CHARACTERIZATION OF THE TURBULENT BOUNDARY LAYER IN AN ATMOSPHERIC WIND TUNNEL AND PRELIMINAR RESULTS OF THE STREET CANYON VENTILATION EFFECT STUDY

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ABSTRACT

In this work the main characteristic of the atmospheric wind tunnel of the Technological Research Institute of São Paulo are described. The roughness length, friction velocity and the thickness of the inertial sub-layer were estimated from a set of vertical profiles of the horizontal component of the mean flow (measured with Pitot tube) for two types of surface (smooth and rough) and three rotation rates of the wind tunnel fan (200, 300 and 400 rpm). These parameters are more sensitive to the presence vortex generators than roughness elements configuration at the wind tunnel floor. The velocity variance spectra obtained from times series measured with hot-wire anemometer obeys the Kolmogorov laws for different distances from the floor and for different wind tunnel fan rotation rate. A stagnation area induced by street canyon prototype was identified at lee-side of the main building area.

RESUMO

Uma caracterização do túnel de vento atmosférico do Instituto de Pesquisas tecnológicas de São Paulo é apresentada neste trabalho. O comprimento de rugosidade aerodinâmica, a velocidade de atrito e a espessura da sub-camada inercial foram estimados a partir de um conjunto de perfis verticais da velocidade média horizontal (medidas com tubo de Pitot) considerando-se dois tipos de superfície (lisa e rugosa) e três taxas de rotação do ventilador (200, 300 e 400 rpm). Estes parâmetros são mais sensíveis à presença do gerador de vorticidade do que da configuração dos elementos de rugosidade na superfície do túnel de vento. Os espectros de variância de velocidade obtidos a partir de séries temporais medidas com anemômetro de fio quente, obedecem as leis de Kolmogorov para diferentes alturas e taxas de rotação do ventilador. Uma área de estagnação induzida por um modelo de *street canyon* foi identificado à jusante da estrutura principal.

Keywords: atmospheric wind tunnel, turbulent boundary layer, spectral analysis, street canyon; ventilation effect.

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INTRODUCTION

Testing an atmospheric wind tunnel involves more than just applying the most appropriate instrumentation to measure flow properties. It requires assessing how well the boundary layer is modeled by the wind tunnel. Therefore, a characterization of wind tunnel implies also in to evaluate how accurate the wind tunnel reproduces the relevant properties of the boundary layer.

The simulation of turbulent boundary layer (TBL) in wind tunnels require the knowledge of the dynamical properties of flow, e.g. mean velocity and turbulence intensity, in several positions and when the model prototypes are not present. In this case, the dynamic properties of the undisturbed flow (by the model prototypes) will depend on the fan rotation rate and on elements that generate turbulence, namely: floor roughness, barrier-vortex generator system, lateral walls and ceiling.

The flow response due changes in those elements must therefore be well documented in order to identify and isolate the influence of the model prototypes on the simulated TBL. Thus, the main goal of this work is to describe the dynamic properties of atmospheric wind tunnel at the Technological Research Institute of São Paulo (IPT). In addition, it will also be investigated the ventilation effect caused by street canyon on the pollutant dispersion by mapping the flow cross section and compared with results available in the literature (Kastner-Klein *et al.*, 2001).

METHODOLOGY

Construction details about the IPT wind tunnel (Fig. 1) are described in Marciotto *et al.* (2005). In this work will be focused in two parts. The first one comprises measurements of flow velocity and pressure performed with an airflow static Pitot tube and a Scanivalve pressure transducer, respectively. In the second part, turbulence intensity of the flow is directly measured using a unidirectional Dantec hot-wire anemometer.

The hot-wire anemometer has been calibrated systematically before all simulations by fitting a fourth-order polynomial. The velocity range of calibration was kept from 1 to 25 m s^{-1}. All flow parameters are obtained at different positions in the wind tunnel test area using an automated robot coupled to acquisition data system.

Two types of surface roughness are considered in this study: smooth and rough. The smooth surface is given by the actual surface of the wind tunnel floor. Artificial rough surface was obtained by covering it with set of 1 or 2 cm wooden blocks. The disposition of the blocks on the floor varied. One set of simulations are carried out with presence of the barrier vortex-generator system (BVG) and, another without the BVG. During the simulations the fan rotation rate was set equal to 200, 300 and 400 rpm.

The pressure transducer carries out measurements with sampling frequency of 120 Hz, which enabled to obtain time series of pressure and so, indirectly, the intensity of turbulence of the flow.

