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LARGE ARTIFICIALLY GENERATED TURBULENT BOUNDARY LAYERS FOR THE STUDY OF ATMOSPHERIC FLOWS

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Abstract. *The present work discusses in detail the experimental conditions for the establishment of thick artificially generated turbulent boundary layer which can be classified as having the near characteristics of an atmospheric boundary layer. The paper describes the experimental arrangement, including the features of the designed wind tunnel and of the instrumentation. The boundary layer is made to develop over a surface fitted with wedge generators which are used to yield a very thick boundary layer. The flow conditions were validated against the following features: growth, structure, equilibrium and turbulent transport momentum. Results are presented for the following main flow variables: mean velocity, local skin-friction coefficient, boundary layer momentum thicknesses and the Clauser factor. The velocity boundary layer characteristics were shown to be in good agreement with the expected trend in view of the classical expressions found in literature.*

Key words: *Turbulence, roughness, boundary layer, atmospheric flows*

1. INTRODUCTION

The lowest 1-2 km of the atmosphere comprises the boundary layer. This region is the most directly influenced by the local fluxes of momentum, heat and water vapor at earth's surface. In the outer region, extending from 500 to 2000 m, the shearing stress is variable and the wind structure influenced by surface friction, temperature gradients and the earth's rotation; the flow is strongly dominated by turbulent motions, resulting in fairly uniform profiles. In the surface region, extending from 0-100 m, steep gradients control the local fluxes and hence the state of the entire boundary layer.

Despite the great importance that the atmospheric boundary layer exerts on our daily lives, having such commanding effects on issues such as the dispersion of pollutants and the distribution of wind forces on structures, it is really surprising to find that systematic investigation on the subject has been restricted to the last 40 years. The reasons are obvious: the difficulty in performing on site measurements and the inherent mathematical difficulty in dealing with the Navier-Stokes equation.

For the above reasons, the performance of wind tunnel simulations of the atmospheric boundary layer has become a very important tool in the understanding and modelling of the phenomenon (Cermak(1971,1975)). The neutral boundary layer can be simulated in a wind tunnel by artificially creating a thick boundary layer so that measurements can be made with appropriatedly scaled models.

The purpose of the present work is to show how a combination of spires and trips placed upstream of the models can be used to produce boundary layers with characteristics similar to the atmospheric boundary layer. Five different geometrical arrangements will be tried here to produce boundary layers of thickness varying from 9 to 20cm. The ability to thicken a boundary layer provides a useful way of expanding the operational range of a wind tunnel, without all associated costs of increasing the length of the test surface. However, whatever true this may be, one must be sure that the artificially grown boundary layer has the same properties as would a naturally developed boundary layer of the same thickness. To qualify the boundary layers produced in this work, the following characteristics were examined: growth, structure, equilibrium and turbulent transport of momentum.

In what follows, a short review on the techniques used to thicken the boundary layer will be presented. Next, the experimental apparatus and procedure will be described. The experimental results and comparison with other works are given in section four.

2. SIMULATION METHODS

A variety of techniques have been devised to artificially thicken the boundary layer. Typical examples are the use of fences, uniform grids, graded or sheared grids, jets, pulsation, wall roughness, steps, screens, vortex generators and thermal stratification (Hunt and Fernholz(1975)). Accordingly, these techniques can be compared by considering the type of disturbances caused on the flow by the thickening device and how they interact with the shear flows that would exist in a wind tunnel without the thickening devices. Thus, according to Ligrani et al.(1983), and after the classical two-layer model for the boundary layer, three different categories can be defined.

In the first category, the simplest of all, the boundary layer is artificially thickened by altering the surface conditions to increase the shear. Classically, boundary layer trips or rough elements are used to achieve this effect.

In the second category, devices are used to alter both the inner and the outer regions of the boundary layer. Typical examples are: i) directional jets placed in the floor at the entrance to the working section, and ii) multiple horizontal jets of variable strength directed at each other from either side of the wind tunnel.

In the third category, devices are deployed that produce a large momentum deficit and extract turbulent energy from previously irrotational flow. In this method, an array of spires is used extending all the way from the wall to the oncoming potential flow. The turbulent wakes formed by the spires convect downstream to merge with the existing boundar layer resulting in a new structure which, in some cases, may resemble a thick boundary layer.

