NEAR WALL PIV-MEASUREMENTS ON THE WINDWARD SLOPE OF A HILL

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Abstract The turbulent flow over periodic hills was measured near to the wall, using planar Particle-Image-Velocimetry (PIV) at high spatial resolution. Our focus is on the near wall turbulence structure on the windward slope of the hill. For large-eddy simulation (LES) we suspect that, if this was not predicted accurately, it affects the prediction of the velocity profiles over the hill crest which in turn will affect the recirculation length downstream of the hill. Regarding the time averaged velocities, we were able to resolve the linear viscous region of the boundary layer. The velocity distribution and also the Reynolds stress does not comply with the law of the wall as it is valid for a turbulent boundary layer at equilibrium.

INTRODUCTION

We investigated the flow over smoothly contoured hills experimentally. The setup consists of ten hills at large aspect ratio (18/1) in a closed flow channel with a rectangular cross section which gives 2D flow with streamwise periodicity. It provides an opportunity to study flow detachment under well defined conditions and to validate numerical methods and turbulence models. The setup has been a benchmark for large-eddy simulations and direct numerical simulations. The flow is characterized by an acceleration of the fluid at the windward side of the hill and an overspeed at the top, that leads to a second maximum of the streamwise velocity component close to the wall. Due to flow detachment a recirculation zone develops at the lee side of the hill. The separation length predicted by LES tends to be larger, than it has been observed in our previous experiments [1, 3]. Larger recirculation lengths were observed to be linked to wrong predictions of the streamwise velocity profile over the hill crest (Figure 1a) which in turn could be induced by a wrong prediction of the turbulence structure on the windward slope of the hill. With increasing Reynolds number the problem exacerbates. Therefore we conducted near wall measurements in the middle region of the windward side of the hill and close to the top ($x/h = 8$ and $x/h = 8.7$, Figure 1b) at Reynolds numbers $Re = 10600$ and $Re = 37000$. Our aim was to measure the time averaged velocity components and Reynolds stresses with high spatial resolution.

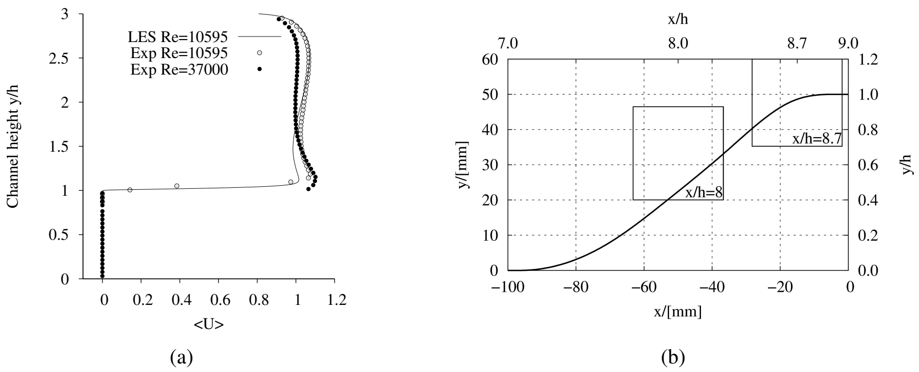
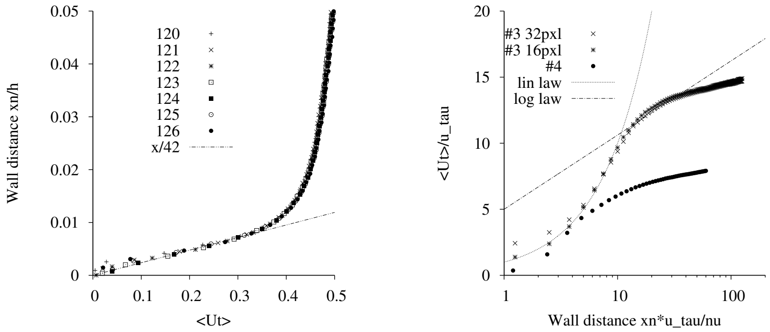


Figure 1: Comparison of the velocity distributions on the top of the hill, determined by previous PIV-measurements and LES (a). Positions of current measurements (b).

