ATMOSPHERIC BOUNDARY LAYER STUDY INSIDE A WIND TUNNEL: VELOCITY PROFILE ANALISYS

Suelen Trindade Roballo, suelen@cptec.inpe.br
Instituto Nacional de Pesquisas Espaciais (INPE)- Avenida dos Astronautas, 1.758, S J Campos – SP, Brasil
Roberto da Motta Girardi, girardi@ita.br
Instituto Tecnológico de Aeronáutica (ITA). Praça Mal. Eduardo Gomes, 50, S J Campos – SP, Brasil
Gilberto Fisch, gfisch@iae.cta.br
Instituto de Aeronáutica e Espaço (IAE). Praça Mal. Eduardo Gomes, 50, S J Campos – SP, Brasil

Abstract. *At the Alcantara Launching Center (CLA), the brazilian rockets and space vehicles launching base, situated in the north coast of the Maranhão state, there is a relative topographical variation which modifies the atmospheric boundary layer characteristics and can cause some danger to launching operations. In the present work a simplified model was studied in a wind tunnel by using a hot wire anemometer. The first task is to produce a thicker boundary layer in the test section of the wind tunnel in order to simulate the atmospheric boundary layer characteristic of smooth surface, normally observed at oceanic surfaces and this is performed by using spires located at the beginning of the test section in conjunction to a rough surface. A forward facing step was placed in order to simulate the local topography variation and average and fluctuating velocity profiles were measured at a set of positions in order to verify the profile changes. Comparison with data obtained at CLA is performed in order to verify the validity of the wind tunnel experiments.*

Keywords*: boundary Layer, Wind tunnel experiments, Hot wire anemometer, velocity profiles*

1.INTRODUCTION

The knowledge of the atmospheric flow at the Space Launch Centers (like Kennedy Space Center – the US Space Port and Kouru Space Center – French/Europe Port) is a very important issue due to its influence on the research & development of the rockets to support the wind loads. Also, the trajectory, guidance and control of the rockets are very influenced by the wind profile, especially near the surface. Up to a height of 1000 m, 88% of the trajectory corrections are due to the winds while there are only 3 % of wind corrections above 5000 m (Fisch, 1999).

The region of the Alcântara Space Center is located at the north coast of Maranhão State. This region has a very special topography with a smooth surface (ocean) close to a rough surface (continent). At the border there is a sudden step or cliff (“falésia”) with a 50 m of height. The launch pad of the rockets is located close to this border (150 m) and the rockets suffers an intense turbulence due to the modification of the wind profile blowing from the ocean (smooth surface) to the continent (rough surface). This work aims to study the atmospheric flow at this particularly site using wind tunnel techniques.

Recently the wind tunnels are being used by micrometeorology science due to its advantage of control the flow, which optimize the data collection. Within the recent applications find in the literature, it can be cited simulations with the coupling between forest and atmosphere (Novak et al., 2000) that analyzed the turbulent structure of the atmosphere within and above canopy, simulations of the atmospheric wind field at a complex topography in order to plan the Naro Space Center at South Korea (Kwon et al., 2003), pollutant dispersion fields immersed in obstacles (Mavroidis and Griffiths, 2003) besides simulation of the air flow for complex topography (Cao and Tamura, 2006).

2. SITE, INSTRUMENTATION AND METHODOLOGY

2.1. Site

The Space Launch Center (CLA in Portuguese) is situated at the village of Alcântara at the north coast of the Maranhão State at geographic coordinates 2°19’ S, 44°22’ W, 49 m and a distance of 30 km to the city of São Luiz - MA. CLA is the main Brazilian Space Center where Satellite Vehicle Launcher (VLS in Portuguese) and rocket soundings (like SONDA II, SONDA III, VS30, VS40 and VSB-30) are being launched during the last 20 years. The vegetation is characteristics of *restinga* with trees with from 2.0 up to 3.0 m height. The climate of Alcântara shows a rainfall regime divided in 2 different periods: a wet period from january up to june and a dry period from july up to december. During the wet period, the precipitation is around 200 mm per month while at the dry season the rainfall is lower than 20 mm per month. The winds are very distinct between both seasons: during the wet season (march is a characteristic month) the winds is weaker and associated to the trade winds. The wind direction is from east up to 5000 m, with windspeed around 7.0 and 8.0 m/s between the levels of 1000 and 3000 m. For the dry season (september) there is a superposition between the trade winds and the sea breeze, producing stronger winds. The direction is from east up to 8000 m height, reaching maximum velocities between 10.0 and 15.0 m/s at 2000 m. The sea breeze is more intense during the dry period because the thermal difference between ocean and continent. The air temperature and humidity does not present seasonality and their values are very typical of the tropics (Fisch, 1999).