Irrespective of the method considered, one must be aware that obtainig a boundary layer with a certain degree of normality is a very difficult task. The turbulent structure in a normally developed boundary layer is a result of the development of large scales structures originating from the interaction between eddies formed by near-wall turbulent bursts and by the inflow of high-speed flow towards the wall. The structures convected away from the spires have a lifetime that must be exceeded before the flow is likely to conforme to the boundary layer properties.

When rough elements are used to thicken the boundary layer, some simple calculations (see Gartshore and Croos(1977)) can be made to produce wall shear stress and velocity distributions of a desired shape. In most simulations, the term equilibrium boundary layer is often used. This term has a precise meaning implying a flow whose turbulence is in exact dynamic equilibrium so that the mean distributions of turbulence, as non-dimensionalized by a single velocity and length scales, do not change in the streamwise direction. Such equilibrium flow can be shown to exist for some very particular conditions. A boundary layer developing under a zero pressure gradient and over rough elements with constant height and spacing is in approximate equilibrium condition, provided any step change in conditions is far from the considered region. The calculations derived by Garshore and Croos(1977) use an integral method to predict the development of the boundary layer. Basically, an empirical equation derived by Head(1960) to estimate the amount of entrained fluid in the outer region of the boundary layer is used. This procedure is preferable to those that resort to integral properties of shear stress or kinetic energy, since the latter are very sensitive to the uncertain conditions very close to individual roughness elements. For exact equilibrium conditions, graphs were constructed by Garshore and Croos(1977) which established a direct relation between u_τ/U_∞ and δ^*/K, λ/K, where δ^* represents the displacement thickness, K the height of the roughness elements, and λ the pitch of the roughness elements. In the same way, if a power law exists, a graph relating n with $\delta * /K$ and λ/K can be constructed.

The advantage of thickening the boundary layer with roughness elements is, as said before, that this method permits equilibrium flow to be reached with more ease. When very large initial roughness elements in the form of spires or wedges are used, the likelihood of the boundary layer reaching equilibrium condition seems very remote. In fact, much more work needs to be done in flow geometries of this kind to assess the degree of equilibrium present downstream of the spires. This is exactly what will be made here.

3. EXPERIMENTAL APPARATUS

The elements used to artificially thicken the boundary layer consisted of two basic components: cylindrical rods and rectangular bars. Different combinations of these two elements were made to produce four different types of apparatus. In all configurations, an array of rods which extended across the width of the wind tunnel was used. A rectangular bar located on the downstream side of the rods was also used to achieve normal turbulence structure. As the flow approached the rods, a trip was placed over the wall.

The four geometrical configurations of the thickening apparatus are shown in Figure 1, including the relevant dimensions. The present design was derived from a device developed by Ligrani et al.(1983), who in turn based their design on an apparatus developed by Peterka and Cemark(1974) to simulate the atmospheric boundary layer.

The shape and location of the components was determined by comparison with the already mentioned works of Ligrani et al. and Peterka and Cemark. To have a clear assessment of the effects of every component on the flow properties, the geometries were made to escalate in complexity, with the thickening device being assembled from one element (Figure 1a) to four elements (Figure 1d).

The thickening apparatus was tested for just one freestream velocity. The wind tunnel used was the high turbulence rig sited in the Laboratory of Turbulence Mechanics of the Mechanical Engineering Program of COPPE/UFRJ; for flows over a uniformly smooth surface, the free stream level of turbulence was about 2%. The tunnel is an open circuit tunnel with a test section of dimensions 67x67x300 cm; the test section has a roof with adjustable inclination to permit the development of flows with zero pressure gradient.

Measurements were performed for values of the free-stream velocity of 3.12 m/s. The stream-wise pressure gradient was closely set to zero by adjusting the roof of the tunnel according to the readings of eight equally spaced pressure taps.

Mean velocity profiles and turbulence intensity levels were obtained using a DANTEC hot-wire system series 56N. The boundary layer probe was of the type 55P15. A Pitot tube, an electronic manometer, and a computer controlled traverse gear were also used. In getting the data, 10,000 samples were considered which yielded a precision of 0.6% in the mean velocity data. The profiles were constructed from about 100 points taken at stations separated by 0.1mm.

