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FAR-FIELD EFFECT OF A TALL BUILDING ON THE SHEAR LAYER ABOVE STREET CANYONS

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Abstract: It was shown by several previous studies that tall buildings improve ventilation in their immediate neighbourhood by the frontal downwash effect and the vertical velocity directed upwards in the separation zone on their backward side (Brixey et al., 2009). These effects improve local air quality near the ground. On the upwind side the downwash transports clean air to the ground. On the backward side of the building, polluted air is elevated to larger heights, thus local ground level concentrations decreases. However, there is no clear understanding in the literature what is the far field effect of a single tall building.

To develop tangible guidelines for urban planners, how and where to place tall buildings in a low-rise urban area in order to avoid the increase of local pollutant concentrations or even to utilise them in reducing the air pollution at pedestrian level, a series of wind tunnel tests is planned, the first of which is presented in this paper.

Key words: *Street canyon, urban flow, wind tunnel, quadrant analysis*

INTRODUCTION

Significant amount of human population lives in urban areas, where one of the major problems is atmospheric pollution. The air quality is mainly influenced by the mixing and propagation of pollutants, driven by the complex turbulent atmospheric flow structures above the urban environment. To understand the basics of these complex flow patterns, both experimental and computational fluid dynamics (CFD) studies use strongly idealized, simplified geometries which represent simplified urban architectural environments (Kastner-Klein et al. 2004). One of these simplified geometries is the row of street-canyons, in which the long, continuous building blocks are followed by empty spaces, corresponding the streets of the city. In the most basic, fundamental case the main flow direction is perpendicular to the streets, the roofs of the building blocks are flat, the height, width of the building blocks and the width of the streets are equal (distance H, Figure 1.). Based on these considerations, wind tunnel model was constructed and placed in to the test section of the Large Wind Tunnel of the Theodore von Kármán Wind Tunnel Laboratory, containing 22 street canyons. with height of 0.1 m and with width of 1.25 m. The scale of the model was 1:300.

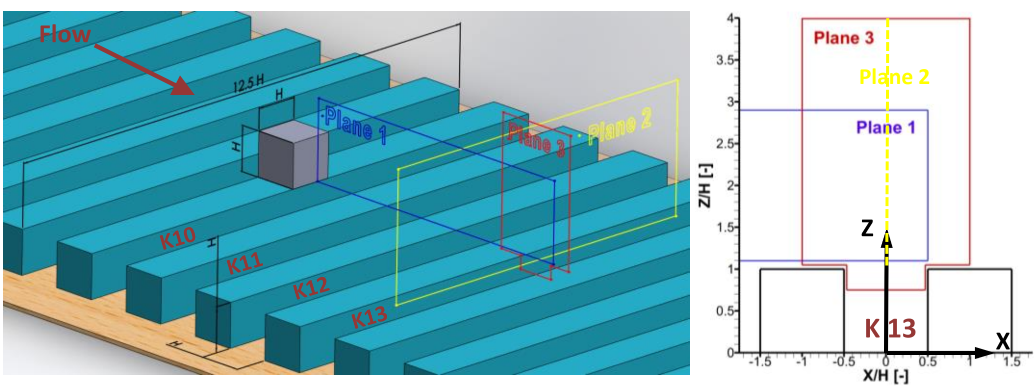

Figure 1. Scheme of the wind tunnel model with the cubic tall building, the measurement planes and the used coordinate system

MEASUREMENT TECHNIQUE AND BOUNDARY LAYER CHARACTERISTICS ABOVE THE WIND TUNNEL MODEL

During the measurements presented in this paper a 55P51 type two-component constant temperature hot-wire anemometer was used, manufactured by DANTEC. This instruments consist of two 9 µm thick, gold-coated electrically heated tungsten wire, suitable for measuring two velocity components simultaneously, if the flow angle does not exceeds +45° or -45°. The width of the anemometer was 2.5 mm. Calibration of the instrument was carried out in a blower-type open test section wind tunnel. The flow angle was varied by rotating the probe support relative to the incoming flow. During the calibration process the velocity of the incoming flow (measured by a TSI Pitot-static-tube as a reference) varied between 1-16 ms^{-1} in 0.6 ms^{-1} steps and the flow angle between -40° to +40° in 4° steps. According to the control measurements, the error of the device for the velocity measurement is less than 0.05 ms^{-1} and 0.8° for the angle. After the calibration the support of the anemometer was mounted on the probe holding arm of the traversing system, integrated into the test section of the Large Wind Tunnel.

