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P6B.2 EXPERIMENTAL STUDY ON MEAN FLOW AND TURBULENCE CHARACTERISTICS IN AN URBAN ROUGHNESS SUBLAYER

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1. INTRODUCTION

The structure of the atmospheric boundary layer in urban areas is of particular interest for air pollution modeling. In urban-scale dispersion models, the lowest portion of the boundary layer is often represented using surface layer similarity parameterizations. The urban effects are taken into account by changes of surface roughness and heat flux. Strictly speaking, boundary layer formulations of this type are only applicable in the inertial sublayer well above the building tops, but not in the so-called roughness sublayer - the flow region in the immediate vicinity of the urban canopy elements where the flow locally depends on the particular building arrangement and thus has a rather complex structure. In the vertical, the roughness sublayer extends from the surface up to a level, at which horizontal homogeneity of the flow is achieved, that is at 2 to 5 times the average canopy-element height. In areas with high buildings, it can occupy a significant portion of the boundary layer where most of the pollution problems occur. Thus urban air pollution modeling requires also information on flow characteristics in the roughness sublayer.

There have been only a limited number of field observations, which provide information on the mean flow and turbulence characteristics in the urban roughness sublayer. Rotach (1993a,b; 1995) analyzed mean flow and turbulence parameters inside and above an urban street canyon. He found that one of the characteristic features of the roughness sublayer is an increase in the absolute values of turbulent shear stress from essentially zero at the average zero plane displacement height up to a maximum value, which was observed at about two times the average building height. One may argue that the maximum value marks the level of transition from the roughness sublayer to the inertial sublayer, so that the maximum flux value is a good estimate for a scaling velocity u_{*IS} of the inertial sublayer. Additionally he found the concept of local scaling (using local shear stress for normalization) to be valid for the description of velocity variances and wind shear (Rotach, 1993b).

Similar shear stress profiles were observed by Oikawa and Meng (1995). The profile peaked at a level 1.5 times the average building height H. The scaling velocity u_{*IS} was determined from flux measurements at 2.6 H, a level, which they considered to be above the roughness sublayer. This u_{*IS}-value was about 7% smaller than the peak value. Feigenwinter et al. (1999), who measured in three levels (z/H=1.5, 2.1, 3.2) above an urban canopy, under neutral conditions also observed a significant increase of Reynolds stress between the two lower levels, whereas the values were almost constant between the second and third level.

Even more pronounced peaks were observed by Louka (1999) within an array of four canyon type buildings. The maximum values were found close to the building tops and were between 2 and 5 times higher than the results at the highest measurement level which was at z/H = 2.26. The higher peak values occurred for situations with an attributed smooth - rough transition. Like Oikawa and Meng (1995) Louka (1999) also determined u_{*IS} from the flux measurements at a level (z/H = 2.26) which was considered to be above the roughness sublayer.

Although some important features of flow and turbulence fields in the urban roughness sublayer could be identified by these field studies, there are still open questions concerning appropriate scaling concepts and a lack of high resolution datasets, which cover a wider range of sampling positions and also a variety of building arrangements.

Wind tunnel modeling of flow field characteristics in the near field of obstacles is a good opportunity to get high resolution measurement data. There have been several wind tunnel studies on flow over plant canopies (see e.g. review in Kaimal and Finnigan, 1994) and internal boundary layer development behind a step change in surface roughness (e.g. Garratt, 1990; Pendergrass and Arya, 1984). Inside plant canopies, the turbulent stress usually strongly decreases downwards to almost zero at half canopy height. Above the canopy, the vertical profiles of Reynolds stress and velocity variances are practically constant with height. The internal boundary layer studies have shown that profiles of turbulence characteristics with significant peak values can be observed in the region close to a change of surface roughness. To what extent these results are applicable to urban canopies, which are characterized by significantly higher roughness elements and variable building geometry, has to be further investigated.

Recently, Brown et al. (2000) investigated the flow inside and above an array of two-dimensional

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idealized street canyons and found that profiles with pronounced peak values of turbulence characteristics are typical for the first two canyons whereas the flow is vertically more homogenous after a fetch of 3-4 canyons. In a similar study, Rafailidis (1997) still found pronounced peaks in shear stress and turbulence intensity profiles above an array of idealized street canyons for particular roof shapes. Although a substantial effort have been put in tunnel studies on flow and dispersion inside and above regular obstacle arrays (see e.g. MacDonald, 1998; Theurer, 1999), their information on the mean flow and turbulence characteristics in the urban roughness sublayer is rather limited.

