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

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Abstract. *The velocity and temperature fields around smooth and steep two-dimesional hills were experimentally studied in a simulated neutral atmospheric boundary layer in a wind tunnel. Two different flow patterns were studied, attached and separated flows. 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 the velocity field has on the temperature scalar fields is particularly investigated.*

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

1. INTRODUCTION

In micrometeorology, the mathematical description of the flow field over an arbitrary terrain is always a difficult exercise. In fact, the non uniformity resulting from changes in the land surface and hills poses many problems of difficult modelling and solution.

In the past, owing to its simplicity, most of the systematic investigation on the surface layer and on its overlying boundary layer have been confined to the simplest topography, the boundary layer over a flat, open land. Studies involving more complex situations such as flows over flat but heterogeneous surfaces and hills are still only a few. The reason for the scarcity in data is clear: the difficulties in realizing field measurements may touch on logistical requirements of an unsurpassable nature. A typical example is the large scale recirculating flow region that forms behind steep hills. This region is normally of the order of the hill height.

In practice, this has meant that most of the understanding we have on flow over complex terrain comes from mathematical modelling and wind tunnel simulations. Modelling hills in the wind tunnel always presents the difficult problem of obtaining a realistic reduction in scale. The alternative is to work with an aerodynamically smooth model or to increase disproportionately the surface roughness.

The purpose of this work is to carry out an experimental study of the effects that a hill has on the properties of the boundary layer under near neutral conditions. Particularly, we are interested in understanding the effects that low hills with moderate slope exert upon the temperature field. Because of the great difficulties in measuring the properties of real natural flows, the present work resorts to a wind tunnel simulation of the phenomenon. An adequate representation of the atmospheric surface layer was obtained with the help of vortice generators; these provided a very thick boundary layer which was validated through local and integral parameters, including the boundary layer spectrum.

Two different hills with different flow characteristics were studied. They were both based on a geometrical form that has been studied by other authors. The first hill aimed at achieving fully attached turbulent flow whereas the second hill aimed at provoking a large downstream separation bubble. In this part of the paper, only the results obtained with the first hill will be presented. The results obtained with the second hill are presented in part two.

In the wind tunnel, an aerodynamically smooth model of a hill was used. The hill was two-dimensional, with a Witch of Agnesi profile; its surface could be heated at will so as to simulate ground heating conditions. The work presents local measurements of mean velocity and temperature. A two-channel hot-wire system was used so that two components of the flow mean velocity and of its fluctuations were obtained. The temperature data was obtained with the help of micro-termocouples. A flow visualization study was also made.

2. SOME COMMENTS ON PREVIOUS WORKS

Many theoretical and experimental studies have been carried out to analyse the effects that two and three-dimensional hills cause on the mean velocity and turbulence fields of the atmospheric boundary layer. In the following we will present some representative work of what has been done.

Without any doubt, the works that have had a most profound influence on the way we think about the problem are the works of Hunt and his co-workers. These works have resorted to asymptotic methods to describe the flow over low hills, where the equations of motion can be linearized. Hunt has suggested the existence of a flow structure equivalent to the classical two-layered model developed for the aerodynamic boundary layer. In the inner layer, the flow is expected to be in equilibrium with the current boundary conditions so that its structure can be predicted on the basis of the wall laws. In the outer layer, turbulence is expected to be modified according to the rapid distortion theory of Townsend(1972). This will be better detailed below.

In a seminal work, Jackson and Hunt(1975) showed that, for a low hill, the eddy viscosity distribution for equilibrium flow near a wall can still be used to determine the changes in Reynolds stress. The theory also showed that for a log-profile upwind the increase in wind speed near the surface of the hill is $O((H/L)u_o(L))$ where H is the height of the hill and $u_o(L)$ is the velocity of incidence wind at a height L. The conclusion was that the increase in surface winds could be greater than that furnished by potential flow theory. Another conclusion was that at the point above the top of the hill where velocity reaches its maximum value, the velocity is equal to the velocity at the same distance from the ground upwind of the hill.

Mason and Sykes in 1979 extended the theory of Jackson and Hunt(1975) to three-dimensional topography. The results were compared with wind measurements taken on a nearly circular isolated hill, the Brent Knoll hill located in the U.K.

Carruthers and Choularton(1982) developed a three-layered model to describe the inviscid flow of an inversion capped boundary layer over hills of moderate size and slope. The pressure field kept in the lowest neutral layer was employed to recalculate the inner mean velocity field proposed by Jackson and Hunt(1976).