2.2. Wind Profiles at near-neutral conditions

Neutral stability conditions are very rare to be finding at the atmosphere (Arya, 2001). For strong winds with mean hourly windspeed higher than 10.0 m/s, the flow is sufficient turbulent to mix the atmosphere in the vertical and suppress the thermal (bouyancy) effects. Consequently, the atmosphere stability can be assumed close to the neutrality (Loredo-Souza et al., 2004). This work assumes a neutral stability at CLA due to the strong winds. The Reynolds number for the atmosphere is around 10^7 for both periods (wet and dry).

There are some experimental laws to represent the wind profile. Among them it can be cited the Logarithmic Law and Power Law. The vertical variation of the mean windspeed (U) up to approximately 100 m above a roughness surface can be represented as:

$$U(z) = \left(\frac{u_*}{k}\right) \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where u_* is the friction velocity (m/s), k is the Von Karman´s constant and assumed as 0.40 and z_0 is the roughness aerodynamic (m) of the site.

An observational analysis (Roballo and Fisch, 2006) with a wind tower at CLA has obtained values of roughness aerodynamic between the class 0.0-0.1 m. The friction velocity was in the interval between 0.3 and 0.4 m/s for the wet period and between 0.4 – 0.5 m/s for the dry period. These values will be compared with the simulated measurements at the wind tunnel.

The Power or Wall Law can be defined by the equation (2), where U(z) and $U(z_r)$ are mean windspeed equivalent to a height z and a reference height z_r .

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

The exponent alpha for the observational study described earlier (Roballo and Fisch, 2006) was between 0.20 and 0.25 for CLA.

At the near neutral conditions, the atmospheric turbulence is purely originated from the windshear (mechanically driven) and depends of the friction of the surface and the vertical windshear. Usually a statistical means and fluctuations are used to represent the turbulent structure but it will be used, in this work, the concept of the turbulence intensity, defined as the ratio between the standard deviation (σ) and the mean windspeed (U), e.g.:

$$I = \sigma/U \tag{3}$$

2.3. Wind Tunnel Simulations

The wind tunnel used is of open circuit (the air is absorbed at one extreme and released at the other) and it is located at *Laboratory Kwein Lien Feng* at Technology Institute of Aeronautics (ITA in portuguese). The measurement chamber has height and width of 460 mm e length of 1200 mm. There is an extension of the length made by wood (with an open lid and internal width of 410 mm), to permit the fully development of the boundary layer profile (Figure 1).

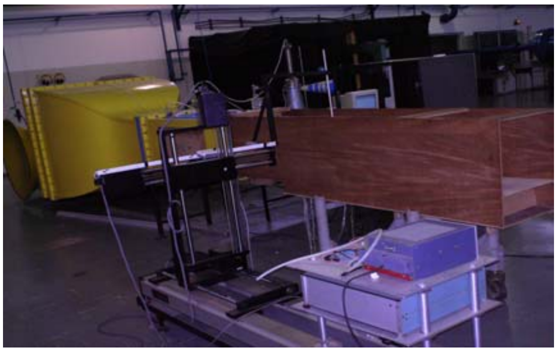


Figure 1. An overview of the wind tunnel with the extension.

In order to simulate the atmospheric wind that occurs at Alcântara at the wind tunnel, it was necessary to install few spires. These spires consist of triangular plates, confectioned using steel plates. The "spires" is collocated in the entrance of the chamber of measurements and combined with the roughness (in the case it was used a carpet of 131 cm settled in the floor of the tunnel) to produce the boundary layer profile for the wind flow (Santa Catarina, 1999). The dimensions of "spires" depend on the type of boundary layer that would like to simulate and the dimensions of the tunnel. They should follow the recommendation of that in the distance between one "spire" and another one must possess the half of the height of one "spire" and the fact of that the heights of "spires" must be lesser that the height of the wind tunnel. Consequently, 3 spires have been used as shown in Figure 2. Due to the dimensions of the tunnel, a scalling factor of 1:1000 was used (e.g. 1 mm in the wind tunnel was equivalent the 1 m in the real scale). The technique of hot wire anemometry was used for the measurements of the windspeed.

