{H}\right)\alpha/(1 + \alpha) \tag{6}$$

where H is the working-section height.

Through these equations with α and β pre-established, the obtained height and base are 609 mm and 92 mm, respectively. So, as the corresponding number of spires is 3.28, the experiments were carried out with three and four spires for comparison. Four spires were constructed.

According to this method, the atmospheric boundary layer will be established at a distance of 6h downstream of the spires array. So, as the results show that the boundary layer will be developed in 3.65 m after the tunnel entrance section, the measurement section was chosen to be placed at x =4 m. Figures 4 and 5 show the three and four spires placed in the wind tunnel. The spires should be laterally spaced with their center-lines at intervals of $h/2$.
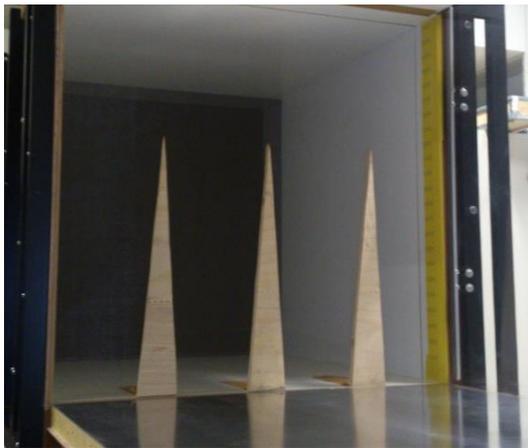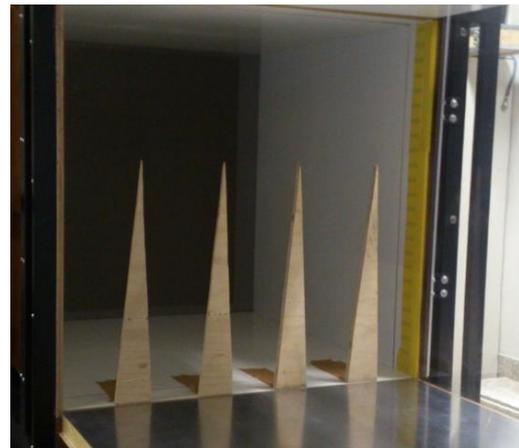

Figure 4. Three Spires arrangement

Figure 5. Four Spires arrangement

3.4 Measurement procedure

By using the hot wire anemometry technique, the velocity profiles were outlined in 03 cross section of the tunnel: i) in a region positioned immediately after the accommodation section (the tunnel entrance); ii) in a section positioned at x = 4 m (i.e. 4 m downstream the tunnel entrance); iii) in a section positioned 7m downstream the tunnel entrance. It were outlined 07 velocity profiles along the width (i.e., the z axis) of each transversal section, and each velocity profile was a result of 72 measured points along the tunnel height (y). The velocity profiles were mapped for two different mean velocities, both with and without spires inside the tunnel (under the condition of 03 and 04 spires installed). The ranges of the wind mean velocity were controlled by the frequency inverter coupled to the tunnel fan.
The experimental data were compared to the results of a simulation in the OpenFOAM software, with K-Epsilon turbulence model.

4. MATHEMATICAL MODEL AND COMPUTATIONAL SIMULATION

The fluid flow in the wind tunnel was discretized by partial differential equations describing the conservation of mass and momentum in 3D Cartesian coordinates system for steady and incompressible flow. The computational study was carried out through the OpenFOAM software version 3.0.1, based on a finite-volume discretization method and the geometry was built with Gmsh-2.11.0 software. The governing equations for the flow, based on the Reynolds-averaged Navier–Stokes (RANS) approach with standard $k -$ models are:

Continuity equation:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{7}$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(u_i u_j) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{ \nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \overline{u_i' u_j'} \right\} \tag{8}$$

where x_i are the Cartesian coordinates, ρ is the air density and is its kinematic viscosity, u_i and p are the ith mean velocity component and mean static pressure, respectively. u_i' and u_j' are the fluctuating components of velocity, $\overline{u_i' u_j'}$ are the Reynolds stresses. The Reynolds stresses are parameterized as

$$-\overline{u_i' u_j'} = \nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{3}{2}k\delta_{ij} \tag{9}$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \tag{10}$$

where ν_t is the turbulent kinematic viscosity of momentum, δ_{ij} is the kronecker delta ($\delta_{ij} = 1$, if i = j, otherwise 0), k is the turbulent kinetic energy, ϵ is the dissipation rate of the kinetic energy, and the C is a constant having a value of 0.09. The turbulence kinetic energy, k, and its rate of dissipation, ε, are obtained from the following transport equations:

$$\frac{\partial}{\partial x_j}(k u_j) = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + \nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} - \varepsilon \tag{11}$$

$$\frac{\partial}{\partial x_j}(\varepsilon u_j) = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}\nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} - C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{12}$$

where $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ are turbulent Prandtl numbers for k and, respectively, and $C_{1\varepsilon} = 1.44$ and $C_{2\varepsilon} = 1.92$ are constants. In modeling of urban flow, smaller grid size is desirable around building model to better resolve flow and dispersion field there.

The inlet velocity profile for the simulation is applied based on the experimental measurements in the tunnel entrance. It was employed uniform streamwise velocity and the turbulence kinetic energy k turbulent dissipation rate is:

$$k = 1.5(I\ U)^2 \tag{13}$$

$$\varepsilon = \frac{C_\mu^{3/4} k^{3/2}}{0.07 L} \tag{14}$$

where I is the turbulence intensity of the flow at the entrance of the test section, L is the characteristic length and C_μ is a constant equal 0.09. The slip boundary conditions were used to the tunnel and spires wall. The outflow boundary condition is set to be zero gradient, as default of OpenFOAM.

5. RESULTS

Experiments were accomplished with the frequency inverter at 7 Hz and 13 Hz, resulting in wind mean velocity 0.495 m/s and 1.212 m/s, respectively. For calculations performed numerically in the OpenFOAM software, it was used the average of the velocity profiles achieved in the center of the test section (z = 490 mm).

The graphs in Fig. 6 and Fig.7 show the velocity profiles at the entrance of the wind tunnel (without spires), which corresponds to, respectively, 7 Hz and 13 Hz on the frequency inverter. It was observed that for higher velocities the profile was not uniform. However, although the Irwin method considers a condition of uniform flow upstream of the spire array, one goal of this work is to analyze the boundary layer formation on a non-uniform velocity profile.
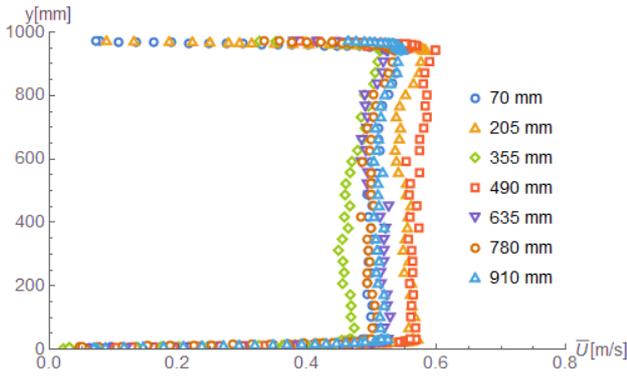
Figure 6. Velocity profile in the wind tunnel entrance for 7 Hz – Experimental data
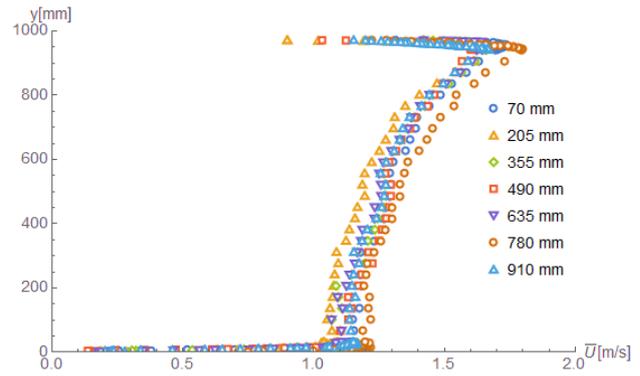

Figure 7. Velocity profile in the wind tunnel entrance for 13 Hz - Experimental data

Following, the Figs.8-11 show the experimental and numerical velocity profiles on the cross section positioned at x = 4 m, at frequencies of 7 Hz and 13 Hz, using 3 and 4 spires. Those profiles are compared to Figs.12-15, that show the experimental and numerical velocity profiles for x = 7 m, at the same frequencies and spires quantities.

