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Influence of Gaussian hill on concentration of solid particles in suspension inside Turbulent Boudary Layer

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Abstract

The soil erosion is a major problem that affects the agriculture, climate and health. It is therefore necessary to understand the phenomena that are its wheels in order to either predict or limit it. One of the main problem of this kind of study is the presence of high particle concentration that restricts measurements of either particle concentration or carrier flow rate. In so numerical simulations are essential for detailed studies. Nevertheless these numerical models have to be performant enough and validated with situations that if they are not realistic are representative of phenomena involved. So here we focused on the problem of the possibility of trapping the solid particles in the recirculation zones. We have reproduced in laboratory a configuration representative of sites with enough steep hills to generate recirculation zones during saltation regimes.

Measurements have been made of the dispersion of solid particles released from a rectangular area flushed at the ground of a flat plate on which evolved a turbulent boundary layer. The originality here is that it is flushed at the ground and push up the particles to continuously feed the ground at the same mean rate as the mean local erosion rate. One or more Gaussian hills were disposed transversally to the flow downstream the solid particle injection. Various Reynolds number where chosen to caracterise take-off regimes and recirculation regime behind the Gaussian hill(s). One optical system combined with CMOS camera is used successively to measure the velocity of career fluid or solid particles by PIV. Digital Image treatment is used to separate fluid seeding from solid particle images. Supplementary comparison was done to compare velocity field of the career flow for smooth and rough floor only for kinematic around the hill(s).

In this paper, in a first part we will present kinematic caracteristics of the flow whereas in a second part of this work, the data will provide some concentration profiles of solid particles. The results presented concerning the velocity and concentration field are related to streamwise vertical planes at the center of the wind tunnel at successive longitudinal positions. For velocity field we will report different regimes for smooth and rough plate. Only one regime will be presented for solid particles. We present in a first part the kinematic study and in the second part results on the concentrations of solid particles.

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1. Introduction

Understanding and predicting solid particle dispersion from ground level into the upper boundary layer strates, over desert landscapes or urban canopies continue to be a problem for prediction, for global earth nets of solid material transport or for stopping desertification progressions.

In spite of the increasing capabilities of experimental set-up and technics the problem is so complex that schematic process have still to be studied before built up complete physical process modeling for numerical predictions. Enough complete data basis is still necessary to validate the different modeling proposals. Laboratory flows, such as the one described in this paper, provide the controlled conditions needed to understand the underlying physics of the solid particle trapping processes over obstacles and to test predictive models, even though they have orders of magnitude lower gravity numbers and Reynolds numbers than for real desert atmospheric flows. The main problem is to correctly design hill shapes in order to preserves recirculation zones for take-off regimes of the present solid particles and roughness length. There are only a few techniques that have been developed to measure simultaneously particles (solid or droplets) velocity field and flow velocity field. Details of such technique for spray experiments and air/droplet mixing were developed in Boëdec and Simoëns[1] or directly for velocity measurements with submicronic solid particles by Simoëns et al.[2]. In the first one, investigated droplets were tagged with fluorescent dye and recorded simultaneously with a first CCD camera with a filter for fluorescent wavelength and by a second CCD camera for both droplets and smoke incense particles. By digital image treatment it was possible to remove droplet images from the images of the second CCD camera leaving only incense particles seeding air on the image. Velocity field of gas was obtained from these last images without taking into account for droplets images. From the first CCD camera droplet velocity was acquired. In so simultaneous droplets and gas velocity was obtained for the same locations. The same kind of digital image treatment was developed here to remove solid particle images from images where were also incense particle images. This was done with only one CMOS camera as the solid particles was 100 to 1000 time larger than incense particles, releasing thus more light intensity when present in the sheet of light necessary for PIV measurements.

In so it was possible to obtain velocity field from air in presence of solid particles behind the hill. The configuration of two dimensional Gaussian hill on the wall, perpendicular to the mean flow of an upstream turbulent boundary layer has been investigated relatively frequently in the litterature[3, 4, 5, 6, 7, 8]. In our case it is an ideal configuration for which solid particles tends to be trapped there and that could correspond to events with natural hills and not so far with static dunes. In function of the half hill width W to hill height H (giving the ratio R = W/H) and of the free-stream velocity of the flow, Ue, above the hill, first trends could be designed on the existence or not of recirculation zones responsible for trapping events. For large W/H, the recirculation zone tends to disappear removing any kind of trapping events. For large velocities the recirculation zone tends also to disappear prohibiting any kind of trapping events. Some uncertainties still exist concerning the fluctuating behavior behind the hill. Such process could considerably modify the modeling responsible for sweeping solid particles trapped behind the hill. An other parameter is clearly the roughness parameters that modify the recirculation behavior compared to the smooth cases. An other point is that with two dimensional case it is relatively easier to simulate numerically for validation of the models.