Figure 2. The spires at the entrance of the chamber of measurements

The Figure 3 represents a lateral view of the mounted mockup of the wind tunnel. It is possible to observe the experimental design and, after the adjustment of the boundary layer inside the wind tunnel, an apparatus (to represent the falesia) was inserting.

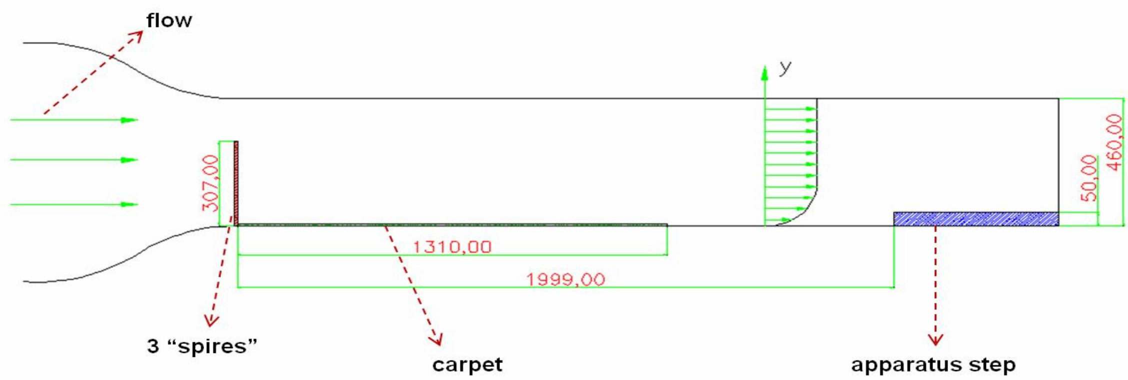


Figure 3. Lateral view of the mounted mockup.

2.4. Methodology

Initially some measurements have been made without the "apparatus step" (shown in Figure 3) in order to adjust the exponent alpha of the Power Law (Eq.(2)) to a value of 0.15. This value is typical of smooth surface as the ocean (Blesmann, 1973). Several tests were made, changing the length and the type of the carpet in order to obtain this alpha. As the exponent alpha was obtained at position 1 (Figure 4), others positions (e.g. position 2 and 3 from Figure 4) were also measured. Also the evolution of the profile at positions 4 and 5 were made to verify the spatial variation of alpha.

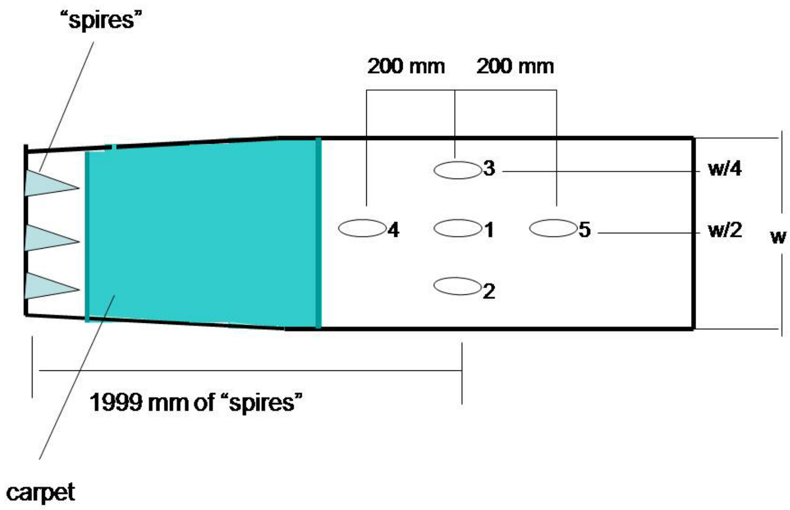


Figure 4. Superior view of the wind tunnel showing the points of the measurements for the boundary layer profile.

After the adjustment of the boundary layer profile, a step apparatus was insert inside the wind tunnel (Figure 5) in order to represent the "falésia". This cliff was put at a distance of 1990 mm of "spires" and the results obtained were called Experiment 1.

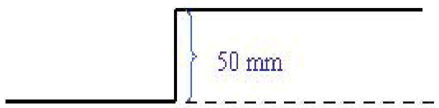


Figure 5: Schematic illustration of the step

The measured heights had been controlled using a milimetric ruler that was part of a positioning system. This system is able to move in three directions. The heights of measurements are: 6.0, 10.0, 16.3, 28.5, 43.0, 70.0, 90.0 110.0, 130.0, 150.0, 170.0, 190.0 and 210.0 mm and the first six correspond to the levels of the anemometric tower (Roballo and Fisch, 2006). The maximum speed obtained was close to 22.0 m/s corresponding a Reynolds number in the order of 10^4.

