5.38 EFFECT OF ROUGHNESS INHOMOGENITIES ON THE DEVELOPMENT OF THE URBAN BOUNDARY LAYER

M. Schultz, B. Leitl, M. Schatzmann
Meteorological Institute, University of Hamburg, Germany

INTRODUCTION

One focus on the FUMAPEX project is to “urbanize” National Weather Prediction (NWP) models, i.e. to make them fit for urban air pollution forecasts. Generally, most operational NWP models and meso-scale models work with horizontal resolutions of several km. This resolution is too coarse to resolve buildings and other obstructions. Obstacles that shape the urban canopy can only be taken into account by means of a roughness parameterisation. Since the flow in the lowest (about) 100m is strongly affected by the obstacles, the quality of predictions obtained with urbanized meso-scale models depends on the quality of the urban roughness parameterisation these models apply.

It is common practise in numerical modelling to adjust roughness characteristics from grid cell to grid cell, but within an individual grid cell which covers several square km the roughness properties are assumed to be everywhere the same. Although the values chosen might be a representative average for the grid cell as a whole, locally large deviations from the average must be expected since the roughness structure in real urban sites is typically non-uniform.

The aim of the present work is to generate data that are suitable for the improvement and validation of roughness parameterisation as they are used in NWPs. Therefore a few wind tunnel experiments with uniform cube roughness elements were carried out to investigate the dependence of flow properties on urban canopy characteristics.

EXPERIMENTAL SET-UP

All experiments were carried out in the “small” boundary layer wind tunnel “Blasius” at the meteorological institute of the University of Hamburg. The wind tunnel has a total length of 16 m and has a test section, which is 4.5 m long, 1.5 m wide and 1 m high. The boundary layer development section amounts to 7.5 m. The tunnel is equipped with an adjustable ceiling (See Figure 1).

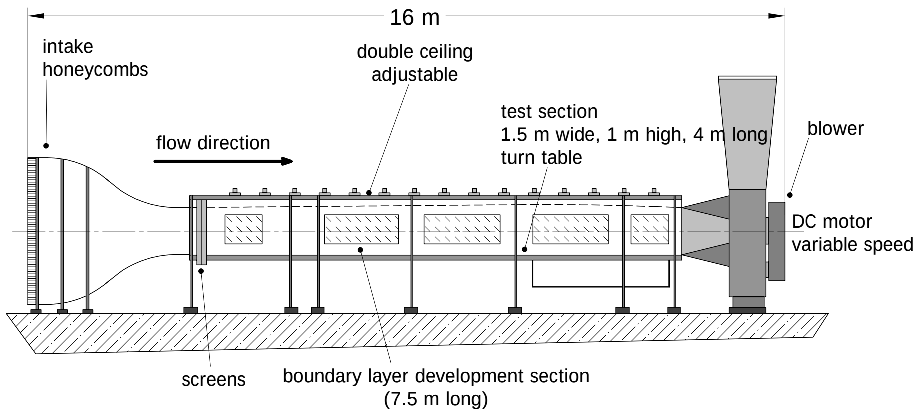

Figure 1. Sketch of the boundary layer wind tunnel “Blasius” at the Meteorological Institute of Hamburg University.

An array of regularly arranged sharp-edged wooden cubes with a height of h = 25 mm was put inside the test section of the tunnel. Measurements were carried out with a 2-dimensional Dantec© fiber probe LDA. The probe had a focal length of 50 mm and a measuring volume of d_x = 0.121 mm, d_y = 0.122 mm and d_z = 1.151 mm. The measured components were *u* and *w* for all measurements. An idealized urban roughness represented by a regularly arranged array of cubes with size h = 25 mm was positioned in the test section of the wind tunnel.

The main focus of the first series of measurements aimed on getting orientation. Therefore, three different configurations were measured with spacing between the cubes varying from 0.5h, over 1h to 2h (aspect ratio 2, 1 and 0.5, respectively). During this first campaign the array of cubes consisted of 38 rows. After row 32 in the centre of the tunnel a small array of 3 x 3 cubes was selected to be the intensive measurement area. Here the cubes were painted black in order to minimize reflections during the LDA measurements. The last three rows were placeholders to guarantee undisturbed measurements inside the black array. A schematic sketch of the experimental set-up is shown in *Figure 2*.