For this presentation we will only consider the Gaussian hill studies without detailing solid particle trapping problem. For roughness problem we will refer to Jimenez[9] that correctly describe the complexity of the problem that is largely enhanced as soon as we add the solid particle transport that, for any reptation, saltation or suspension regime modify the roughness wall structure permanently implying a large amount of supplementary difficulties for which numerical simulations have to account for such permanent wall or wall characteristic modifications.

Studies with three dimensional hill cases exist in the literature and we first refer to Zegadi et al. [12] for example for such case. More recent work by Ohba et al. [13] was carried out inside wind tunnel with an isolated three dimensional hill under neutral, stable and unstable conditions. Experiments results were compared with Direct Numerical Simulation for the neutral condition. Their objectives was linked with pollutant dispersion over complex terrain. For the neutral conditions they shown velocity field profiles all along a vertical plane aligned with the longitudinal axis of the wind tunnel and passing by the top of the hill. No recirculation zone was noted for the chosen regime Re =

5000 based on the hill height H. The ratio R was 2 and the boundary layer thickness δ was about 3H for the location 5H upstream the top of the hill. The top of the hill was too flat and didn't allow to generate recirculation for trapping situation.

The 2D experiments by Cao and Tamura[7,8] were carried out in a wind tunnel to test effects of certain kind of roughness on the flow over a two dimensional hill. They first compared smooth and rough flow and worked on sudden change effect of roughness ground on the flow over the hill. Small squared cubes of height h with H/h= 9 were disposed regularly on the ground to generate rough flow. This disposition is characterised by the frontal area coefficient $\lambda = 0.041$ that is the ratio between the total front area of the roughness elements to the total surface where they are spread. The shape of the hill was a $\cos^2$ shape with a ratio R equal to 1. The main conclusions that we could draw is an increase of the length of the recirculation zone with the decrease of the ratio R . The presence of roughness elements (that could be characterised by the parameter λ) seems to increase the recirculation zone length as it decreases. A third parameter is the Reynolds number, the length of the recirculation zone seems to decrease with its increase.

Although the investigations cited above (or few others not cited here) have revealed considerable information about this kind of flow configuration, there is still few works with sand transportation and associated roughness over hills. In particular a detailed description of the velocity of the career flow and its effect on solid particles spreading over will be valuable to modelers attempting to predict such flows or more complex flows for desertification studies. First the present experimental details will be given. In a second part characteristics of the velocity field will be detailed and comparison between smooth and rough cases detailed. In a third part, the characteristics of the concentration of solid particles will be described. At the end, conclusions will be drawn and perspective of this work, in the frame of larger scale studies, will be given.

Nomenclature

X	Longitudinal location
Z	Vertical level
δ	Boundary Layer thickness
Ue	External velocity
Re	global Reynolds number based on Ue and d
H	Gaussian hill height
λ	Frontal area
ρ_p	solid particle density
γ_p	gravity number
St	Integral Stokes number
τ_p	Particle relaxation time
d_p	particle diameter

2. Experiment

The flow field for this study was a flat plate turbulent boundary layer emerging on a two dimensional Gaussian hill of height H, whose longitudinal shape follows the equation (1), located on the wall and oriented perpendicular to the mean flow direction. A rectangular source of 20 H length and 10H width, is flushed at the wall and emits continuously, solid particles, taking into account mean erosion. It was aligned perpendicular to the hill. Its downstream side was located 25H upstream the center of the hill (see figure 1).