3. RESULTS AND DISCUSSION

Figure 6 represents a schematic design of the measurements. A coordinate system (x,y) was used as a reference system, where the negative x values corresponds to the ocean (left of the cliff) and the positive x values corresponds to the continent (right).

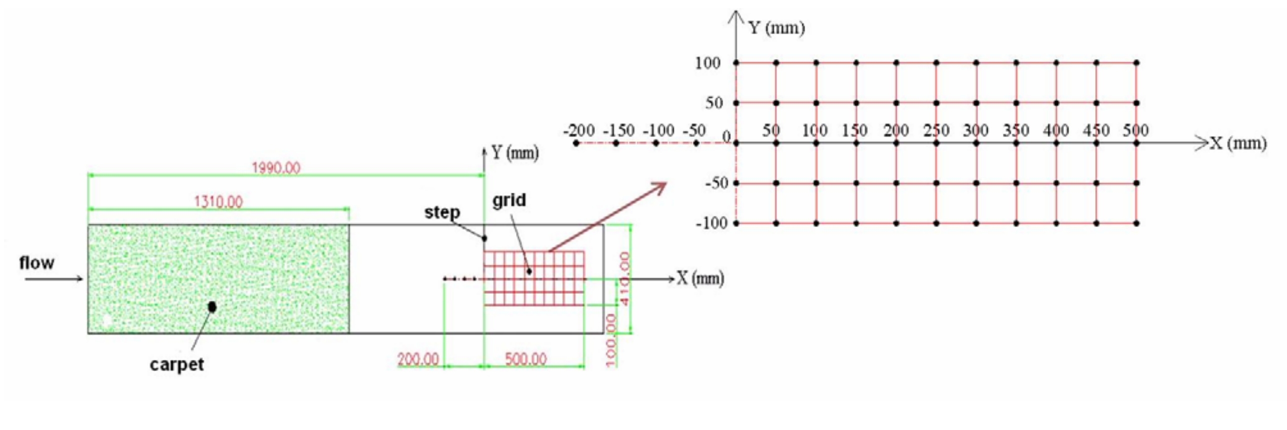
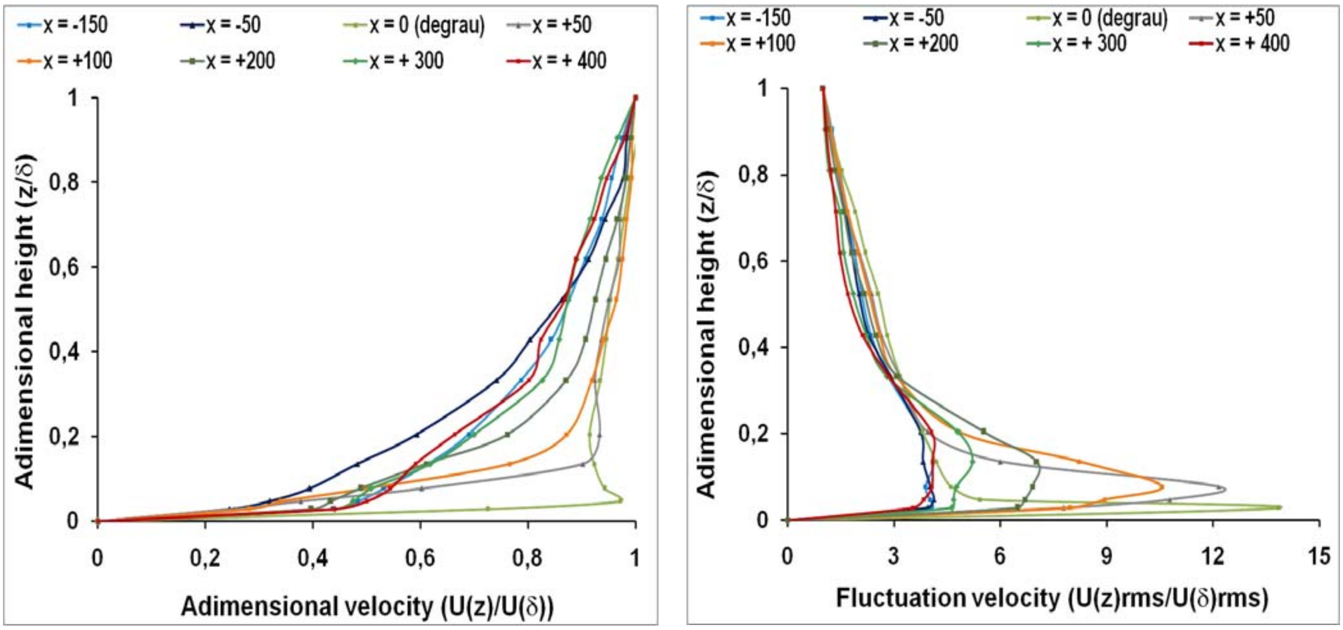


