A WIND TUNNEL STUDY OF TURBULENT FLOW OVER HILLS. PART II: LARGE CHANGES IN SURFACE ELEVATION

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Abstract. *In the second part of the paper, an experimental study of the velocity and temperature fields around a steep two-dimesional hill was carried out in a wind tunnel simulated neutral atmospheric boundary layer. The large separated region that forms behind the hill was characterized by smoke visualization. Mean velocity, mean temperature and turbulence quantities were measured at various positions. The speed up of flow on top of the hill was compared with the theoretical predictions of other authors. The effects that turbulent transfer has on near wall scalar fields was particularly investigated.*

Key words: *turbulence, hill, temperature surface flux, stable boundary layer*

1. INTRODUCTION

In the first part of the paper, a thorough description of turbulent flow over hills that have a small elevation was presented. Here we are particularly interested on the flow over hills which are steep enough so that large recirculating flow regions are formed on its lee side.

The existence of a region of reverse flow, of course, adds much complexity to the problem. In fact, when hills become steep enough to form large downstream separation regions, many of the classical theories based on perturbation techniques break down. The pressure field cannot be simply approximated by the potential flow around the hill shape, but must be calculated considering the hill shape and the separation region. Thus, when separation occurs, not only the flow in the separation region changes. Significant changes occur in the whole flow field over the hill.

In view of the above remarks, it becomes evident that the correct assessement of the location of the separation point is a crucial step on the development of theories for the description of the velocity field. The large-scale pressure field that develops over the hill results from the flow in the outer region of the boundary layer which in turn reacts as if the hill and the separation region formed a single obstacle. It follows that quantifying the onset and extent of separation is a necessary and fundamental step for the characterization of the velocity field. As a matter of illustration, some authors in the past had difficulties in explaining some non-expected behaviour of the speed up factor due to uncertainties in the characterization of the separation point.

Unfortunately, the development of a comprehensive theory for the prediction of the correct location of a separation point is a very difficult problem. In turbulent flows, the mechanism of flow separation is poorly understood so that the classical logarithmic expressions used to represent the flow in the near wall region do not find their counterpart near the separation point and in the reverse flow region. This poses severe difficulties for a numerical simulation of the flow field, for the working turbulence model must be capable of incorporating all turbulence features down to the wall.

The purpose of this work is to make a study of the effects that a hill with large elevation may have on the properties of a neutrally stable boundary layer. Mainly, experimental aspects of the problem are investigated here. All experimental simulations were carried out in the high turbulence wind tunnel located at the Laboratory of Turbulence Mechanics (PEM/COPPE/UFRJ). The thick atmospheric boundary layer was formed with the help of vortice generators; its properties were validated through global and local parameters, including the energy spectrum.

In the wind tunnel, a hill model with an aerodynamically rough surface was used. The hill follows a Witch of Agnesi profile; it is two-dimensional with a maximum 30^o slope. The hill's surface can be heated at will so as to simulate ground heating conditions.

The work presents local measurements of mean velocity and temperature and of turbulent quantities. A two-channel cross hot-wire system was used so that two components of the flow mean velocity and of its fluctuations were obtained ouside the reverse flow region. The temperature data was obtained with the help of micro-thermocouples. A flow visualization study was also performed.

Following the procedure of Part I, the speed up factor was evaluated and compared with the theory of Hunt et al.(1988). In collecting the data, special attention was given to the characterization of the velocity and temperature fields in the reversed flow region downstream of the hill. Temperature profiles were measured at several streamwise distances with a particular concentration of points near the reattachment point. We have seen in previous works (see, e.g., Cruz and Silva Freire(1998, 1999)) that near to a separation point the near wall logarithmic profile ceases to be valid and that a power law takes place. Here, the behaviour of the temperature profile at the reattachment point was studied to assess the existence of any Reynolds analogy in that point.

2. SOME COMMENTS ON PREVIOUS WORKS

Because a fairly good review on the theoretical works on flows over hills has been made in Part I of the paper, here we will concentrate only on experimental works dedicated to the subject. Still following the same procedure, we present only some representative work of what has been done.