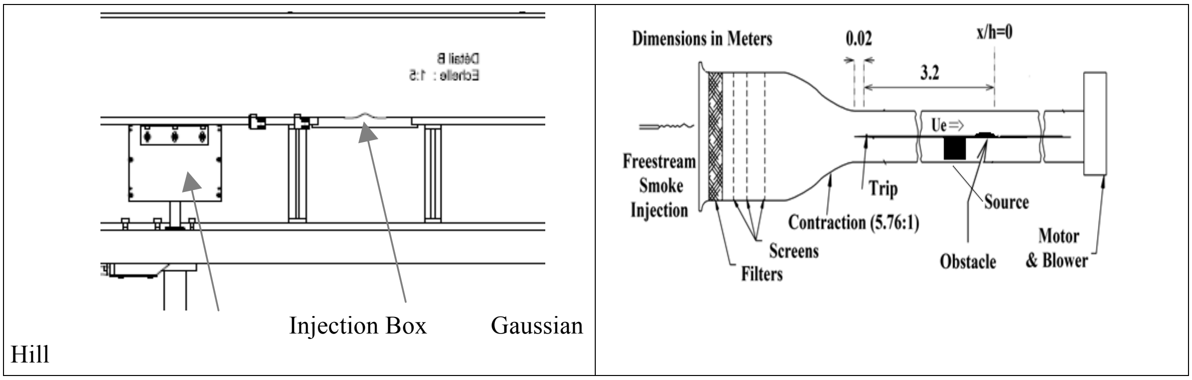

Figure 1: Injection Box and Gaussian Hill and Experimental wind tunnel.

For the first set of experiments (without injection) the box is closed with a cover perfectly aligned with the ground level avoiding any kind of disturbance. Two synchronized YAG lasers, for flow illumination, and one CMOS camera (PCO 4000), for image capture, were used. The YAG lasers provide 150 mJ of energy per pulse and have a recharging frequency of 4 Hz which is the image acquisition frequency. The optical arrangement was shown schematically in Vinçont et al. [11]. In this work only one CMOS camera is used. The turbulent boundary layer developed on a flat plate with a sharp leading edge that was mounted at the horizontal mid-plane of the 0.5 m×0.5 m test section of the wind tunnel as in Simoëns et al. [12]. Two sets of experiments were first carried out. The first one consists in the smooth case (SC) with a perfectly flat plate whereas the second one consists in rough case (RC) flat plate. Both for SC and RC, to initialize and stabilize the laminar-turbulent transition of the boundary layer, sandpaper and a 5 mm diameter round rod were attached to the flat plate about 2cm downstream of the leading edge. The downstream side of the rectangular box was located 2.5 m downstream of the at plate leading edge in order to allow a sufficiently thick turbulent boundary layer (TBL) to develop before reaching the solid particle box and the hill. For the rough case (RC), a high density of solid particles was stuck at the ground to simulate natural roughness of sand deserts.

Rough case	2,98 m/s	7,92 m/s	11.2 m/s
u_f (m/s)	0.142	0.422	0.594
Re	1967	5280	7347
Ue (m/s)	2,98	7,92	11,20
Z_d(µm)	195	195	195
Z_0 (µm)	8.2	8.2	8.2
δ (cm)	7	7	7

Table 1: Characteristics at X/H = 200 after the boundary layer departure. Three rough regimes.

Characteristic of these particles are the same as those injected during the study. Solid particle diameters range from 170µm to 250µm with a mean diameter about 200 µm. Three freestream flow speeds were chosen for the SC and the RC : Ue=2.9m/s, Ue=7.9m/s and Ue=11.2m/s. Characteristics of the boundary layer for SC and RC without the hill are detailed in table 1. The Reynolds number, Re is based on the height of the BL, δ, and the free-stream velocity, Ue. The friction velocities, u_f, and the roughness length, z_0, were estimated with a closer fit of the mean velocity profiles in the logarithmic region. The friction velocities are in agreement with the literature cases with similar external velocities Ue. In figure 1 we show only vertical profiles of the mean velocity longitudinal component, U(z), are normalized by the determined friction velocity, u_f.

The 2D Gaussian hill has the following shape (x in mm):

$$x = 10 * e^{-(7 * \frac{z}{100})^2} \quad (1)$$

Its height is of H=1cm. This allows a 1/7 ratio of the obstacle height to the boundary layer thickness of the free TBL at the location of the hill. The hill had an aspect ratio of 50 and spanned the complete width of the wind tunnel test section.

For PIV seeding, incense particles were used with a diameter range about 0.1-3.0 µm, with a mean diameter of about 0.9 µm and a standard deviation of about 0.5µm. The same particles used to determine the velocity field without solid particle injection were also used for the PIV measurements with injection of the solid particles. Incense particles in this size range follow the flow quite faithfully for flows with Reynolds numbers of the present magnitude. Details of the use of such particles for PIV measurements are given in[10].

