COMPARISON OF BOUNDARY LAYER PROPERTIES FROM FIELD AND WIND TUNNEL MEASUREMENTS

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INTRODUCTION

In modern times of urbanisation, a large number of investigations are carried out in order to improve quality of life in urban areas. The effects of building arrays and streets on local flow structures and consequently on pollutant dispersion processes are strong. Meteorological conditions also have a significant influence. Therefore, the collaboration of fluid mechanists and meteorologists is reasonable and necessary to optimise conclusions from both sciences. The combination of field measurements and physical modelling is a forward-looking research method, which helps to understand and to predict the development and behaviour of currents in urban areas.

Special care must be taken on the reliability of the obtained data. Results from wind tunnel simulations are similar to corresponding field studies only if the physical model as well as the scale of the boundary layer turbulence are identical. To generate a wind tunnel boundary layer, which only matches e.g., the roughness length or the vertical profile of the mean wind velocity is insufficient and does not necessarily ensure model/prototype similarity.

The wind tunnel laboratory of the Meteorological Institute at Hamburg University embarks on a special strategy for the boundary layer set-up. For each test case, combinations of passive devices at the tunnel entrance and roughness elements at the wind tunnel floor are modified individually. From this it is possible to generate in a conventional boundary layer wind tunnel model scales of 1:500 up to 1:200 especially for micro-scale modelling. The presented study shows the agreements and discrepancies of boundary layer properties, which are generated in a boundary layer wind tunnel and those, found in corresponding field site measurements.

FIELD MEASUREMENT

The field data were acquired using a monitoring system operated by the Meteorological Institute of Hamburg University at a 300m radio transmitter tower (*Brümmer et al.,* 1995). This tower is located in a clearing at the southeastern edge of Hamburg about 100m apart from the nearest built-up area. The system consists of five measuring platforms of different heights ranging from 50m up to 250m. In addition to conventional meteorological instrumentation, the platforms are equipped with ultrasonic anemometers/thermometers (USAT, METEK®). A second meteorological mast is situated 200m apart from the radio transmitter tower and equipped with cup anemometer, wind vane, thermometer and USAT at a height of 10m and thermometers at a height of 2m. To complete the data set, air pressure, cloudiness and precipitation is also recorded.

In this study, a reference height of 50m was chosen for the comparison of field data and wind tunnel measurements. It was assumed that at this height the data were already independent of individual buildings or trees. For winds from the west (210° …360°), the urban fetch was longer than 30km, which ensured that the 50m data have fully adjusted to the urban conditions. During January and February 2000, time series of all three velocity components of the wind vector and of temperature were recorded at a sampling frequency of 10Hz. The recorded data include several strong wind periods.

WIND TUNNEL MEASUREMENT

The wind tunnel measurements were carried out in the BLASIUS wind tunnel of Hamburg University. The intension was to model boundary layers at scales of 1:400 up to 1:200 for investigations of dispersion processes in the urban canopy layer. The wind tunnel boundary layer set-up was restricted to only modelling the surface layer and neutral stability cases. All measurements were carried out with a 2D-Laser-Doppler-Anemometer (DANTEC®).

First, the homogeneity of the wind tunnel flow was verified. Then time series for all velocity components were recorded at heights according to 50m in the model scales 1:400, 1:333 and 1:200.

DATA ANALYSIS

For the comparison of wind tunnel and field conditions, special software routines were developed to ensure consistent analysis of the acquired data.

First, the raw field data were cut into time series with a block length of 2^{14} samples corresponding to 27 minutes. In total 135 time series with an urban fetch and classified near neutral using the Richardson-Flux number ($0.02 \geq Ri_f \geq -0.02$) were available for the detailed analysis.

$$Ri_f = -\frac{\kappa g}{T_0}\frac{\overline{w'T'}}{u_*^3}z \qquad (1)$$

$T_0 = \overline{T}(50m)$, $\kappa = 0.4$. On the assumption that the measurement position was within the constant flux layer, the shear velocity was determined to be

$$u_* = \sqrt{-\overline{u'w'}} \qquad (2)$$

The coordinate system was chosen so that the mean horizontal wind vector lay on the x-axes ($\overline{v} = 0$). Included linear trends were numerically removed since some of the analysis methods were based on autocorrelation functions.

