Parameterization of wind and turbulent shear stress profiles in the urban roughness sublayer

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1. Introduction

Parameterizations for mean flow and turbulence characteristics are important prerequisites for air pollution modeling. One of the major urban air pollution problems is caused by vehicle exhaust gases. Since traffic emissions are released near the ground their dispersion is strongly affected by urban building configurations. The flow and turbulence fields inside the urban roughness sublayer - the region in the immediate vicinity of the urban canopy elements - depend on the particular building arrangements and have a rather complex structure. Thus, surface layer similarity parameterizations, which are typically implemented in dispersion models, are not applicable in the roughness sublayer (RSL). The lack of information concerning the flow characteristics inside the roughness sublayer gave the motivation for a real-array wind tunnel study. Profiles of all three velocity components and turbulence characteristics were measured inside and above canopy. The paper presents an analysis of these wind tunnel data following a recently developed conceptual framework by Rotach (2000) for the scaling of shear stress and mean wind profiles inside the RSL.

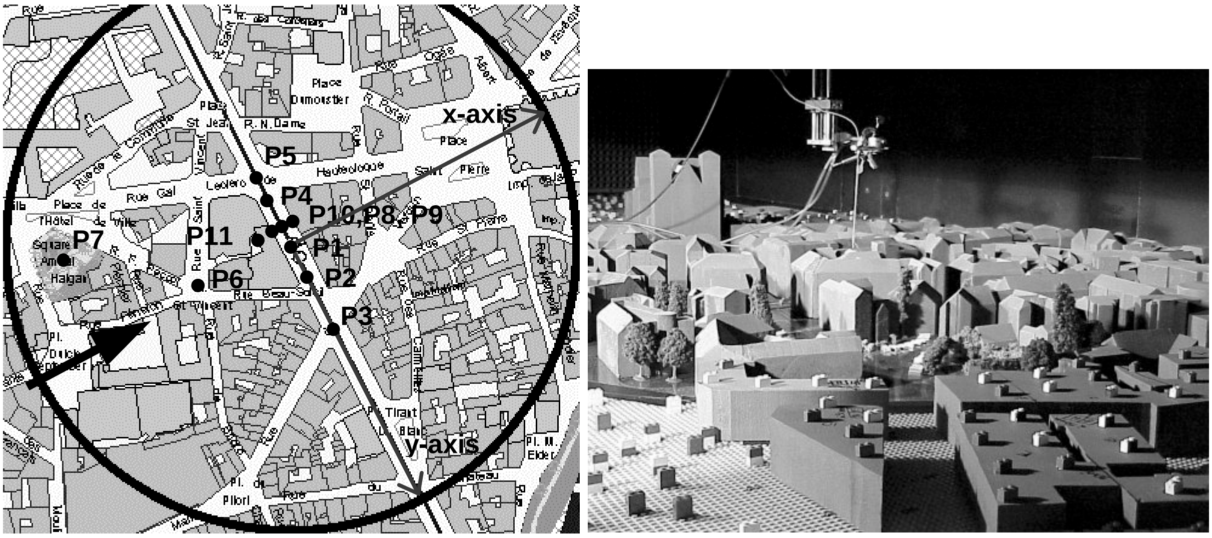

Fig. 2.1: Area in the center of Nantes reconstructed in the wind tunnel model (circle) with the profile locations (left) and photo of the model installed in the boundary layer wind tunnel (right).

2. Experimental Setup

A detailed model of the building structure in a region of about 400 m in diameter in the central part of the city Nantes, France was constructed in the scale 1:200 and investigated in a neutral boundary layer wind tunnel at the University of Karlsruhe, Germany. 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. 2.1 together with a photo of the wind tunnel model. 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. Vertical profiles of mean and turbulent velocity components were measured with a Laser Doppler velocimeter at the eleven positions marked in Fig. 2.1. The sampling frequency was 20 Hz and the sampling time 102 s.