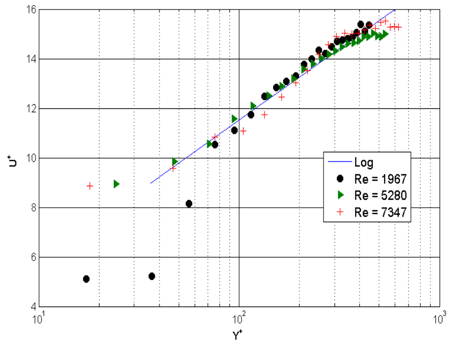

Figure 2: Mean velocity for rough case, 3 regimes and log law.

Particle images of solid particles are largely greater than particle images of incense particles. In figure 3 it can be shown that after some digital image treatment only solid particles could be treated removing smoke particles (or the inverse). Digital image treatment as in[1,2] allows to determine separately flow velocity, solid particle velocity field and solid particle concentration field over the same instantaneous image.

A first set of experiment was first done without solid particle injections allowing PIV measurements with only smoke particles present on the images. No digital treatment was necessary. The smoke incense was injected everywhere at the entrance of the homogeneous chamber of the tunnel.

Regime	R3 (11.2m/s)
ρ_p (Kg/m^3)	1000
d_p (m)	2.10^{-4}
St	15
γ_p	0.15
τ_p (s)	0.15

Table 2: Characteristics of the solid particles for the third rough regime

For the velocity field, the CMOS camera had a field of view about 100 mm in the horizontal direction and 50 mm in the vertical direction. In this set cases were with smooth plate and cases were with stuck particles on the floor.

A second set of experiments was done with solid particle injections only with rough plate. Solid particles injection details are given in table 2 for the third regime of the RC. The PIV subfield was further divided into small subzones with dimensions of about 0.06H in the x and z directions in which the local U and V velocity components were determined.

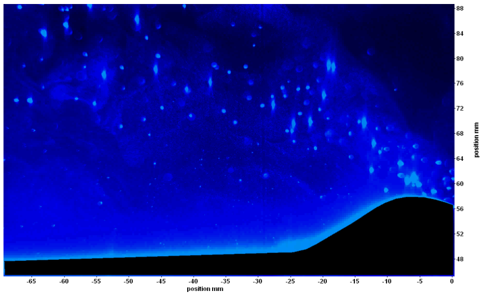

Fig. 3. (a) Instantaneous planar view of solid particle and smoke seeding flow.

On figure 2 the mean longitudinal velocity U profiles for the boundary layer in the RC without the hill are shown. Here the normalization was done with the friction velocity. For the smooth case, the PIV mean velocity measurements are compared to a curve of Spalding[16] at the three Reynolds numbers. The agreement is reasonably good. For the rough case, the PIV mean velocity measurements are compared to the classical log law (for rough cases) for the three regimes. Again the agreement is reasonably good.

3. Results for flow and solid particles across two dimensional Gaussian hill on the wall

3.1 Velocity field and streamlines

For these kinematic results, we show only results for smooth (SC) and rough (RC) cases for the three chosen regimes without solid particle injection. All regimes exhibit a vortex, with negative spanwise vorticity, downstream the hill along the downstream slope of the hill. For both cases, the center of the vortex core is around X/H = 3.5 with respect to the center of the hill and Z/H = 2 with respect to the ground level. The length of the vortex zone is about 7 H and the main vortex diameter is along the slope. This length can be compared to the one of the primary vortex with isolated square 2D-obstacle[10]. Concerning this mean field the SC and RC are relatively similar and no noticeable difference was noted concerning vortex shape and magnitude.