RESULTS

From the mean wind tunnel velocity profile, a power law exponent of $\alpha = 0.18$ was derived. A fit of the logarithmic wind profile lead to a roughness length of $z_0 = 0.35$mm. Sub-urban roughness structures made up by low-rise residential and industrial buildings generate power law exponents between 0.18 and 0.24 and roughness lengths between 0.1m and 0.5m (*VDI-Richtlinie 3783*, 1999). Thus, a first fixing of the model scale lead to:

$$Scale = \frac{0.34\,mm}{0.1\ ...0.5\,m} \approx \frac{1}{300\ ...1500} \qquad (3)$$

Since there was no possibility to use the logarithmic profile fitting method for deriving the roughness length at the field site, it was calculated using Equation (2) set in the logarithmic wind law, again assuming the validity of constant fluxes within the surface layer. Resulting values from that method are given in Table 1. In the margin of error, the wind tunnel value measured at the scale 1:333 made the best match, the agreement at the other scales was also fair.

Table 1. Roughness lengths, calculated by equation (2) set in the logarithmic wind law.

	Field site	Wt 1:200	Wt 1:333	Wt 1:400
z_0 [m]	0.8 ± 0.3	≈ 0.4	≈ 0.5	≈ 0.4

Variances of velocity components give good information about turbulence characteristics and roughness effects. In pure mechanical turbulence, normalized standard deviations are independent of height and roughness. *Panofsky and Dutton* (1984) compiled a list of values from observations at several locations characterized by uniform terrain. Ratios of velocity standard deviations to friction velocity found in this study are given in Table 2.

Table 2. Ratios of standard deviations to friction velocity for the three velocity components.

	Panofsky / Dutton	Field site	Wt 1:200	Wt 1:333	Wt 1:400
$\sigma_u \big/ \sqrt{-\overline{u'w'}}$	2.4	2.3 ± 0.1	1.9 ± 0.1	2.1 ± 0.1	2.2 ± 0.1
$\sigma_v \big/ \sqrt{-\overline{u'w'}}$	1.9	1.7 ± 0.1	1.6 ± 0.1	1.7 ± 0.1	1.8 ± 0.1
$\sigma_w \big/ \sqrt{-\overline{u'w'}}$	1.3	1.1 ± 0.1	1.4 ± 0.1	1.5 ± 0.1	1.5 ± 0.1

An analogue representation results from turbulence intensities ($\sigma_i / \overline{u}$), which in neutral case are independent of wind speed and friction velocity. The results are displayed in Figure 1. In addition, values given in *ESDU* (1985), valid for atmospheric boundary layers in the state of dynamical equilibrium, are shown for the above-mentioned roughness class. Both studies indicated similar trends. The best agreement was found for the model scale 1:400. In the wind tunnel boundary layer, the turbulence rate produced in the vertical component was comparatively too high, whereas the u-component generated lower turbulence intensities/standard deviations. The best match was found for the v-component. It also became evident, that the field data did not fully support the *ESDU* guidelines. For all three components, the turbulence intensities were located in the lower z_0-range or even below.

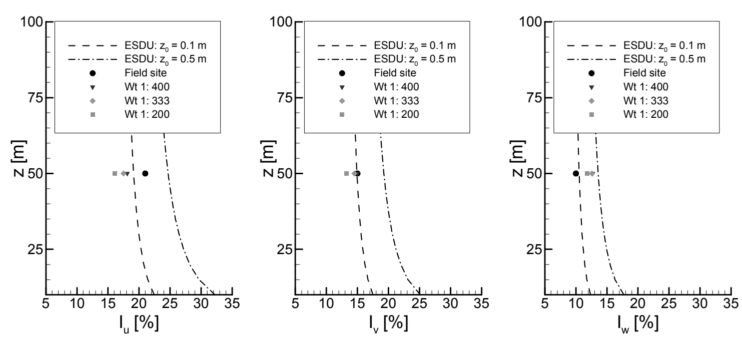

Figure 1. Comparison of turbulence intensities of all velocity components.

Power spectral densities for the u-, v- and w-components were calculated utilizing the discrete Fourier transformation. For the u-spectrum, the best agreement was found at the scale 1:400. The energy maximum was slightly shifted to higher frequencies, which signifies a smaller characteristic vortex size. Figure 2 displays the comparison between wind tunnel and corresponding field site spectra. In addition, the theoretical *Kaimal* curves are shown (*Kaimal et al.,* 1972).

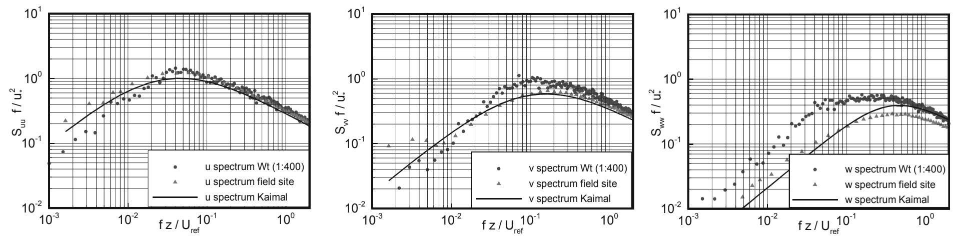

Figure 2. Comparison of field spectra to wind tunnel spectra taken at the scale 1:400 and to Kaimal spectra.