Figure 6. Superior view of the experimental design with the coordinates x (longitudinal) and y (lateral).

Figure 7 represents the profiles of the windspeed (or velocity) and the fluctuation (or deviation) of the wind along the central lane (keeping the position y = 0 at Figure 6). It is possible to observe the modification of the profiles at the cliff (position x = 0). Also, it can be noticed that the values of the windspeed are lower after the cliff associated with the higher values of the fluctuation, mainly close to the surface. This is an indication of the turbulence, due to the step, up to a distance around 300 m from the discontinuity (cliff). The bigger fluctuations values for a height lower than 0.2 represents the influence of the surface, which creates strong turbulence.



(a) (b)

Figure 7. Average velocity profile (a) and fluctuating velocity profiles (b) along the central lane.

The turbulent intensity (Eq. 3) was computed with the windspeed and its deviation measured at the heights correspondents to the levels of the anemometric tower (e.g. 6, 10, 16.3, 28.5, 43 e 70 m) and is presented at Figure 8. It is possible to observe that I is very high close to the surface, specially close to the discontinuity, reaching values of 0.7 at level 1. There is also a significant decrease of I with height and in the level 6 (equivalent of 70 m height) the turbulent intensity is around 0.1 for all positions along the central line. The distance of 300 m is estimated to be the distance where the turbulence originated by the edge has disappeared.

The values of the exponent alpha from the Power Law were obtained from the linearization of the Eq. 2:

$$\log\left(\frac{U(z)}{U(z_r)}\right) = \alpha\left[\log\left(\frac{z}{z_r}\right)\right] \tag{4}$$

and by plotting *log (U(z)/U(z*$_r$*))* against *log (z/z*$_r$*)*. The alpha is computed from the adjusted regression (angular coefficient) and Figure 9 shows an example of the procedure.

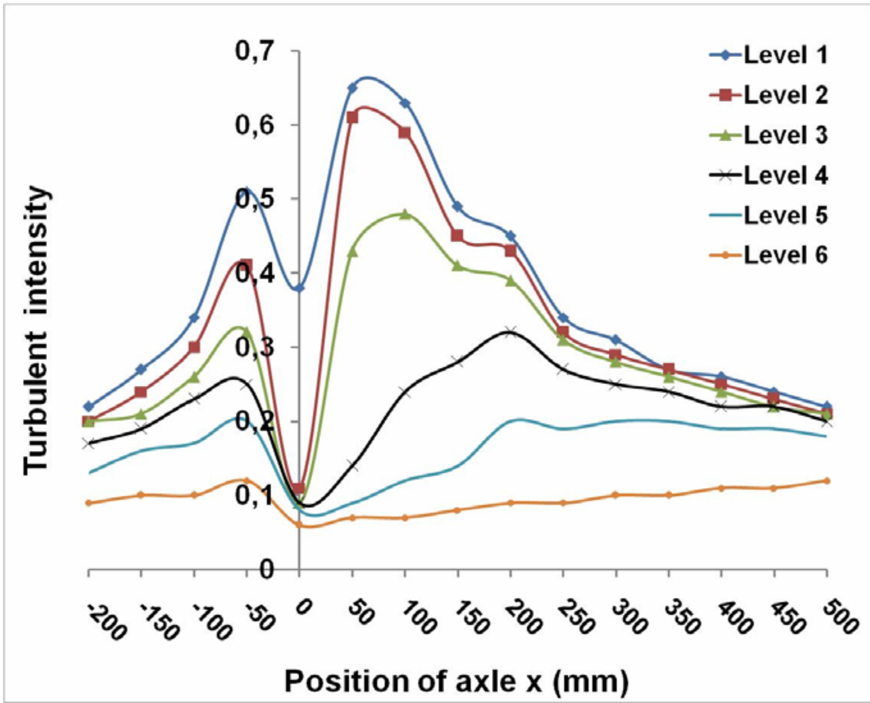


Figure 8: Turbulence Intensity distribution along the central lane (position y = 0)