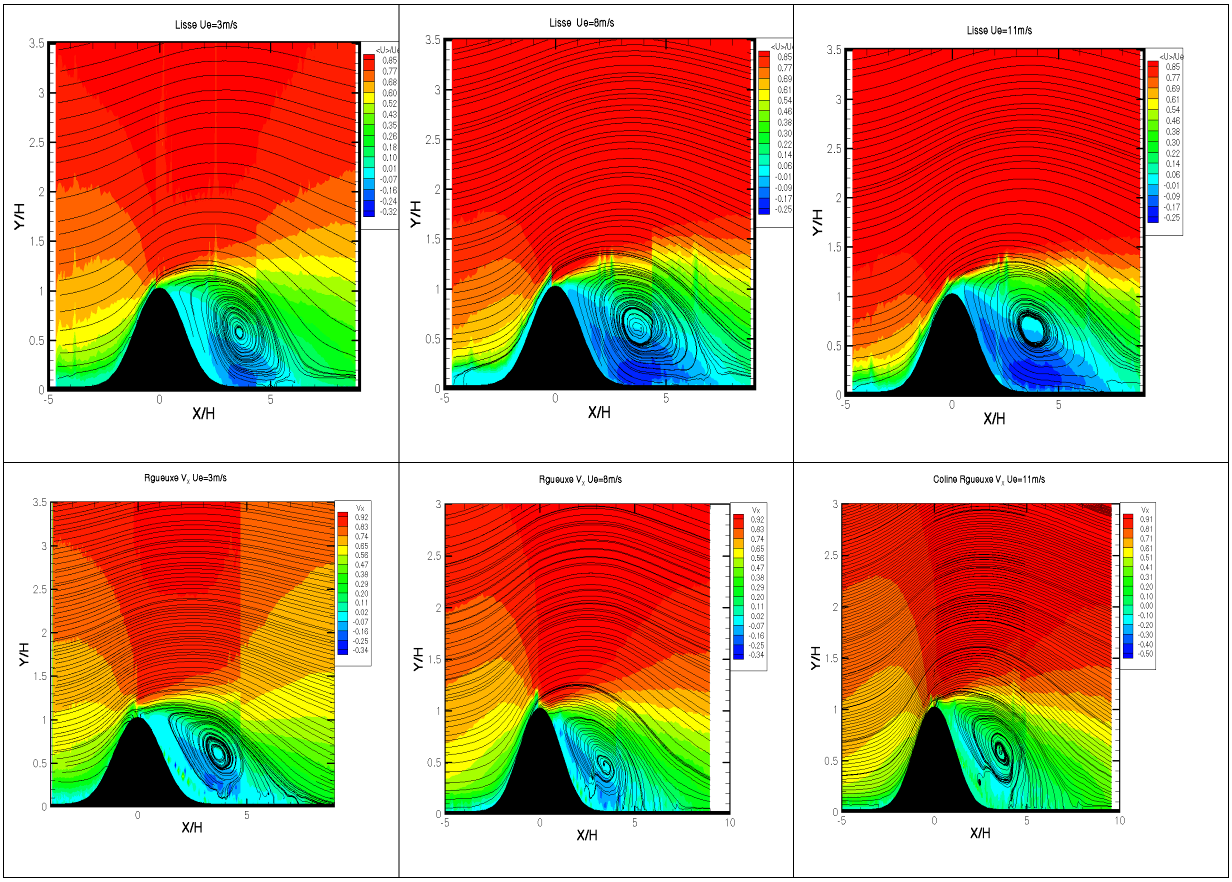

Fig. 4. Three increasing regime for SC a, b, c); three increasing regimes for the SC d,e,f). Colors are magnitude of longitudinal component (divide by Ue). Streamlines are superimposed.

Streamline patterns exhibit clearly recirculation zones and acceleration zones that solid particles have to follow when they arrive on the hill if they arrive at the same speed and if they don't modify the vortex and the speed up zone (that will be deduced from cases with injection and not shown here).

3.2.Mean Concentration field.

Here we show results for RC with solid particle injection. With show only the higher regime (R3) with 11.2m/s. For injection of the solid particles at the ground preliminary tests were done to determine the best as possible the mean injection rate which preserves the initial shape of the top of the box (moving solid particle ground) during the tests. The determined upward injection rate is 9 mm/mn for R3.

As explained above solid particle images are recognised with the used of digital image treatment that is possible here only due to the experimental configuration and that is not possible as soon as you have a sand bed that would provide too high solid particle concentration level.

During the digital image treatment process, location, of all solid particles, was attached to the centroid of the detected pattern associated with all solid particles. In so instantaneous images in a vertical 2D plane were determined for around 1000 samples (images). Some band profiles were selected on the field of the images giving instantaneous presence of solid particles on a vertical line (thus 1 for presence in a Z location and 0 otherwise at a fixed X location). Average of 1000 vertical lines were done. This allows to determine here the mean particle number of solid particles present on a vertical line. Such profiles are presented on figure 5. Note that we use a best polynomial fitting to obtain smooth profiles, a profile corresponding to an x-depth around 50 μm).