To obtain accurate measurements, the mean and fluctuating components of the analogic signal given by the anemometer were treated separately. Two output channels of the anemometer were used. The mean velocity profiles were calculated directly from the untreated signal of channel one. The signal given by channel two was 1 Hz high-pass filtered leaving, therefore, only the fluctuating velocity. The latter signal was then amplified with a gain controlled between 1 and 500 and shifted by an offset so as to adjust the amplitude of the signal to the range of the A/N converter.

4. EXPERIMENTAL RESULTS

The properties in the thickened boundary layer depend strongly on the geometry of the spires. The total thickness of the shear flow just downstream of the spires is directly proportional to their height. The momentum thickness at this location can be expressed as $\theta = (C_d/2)A_f/\omega$ where C_d is the drag coefficient of the spires based on the frontal area A_f, and ω is the distance between two spires. Thus, altering the shape of the spires, and, therefore, of C_d the wave flow is completely changed. Several authors have used some very sophisticated design for the blades. Here we have opted for the simplest possible design, the circular rod.

4.1. Integral properties

The boundary layer growth can be characterized through variation of the momentum thickness with the downstream distance, and through variation of the skin-friction coefficient with the momentum thickness.

The momentum thickness was evaluated directly from the mean velocity profile through a simple numerical quadrature. The results are shown in Figure 2. The points in this figure have been plotted taking the origin that an artificially generated boundary layer would have if it were a naturally developed boundary layer. The distance from the rods where the velocity profiles were actually taken were 1990, 2090, 2190 and 2290 mm. To this values, an extra lenght, dependent from the thickening device, was added to simulate the distance that a naturally developed boundary layer would need to flow to achieve the measured properties. This distance is a function of several factors; however, we may say

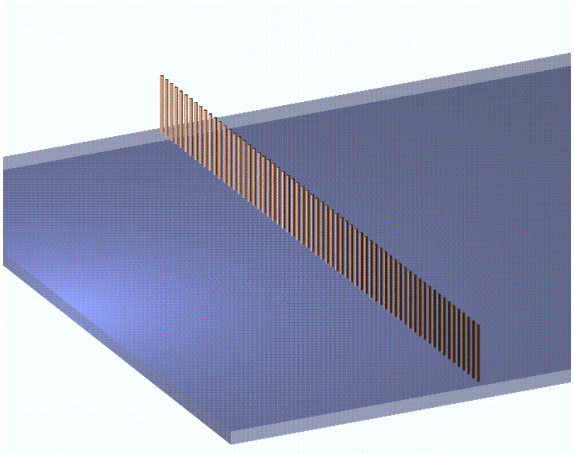

Figure 1a. Wake generators.

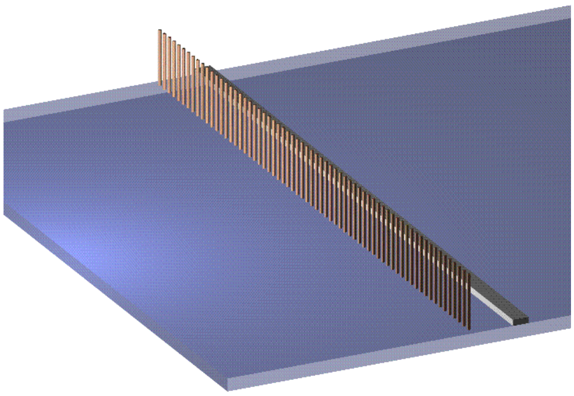

Figure 1b. Wake generators and trailing trip.

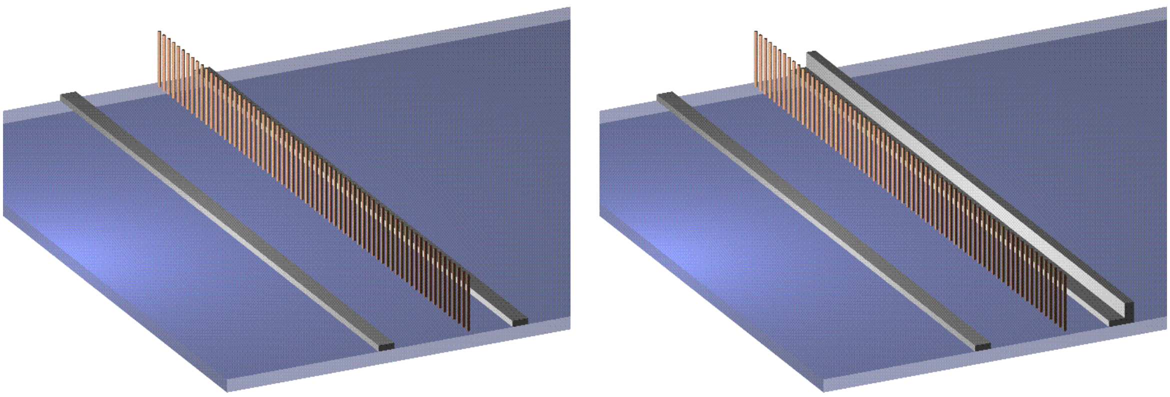

Figure 1c,d. Wake generators, leading and trailing trip (I,II).