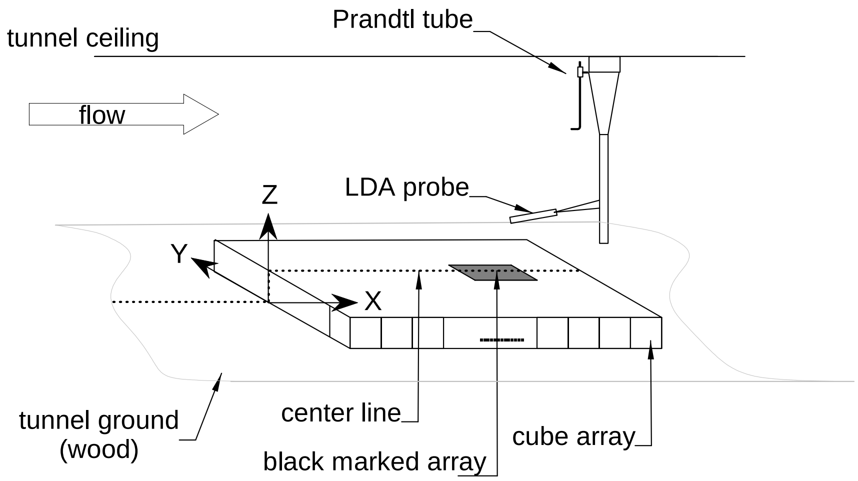

Figure 2. Sketch of the experimental set-up in the wind tunnel.

For all three configurations the following measurements were carried out:

1. A Profile was measured upstream of the cube array to determine the characteristics of the approach flow.
2. Along the centreline of the whole cube array profiles were measured between the levels 1.2h and 15.6h with a vertical resolution of 1.6h and a horizontal distance of 2h. This should give a fair representation of the development of the flow.
3. Above the black array the density of measurement points was increased to 21 spatially distributed profiles each with 29 points between the levels 1h and 15.6h.

The tunnel floor upstream of the cubes was smooth. The vertical distribution of the flow approaching the cube array followed a power law profile

$$\frac{\bar{u}(z)}{u_{ref}} = \left(\frac{z - d_0}{d_0}\right)^{\alpha}$$

with profile exponent α = 0.16 and displacement thickness d_0 = 0 mm. Spires or other devices to trigger the approach flow were not used. The flow development was solely regulated by the roughness elements. Reynolds number independence for fully rough flow conditions was obtained.

EXPERIMENTAL RESULTS AND DISCUSSION

After a step change in roughness the approach flow needs some time to adjust to the new underlying surface and to reach a new equilibrium. The height of influence increases with increasing fetch like it is shown in *Figure 3*, which is freely adopted from Cheng and Castro (2002). Within the range of influence an equilibrium layer develops, which is made up by the roughness sublayer and the inertial sublayer. Between the outer layer, which maintains the features of the approach flow, and the equilibrium layer there is a transition region.

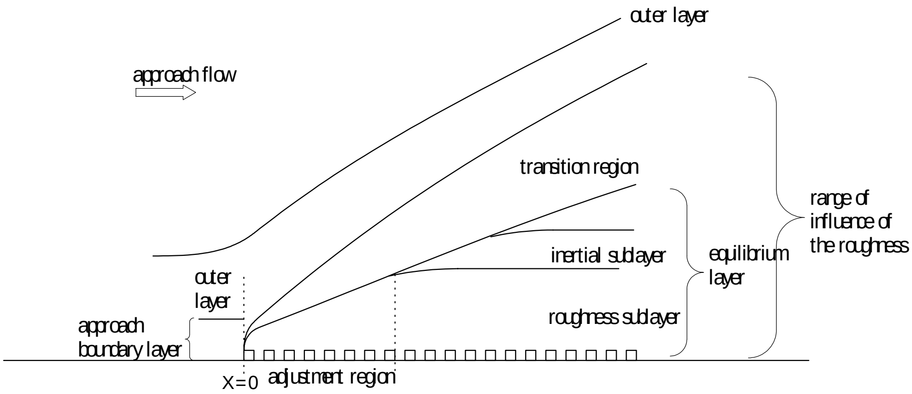

Figure 3. Sketch of the flow development after a step change of roughness. (From Cheng and Castro, 2002).