The structure of strongly stratified flow over three-dimensional hills was discussed by Snyder et al.(1985) both from a theoretical and experimental point of view. The paper discusses extensively the dividing streamline concept, taking as a basis for the analysis Sheppard's energy arguments for an estimation of the height of this dividing streamline. The authors analyse an extensive range of laboratory observations and measurements of stratified flows over a range of hills with different geometries subjected to different oncomimg flows.

Concerned with the effects that hills provoke on turbulence, Zeman and Jensen(1987) developed a new model where the von Mises transformation was applied to the mean momentum equations and the second-order closure type turbulence equations were solved. All predictions were compared with results from the Askervien Hill project.

In spite of all the extensive work previously done on the subject, in the eighties some basic questions still needed to be answered. The following three were the concern of two papers published by Hunt et al.(1988a, 1988b).

1. How does the location and intensity of the maximum wind speed vary with upwind stable or unstable stratification?
2. Does the shape of the hill have a similar effect on the wind speed in stratified and neutral conditions?
3. Where do streamlines come closest to the hill surface, and where is the greatest lateral deflection of the flow?

In the paper of 1988a, Hunt et al. showed theoretically that "a weak temperature gradient can increase the upwind velocity gradient sufficiently to magnify significantly the mean velocity over the hill, while being too weak to affect the dynamics of the flow". This paper considered the effects of buoyancy forces when the upwind flow is stably stratified. In a sequence to this work, Hunt et al.(1988b) accounted for the flow near a surface.

The number of works that deal with scalar fields over hills can still be considered very small. More recently, Raupach et al. (1992) developed a model for the description of the effects that low hills have on scalar fields, in special, the temperature and humidity fields, in boundary layers under near neutral conditions. The analysis was confined to the inner flow regions and the following processes were considered: convergence and divergence of the mean flow, changes in the eddy diffusivity caused by changes in turbulence and changes in scalar fluxes at the surface.

3. SPEEDUP AND SEPARATION

Two important issues to be observed in our study are the speedup and separation phenomena. Because our data will be compared with the theory of Hunt et al.(1988a), a short review of it is presented below.

The speedup on hilltops is of large interest for the siting of wind turbines. 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.

In the two layered model of Hunt et al.(1988a) the height at which the shear in the upwind profile ceases to be important is defined by

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

where z_o denotes the surface roughness length. This definition results in a subdivision of the outer layer by specifying a middle layer where the flow is still inviscid but rotational. L_H is the distance from the crest to the half-way point.

The inner layer is the flow region where turbulent stresses affect the changes in the mean velocity. Then, considering that the hill provokes only a small perturbation to an existing logarithmic velocity profile, the inner layer thickness is given by

$$\frac{l}{L_H} \ln\left(\frac{l}{z_o}\right) = 2\varkappa^2, \tag{3}$$

and $\varkappa$ is von Karman's constant ($= 0.4$).

The theory of Hunt et al.(1988a) furnishes the following expression for speedup

$$\Delta s = \frac{H}{L_H} \left(\frac{\overline{u}_o^2(h_m)}{\overline{u}_o(l)\overline{u}_o(z)} \right) \zeta(x, z_o), \tag{4}$$

where ζ is a function that depends on the shape of the hill and the surface roughness.

For a Witch of Agnesi profile, function ζ can be computed to give

$$\Delta s_{max} = \frac{H}{L_H} \left(\frac{\overline{u}_o^2(h_m)}{\overline{u}_o(l)\overline{u}_o(l/3)} \right) (1 + 1.8\,\delta), \tag{5}$$

where $\delta = [\ln(l/z_o)]^{-1}$.

Measurements taken on Askervein Hill and Cooper's Ridge match closely the results given by the above equation. $l/3$ seems to be a good estimate of the height of Δs_{max}.

Flow separation is a complex and ill understood problem. However, it is a generally accepted fact that the extent of the separation bubble depends significantly on the angle the separating boundary makes with the mean flow direction. For the smooth hill constructed here special care was taken to assure that no separation occured.

4. EXPERIMENTAL SET UP AND MEASUREMENTS

All 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/UFRJ). This tunnel has a working section 0.67 m wide, 0.67 m high and 6 m long. An artificially thickened boundary layer was generated to simulate a neutrally stable boundary layer using the vortice generators developed by Guimaraes et al. (1999) and by Barbosa et al.(2000). The thickening device consisted of equally spaced 16 mm vertical rods. In the configuration used, 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. An assessment of the flow properties was carried out considering the integral properties of the flow, skin-friction, mean velocity profiles in inner and outer coordinates and turbulence. The characteristics of the boundary layer will be shown in the next section.

The flows over two different hills were studied in this and in an accompaning paper. The hills were two-dimensional and similar in shape to those studied in Britter and Hunt(1981).