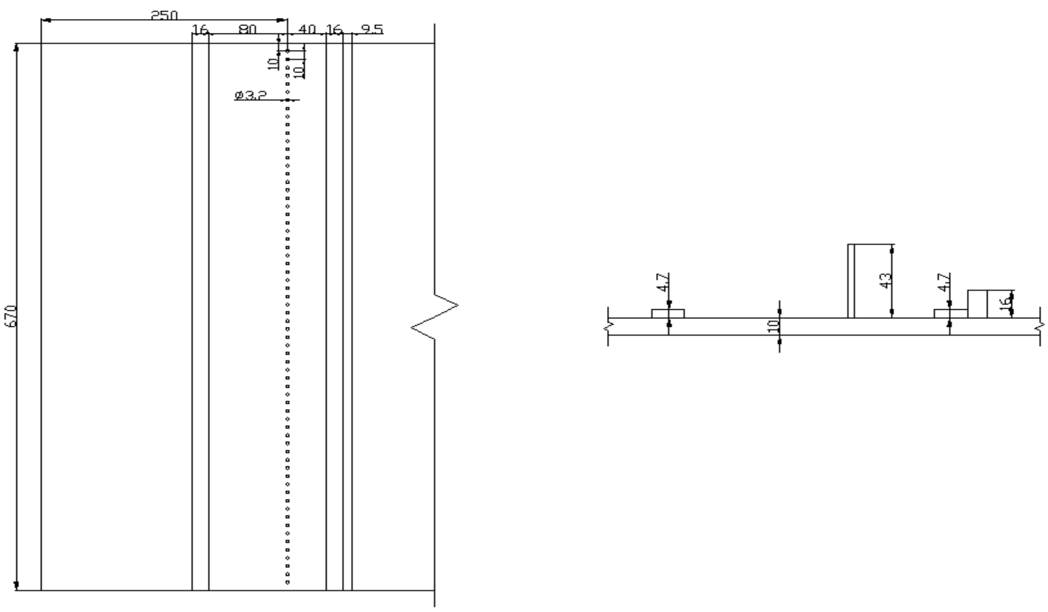

Figure 1e. Geometry of thickening device. Dimensions in mm.

that the larger the loss of momentum provoked by the thickening device, the further the virtual origin will be extended upstream. The extent in origin is shown in Table 1.

Table 1: Upstream extent in origin.

Configuration 1a	1.82 m
Configuration 1b	3.58 m
Configuration 1c	3.24 m
Configuration 1d	4.0 m
Configuration 1e	6.6 m

Figure 2 shows that, overall, the results found for δ_2 are consistent with those predicted by the integral methods.

Skin-friction is shown in Figure 3. The skin friction coefficients were determined directly from the velocity profile through the gradient of the logarithmic profile. Alternatively, C_f could had beeb obtained through the momentum-integral equation. This method, however, is very sensitive to any three-dimensionality in the flow and to the determination of the derivatives of the various mean flow parameters.

For all configurations, the experimental values of C_f were below the expected values for naturally developed flows. Configuration 1a gave values which were almost 50% lower than the expected values. However, configurations 1c, 1d and 1e provided values just below the expected values.

4.2. Local properties

Velocity profiles in inner coordinates are shown in Figure 4. This figure was prepared with values of C_f taken from the previous section. In all cases they were compared with the classical law of the wall formulation

$$\frac{u}{u_\tau} = \frac{1}{\varkappa} \ln \frac{y u_\tau}{\nu} + A, \tag{1}$$

where $\varkappa = 0.4$ and $A = 5.0$.

The resulting values of constants $\varkappa$ and A are shown in Table 2.

Table 2: Parameters in law of the wall.