All the results were compared to the power law profile, for $\alpha = 0.28$ and boundary layer thickness 500 mm.
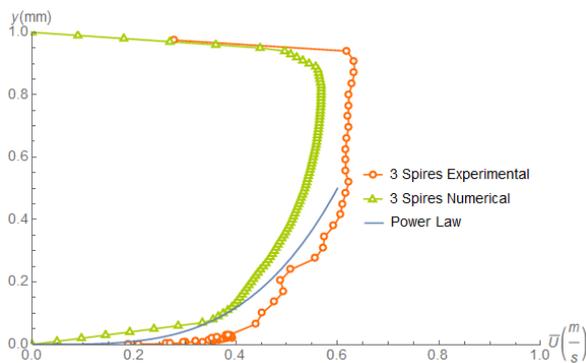
Figure 8. Velocity profile for 7 Hz and x = 4 m (3 Spires)
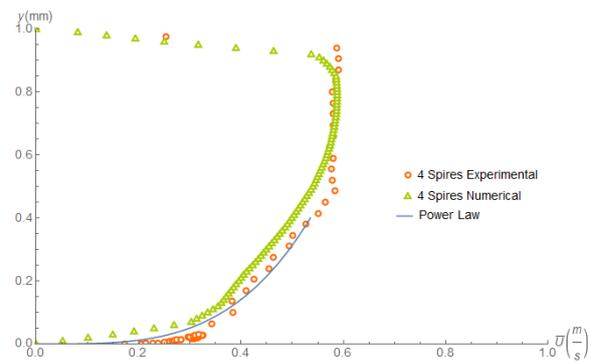
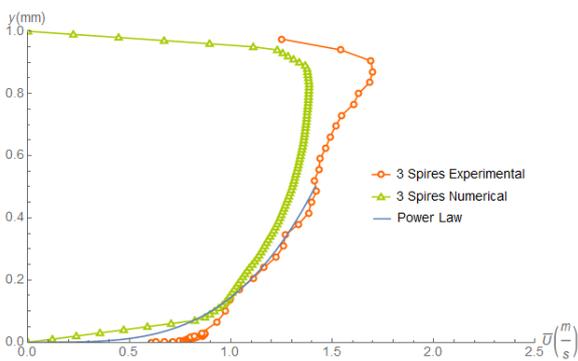Figure 9. Velocity profile for 7 Hz and x = 4 m (4 Spires)

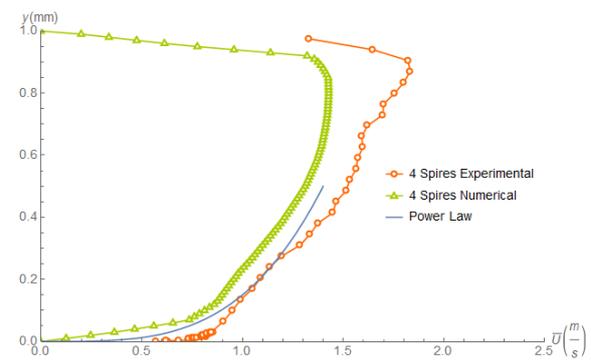Figure 10. Velocity profile for 13 Hz and x = 4 m (3 Spires)

Figure 11. Velocity profile for 13 Hz and x = 4 m (4 Spires)