Britter et al.(1981) studied an air flow over a two-dimensional hill. The emphasis was on characterizing the velocity speed up, the surface roughness effects and the properties of turbulence. The hill was two-dimensional, bell shaped, with a maximum slope 0.26. The artificially generated boundary layer had a thickness of $10H$, where H denotes the height of the hill, and roughness length $z_0 = 0.02H$. The mean velocity profiles were compared with predictions given by the two-layered model of Jackson and Hunt(1975) furnishing close agreement for locations upwind of the hill top but not in the separated flow region. In a second experiment, flow over a smooth hill with a rough surface was studied. The authors showed that, for this geometry, flow speedup can be evaluated by a linear superposition of effects provoked by the changes in elevation and in roughness. In the lee of the hill, however, the roughness completely changed the flow configuration suppressing separation and the linear superposition effect.

Arya and Shipman(1981) investigated the flow and diffusion in the disturbed boundary layer over a two-dimensional triangular ridge. The ridge had a slope of 2 to 1 and height, H, of about 1/10 of the boundary layer thickness. The biggest effect of the ridge on the flow was to provoke a separation region which extended $13H$ downstream and had a maximum height of $2.5H$. Furthermore, an extended wake region was observed which increased in proportion to $(x/H)^{1/2}$, while the perturbations in mean velocity, Reynolds stress and variances of velocity fluctuations decayed as $(x/H)^{-1}$.

A wind tunnel study of dispersion from sources downwind of three-dimensional hills was made by Castro and Snyder(1982). The hills ranged from an axisymmetric cone to a two-dimensional geometry; they were moderately steep and presented a varying crosswind aspect ratios. Concentration patterns resulting from sources placed at several positions downwind of the hills were observed. The effects of the hills on plume transport and diffusion were characterizad through effective stack heights and amplification factors.

The flow and dispersion in the wakes of three dimensional low hills were also studied by Arya and Gadiyaram(1986). Two conical hills with slopes of 26.5^o and 17.5^o and height about one quarter of the simulated boundary layer were tested. Velocity measurements downstream of the steeper hill revelead a well defined flow recirculation zone and the presence of weak trailing vortices in the lower region. No such flow pattern could be identified downstream of the gentler hill. Diffusion measurements made at several distances from a point source showed that a 40 to 65% reduction in maximum ground-level concentration was observed when the source was placed at the top of the hill. When the source was moved to the downwind base of the hill an increase of up to six times in ground-level concentration was observed.

Arya et al.(1986) studied experimentally the flow and dispersion over two-dimensional low and gentle hills of different shapes and aspect ratio. The flow speedup on top of the hills was shown to have an inverse relationship with the aspect ratio. The Reynolds stress was observed to increase rapidly in the near wake region in the lee of the hills. In the far wake region, all perturbations on the flow parameters decayed with the inverse proportion to the distance behind the hill. Low level sources on the top of the steeper hills resulted in much reduced ground level concentration (by as much as a factor of 3). On the other hand, sources on the lee side of the hill resulted in considerable increase in ground level concentration (by as much as a factor of 15).

At around the same time, Snyder and Britter(1987) carried out an experimental research very similar to those just described. However, unlikely Arya and Gadiyaram(1986), triangular and bell shaped hills with varying crosswind aspect ratio were studied. Concentration patterns resulting from sources placed at three different positions upwind of the hills were examined to determine plume deformation and terrain amplification factors. The separation region was observed to decrease in size with increasing aspect ratio and changes in the flow parameters were explained with the notion that the effective hill shape was formed by the hill and the resulting recirculation region. Concentration measurements showed strong distortion in plume shapes with convergence in vertical planes and divergence in horizontal planes. Plumes from elevated sources were observed to approach the hill surface much more closely the smaller the aspect ratio.

3. SPEEDUP AND SEPARATION

Two important effects that the disturbances provoked by the hill cause on the mean flow are studied here: speedup and separation. Following the same approach of Part I, our data will be compared with the theory of Hunt et al.(1988). However, since a short review of their theory was presented in Part I, only the main definitions are repeated here.