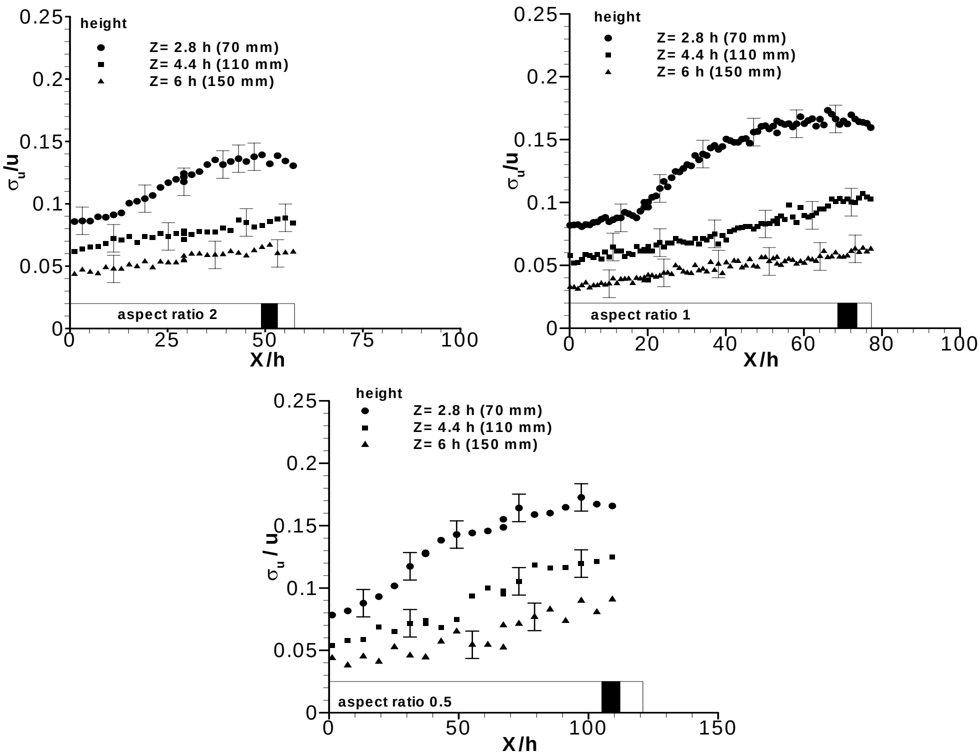

Figure 4. Development of the longitudinal turbulent intensity σ_u/u with distance and height for cubes with identical height but different spacing (aspect ratios vary from 0.5 to 2).

Due to the rapid change in roughness height, there is a lift-up of the boundary layer flow to the level of cube top height. A long transition region can be observed. To identify the vertical extend of the equilibrium layer, turbulence intensities are plotted in
Figure 4. As can be seen, only at the lowest height investigated (z = 2.8h) equilibrium seems to occur. At higher elevations neither the mean nor the turbulent properties reached equilibrium over the distance covered by the 38 rows of cubes. The influence of particular aspect ratios seems to be small over the range investigated.

In order to achieve more knowledge about the vertical profiles of mean and turbulent properties and their variation as a function of horizontal distance from an individual cube, the profiles measured above the black marked array were analysed. The results are shown in *Figure 5* only for the turbulent fluxes. The turbulent fluxes are normalized with the reference wind speed u_{ref} measured well above the boundary layer in the free stream at height z = 15.6h.