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

$$z = H\left[1 + \left(\frac{x}{L_H}\right)\right]^{-1}, \tag{6}$$

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 geometry of the hills were chosen so as to yield two very distinct flow configurations. The first hill was constructed with $H = 6.0$ cm and $L_H = 35$ cm. This was a smoothly curved hill with very moderate slope angle. The critical downwind hill slope angle for steady separation is, according to Finnigan(1988), about 18^o, so that care was taken to assure that this value was not exceeded.

The second hill was constructed with $H = 6.0$ cm and $L_H = 15$ cm. This was a much steeper hill where flow separation was expected to occur. Results regarding this hill are presented in Part II.

The topographic profiles of the hills are shown in Figure 1.

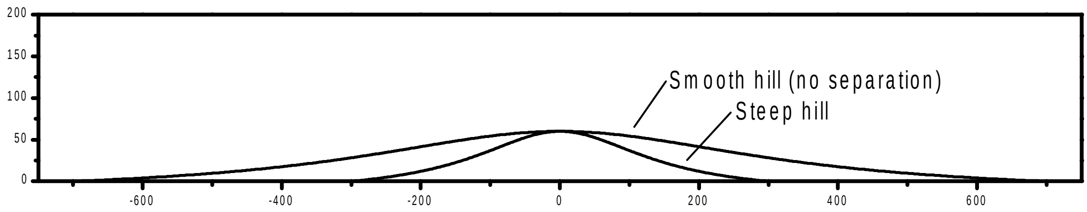


Figure 1: The topographic profiles of considered hills.

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. In getting the data, 10,000 samples were considered which yielded a precision of 0.6% in the mean velocity data. The mean temperature profiles were obtained through a chromel-constantan micro-termocouple mounted on the same traverse gear system used for the hot-wire probe.

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.

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.

5. RESULTS

The structure of the undistuburbed boundary layer is shown in Figures 2 through 5. The mean velocity profiles satisfy the law of the wall and the law of the wake. When plotted in linear coordinates the boundary layer followed a power law with an exponent n=0.253. Thus, our flow is typical of a rural type boundary layer.

δ_1 (m)	0.43
δ_2 (m)	0.041
G	6.03
n	0.253
$C_f/2$	0.00135

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

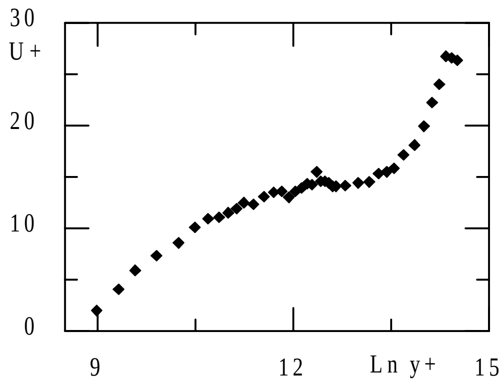
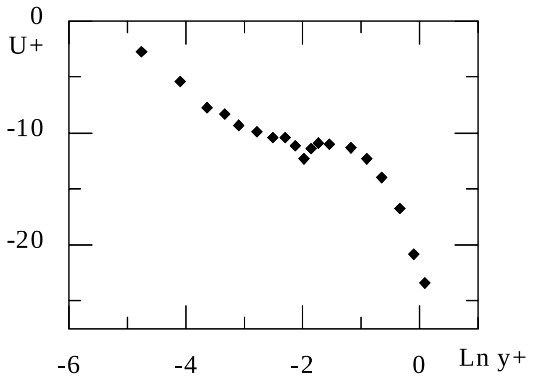


Figure 3: Undisturbed velocity profile in inner coordinates, where $y^+ = yu_\tau/\nu$ and $u^+ = u/u_\tau$

In the flow visualization experiments, the smoke wand was placed at several positions in the flow and any existing separation was determined. For the smooth hill, no separated region was found. The general flow pattern can be seen in Figure 6.