Configuration	Station	$1/\varkappa$	A
1a	2	2.49	6.33
1b	3	2.51	5.70
1c	3	2.48	4.56
1d	2	1.88	9.40
1e	3	2.52	10.08

Key to figures

▲ Naturally developing flows

✚ Configuration 1a, 43 mm rods.

◇ Configuration 1b, 43 mm rods.

△ Configuration 1c, 43 mm rods.

✶ Configuration 1d, 43 mm rods.

★ Configuration 1d, 80 mm rods.

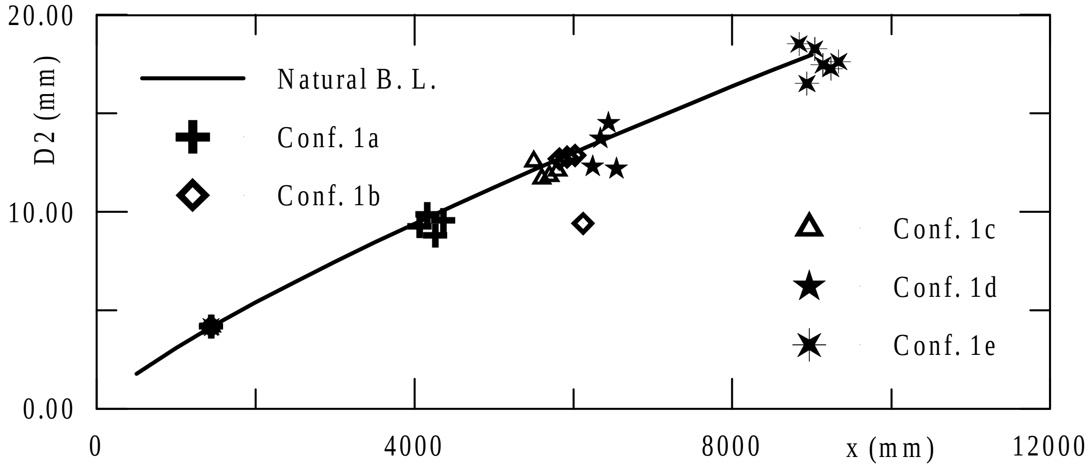

Figure 2. Momentum thickness.

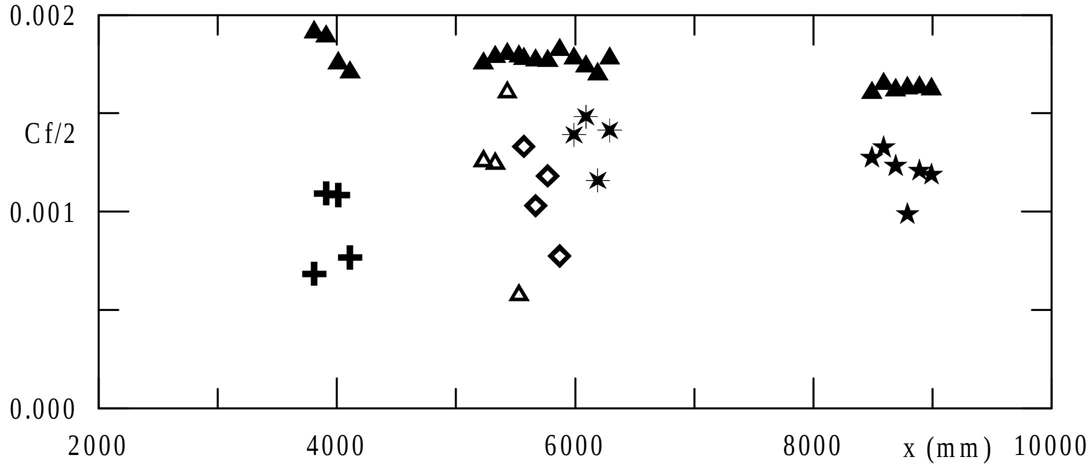

Figure 3. Skin-friction coefficient.

The configuration that best reproduced the law of the wall as configuration 1c. For this configuration, the scater in data was relatively small and the natural flow conditions well simulated. Configuration 1d, with the thick dowstream transverse bar gave the worst results.

For large values of yu_τ/ν, the velocity profile starts to deviate from the law of the wall giving form to the law of the wake. In wake coordinates, the velocity profile shows good agreement with the law of the wake of Coles (Figure 5).