The fractional speedup, Δs, is defined as

$$\Delta s = \frac{\overline{u}(x,z) - \overline{u}_o(z)}{\overline{u}_o(z)} = \frac{\Delta \overline{u}(x,z)}{\overline{u}_o(z)}, \tag{1}$$

where $\overline{u}_o(z)$ is an undisturbed upstream reference wind profile. The value of Δs where $\overline{u}(x,z)$ is maximum is defined as Δs_{max}; it occurs some point above the hill top.

If the two layered model of Hunt et al.(1988) is applied to a flow disturbed by a Witch of Agnesi hill profile, speed up can be evaluated from

$$\Delta s_{max} = \frac{H}{L_H}\Big(\frac{\overline{u}_o^2(h_m)}{\overline{u}_o(l)\overline{u}_o(l/3)}\Big)(1 + 1.8\,\delta), \tag{2}$$

where

$$h_m = L_H\left[\ln\Big(\frac{L_H}{z_o}\Big)\right]^{-1/2}, \tag{3}$$

$$\frac{l}{L_H}\ln\Big(\frac{l}{z_o}\Big) = 2\varkappa^2, \tag{4}$$

and $\varkappa$ is von Karman's constant ($= 0.4$), z_o denotes the surface roughness length, L_H is the distance from the crest to the half-way point, and $\delta = [\ln(l/z_o)]^{-1}$

Measurements taken on Askervein Hill and Cooper's Ridge match closely the results given by the above equation.

Flow separation is a very complex phenomenon that many times has a dramatic effect on all flow properties. The large reverse flow region that forms on the lee of a hill works in effect as if the hill and its attached bubble formed a single obstacle resulting in large-scale pressure perturbations.

Because of the difficulties associated with the measurement of flow properties in reverse flow regions and, as a matter of fact, with their interpretation, many works have limited to characterize the extent of separation and some of its general features. As pointed out by Finnigan(1988) the streamwise extent of separation depends significantly on the angle the separating boundary layer makes with the mean flow direction. Another important conclusion of previous works is the sensitivity of separation to surface roughness even on abrupt hills where topographycal effects would be expected to play the most important role. The development of a comprehensive theory to account for separation on rough surfaces is still far from being completed so that making useful theoretical predictions is always difficult.

Within the separation region the flow structure is very complex, almost untreatable. Separated shear layers are so unstable that even large bubbles behind two-dimensional hill can break up yielding three dimensional cells. An important observation, however, is that separation bubbles behind three dimensional obstacles are not closed, there is a mean inflow and outflow in the separation region.

One of the objetives of this work is to investigate the flow near the reattachment point behind a steep hill. In particular, we would like to investigate the shape of the velocity and temperature profiles so as to see if they follow a Stratford law of the wall.

The general form of a velocity and temperature profile near a separation point was deduced by Cruz and Silva Freire(1998). Here only the main results of their theory is reproduced.

According to Cruz and Silva Freire(1999), the law of the wall for a separating flow can be written as

$$u = \frac{\tau_w}{|\tau_w|}\frac{2}{\varkappa}\sqrt{\frac{\tau_w}{\rho} + \frac{1}{\rho}\frac{dP_w}{dx}y} + \frac{\tau_w}{|\tau_w|}\frac{u_\tau}{\varkappa}\ln\big(\frac{y}{L_c}\big). \tag{5}$$

where

$$L_c = \frac{\sqrt{\left(\frac{\tau_w}{\rho}\right)^2 + 2\nu\frac{dP_w}{dx}u_R} - \frac{\tau_w}{\rho}}{\frac{1}{\rho}\frac{dP_w}{dx}} \tag{6}$$

and all symbols have their classical meaning; $\varkappa$ is the von Kármán constant (=0.4), u_τ is the friction velocity, and u_R $(= \sqrt{\tau}$, τ = total shear stress) is a reference velocity.