The agreement between the v- and w-spectra were less satisfying. In the wind tunnel boundary layer, both components contained comparatively more energy. Furthermore, the maximums were shifted to lower frequencies owing to bigger vortex sizes. The agreement between *Kaimal* and the field site horizontal velocity spectra was generally fair, whereas the field w-spectrum contained less energy. The significant energy increase in the lower frequency range of the v-spectrum (field site) was related to very slow fluctuations of the radio transmitter tower itself.

Integral length scales also give basic information about vortex sizes. For calculation, the *'autocorrelation integral method'* was chosen, integrating the autocorrelation function of the velocity fluctuations until the first zero crossing. The derived time scales were converted into length scales assuming Taylor's hypothesis of 'frozen turbulence'.

Table 3. Integral length scales.

	Field site [m]	Wt 1:200 [m]	Wt 1:333 [m]	Wt 1:400 [m]
L_{ux}	161 ± 52	≈ 60	≈ 100	≈ 130
L_{vx}	49 ± 15	≈ 36	≈ 51	≈ 70
L_{wx}	28 ± 12	≈ 31	≈ 48	≈ 63

In all investigated wind tunnel heights/model scales, the size of L_{ux} was less than the corresponding field data average value. Considering the large variability, tolerable values were achieved at least in the model scales 1:333 and 1:400. L_{vx} was best reproduced in the model scale 1:333 whereas L_{wx} matched best in the scale 1:200. Overall, these findings were consistent with all previous results and illustrated that the large eddies in this particular wind tunnel boundary layer were somewhat 'rounder' than in the field. This was supported by the fact that the roughness length was only about half of the corresponding field value. Since an increase of z_0 leads to a decrease of the integral scales, a further improvement of the boundary layer similarity can be expected from increasing the roughness elements and decreasing the size of vortex generators.

It is often claimed that low frequency wind directional variations were not proper replicated in wind tunnels since the flow is ducted by solid sidewalls. More recent results show that this physical notion needs some revision. The data were analysed with respect to the instantaneous horizontal and vertical wind directions. If we refer to ≈ 30min intervals, which are often used in dispersion statistics, a mean wind direction and the deviation of each single measured value can be defined. This was done for both the field data and the wind tunnel data (Figure 3).

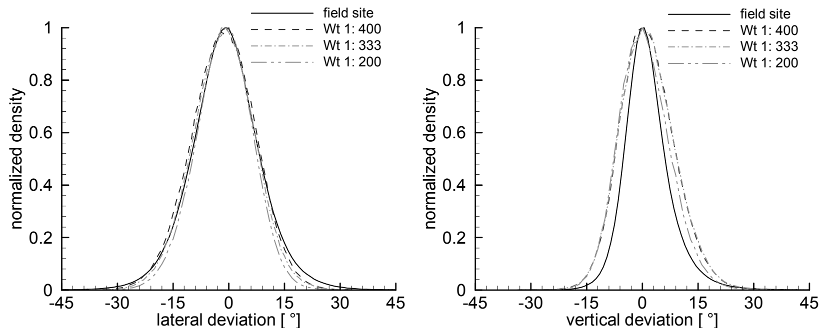

Figure 3. Deviation of the instantaneous horizontal and vertical wind directions from the mean wind direction (30 min average).

The wind tunnel boundary layer exhibited the same probability density of horizontal wind direction fluctuations at least for the model scale 1:400. Vertical deviations were even larger than in the field. The curve shape asymmetry was caused by the limited distance to the ground.

This result is of particular importance for wind tunnel studies which focus on the investigation of fluctuating properties (dispersion of odours, accidental releases of toxics of flammables in chemical industry). In a carefully generated wind tunnel boundary layer and within certain constraints with respect to geometrical scale and averaging time, it is possible to also simulate dispersion processes dominated by low frequency wind directional variations.

CONCLUSIONS

The work reflects the improved degree of insight into the structure of atmospheric turbulence, which can presently be gained. It furthermore demonstrates the advanced potential of carefully set-up boundary layer wind tunnel experiments. It is strongly recommended to use this potential and to produce enhanced data sets that are based on a combination of field and laboratory experiments. Such combined data sets allow a deeper insight into the nature of flow and dispersion processes, which occur within and above the urban canopy layer. They form the basis for any veritable numerical model validation work.

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