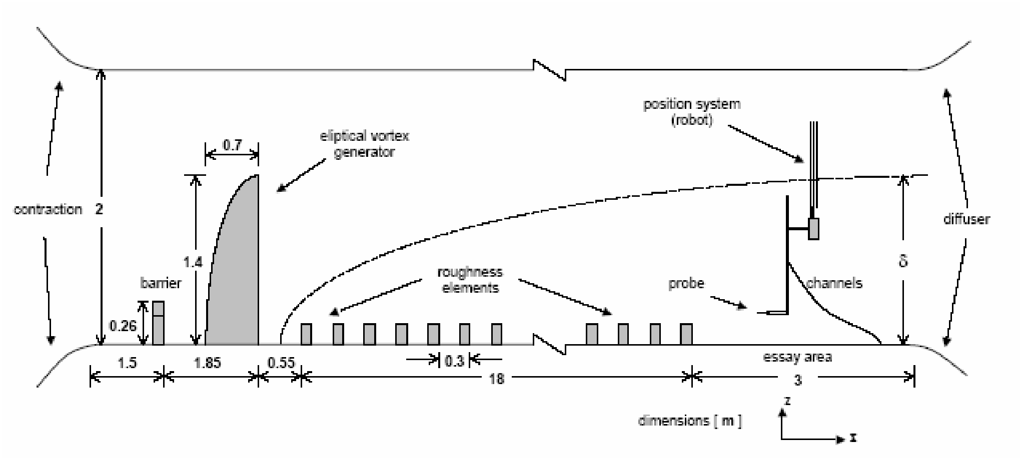

Figure 1. Schematic drawn of the IPT wind tunnel. Details about the tunnel are available in Marciottto *et al*. (2005).

RESULTS AND DISCUSSION

Mean velocity profiles and pressure fluctuation

Figure 2 shows vertical profiles of the mean horizontal flow velocity calculated by averaging ten vertical profiles of instantaneous horizontal flow velocity.

The presence of BVG increases the background turbulence and makes the flow velocity smaller than the case without BVG because of removing of momentum from the mean flow (Fig. 2a). In both cases, the mean flow velocities are practically equal for heights inferior to 0.1 m in the central region of tunnel (Fig. 2b). Near the lateral wall of tunnel, the flow velocity with BVG is smaller than without BVG over all vertical levels, as it can be seen in Fig. 2c. Without BVG, the TBL height is about 0.3 m and very well defined (Fig. 2a and 2c). On the contrary, with BVG, the shearing of the flow does not vanish in the vertical domain studied (0.5 m). Without BGV, the TBL height is of about 0.350 m (Fig. 2a).

Roughness length, z_0, and friction velocity, u_*, are estimated by fitting a logarithmic profile to the observed horizontal mean wind profiles (Fig. 3). The best fit was found for z_0 and u_* values between 0.2 mm─0.5 mm and 0.47 m s^{-1}─0.51 m s^{-1}, respectively. In this fitting procedure it was select only the set of values of wind speed that lay within the vertical extent of the inertial sub-layer. The selection of these sets was carried out by try-and-error, using as criteria the variation in z_0 and u_*. It was considered only the sets that yield the smallest variation of z_0 and u_*, simultaneously. This criterion is also used to identify the vertical extension of the inertial sub-layer. The layer that yields the smallest variation of z_0 and u_* is the inertial sub-layer. The best linear fit was obtained with set of points between Z = 0.060 m and

Z = 0.047 m. This indicates a vertical extent for the inertial sub-layer equal to 0.041 m. This value is about 12% of the TBL height (without BVG), and it is compatible with values adopted in literature (Stull, 1988).

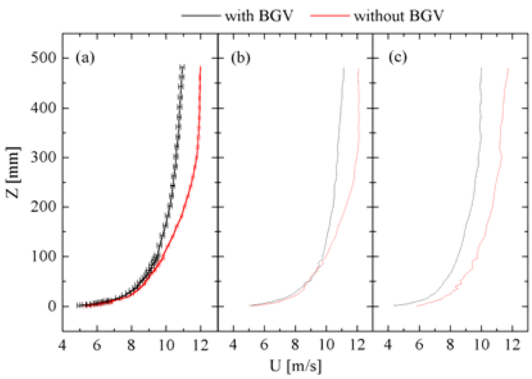

Figure 2. Vertical profiles of (a) Spatially averaged horizontal velocity, (b) observed in central part of the tunnel, and (c) observed near to the lateral wall. Continuous and dashed lines indicate *with BGV* and *without BGV, respectively*..