The mean profiles were divided by their local maximum, giving a maximum of 1 for every profile. In so it is better to see the progression of the vertical solid particle distribution and the effect of the hill on this distribution. Note here that for the present figure, 3 different experiments (thus CMOS and optical displacement along the x axis) were done to obtain enough spatial resolution (thus to be able to determine, by digital image treatment, every solid particle image) whereas a large field from injection box to the foot of the hill was inspected.

The first experiment corresponds to the end of the downstream zone of the sand box. This corresponds to the first profile (left) of the figure 5. The second experiment corresponds to the upstream zone of the hill, from the foot to the top. This corresponds to the three following profiles (moving to the right of the figure). The last experiment corresponds to the top of the hill to the foot of the hill along the downstream part of the hill. These are the three last profiles.

The first profile could be considered as an initial condition of solid particle injection for a future numerical simulation. The second profile corresponds to the hill foot. At this location exists a trend to upper spread particles, that were initially very close to the ground. This provides a flatter profile (giving probably a more homogeneous vertical distribution of solid particles). The third profile is at mid height of the hill slope on the upstream part of the hill. Hill involves here the same effect of flattening of the mean concentration profile as for the previous location. The fourth and fifth profiles are at the same top location of the hill for two last different experiments.

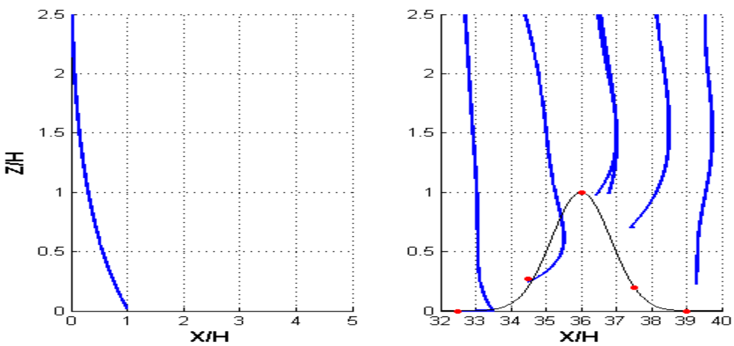

Fig. 5. Mean solid particle number along the flow (the 4th profile correspond to the top of the hill).

The increase of the longitudinal velocity at the top (shown in figure 4) create a zone upper to Z/H=1, where the particles are accelerated, in so they are more sparse. The steep slope tends also (with rebound) to concentrate particles above the ground with a maximum around z/H=0.25. The following profiles correspond to the mid height on the downstream slope part of the hill and the foot of the hill respectively. The trend induced by the hill on the concentration is preserved and enforced. The maximum of solid particles concentration is at z/H = 0.5 but the maximum of concentration stay at the same level for both last profiles. Note here that vortex is present without injection. Such vortex could capture particles that will induce higher concentration. This is not the case.

Remember that these profiles are fitted with polynomials. The number of sample was too low to have smooth curves.

The results for the top profiles from two different experiments and optical arrangements demonstrate that the obtained profiles are very similar giving the error due to the digital treatment. These results clearly depend a lot on the thickness of the light sheet and care have to be to maintain the same thickness for all displacement of the optical set-up.

Integral (over z) of these profiles were done to check for the mass conservation (compared to the injection rate). Some variation about 20% with some maximum of 50% exists for a same regime for different experiments and for locations all along the tunnel. The ratio of these profile integrals at the same location with different regime (thus with different injection rate) globally corresponds to the associate ratio of the initial box injection rate between these regimes. Thus the method seems strong enough to have the exact trends of modification of vertical concentration for all the longitudinal evolution.

4. Conclusions

Idealized laboratory experiments related to the flow field kinematics around a Gaussian hill embedded in a turbulent boundary layer were carried out with PIV measurements and digital image treatment. The hill was formed by a two dimensional Gaussian shape of 1cm height and spanned the wind tunnel. Mean solid particle injection was done upstream the hill to obtain 1) some information on the way the hill modifies the concentration levels of solid particles; 2) some data basis for numerical code validation.

Interesting but classical information was obtained on the way recirculation zone is modified by the regimes and the roughness. Original information was obtained for a given regime concerning the effect of hill on the solid particle concentration.

Numerical simulation is on the way to reproduce such case and other regime in order to validate deeply the LES code that we used for more systematic parameter studies as in [14,15] that was one of the final aims of this work.

In future papers we will present more complete solid particle concentration evolution along more complex terrains and other regimes.

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