Above the series of street canyons a boundary layer develops the depth of which is increasing into the main flow direction. In case of the first experiment series vertical profiles was measured in the vertical symmetry plane of the model parallel to the main flow direction at the centreline of each second canyon (K1-3-5-7-9-11-13-15-17). The sampling time at each point was 25 s, the sampling rate was 500 Hz and the measurements were carried out at reference velocity $U_{Pr,ref}$ =10.5-11.5 [ms^{-1}], measured by a Pitot-static-tube, placed in an undisturbed flow above the model (10-12 H). The dimensionless velocity (U) profiles are rapidly changing in case of K1-5, showing rapidly thickening boundary layer, but after K9 the profiles are the same in the shear layer at $Z_{fs} \approx$30 m and in the lower part of the external flow region up to Z_{fs}=60 m (Figure 2.). In case of the I_u and I_w longitudinal and vertical turbulent-intensity profiles the differences are larger, but the profiles are still nearly the same in the shear layer up to $Z_{fs} \approx$40 m. For further investigations the K13 was chosen, as the flow in the shear layer of this canyon is similar to any other subsequent canyons. The atmospheric boundary layer above K13 can be characterised with α=0.18 power-law exponent, which corresponds to moderately rough terrain, the profile is elevated with d_0=30 m. The longitudinal and vertical turbulent intensities are also compared to the limits recommended by VDI (2000) guidelines for the atmospheric boundary layer above moderately rough and rough terrains. The values of I_u are inside the band for moderately rough terrains, while the I_w values mainly in the domain recommended for rough terrains. Here can be noticed, that during the experiments there were no additional turbulence-generating elements (spires, roughness elements etc.) involved. In a selected point (Z_{fs}=57 m at K13) a measurement was carried out with 100 s sampling time and the dimensionless spectral power density distribution was determined and compared with the theoretical von-Kármán spectral distribution function, showing a reasonable correspondence.

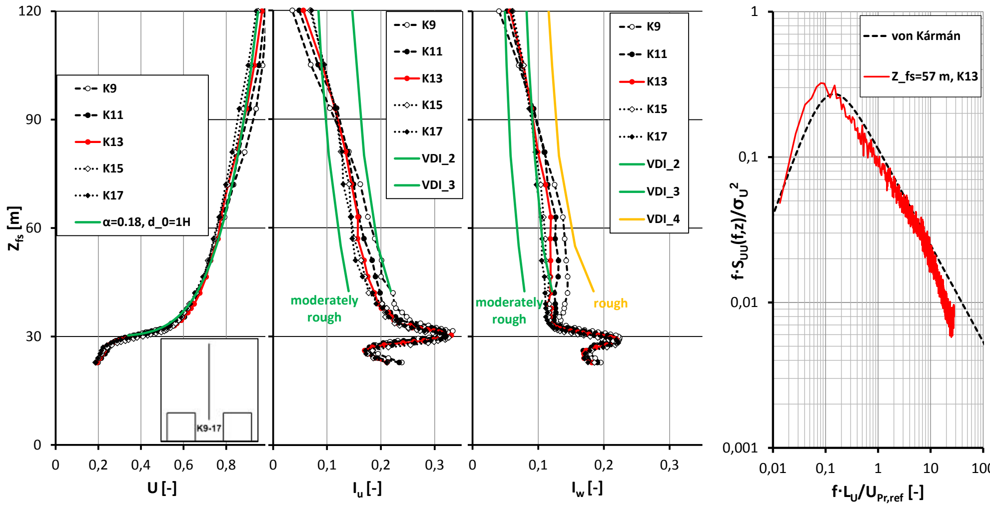

Figure 2. Dimensionless velocity (U), longitudinal (I_u) and vertical (I_w) turbulent intensity profiles at the centreline of canyons K9-17 (the height above the surface is expressed in full scale, therefore the top of the building blocks are at Z_{fs}=30 m). Left: dimensionless power spectral density of the longitudinal velocity fluctuations at height Z_{fs}=57 m (K13) compared to the theoretical von Kármán spectrum.