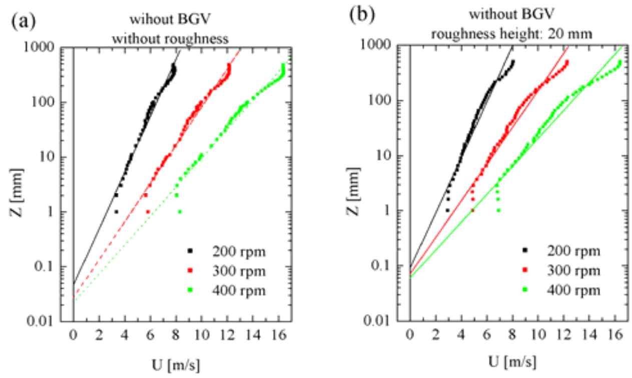

Figure 3. Linear fitting of logarithm wall law expression to estimate u_* and z_0 for (a) Smooth surface without BGV and (b) rough surface with BGV. In both plots can noted that the fitted lines converge for U = 0, implying a unique z_0, even if the fit slope diminishes as the rotation rate increase.

In Fig. 4 is shown two time series of the static and dynamical pressure *fluctuations* at 0.050 m and 0.500 m with sampling rate of 110 Hz. The turbulence intensity of dynamical pressure falls from 17.5% (p_d = 37.8 Pa, mean value) at 0.050 m to 1.4% (p_d = 82.6 Pa) at 0.500 m. On the other hand, the turbulence intensity of static pressure (as well as its mean value, p_e) is practically constant and equal to 1.2% ($p_e \approx$ 108 Pa). The first case, the turbulence intensity is directly associated with the velocity fluctuations within the boundary layer. In the second case, the intensity of turbulence is independent of BL height according to the classical Prandtl theory of the TBL (Monin and Yaglom, 1971; Cebice and Bradshaw, 1984). The importance of this study is that in most of geophysical applications pressure fluctuations terms is obtained as residues from the TKE equation (Stull, 1988), which can masquerade an eventual non-balance.

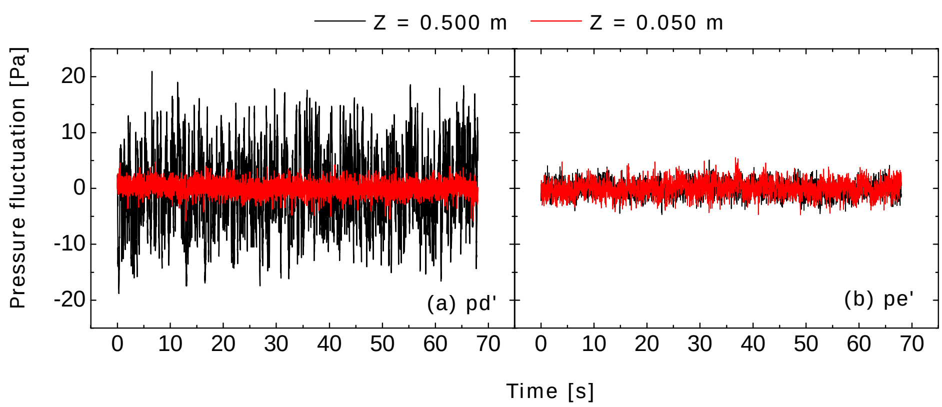

Figure 4. Times series of pressure fluctuation around the mean value: (a) dynamical, (b) static. Notice that the static pressure fluctuation variance (indicated by fluctuation amplitude) does not change with height, whereas the dynamical one varies sensibly.

Spectral analysis

As part of the wind tunnel characterization a set of 180 s long wind speed measurements was carried out with sampling rate of 3 kHz and using a hot-wire anemometer. Each set correspond to three different flow velocity, given by fan rotation rates of 200, 300 and 400 rpm, and measurements at 0.015, 0.030, 0.050, 0.100, 0.200, 0.300 and 0.400 m from the floor, totaling 21 time series. Figure 5 shows the velocity variance spectra for 0.015 m and 0.400 m above the floor. The universal Kolmogorov law is represented by the dashed line and corresponds to that range from 20 to 200 Hz, in which the turbulent kinetic energy is cascading from large to small eddy.

Mean and variance velocity fields over an urban canyon

A common procedure in urban dispersion studies is to use street canyon prototypes (Kastner-Klein and Plate, 1999; Kastner-Klein et al., 2001; Kastner-Klein and Rotach, 2004). To represent a street canyon it was used two parallel blocks, 16 cm wide and 64 cm long. In the test section the canyon was oriented perpendicular to flow. The mean and standard deviation of the velocity field was estimated for a cross section in middle of the canyon, using instantaneous values of velocity measurements (Fig. 6a-b). This simulation was carried out without BVG and roughness elements. The fan rotation rate was set equal to 300 rpm.