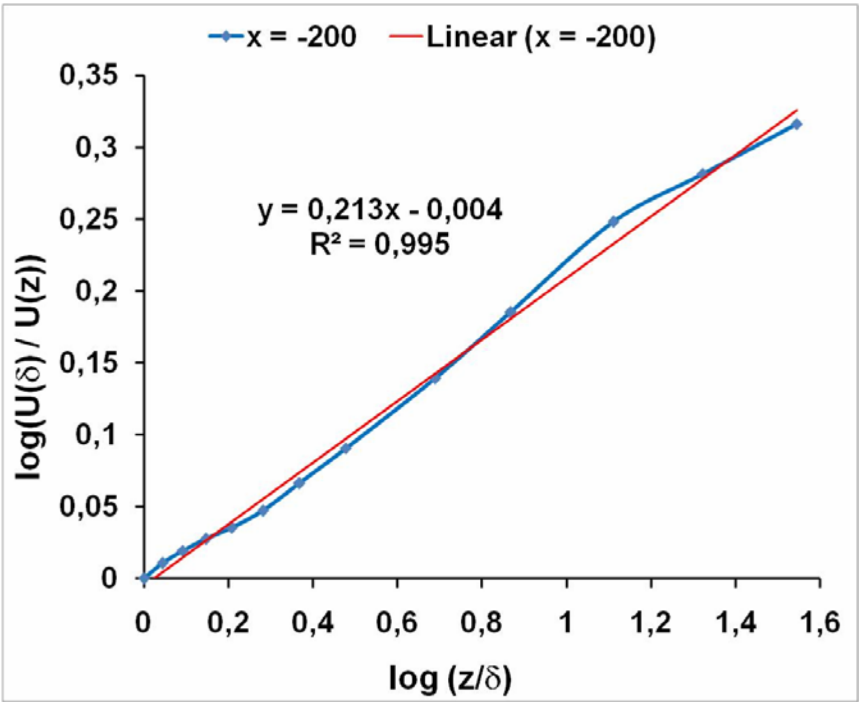
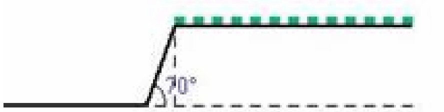


Figure 9. Example of the determination of alpha by Eq. 4

In order to fully investigate the role of the cliff in creating turbulence, 3 others experiments were designed and simulated at the wind tunnel, e.g.:

a) Apparatus smooth step (70 °) – Experiment 2

b) Aparatus smooth step (70 °) with local vegetation (simulated by woody cubes of 3 mm) **-** Experiment 3



c) Apparatus perpendicular step (90°) with local vegetation – Experiment 4

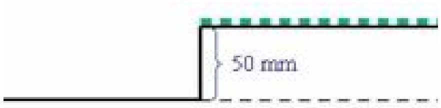


Table 1. The alpha values for the central lane (position y=0)

Position (axle x)	ALPHAS			
	Experiment 1	Experiment 2	Experiment 3	Experiment 4
X = -200	0.21	0.20	0.21	0.22
X = -150	0.24	0.24	0.22	0.22
X = -100	0.31	0.34	0.36	0.28
X = -50	0.40	0.41	0.41	0.41
X = 0	-	-	-	-
X = 50	-	-	-	-
X = 100	-	-	-	-
X = 150	-	-	-	-
X = 200	-	0.46	0.34	0.35
X = 250	0.24	0.39	0.27	0.28
X = 300	0.24	0.30	0.24	0.28

From Table 1, which summarizes the results from all experiments, it is possible to notice that the Power law can not be applied close to the border due to region of re-circulation, triggered by the roughness change. Before the cliff, all alphas were approximately equal, especially at the far distance (x= **-** 300 m). This is an indication that the cliff will not influence this position. The values of alpha at 200 m (which corresponds to the distance of the anemometric tower to the edge of the cliff) are higher than the observations (Roballo and Fisch, 2006). At a distance of 300 m from the edge, the values are close to the observed values obtained by the wind mast.