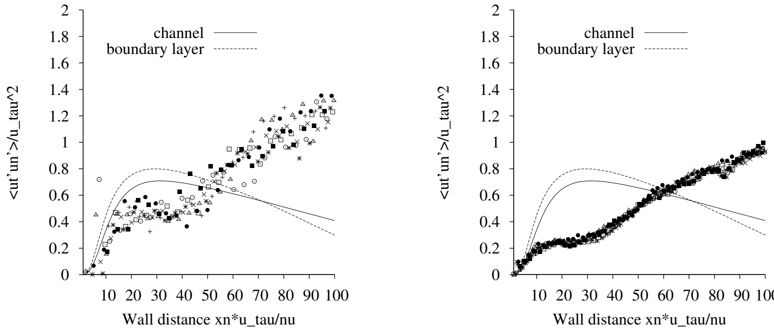
METHODS

To achieve high spatial resolution, we used an objective with a focal length of $f = 105mm$ that was equipped with a teleconverter to reach a spatial resolution of $12.8\mu m/pixel$. Since the near wall position in our experiment is prone to reflections that can lead to an overexposure of the camera, we did experiments with fluorescent particles and fluorescent paint coats (Rhodamine B). Velocity vectors were computed by using interrogation areas of 16×16 and 32×32 pixels.
For the purpose of data evaluation the velocity components were transformed from Cartesian coordinates (x, y) to a rotated coordinate system with axes that were tangential and normal to the wall (x_t, x_n). We found that determining the wall position with the help of a calibration target was insufficient, so we applied an iterative method, using the measured velocity profiles. Therefore adjacent velocity profiles were moved by the wall distance at their specific x-position. In the next step a global shift of the image was introduced, so the extended profiles intersected with the wall. This procedure allows to determine the wall position precisely, if the linear region of the boundary layer is met, which was the case.



(a) (b)

Figure 2: Adjacent profiles of the tangential velocity component at $x/h = 8$ (16×16 pixels) (a). Profiles of the tangential velocity component, expressed in inner coordinates, compared to the linear law and to the logarithmic law (b).



(a) (b)

Figure 3: Reynolds shear stress of adjacent profiles in a coordinate system parallel to the wall (x_t, x_n), expressed in inner coordinates at $x/h = 8$ for $Re = 37000$ (a) and $Re = 10600$ (b).

RESULTS

Figure 2a depicts a series of adjacent velocity profiles in the rotated coordinate system at $x/h = 8$. Apparently the linear region of the boundary layer extending to about $0.25mm$ was reached. Therefore the wall shear stress and the skin friction coefficient could be computed and the results could be expressed in inner coordinates.

As it is depicted in Figure 2b, the velocity profiles in inner coordinates for both Reynolds numbers do not correspond well with the log law. For $Re = 37000$ ($\#3$) a linear behavior can be observed below of $x_n u_\tau/\nu \approx 10$. For the higher Reynolds number the linear range is much wider than for the lower. For $Re = 10600$ ($\#4$) the deviation from the log law is much larger compared to $Re = 37000$. Figure 3a and 3b depict the Reynolds shear stress $\langle u'_t u'_n \rangle$ at $x/h = 8$ compared to numerical results of turbulent channel flow [2] and turbulent boundary layer flow [4] representative for equilibrium boundary layers. For $Re = 37000$ a local maximum can be observed close to the wall at $x_n u_\tau/\nu \approx 20$ and in a range of $x_n u_\tau/\nu \approx 40$ a good agreement with the data [2] and [4] can be found, but our shear stresses are lower. At a lower Reynolds number ($Re = 10600$) the peak values close to the wall are much smaller compared to the ones of equilibrium boundary layers. For wall distances larger than $x_n u_\tau/\nu \approx 40$ the Reynolds stresses do increase linearly with the wall distance for both Reynolds numbers. We conclude that the momentum balance of the boundary layer is governed by the outer flow, since the turbulent stresses that are produced close to the wall are small. Therefore the boundary layer is not able to develop according to the universal law of the wall.

References

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