The mean velocity profile measured by a cross hot-wire anemometer in the disturbed boundary layers over the hill is shown in Figure 7. The speedup factor is shown in Figure 8. According to the measurements Δs_{max} was found to be 0.40 at height 8 mm. This value is quite different from the one obtained through Hunt et al.'s formula which gives h_m = 0.10 m, l = 0.019 m and Δs_{max} = 0.12 at $l/3$ = 0.0063 m. Most of the works of previous authors that have been used to corroborate the theory of Hunt et al. have measured flow



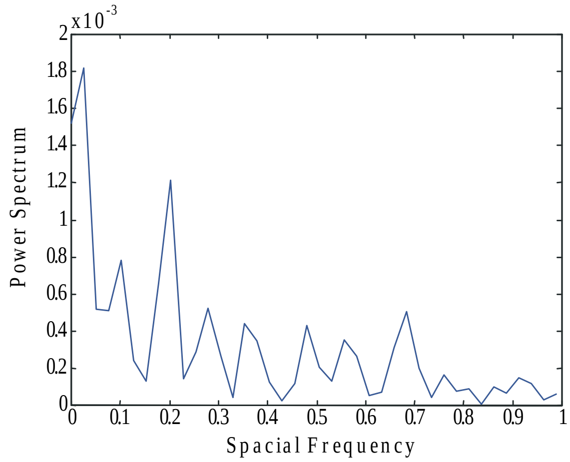


Figure 4: Undisturbed velocity profile in outer coordinates, where $u^+ = U_\infty - u/u_\tau$ and $y^+ = y/\delta$

Figure 5: Power spectrum of undisturbed boundar layer.

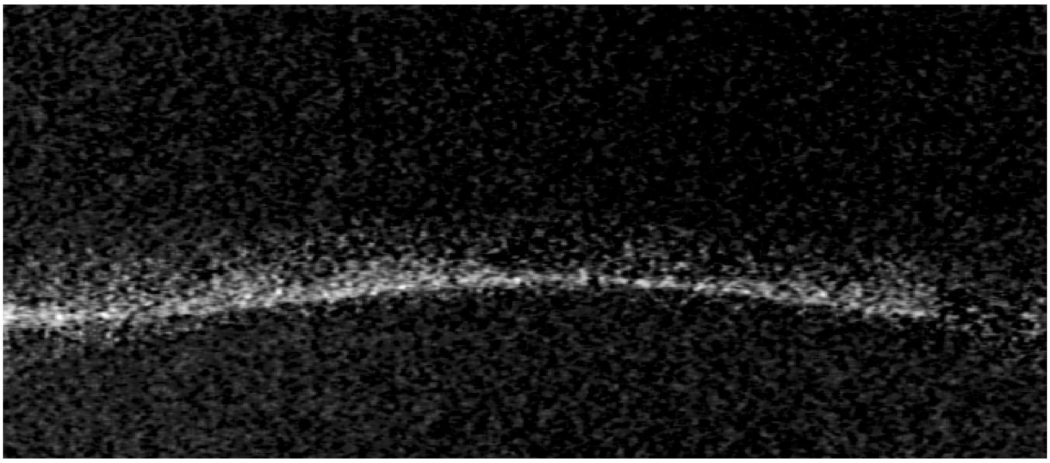


Figure 6: Flow pattern in the lee of smooth hill.

over abrupt hills. As we will reviewed in Part II, they provided good corroboration to the theoretical results. Here, we emphasize, we tried to apply the formulation to attached flow conditions. As seen, the agreement was not good. In Part II, a comparison with separated flow conditions will be made.

The influence of the hill on logitudinal velocity fluctuations above the crest is supposed to reduce them below to the upstream values. Rapid distortion theory applied to the outer region at the crest of a two dimensional hill results that

$$\Delta u'^2/u'^2_o = -(4/5)\Delta U/U_o. \tag{7}$$

This prediction can be compared with the velocity fluctuations presented in Figure 9. The results here are slightly better

To measure the temperature profiles, the following procedure was adopted. First, the heat was turned on so that the wind tunnel surface was kept at a constant temperature ($68^oC \pm 1$) all along the hill length. Next, the fan was turned on so that a mean flow velocity of 3.12 m/s was obtained.

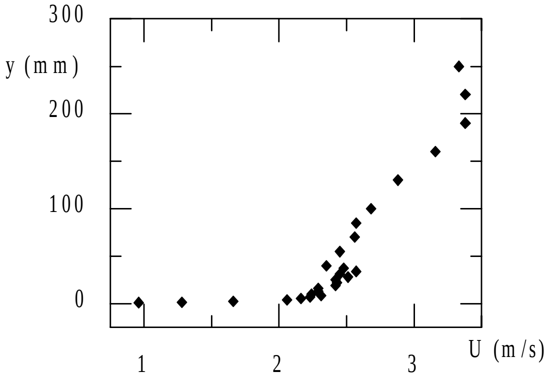


Figure 7: Mean velocity profile above smooth hill crest.