The meteorological parameters (u_* e z_0) of the logarithmic law (Eq. 1) were also been computed and compared with the observations (Roballo and Fisch, 2006). The linear regression obtained plotting *ln z versus ln U* resulted in estimation of k/u_* (angular coeficient) and ln z_0 (linear coefficient). The distribution for u_* e z_0 at the central lane are showed at Figures 10 and 11, respectively. At the position of the edge (x=0), there is an abrupt decrease of the values of u_* e z_0 for Experiment 1. For the others experiments, this variation is not so intense due to the smoothness of the topography (experiments 2 and 3) or the include of the vegetation (Experiment 4). The values of z_0 at the position 200 m showed very high numbers and this situation can be associated with lower Reynolds number of 10^4 instead of 10^7, which is typical of the atmosphere. This situation permits that the circulation zone be longer (at the wind tunnel measurements) than it is in reality. This is showed by Figure 11. At the point x=300 mm (300 m from the edge) the roughness presents a value of 0.1 m, similar to the observed values derived by Roballo and Fisch, 2006.

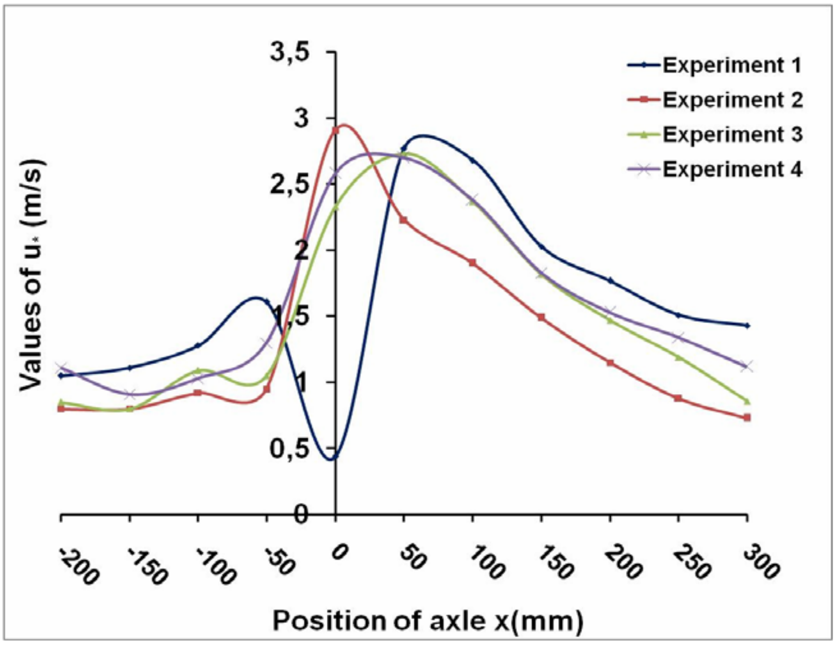


Figure 10. Distribution of u*

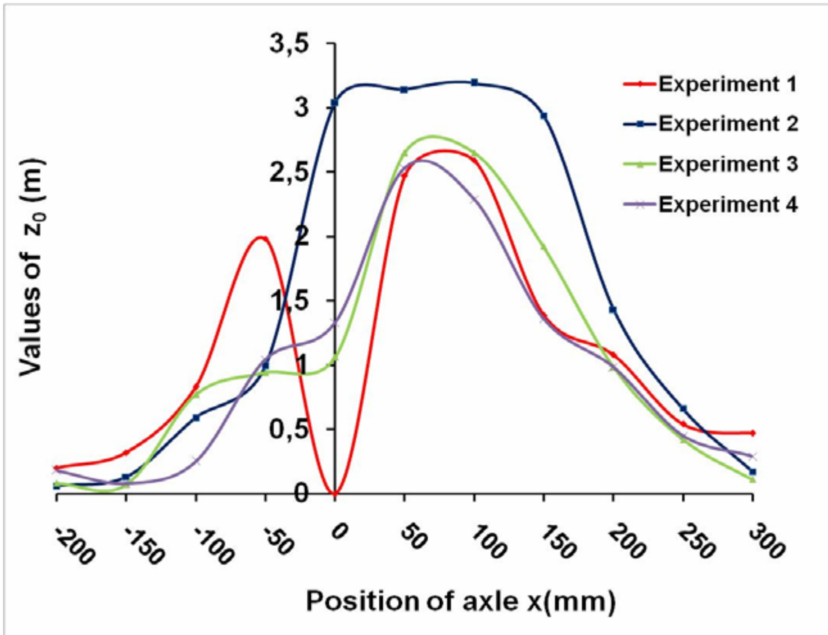


Figure 11. Distribution of z_0

Table 2 presents the results for u* for all the experiments as well as the observations. The results closest to the observations were the results obtained with the Experiment 2.