GLOBAL EFFECTS OF AN OBSTACLE ON A FLOW FIELD ABOVE THE URBAN CANOPY

To simulate the effect of a tall building on the flow above the idealized urban canopy a cubic body was mounted at the top of the building block located directly in front of K10. The height, width and the length of the body was 1 H, the total height of the obstacle therefore was 2H. Then measurements were carried out in measurement Planes 1, 2 and 3. (depicted with blue, yellow and red in Figure 1., they contained 350, 403 and 502 single measurement points). Then, the obstacle was removed and the whole measurement campaign for Plane 1, 2, 3 was repeated for the basic, non-disturbed idealized urban canopy configuration, which was handled as the reference case. In the measurement points of Plane 1 and 2 the sampling time was 25 s, which was not enough to record fully statistically representative time series for the longitudinal and vertical velocity (u and w), but still was enough to map and explore the changes caused by the obstacle, relative to the reference case. In case of Plane 3 (located at K13) the sampling time was raised to 100 s, which is already provided statistically representative data set. In case of Plane 3 measurement points with the lowest Z/H coordinate value were below the roof level of the building blocks, and their dense distribution allow to resolve spatially rapidly changing quantities in the shear layer at the top of the canyon. The measurement campaigns with and without the obstacle altogether required approximately 45-50 measurement hour in the Large Wind Tunnel. The measurements were carried out at reference velocity $U_{Pr,ref}$ =10.5-11.5 [ms^{-1}], as in the case of the boundary layer measurements.

After measurements in Plane 1 and 3 the dimensionless mean velocity absolute values (relative to the reference Pitot-static-tube) were determined both for the reference case and for the measurement arrangement with the obstacle. The distribution of the difference in the dimensionless velocity absolute value between the two arrangements relative to the initial state (in percent) in Plane 1, 2 are presented on Figure 3-4. The same procedure was carried out for the dimensionless turbulent kinetic energy ($TKE_d=0.5\cdot\sigma_{|U|}^2/U_{Pr,ref}^2$) for the "disturbed" case (with building) and the reference state.

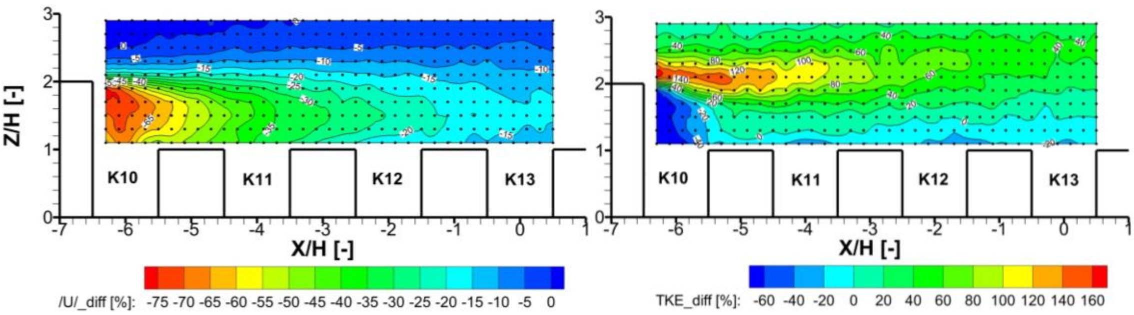

Figure 3. Distribution of the velocity-absolute value and turbulent kinetic energy difference between the reference case and the arrangement with the obstacle, relative to the initial state (in percent) in Plane 1

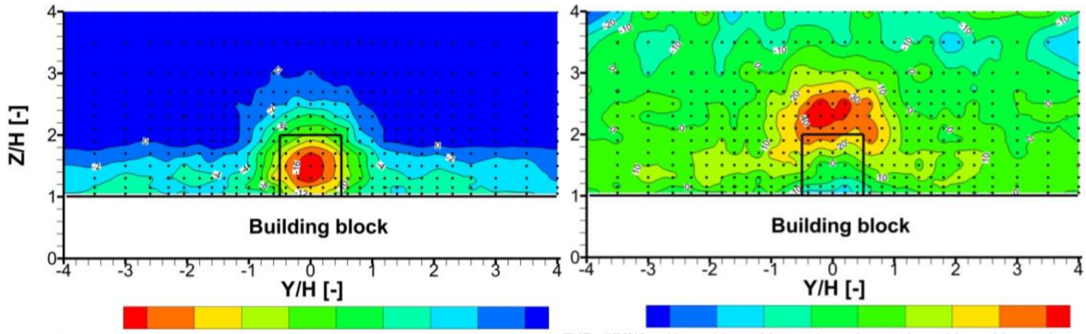

Figure 4. Distribution of the velocity-absolute value and turbulent kinetic energy difference between the reference case and the arrangement with the obstacle, relative to the initial state (in percent) in Plane 2.