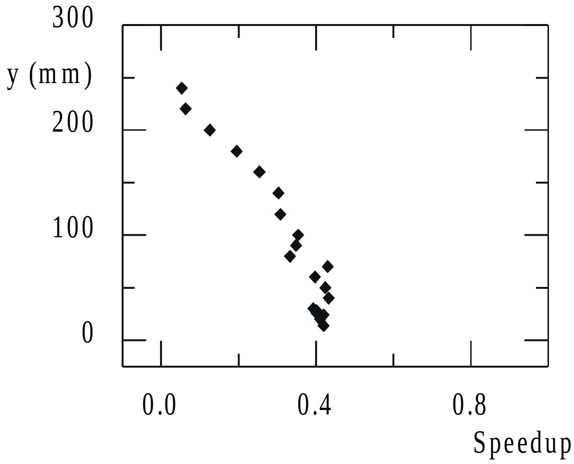


Figure 8: Speedup factor for smooth hill.

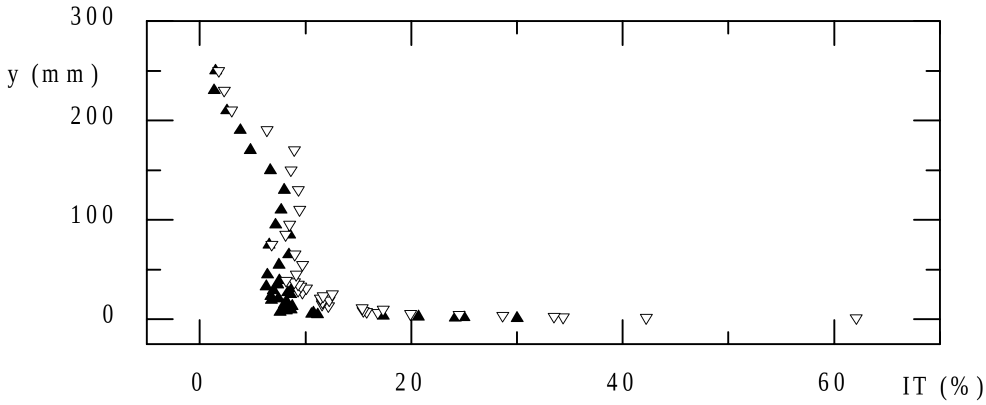


Figure 9: Streamwise turbulence intensity profiles. Full symbols indicate flow on top of hill; open symbols indicate flow in the undisturbed region.

The resulting mean temperature profiles measured by micro thermo-couples in the disturbed boundary layers over the hill are shown in Figure 10. The influence of near wall mixing on the temperature profile is clearly seen. The temperature at the wall after the flow reached a steady state was nearly constant and equal to $37^oC \pm 1$. The interesting aspect to notice here was the form of the temperature profile over the hill which distinctly presented two overshooting points: one rigth above the inner wall layer and another in the outer region. For the rest of the flow region, the temperature behavior closely approximated each other.

6. FINAL REMARKS

In the present work we have performed an experimental analysis of the flow around a smooth two-dimensional hill. Vortice generators were used to generate a neutral atmospheric boundary layer that was made to flow over a heated hill. Flow visualization

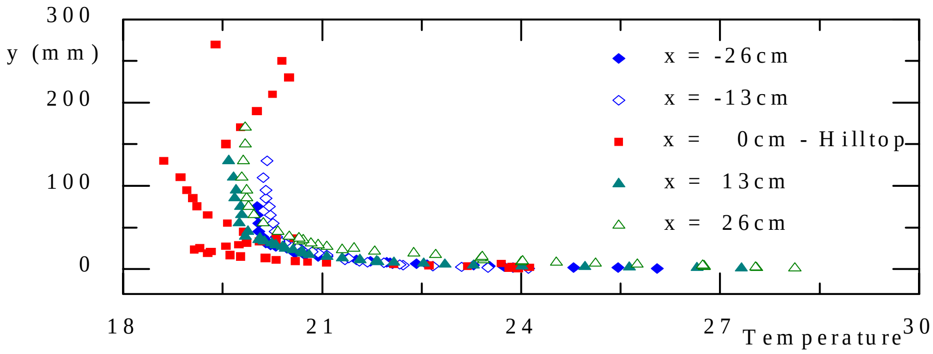


Figure 10: Mean temperature profile.

experiments were performed which assured that the flow was fully attached. Then, velocity and temperature profile measurements were made. The measurements were compared with the theory of Hunt et al. and resulted in poor agreement; they, however, have shown that turbulent transfer has a strong influence on the near wall scalar fields. The bad agreement between the present data and the theory of Hunt et al. may, peharps, be explained by the large height of the hill compared with the boundary layer height (1:4.5); this ratio for most previous works was taken as 1:10. In Part II of the paper, an experimental study of the flow over a abrupt hill will be made.

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