So far no wind tunnel results on flow field structure inside and above a real urban canopy with highly variable building heights and shapes were published. In particular, the mechanism of flow adjustment to spatial variations of the urban-canopy geometry has not been sufficiently investigated and understood.

This gave the motivation for a wind tunnel study on the spatial variability of flow and turbulence characteristics over a central part of the city Nantes, France. The experimental setup and the results will be described in the following sections. New information on the mean flow and turbulence characteristics in the urban roughness sublayer has been obtained. We will discuss whether the observed features of the mean flow and turbulence fields can be attributed to the suburban-urban roughness change or they reflect local flow disturbances by individual canopy elements. Additionally parameterization concepts for profiles of mean flow and turbulence statistics will be outlined.

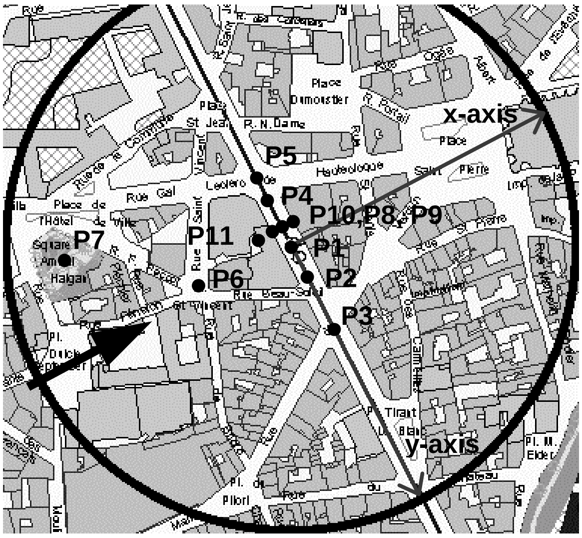

Fig. 1: Area in the center of Nantes modeled in the wind tunnel (circle) with the location of profiles.

2. EXPERIMENTAL SETUP

A detailed model of the building structure in a central part of Nantes of about 400 m in diameter has been constructed in the scale 1:200 and installed in a neutral boundary layer wind tunnel at the University of Karlsruhe. The technical details of the wind tunnel are described in Kastner - Klein (1999). A city map of the area reproduced in the wind tunnel model is shown in Fig. 1. A photo of the wind tunnel model (Fig. 2) gives an impression of the complex geometry of the investigated canopy. The obstacles in the foreground are supplementary idealized urban canopy elements that have been added to the model in order to increase the length of the urban fetch. In total, the extension of urban type buildings up to the center of the wind tunnel model was about 1.30 m. The boundary layer in the approach flow was formed by vortex generators at the entrance and by 20 mm high Lego roughness elements mounted on the wind tunnel floor.

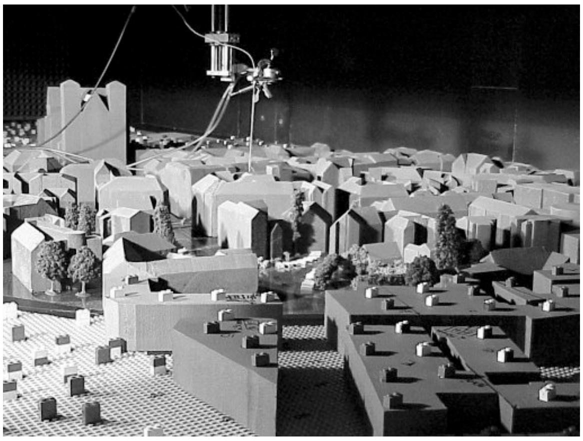

Fig. 2: Model in the boundary layer wind tunnel.

Table 1: Description of sampling point locations

	x cm	*y* cm	d_0 cm	z_0 mm	$u_{*,\log}$ m/s	
P1	0.0	0.0	10.0	6.0	0.67	☆
P2	0.0	12.0	10.0	2.0	0.52	✕
P3	0.0	28.0	10.0	0.6	0.42	✕
P4	0.0	-14.0	10.5	5.9	0.66	○
P5	0.0	-23.0	10.5	5.2	0.65	○
P6	-33.0	0.0	9.0	3.9	0.59	☆
P7	-66.0	-23.0	7.5	0.7	0.42	★
P8	0.0	-7.0	10.5	5.7	0.66	◇
P9	1.8	-7.0	10.5	6.1	0.67	▽
P10	-1.8	-7.0	10.5	5.6	0.66	△
P11	-7.9	-7.0	10.5	4.8	0.63	▲
REF	-180.0	0.0	0.2	0.86	0.42	—

Vertical velocity profiles were measured with a Laser Doppler velocimeter (details in Kastner - Klein, 1999) at the positions P1-P11 marked in Fig. 1 and upstream the model (REF) to control the approach flow conditions. For each location, two profiles with time series of two simultaneously sampled velocity components (*u* plus *w*; and *u* plus *v*) have been measured. The sampling frequency was 20 Hz and the sampling time 102 s. The velocity components have been defined in the following way: the longitudinal component *u* (parallel to *oX)*, the lateral component *v* (parallel to *oY)*, and the vertical component *w*.