The Clauser shape factor G, defined as

$$G = \frac{\int_0^\infty \frac{U_\infty - U}{u_\tau} \, dy}{\int_0^\infty \left(\frac{U_\infty - U}{u_\tau}\right)^2 dy}, \tag{2}$$

is shown in Figure 6. For most configurations, the experimental G was found to lie above the near expected value of 7.5.

5. Data analysis

In this section we will compare our results with some other wind tunnel simulation facilities. In fact, when preparing this work, a comparison with the results of other 29 wind tunnels was made. Here, however, and for the sake of brevity, only 8 different set ups will be considered.

All wind tunnel systems are listed in Table 3.

Table 3: Wind tunnel simulation systems.

Institution	W-T dimensions	S.M.	MS/FS	$\delta(m)$	n	u_τ/U_∞	IT%
Vienna	1.7x1.2x10	F, R	1/200	0.6	–	–	–
Bochum	2.1x2.1x4.3	F, V, R	1/500	0.84	–	–	–
Marseille	3.2x1.5x40	R, T	1/20	0.75	–	0.045	2.0
Poitiers	5.5x5.3x26	GG, R, T	1/200	2.5	–	–	–
Edinburgh	1.5x0.9x9	V,Sc,R	1/350	0.7	0.36	0.05	1.8
Salford	0.5x0.5x1	UG,GG,Sc	–	0.4	–	–	–
Stevenage	4.3x1.5x22	F, V, R	1/50	1.0	–	0.055	1.8
Notre Dame	1.5x1.5x14	J, R T	1/100	1.0	–	0.044	3.1
COPPE/UFRJ	0.67x0.67x3	V, R	–	0.2	0.19	0.042	2.0
Rural A.B.L	–	–	–	500	0.16	0.03	2.6
Urban A.B.L.	–	–	–	600	0.4	0.05	2.6

Key to table: W-T, wind tunnel; S.M., simulation method; MS/FS, model scale over full scale; A.B.L, atmospheric boundary layer; F, fence; GG, graded or shear grid; J, jets; R, roughness; Sc, screen; UG, uniform grid; V, vortex or vorticity generators.

The comparison is, in general, favorable to our results. The form of the profile, the skin-friction and the turbulence intensity are well reproduced. Please note that all tunnels, with the exception of the tunnel in Salford, are much bigger than our tunnel.

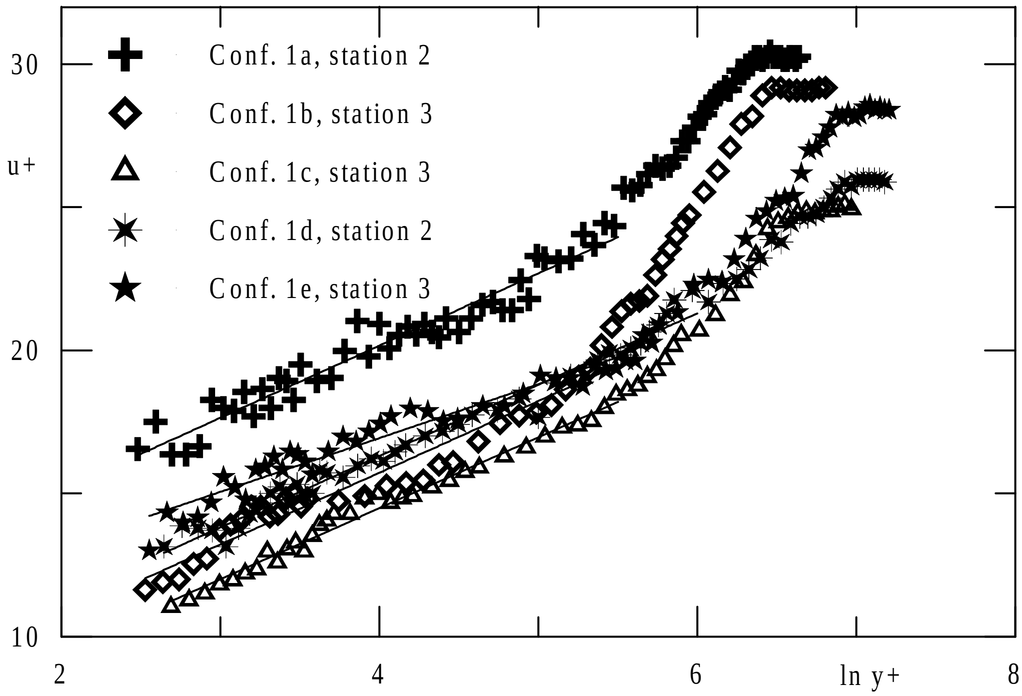

Figure 4. Law of the wall.