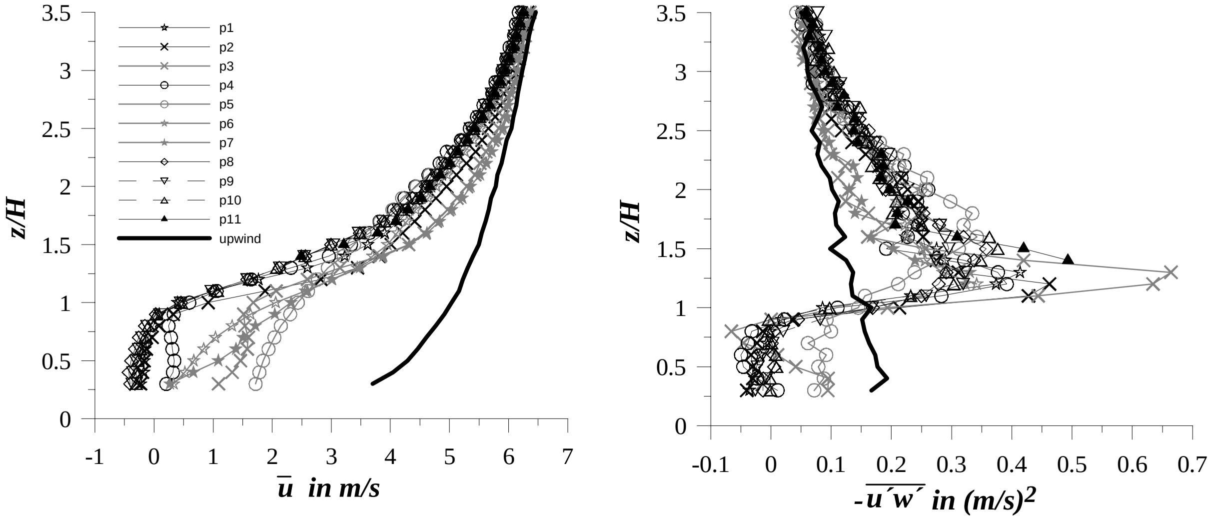

Fig. 3.1: Mean wind (left plot) and shear stress (right plot) profiles measured at the 11 sampling locations (see text for details)

3. Wind tunnel results

Mean velocity and turbulent shear stress profiles are presented in Fig. 3.1. The influence of building pattern irregularities on the mean flow and shear stress distributions range up to a level of about 2.5 times the average building height *H*. Inside the canopy the mean flow profiles differ significantly between street canyon locations (black lines) and positions near intersections or open squares (grey lines). Above the canopy the spatial variability is smaller and mainly related to building density. The shear stress profiles show pronounced maxima in an approximately 0.5 *H* deep flow region above roof level. Except for position P7 where the results are probably affected by the upstream suburban-urban roughness change, these maxima can primarily be attributed to flow disturbances due to urban canopy variations and accordingly considered as characteristics of an urban RSL.

4. Scaling of shear stress and mean wind profiles

Shear stress variations inside the RSL similar to the one discussed in section 3 were also observed in full-scale measurements (e.g., Rotach, 1993, Oikawa and Meng, 1995). The profiles are generally characterized by weak momentum flux inside the canopy, strong gradients near the roof level and a peak value, which is usually observed in the zone $z \approx H - 2.5H$. Based on these findings Rotach (2000) proposes a shear stress parameterization describing the height dependence of momentum flux in the region below the peak level. The magnitude of the shear stress peak value $\overline{u'w'_s}$ and the height z_s, at which the peak is observed are identified as appropriate scaling parameters. Rotach (2000) shows that taking this stress profile into account in the description of the near-surface turbulence in dispersion simulations leads to a better agreement between modeled and measured concentrations.

Starting from the concept of Rotach (2000) a parameterization for the wind-tunnel shear stress profiles is now derived. In order to eliminate extreme peak values, which are related to *local* flow disturbances and do not represent integral flow characteristics, the scaling parameters $\overline{u'w'_s}$ and $\hat{z}_s$ (see below) are not taken directly from the measured data but determined from fitting a profile according to

$$\overline{u'w'}(z) = a \cdot (z - d_s)^2 \cdot \exp\{-b(z - d_s)\} \tag{1}$$

through the measured data. This particular function, that is to some extent arbitrarily chosen, describes the measured results fairly well and has some nice mathematical properties that are advantageous for further processing.