The profile locations were chosen in the way to trace the internal boundary layer development over the urban area and the horizontal variability of the flow inside and above a street canyon (Rue de Strasbourg) oriented perpendicular to the wind direction. The coordinates of the positions are given in Tab. 1 together with symbols that identify each profile in the following diagrams. The parameters displacement height d_0, roughness length z_0 and shear stress velocity $u_{*,\log}$ will be further discussed in the next section.

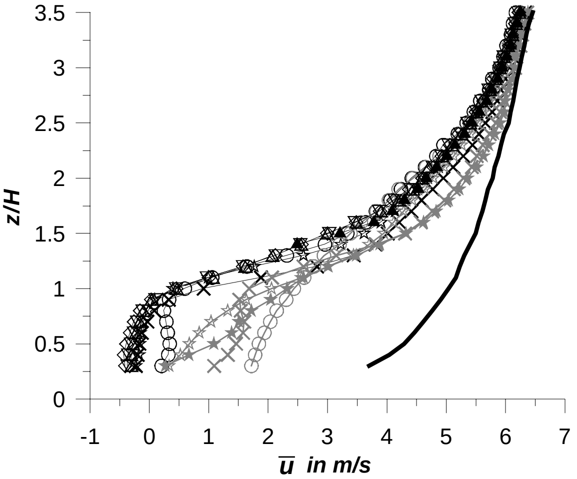

Fig. 3: Mean profiles of the *u* component (for symbols see Tab. 1).

3. RESULTS

Mean velocity profiles, turbulent shear stress and turbulence kinetic profiles are plotted in Figs. 3-5. The influence of building pattern irregularities on the mean flow, shear stress, and turbulence kinetic energy distributions can be identified up to a level of about 2.5 times the average building height *H*. This average building height was estimated to be 10 cm, but the roof levels of several buildings (for instance, the ones flanking Rue de Strasbourg) were up to 13 cm high.

The measured wind profiles can be classified in two types. The first type includes characteristic canyon-flow profiles with almost zero or even negative mean wind velocities below the building roof level (dark curves in Fig. 1). Profiles referring to the second type are representative of the wind regime around street crossings or in open squares. This regime is characterized by higher mean and turbulent flow velocities in the canopy layer (gray curves in Fig. 1). Shear stress and turbulence kinetic energy (TKE) profiles corresponding to both flow types in many cases show pronounced maxima in the flow region about 0.5 *H* deep, just above the building roof level.

The upper part of the mean profiles (*z/H>2.5)* has been approximated by logarithmic profiles

$$u(z) = \frac{u_{*,\log}}{\kappa} \cdot \ln\left(\frac{z - d_0}{z_0}\right), \qquad (1)$$

where the displacement height d_0 has been estimated for each profile taking into account the average roof level in the vicinity of the measurement location and finding the best fit to the data. The d_0 values are presented in Tab. 1. In average, d_0 is about 0.85 times the height of the buildings in the near vicinity, which is quite similar to the result obtained by Feigenwinter et al. (1999).

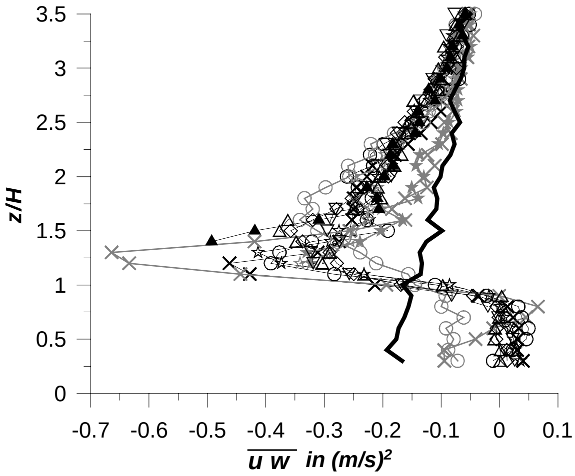

Fig. 4: Turbulent shear stress profiles (for symbols see Tab. 1).