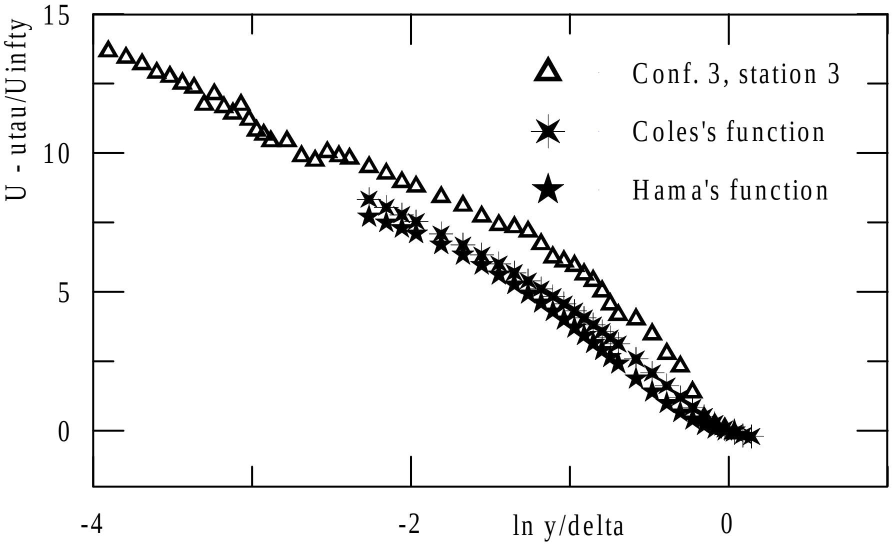

Figure 5. Law of the wake.

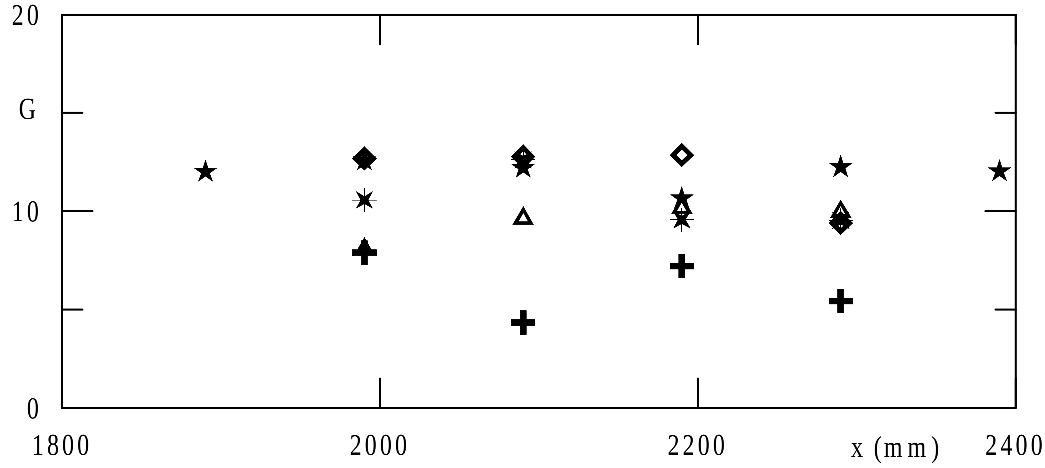

Figure 6. Glauser factor.

6. Conclusion

As shown in the previous sections, the results presently obtained at the high-turbulence wind-tunnel sited at COPPE/UFRJ stand reasonably well a comparison with the results of other authors. Of course, exactly reproducing in a laboratory all features of the atmospheric boundary layer is a very difficult problem which demands a consuming time of testes and development. The present research is, therefore, in its beginning since a great deal more of simulations will have to be made in order to arrive at a final and conclusive experimental set up. Some options had to be made in the present work which will have to be tested at exhaustion in the future. The chosen shape of the spires is one of the them. The position and shape of the trip and of the transversal bars is another. We may, however, conclude that the use of the thicker downstream transversal bar led to a worsening of the experimental simulation. In future works, configurations with more than one transversal downstream bar will be tested.

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