The above equation is a generalisation of the classical law of the wall and replaces the three expressions advanced in Cruz and Silva Freire(1998). Far away from the separation point, where the shear stress is positive and $dP_w/dx << \tau_w$, equation (5) reduces to the classical law of the wall. Close to the separation point where τ_w=0, the equation reduces to Stratford's equation.

In the reverse flow region where $dP_w/dx >> \tau_w$, equation (5) can be written as

$$u = -\frac{2}{\varkappa}u_\tau - \frac{u_\tau}{\varkappa}\ln\big(\frac{y}{L_c}\big), \quad L_c = 2\Big|\frac{\tau_w}{dP_w/dx}\Big|. \tag{7}$$

An asymptotic theory for the temperature boundary layer near a separation point is also given in Cruz and Silva Freire(1998); it results that the temperature law of the wall can be written as

$$\frac{T_w - T}{Q_w} = \frac{P_{rt}}{\varkappa_t \rho c_p u_\tau}\ln\frac{\sqrt{\tau_w/\rho + \frac{1}{\rho}\frac{dP_w}{dx}y} - \sqrt{\tau_w/\rho}}{\sqrt{\tau_w/\rho + \frac{1}{\rho}\frac{dP_w}{dx}y} + \sqrt{\tau_w/\rho}} + C_q, \tag{8}$$

where

$$C_q = \frac{P_{rt}}{\varkappa_t \rho c_p u_R}\ln\frac{4Eu_R^3}{\nu\left|\frac{dP_w}{dx}\right|} + AJ, \tag{9}$$

$$AJ = 1.11 P_{rt} \sqrt{\frac{A}{\varkappa}} \big(\frac{P_r}{P_{rt}} - 1\big) \big(\frac{P_r}{P_{rt}}\big)^{0.25}, \tag{10}$$

$$A = 26 \frac{\tau_w^{1/2}}{u_R}, \quad P_{rt} = 0.9, \tag{11}$$

and all symbols have their classical meaning.

4. EXPERIMENTAL SET UP AND MEASUREMENTS

The general experimental set up was described in Part I of the paper. The experiments were carried out in the high turbulence, low speed, open return wind tunnel located in the Laboratory of Turbulence Mechanics of the Mechanical Engineering Program (PEM/COPPE/UFRL). This tunnel has a workikng section 0.67 m wide, 0.67 m high and 6 m long. The artificially thickened boundary layer was generated using the vortice generators developed by Guimaraes et al.(1999) and Barbosa et al.(2000). Since a complete description of the thickening device can be found in Barbosa et al.(2000) we will omit the details here. The flow properties were assessed considering the integral properties of the flow, skin-friction, mean velocity profiles in inner and outer coordinates and turbulence. The characteristics of the undisturbed boundary layer will be shown in the next section.

The shape of the hill was given by a Witch of Agnesi curve,

$$z = H \left[1 + \left(\frac{x}{L_H} \right) \right]^{-1}, \tag{12}$$

where H denotes the height of the hill, L_H the distance to the half-height point and x the distance from the crest.

The abrupt hill was constructed with $H = 6.0$ cm and $L_H = 15$ cm. This was a very steep hill where flow separation was expected to occur.

The topographic profile of the hill is shown in Figure 1.

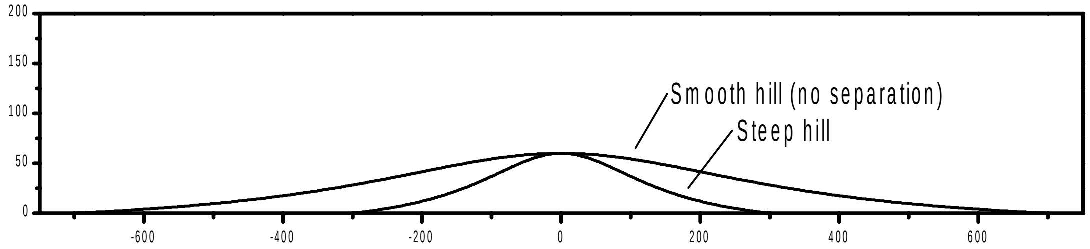

Figure 1: The topographic profiles of considered hills.