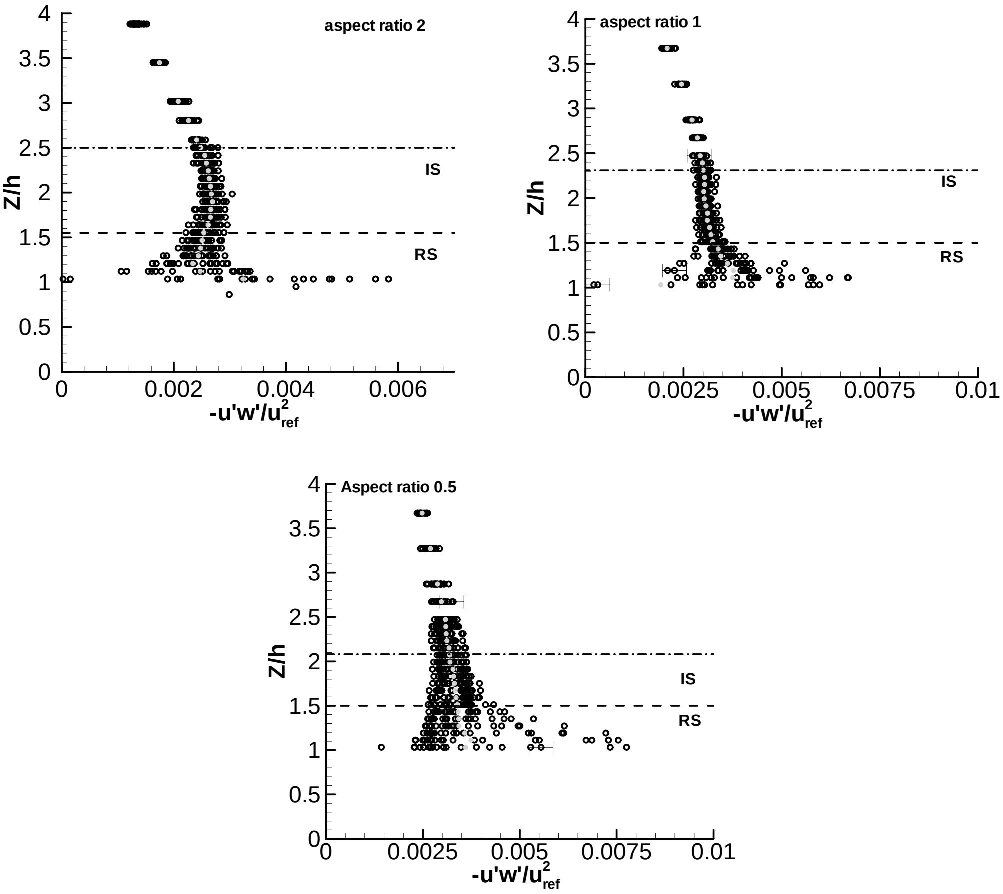

Figure 5. Normalised turbulent fluxes measured behind a fetch of 32 rows for cube arrays with aspect ratios varying from 0.5 to 2. Error bars indicate reproducibility.

Included into Figure 5 are ensemble averaged mean flux profiles (grey dots) and the height and position of the roughness sublayer (RS) and of the inertial sublayer (IS). The height determinations were done according to *Cheng and Castro* (2002), who defined the upper edge of the RS at the position where momentum flux profiles taken at different positions relative to the roughness elements converge. The IS is defined as the region within which the momentum fluxes vary less than 5%. Other possible ways to determine the IS as, e.g. fitting the logarithmic law to the mean velocity profiles give similar results. Figure 5 shows that the height of the RS is about 1.5h for all three aspect ratios. It seems to be independent on the roughness spacing. The vertical extend of the IS, obtained with this method, seems to decrease slightly with roughness density

Rotach (1993) and *Oikawa and Meng* (1995) defined the upper limit of the RS as the height at which the vertical momentum flux profile reaches a maximum. If one compares only the averaged profiles, it can be seen that the turbulent flux profiles for the arrays with aspect ratio 1 and 0.5 fall nearly on top of each other, while the flux profile for the roughness with aspect ratio 2 has smaller values for the turbulent fluxes. The shape for this profile seems to be similar to that found by *Rotach* (1993), who, however, reported an aspect ratio of 1 for the street canyon in which his measurements were accomplished

SUMMARY AND CONCLUSION

The series of measurements was done with a step change in roughness varying from very smooth to very rough. This rapid change in ground roughness is an idealised case and probably not the best approximation to reality. Further more the flow approaching the cube arrays is of low turbulence intensity. Even after a fetch of 38 rows equilibrium was gained only in the lowest part of the boundary layer.

For this reason a second series of measurements will be started. These experiments will comprise the following set-ups:

- The number of rows with roughness elements will be increased in order to support the development of an equilibrium boundary layer.
- The approach flow to the cube array will be made more turbulent by using an appropriate set of vortex generators and ground roughness elements. It is expected that the vertical mixing will be enhanced and therefore equilibrium reached after a shorter fetch.
- An additional series of measurements will be carried out with non-uniform roughness elements.

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