Note that to account for the flow region inside the canopy with weak momentum transport, a shear stress displacement height d_s is introduced in Eq. (1), and the length scales $\hat{z} = z - d_s$ and

$\hat{z}_s = z_s - d_s$ are related to the level d_s. If the parameters *a, b* are expressed in terms of the scales $\overline{u'w'_s}$ and $\hat{z}_s$, Eq. (1) can be reformulated to yield

$$\overline{u'w'}/\overline{u'w'_s} = (\hat{z}/\hat{z}_s)^2 \cdot \exp\{2 \cdot (1 - \hat{z}/\hat{z}_s)\}. \quad (2)$$

A comparison between Eq. (2) and the normalized wind - tunnel shear stress profiles is shown in the left plot of Fig. 4.1. The experimental data are well described by the curve fit according to Eq. (2) except for the peak region, in which extreme values are (intentionally) extenuated. The wind tunnel profiles almost collapse to one line indicating that the shear stress and length scales, $\overline{u'w'_s}$ and $\hat{z}_s$, are properly defined. Moreover, a comparison of full-scale shear stress data and wind tunnel data for regular arrays with Eq. (2) shows a generally good agreement (not presented).

Before adopting the shear stress scaling concept for a mean wind profile analysis, the relation between the shear stress displacement height d_s and the displacement height d_0 in the logarithmic mean wind profile formula

$$u(z) = u_*/\kappa \cdot \ln(z - d_0/z_0) \quad (3)$$

must be clarified. Based on the integral condition (Jackson 1981)

$$(d_0 - d_s) \cdot \overline{u'w'_s} = \int_{d_{0s}}^{z_s - d_{0s}} \left(\overline{u'w'_s} - \overline{u'w'}(z)\right) dz\,. \quad (4)$$

describing d_0 as level of mean momentum absorption (see also illustration in Fig. 4.2), the following relation between d_s and d_0 can be derived if Eq. (2) is used for $\overline{u'w'}(z)$:

$$\hat{d}_0 = (d_0 - d_s) = \left(2.25 - 0.25 \cdot e^2\right) \cdot \hat{z}_s \approx 0.4 \cdot \hat{z}_s\,. \quad (5)$$

Furthermore, the roughness length can be related to the above parameters through $z_0 = a \cdot (z_s - d_0)$ with an average value for the parameter *a* of 0.12 from the measured stress profiles. Using these values for d_0 and z_0, the shear stress velocity u_* is determined according to $u_* = \kappa \cdot u_{ref} / \ln(z_{ref} - d_0/z_0)$, where u_{ref} corresponds to the measured wind velocity at a reference level $z_{ref} = 200\ \text{mm}$. Fig. 4.1 (right plot) shows an excellent correspondence between measured mean wind profiles and the logarithmic profile according to Eq. (3) for the roughness parameters determined according to the described procedure.