Table 2. Comparisons of the values of u_* for all experiments.

Friction velocity (u_*)		Absolute value (m/s)	Characteristic velocity (m/s)	Adimensional value	Reynolds
Wind Tunnel	Experiment 1	1.80	22	0.08	$6.52x10^4$
	Experiment 2	1.20	22	0.05	$6.52x10^4$
	Experiment 3	1.47	22	0.06	$6.52x10^4$
	Experiment 4	1.53	22	0.07	$6.52x10^4$
Alcântara	Wet period	0.3-0.4	8	0.04	$2.37x10^7$
	Dry period	0.4-0.5	10	0.04	$2.92x10^7$

4. CONCLUSIONS

The atmospheric flow at Alcântara has been simulated by wind tunnel measurements. It was not possible to obtain a high Reynolds number typical of the atmosphere, due to the limitations of the windspeed reached by the wind tunnel. As a result, the roughness parameters showed higher values than the observations, because the re-circulation zone is longer. Comparing the different experiments with some observational data (Roballo and Fisch, 2006), the experiment 2 presented the best results for friction velocity. The re-circulation zone driven by the perpendicular cliff is more intense and the case of smoothed cliff. Also, the influence of the vegetation has been studied and the results showed that it decreases the turbulence generated by the cliff.

5. ACKNOWLEDGEMENTS

Thanks are due to the Coordenação de Aperfeiçoamento Pessoal do Ensino Superior (CAPES) for a Master of Science Scholarship for the first author, to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the scholarships of Inovation Technology and Research (Process numbers YYY and 302117/2004-0) for the second and third author, respectively.

6. REFERENCES

Arya, S. P.,2001, "Introduction to Micrometeorology". Academic Press. San Diego. 303p, 2nd edition.

Blessmann, J., 1973 "Simulação da Estrutura do Vento Natural em um Túnel de Vento Aerodinâmico", Tese (Doutor em Ciências). Instituto de Aeronáutica e Espaço – ITA, São José dos Campos, Brazil.

Cao, S. and Tamura, T., 2006, "Experimental study on roughness effects on turbulent boundary layer flow over a two-dimensional steep hill", Journal of Wind Engineering and Industrial Aerodynamics,Vol.94, No.1, pp.1-19.

Fisch, G., 1999, "Características do Perfil Vertical do Vento no Centro de Lançamento de Foguetes de Alcântara (CLA)", Revista Brasileira de Meteorologia, Vol. 14, No.1, pp. 11-22.

Kwon K.J., Lee J.Y, Sung B., 2003, "PIV Measurements on the Boundary Layer Flow around Naro Space Center", 5 th International Symposium on Particle Image Velocimetry, pp.22-24.

Loredo-Souza, A.M, Schettini, E.B.C, Paluch, M.J., 2004, "Simulação da Camada Limite Atmosférica em Túnel de Vento". In: Möler, S.M, Silvestrini, J., Anais da IV Escola de Primavera Transição e Turbulência, Vol.4, Porto Alegre, Brazil, pp. 137-163.

Mavroidis, I. and Griffiths, D.J.H., 2003, "Field and wind tunnel investigations of plume dispersion around single surface obstacles", Atmospheric Environment, Vol.37, No.21, pp.2903-2918.

Novak, M.D., Warland, J.S., Orchansky, A.L., Ketler, R., Green, S., 2000, "Wind Tunnel and Field Measurements of turbulent flow in forests. Part I: Uniformly Thinned Stands", Boundary Layer Meteorology, Vol.95,No.3, pp. 457-495.

Roballo, S. and Fisch, G., 2006, "Estudo das características do perfil vertical do vento no Centro de Lançamento de Alcântara (CLA)", XIV Congresso Brasileiro de Meteorologia. Anais do XIV Congresso Brasileiro de Meteorologia. Florianópolis, Brazil.

Santa Catarina, M. F., 1999, " Avaliação do Escoamento no Centro de Lançamento de Foguetes de Alcântara: Estudo em Túnel de Vento", Relatório Final de Atividades de Iniciação Cientifica. ITA-Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil, 72p.

7. RESPONSIBILITY NOTICE

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