The velocity deficit caused by the building model is the largest directly behind the obstacle (more than 50%), and directly above K13 the velocity is still smaller by 5-15% than in the reference case. Significant rise in turbulent kinetic energy (30-40% relative to the reference case) can be observed at the height of the roof of the high-rise building (*Z/H*≈2-2.5), caused by probably the strong vortices, which are generated on the shear layer, developing above the obstacle. Close to the rooftop level (*Z/H*=1-1.5) TKE level is smaller than in the reference case, the difference directly above K13 is about -20%.

Based on the difference distributions on Plane 2 can be noted, that the "shading" effect of the high-rise building is the strongest behind the projection of its contour lines, the velocity deficit is -16% at *Y/H*=0 and *Z/H*=1.5. Although, it is worth to appreciate, that the effect of the building can be detected at the whole width of the street at the height close to the rooftop level (-12% near *Y/H*=0 and -5% at *Y/H*=4 or -4). The turbulent kinetic energy rises by 30-40% in the vicinity of the upper edge of the obstacle. Near the lower part of the building above the canyon at height *Z/H*=1 from *Y/H*=-0.5 to *Y/H*=0.5 reduction can be observed in the level of the turbulent kinetic energy (-10-20%).

QUADRANT ANALYSIS ON SHEAR LAYER FLOW ABOVE K13

Several contemporary full scale and wind tunnel measurements use the quadrant analysis method to study the turbulent mass and impulse exchange process between the lower and upper regions of the urban canopy. Based on the sign of the fluctuation of the instantaneously measured longitudinal and vertical velocity component relative to the mean values (*u'* and *w'*), four different event types can be distinguished (Figure 5., left). In case of a sweep event relatively fast air particles are transported downwards, while during an ejection a small package of medium with lower momentum moving temporarily upwards. During outward interactions air with relatively higher impulse is moving upwards, and inward interaction indicate movement of medium towards the ground with smaller momentum. From the viewpoint of the turbulent impulse transfer the sweep and ejection events are more favourable, hence they assist the mixing between the low speed air closer to the ground and the air with higher moment at the upper part of the urban canopy.

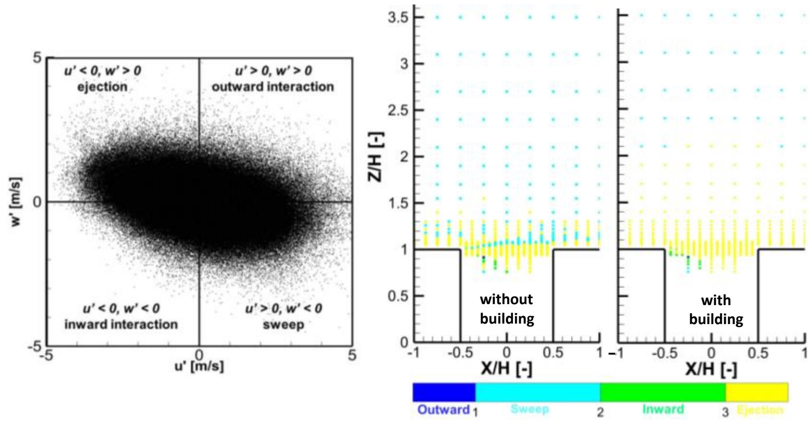

Figure 5. Left: Scheme of the quadrants and scatter plot of the measured velocity fluctuations in a point at *Z/H*=1.1 (at *X/H*=0, without building). Right: distribution of the dominant event in a measurement points at K13 in Plane 3.