The floor of the wind tunnel and the hill surface were made of aluminium.

Measurements were performed for values of the free-stream velocity of 3.12 m/s. Mean velocity profiles and turbulence intensity levels were obtained using a two-channel constant temperature hot-wire anemometer. The boundary layer probe was of the type 55P15. A Pitot tube, an electronic manometer, and a computer controlled traverse gear were also used. The mean temperature profiles were obtained through a chromel-constantan micro-termocouple.

For a more detailed description of the experimental procedure the reader is referred to Part I of the paper.

For an inspection on the existence of separated and recirculating flows along the hill profile, a flow visualization was used. The smoke was produced with glicerin and forced into a wand where it could be released anywhere in the flow. Contrary to Part I of the paper, a large separation region was identified whose extent was about $9H$. Still form the visualization, the separation point appeared to be located very close to the hill top.

5. RESULTS

Because the geometric configuration of the test section was slightly different from Part I, the global properties of the undisturbed boundary layer are presented again in Figures 2 through 5. The mean velocity profiles are observed to satisfy the law of the wall and the law of the wake. When plotted in linear coordinates the boundary layer follows a power law with exponent n=0.273.

δ_1 (m)	0.22
δ_2 (m)	0.038
G	5.57
n	0.273
$C_f/2$	0.00159

Figure 2: Characteristics of the undisturbed boundary layer. δ_1 = displacement thickness, δ_2 = momentum thickness, G = Clauser factor, n = exponent in power law, $C_f/2$ = skin-friction coefficient

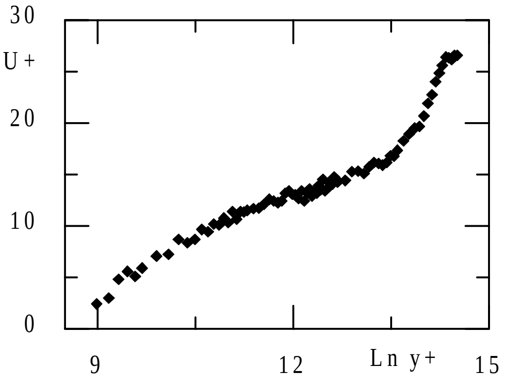

Figure 3: Undisturbed velocity profile in inner coordinates, where $y^+ = yu_\tau/\nu$ and $u^+ = u/u_\tau$

The large flow separated region identified in the downstream side of the hill is illustrated in Figure 6

The mean velocity profile measured by a cross hot-wire anemometer in the disturbed boundary layer on the top of the hill is shown in Figure 7. This Figure clearly indicates the strong acceleration of the flow in approaching the top of the hills and deceleration in the lee.

Figure 8 shows the speed up factor. The predictions of Hunt et al.(1988) lead values

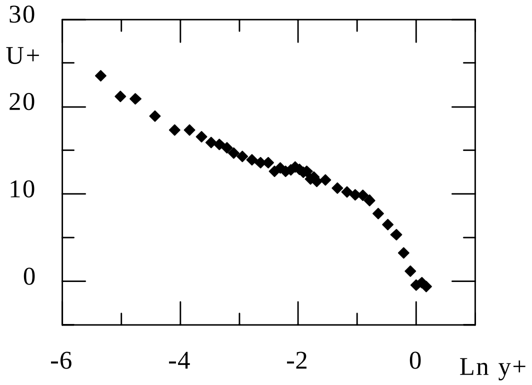

Figure 4: Undisturbed velocity profile in outer coordinates, where $u^+ = U_\infty - u/u_\tau$ and $y^+ = y/\delta$

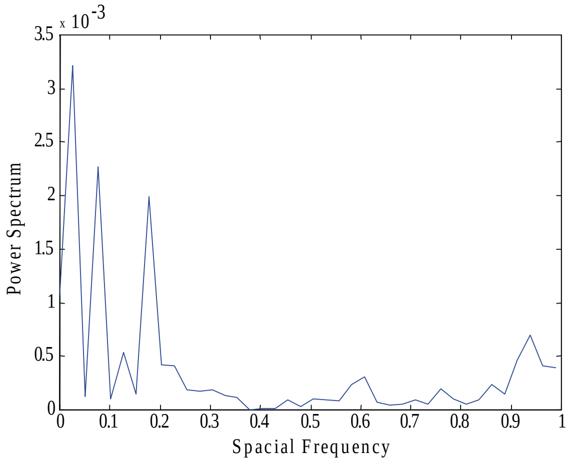

Figure 5: Power spectrum of undisturbed boundar layer.