According to Irwin (1980), at x = 4 m, the atmospheric boundary layer must be developed. It can be seen the Figs. 8-11, that the experimental and numerical velocity profiles showed good agreement with the power law profile. While in low velocities (7 Hz), the best approach can be observed for 4 spires arrangement (Fig.9), under high velocities (13 Hz), the 3 spires arrangement showed the best agreement (Fig. 10).
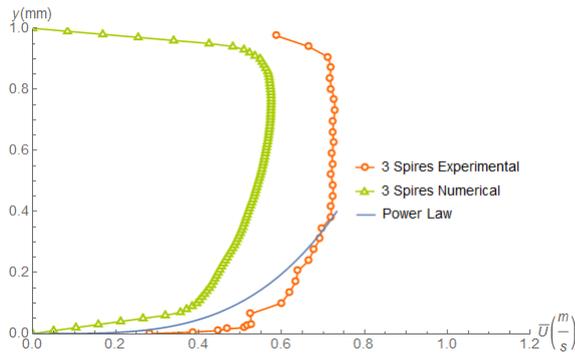
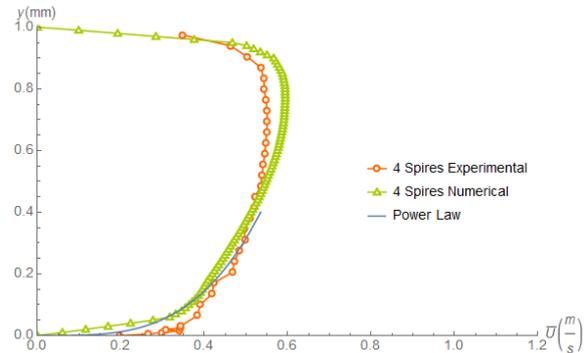Figure 12. Velocity profile for 7 Hz and x = 7 m
(3 Spires)

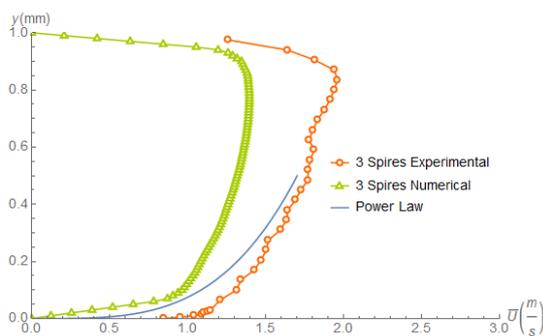Figure 13. Velocity profile for 7 Hz and x = 7 m
(4 Spires)

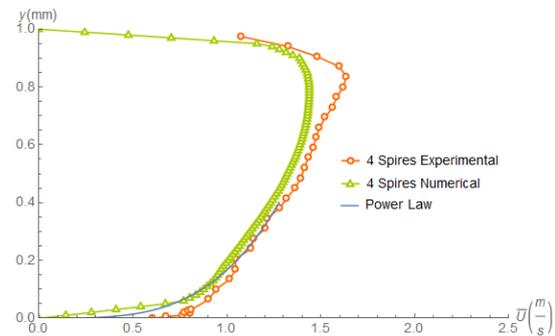Figure 14. Velocity profile for 13 Hz and x = 7 m
(3 Spires)

Figure 15. Velocity profile for 13 Hz and x = 7 m
(4 Spires)

At x = 7 m, from Figs. 12-15 it can be observed the behavior of the experimental and numerical velocity profiles. In that section position, at the two tested mean velocities the best agreement occurs when using 4 spires (Figs. 13 and 15).

Other important observation is that, nonetheless the input profile (at the tunnel entrance) is non uniform for high velocities, it did not interfere markedly on the boundary layer development process under that mean velocity range. Also, although some tests showed a small discrepancy and numerical results showed good agreement for both speeds tested.

Comparing the computational and experimental data, even considering the standard deviation of the experimental data, the results show the same trends.

6. CONCLUSION

This study presents the design, experimental and numerical results of two different inlet configurations that have been applied to the Brazilian National Institute of Metrology wind tunnel to simulate the atmospheric boundary layer. These configurations, with three and four spires, were used to evaluated the growth of the atmospheric boundary layer inside Inmetros´s wind tunnel, using Irwin's spires technique (Irwin, 1980).

It could be seen that there are differences between the development length of the boundary layer according to the expected length based on the literature, and the actual reached length in the wind tunnel. The computational simulation, by using the OpenFOAM software, presented velocity profiles in coherence with the measured profiles, both under initial uniform and non uniform flow conditions.

This work is the beginning of the Inmetro's efforts for having a wind tunnel adapted for pollutant dispersion studies, and in this phase of the work it was shown that the wind tunnel is appropriate for reproducing urban environments.

7. ACKNOWLEDGEMENTS

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