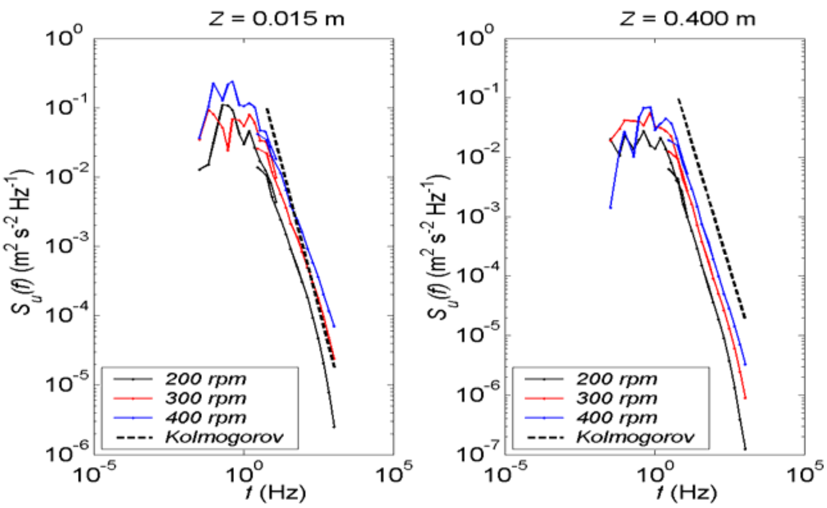

Figure 5. Velocity variance spectra observed in the wind tunnel at two distances of the floor and with three fan rotation rate. Dashed straight lines represent a –5/3 decay in the spectra.

The low velocity area is situated in central part of the canyon cross section, especially in the lee side of the street canyon (dark blue). A low velocity region is also present in center of the cross section between 10 and 12 cm in horizontal direction, and at 4 and 7 cm in vertical direction. Similar pattern was also present in the velocity standard deviation. This field is homogeneous and equal to 0.1 m s^{-1} in the most the canyon cross section. Low values of flow velocity and standard deviation is unfavorable to pollutant dispersion.

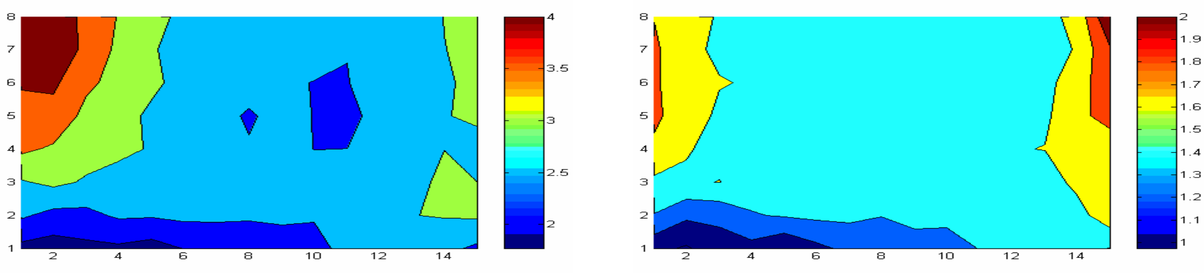

Figure 6. Velocity field (left) and standard deviation field (right) of a cross section in the middle of the canyon. Velocity and standard deviation in m/s, and the distances in cm. The flow over the canyon is from left to right.

CONCLUSIONS

A set of characteristics was obtained for the IPT wind tunnel flow: (a) it was confirmed that the BVG acts to increase the turbulence and to decrease the mean velocity of flow only above 0.1 m height in the absence of roughness. The TBL height is 0.3 m without BVG and greater than 0.5 m with BGV; (b) The z_0 and u_* values corresponding to the best fit are between 0.2 mm─0.5 mm and 0.47 m s^{-1}─0.51 m s^{--1}, respectively. The inertial sub-layer thickness corresponds to about 12% of the entire TBL; (c) The role played by the static pressure fluctuations will be further investigated by comparison with LES numerical simulations results (Marques Filho, 2004); (d) The flow velocity variance, obtained with a hot-wire anemometer over smooth surface and without BVG, follows Kolmogorov; (e) The mean and standard deviation of the flow velocity cross sections over a street canyon indicate a poor ventilation pattern at lee side of the canyon.

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