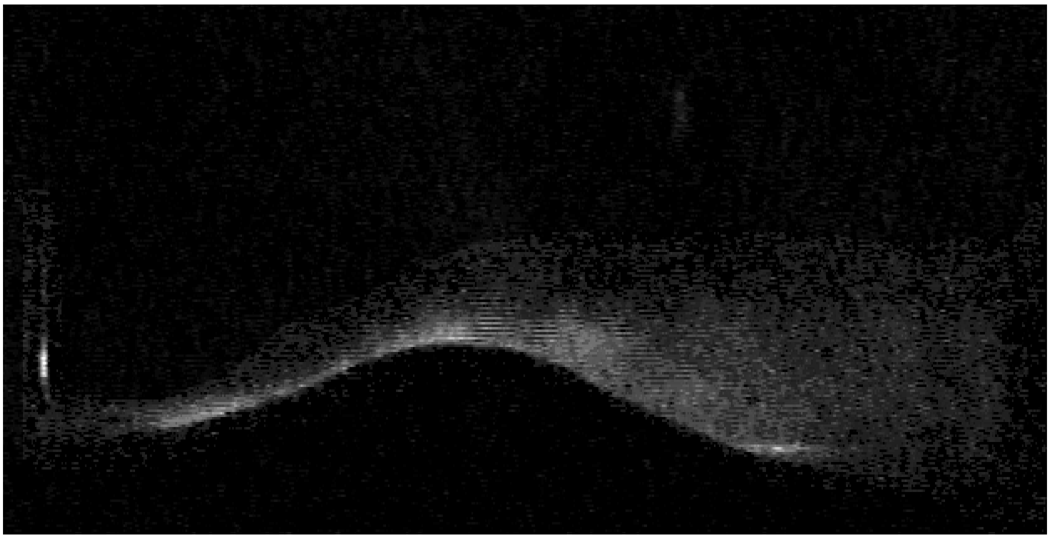

Figure 6: Separation region in the lee of abrupt hill.

of $h_m = 0.11$ m, $l = 0.019$ m and $\Delta s_{max} = 0.12$ at $l/3 = 0.0063$ m. The experiments, however, give values of Δs_{max} as high as 0.9.

The influence of the hill on the logitudinal velocity fluctuations above the crest was supposed to reduce them below to the upstream values, as mentioned in Part I of the paper. This is a classical result of rapid distortion theory. This prediction can be compared with the velocity fluctuations presented in Figure 9.

The mean temperature profiles measured by micro thermo-couples in the disturbed boundary layers over the hill are shown in Figure ??. Because the heating started just at the beginning of the hill, the temperature boundary layer thickness at the first two measuring stations was very small.

The really interesting features occur when we approach the top of the hill. Much in the same way as in Part I, the temperature profile on top of the hill presents two overshooting points: one just above the inner layer and another in the external region. The behaviour of the temperature profile in the recirculation region and in the vicinity of the re-attachment

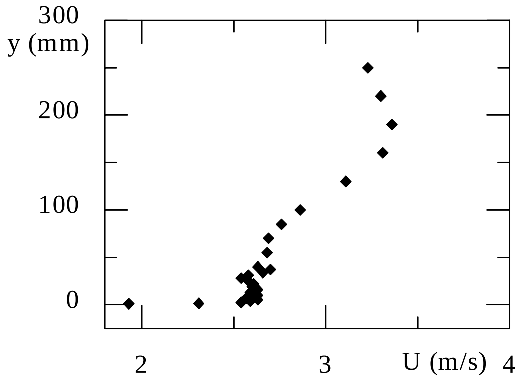

Figure 7: Mean velocity profile above abrupt hill crest.