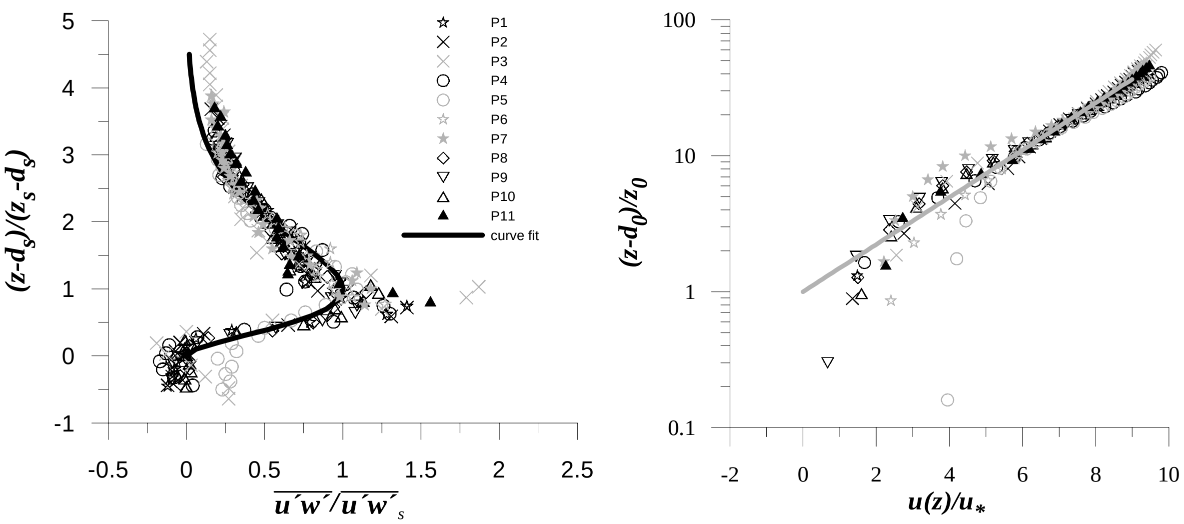

Fig. 4.1: Left panel: Scaling of measured shear stress profiles. Right panel: Comparison of measured mean wind profiles with a logarithmic profile. See text for more details

5. Summary

Reynolds stress data from a real-array wind tunnel study are presented and analyzed in a recently developed conceptual framework by Rotach (2000) that is based on full-scale data. It is shown that a parameterized description of the Reynolds stress profile is possible, provided that the local flow structure is properly taken into account. A method is presented and discussed for this latter task. The maximum (norm) of Reynolds stress that is usually observed at some distance above the average obstacle height, and the height z_s of its occurrence are found to be the relevant velocity and length scales, respectively for describing the flow within the RS. Relating the displacement height d_0 and roughness length z_0 to the peak level z_s yields a good agreement between measured mean wind profiles and a logarithmic wind profile. Above 1.5 times the average building height the differences between measured and calculated profiles has been smaller than $\pm 10\%$.

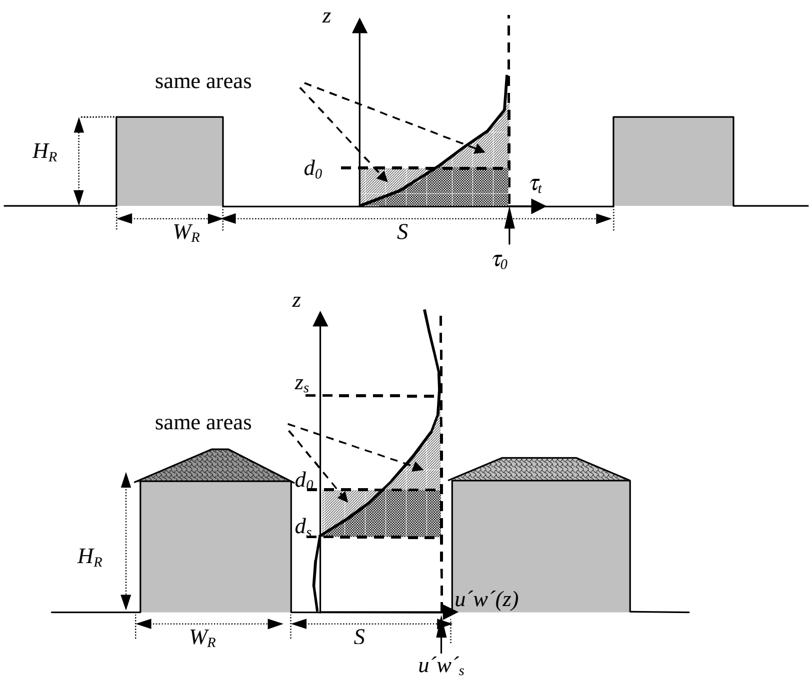

Fig. 4.2: Determination of displacement height d_0 according to the integral condition proposed by Jackson (1981). The upper sketch shows the application to a situation with low building density, the lower one to an urban street canyon configuration with weak momentum flux inside the canopy.

6. References

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Acknowledgements

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