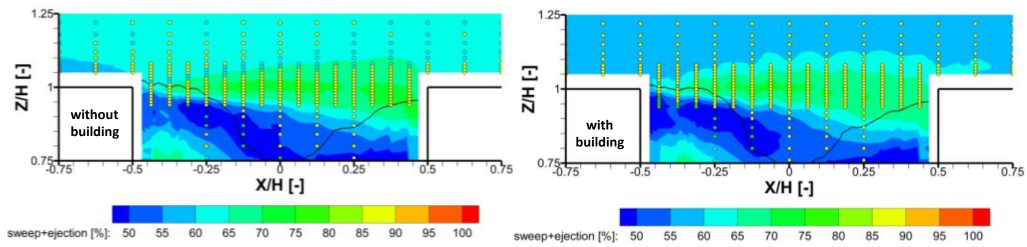

Figure 6. The proportion of sweep and ejection events at the lower part of Plane 3 measured without and with building. The colouring of the discrete measurement points refers to the dominant event according to the colour scheme as on Figure 5. Below the solid black line the proportion of out-of-range incoming hot-wire-probe samples (flow angle is larger than 40° or smaller than -40°) were larger than 5%

Contemporary wind tunnel investigation techniques allow simultaneous point measurements of two velocity components (*u* and *w*) and the concentration of the pollution (c), which is usually modelled with a tracer gas. In a recent wind tunnel study (Nosek et al., 2016) a quadrant analysis method was also employed to the concentration fluctuations and the vertical velocity (c', w') above three-dimensional, more realistic street canyon model. It was found, that there is strong correlation between entrainment of clean air ($c' < 0$, $w' < 0$) and the sweep event, and also between venting of polluted air ($c' > 0$, $w' > 0$) and ejection events. The correlation coefficient reached the highest values (0.7-0.8) near the rooftop level of the modelled canyons. It can be assumed, that the incidence of the sweep and ejection events can forecast the efficiency of the ventilation process of the polluted air released at the bottom of the urban canopy.

Based on the velocity time series measured in plane 3 instantaneous value of velocity fluctuations were calculated and categorized as events corresponding to the quadrant analysis. The most incidentally occurred or dominant event is determined in every spatial measurement point. As the plots on the right side of Figure 5. shows, sweep and ejection were the dominant events in case of both measurement configuration (without and with building), which is typical in case of atmospheric flows, a typical scatter plot depicting the measured velocity fluctuations is also shown on Figure 5. Near the rooftop level (Z/H=1-1.5) in case of reference measurement configuration the sweep and ejection dominant spatial points occur miscellaneously, while arrangement with building has only ejection dominant points at this level. Above Z/H=1.5 only sweep dominant points can be found in both cases. Enlarging the environment of the rooftop level (Figure 6.), it can be seen, that in case of the reference arrangement the sweep dominant points forming a continuous stripe above the street canyon, starting from the upper streamwise edge of the building block.

The proportion of the favourable ejection and sweep events shows a significant rise in both cases in the vicinity of the shear layer above K13 (Figure 6.). Here 75-85% of the events can be categorized as a sweep or an ejection. However, when the “disturbing” building was mounted, the proportion of the sweep and ejection events decreased by 10-15% directly above the shear layer (from 65% to 50%).

CONCLUSIONS AND FUTURE OUTLOOK

The effects of a 2H tall building is significant, even it is situated 7H distance before the investigated street canyon in upstream direction, causing velocity deficit and change the level and distribution of the turbulent kinetic energy. Moreover, according to the quadrant analysis, it can be assumed, that there are also demonstrable changes in the transport process in the shear layer above the canyon. To prove it unambiguously, simultaneous concentration measurements are planned in the future, using an FFID (Fast Flame Ionization Detector) device.

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REFERENCES

Brixey L. A., D. K. Heist, J. Richmond-Bryant, G. E. Bowker, S. G. Perry and R. W. Wienere, 2009: The effect of a tall tower on flow and dispersion through a model urban neighbourhood. *Journal of Environmental Monitoring*, **11**, 2171–2179.

Kastner-Klein P., R. Berkowicz, and R. Britter, 2004: The influence of street architecture on flow and dispersion in street canyons. *Meteorology and Atmospheric Physics*, **87,** 121-131.

Nosek Š., L. Kukačka, R. Kellnerová, K. Jurčáková. and Z. Jaňour, 2016: Ventilation processes in a three-dimensional street canyon. *Boundary-Layer Meteorol*., 10.1007/s10546-016-0132-2, 1-26.

VDI 3783 PART 12 (2000): Environmental meteorology, Physical modelling of flow and dispersion processes in the atmospheric boundary layer, Application of wind tunnels, VDI/DIN-Handbuch Reinhaltung der Luft, Band 1b