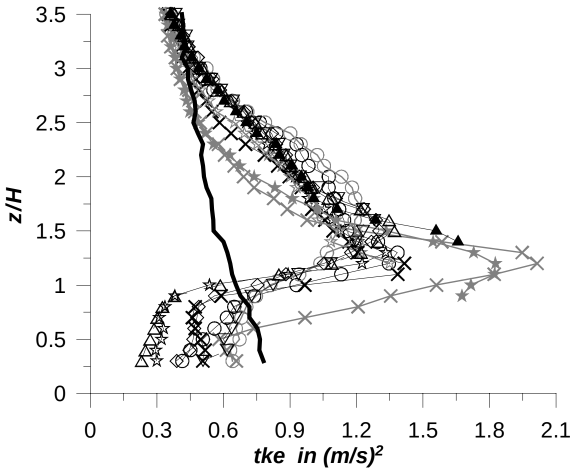

Fig. 5: Turbulence kinetic energy profiles (for symbols see Tab. 1).

The values of shear stress velocity $u_{*,\log}$ (black, filled stars) and roughness length z_0 (black circles) determined by the log-profile fits (1) are plotted in Fig. 6 and also listed in Tab. 1. The values of both parameters are rather uniform, with the exception of $u_{*,\log}$ and z_0 at the positions P2, P3 and P7. Around the first two locations, the building density is very high. There are almost no open spaces between the buildings and the flow feels only the upper portion of the buildings as roughness (e.g. changes in roof geometry or building height). This leads to the smaller values of z_0 and $u_{*,\log}$. Site P7 is located closer to the upwind edge of the model and thus affected by the suburban-urban roughness change. Our estimates show that a fetch of about 1 m is needed for the internal boundary layer to extend up to the highest measurement level (35 cm); whereas urban type buildings cover only 50 cm upwind of P7.

In Fig. 6, we also present local velocity scales $u_{*,\max} = \left(-\overline{u'w'}\right)_{\max}^{0.5}$ (gray, filled stars) calculated from the peak values of shear stress profiles plotted in Fig. 4. For most of the locations the magnitude of $u_{*,\max}$-values provides a good estimate of the profile determined velocity scale $u_{*,\log}$. Nevertheless it is necessary to be careful with general conclusions in this case. The shear stress profile can have a rather pronounced peak just above the roof level (like in the positions P2, P3, and P7) which are probably reflecting only local flow disturbances induced by particular canopy elements rather then representing the integral effect of the canopy. At these positions $u_{*,\log}$ and $u_{*,\max}$ differ markedly. The velocity scales calculated from the shear stress values at z=2.5 H (open, gray stars), which corresponds to the level that can be taken as the upper boundary of the roughness sublayer, are correlated with the $u_{*,\log}$ values, but are significantly smaller.

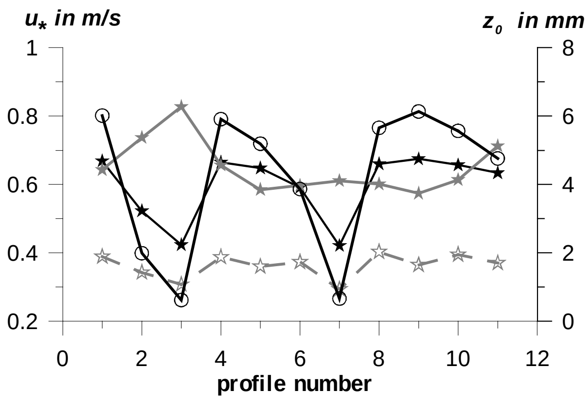

Fig. 6: Shear stress velocity and roughness length values determined from logarithmic-profile fits (1), and velocity scales derived from the shear stress profiles (see text for details).

4. SUMMARY AND CONCLUSIONS

Flow characteristics inside the urban canopy (below the roof level) show strong dependence on the measurement location. At the same time, the mean flow and turbulence profiles above the urban canopy are related to integral properties of the underlying and upwind surface and show much smaller variability. The differences in building density significantly affect the mean flow and turbulence fields inside and above the roughness sublayer. Peak values of TKE and shear stress, which are commonly associated with horizontal transformation of the flow, are observed at all positions. However, it is possible to distinguish between locations where the peak value of shear stress is a representative integral parameter of the flow, and locations where its high values are caused by locally induced flow disturbances.

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