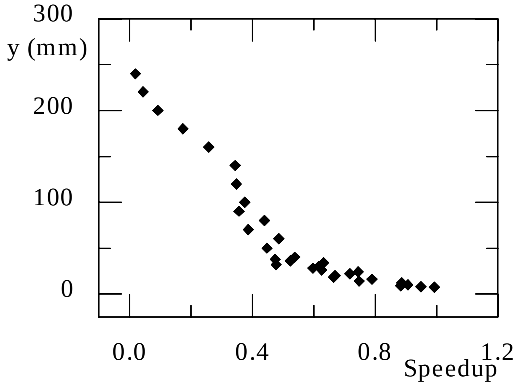

Figure 8: Speed up factor for abrupt hill.

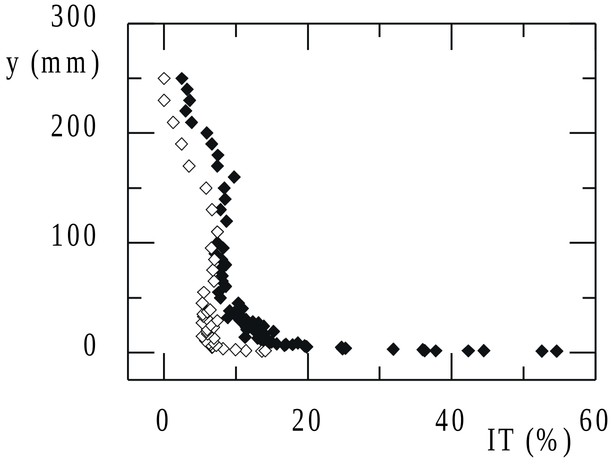

Figure 9: Streamwise turbulence intensity profiles. Full symbols indicate flow on top of hill; open symbols indicate flow in the undisturbed region.

point are clearly illustrated. In the separated region the temperaure becomes nearly constant and almost five degrees above the main stream temperature. Near to the re-attachment point, the classical logarithmic profile ceases to represent well the temperature, which now assumes a power-law behaviour. Thus, this is fully corroboration that an equation with the form of equation 8 must be valid. In fact, in the limit as u_R tends to zero this equation reduces to a $y^{-1/2}$ power law, which is the behaviour folowed by the present data.

6. FINAL REMARKS

In the present work we have performed an experimental analysis of the flow around an abrupt two-dimensional hill. Special emphazis was placed on characterizing the temperature field. Two distinct and interesting features where observed: two overshoot points in the temperature profile on top of the hill and the $y^{-1/2}$ behavior of the temperatute profile near the flow re-attachment point. The results have been compared with the theory of Hunt et al.(1988) showing poor agreement.

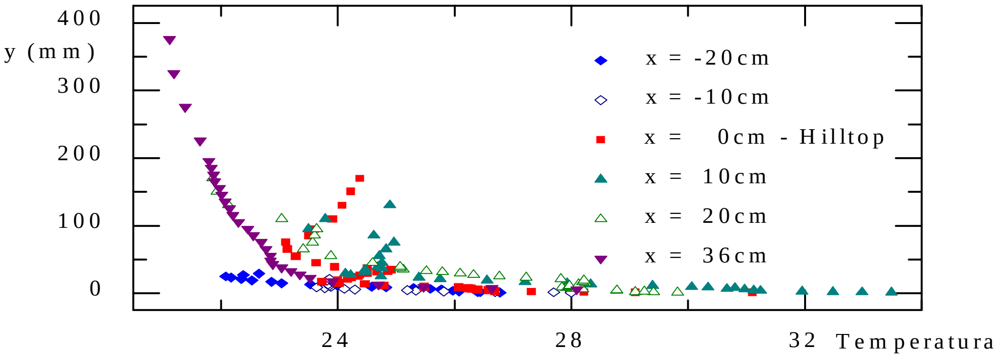

Figure 10: Mean temperature profile.

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