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

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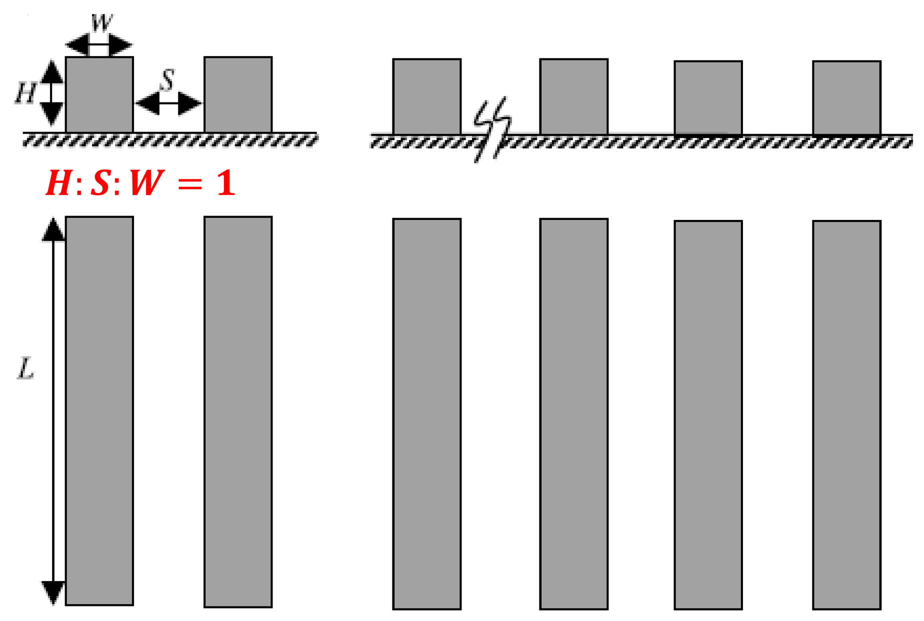
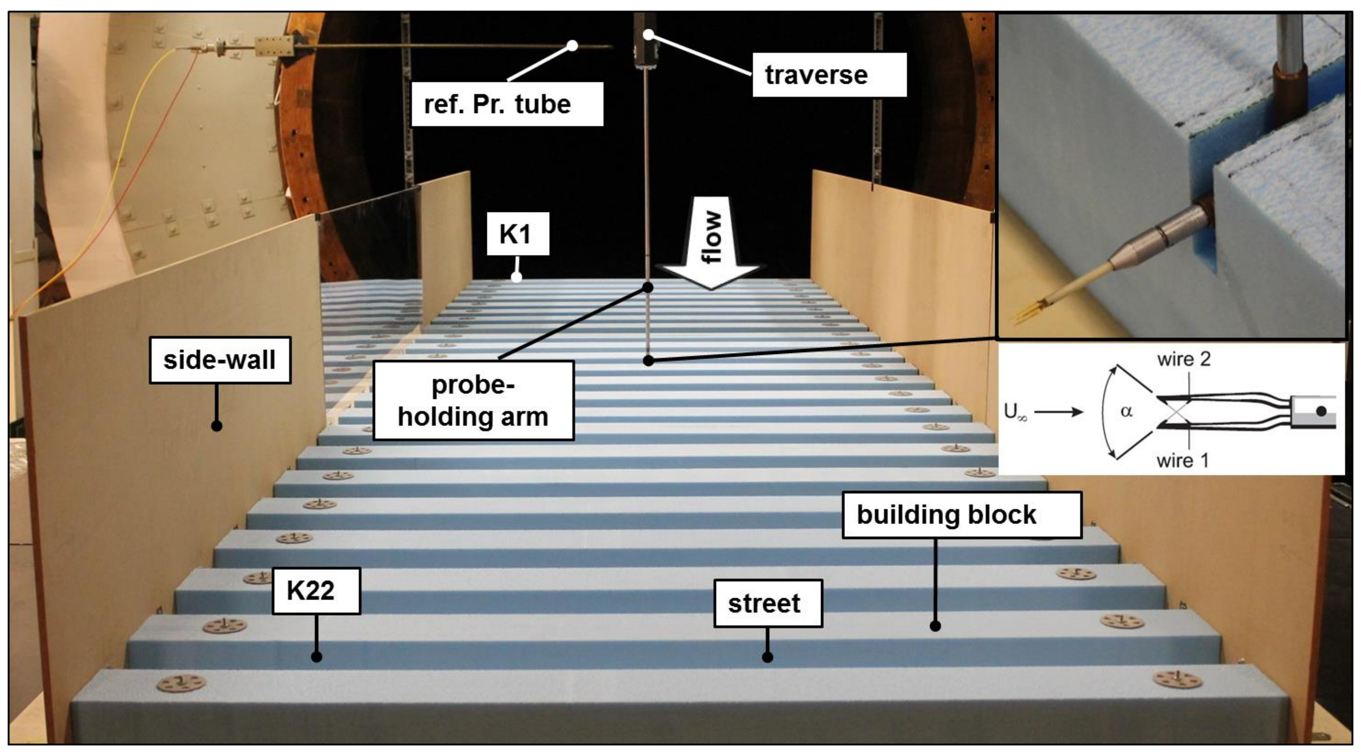
1. SIMPLIFIED, IDEALIZED STREET ARCHITECTURE: ROW OF RECTANGULAR STREET CANYONS



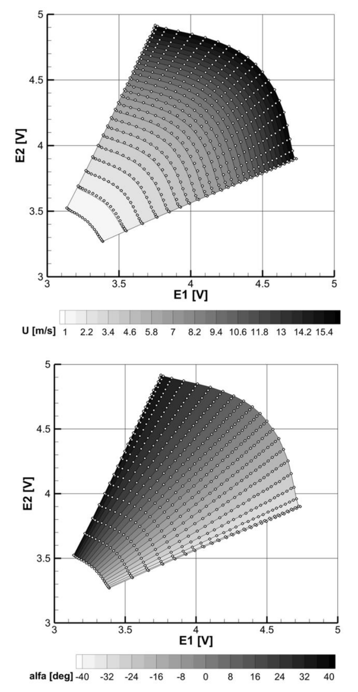
Significant amount of human population lives in urban areas, where one of the major problems is atmospheric pollution. The air quality is mainly influenced by the mixing and propagation of pollutants, driven by the complex turbulent atmospheric flow structures above the urban environment. To understand 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.

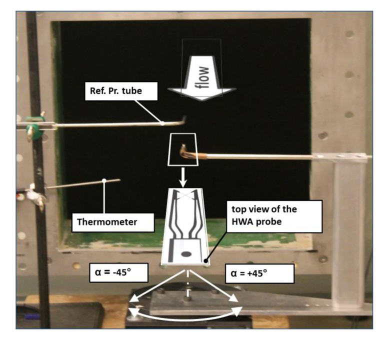
2. THE BUILT WIND TUNNEL MODEL



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 (K1-K22) with height of 100 mm and with width of 1250 mm. The scale of the model was 1:300. The measurements were carried out at reference velocity 10.5-11.5 [m/s].

3. THE MEASUREMENT TECHNIQUE: TWO-COMPONENT HOT WIRE ANEMOMETRY

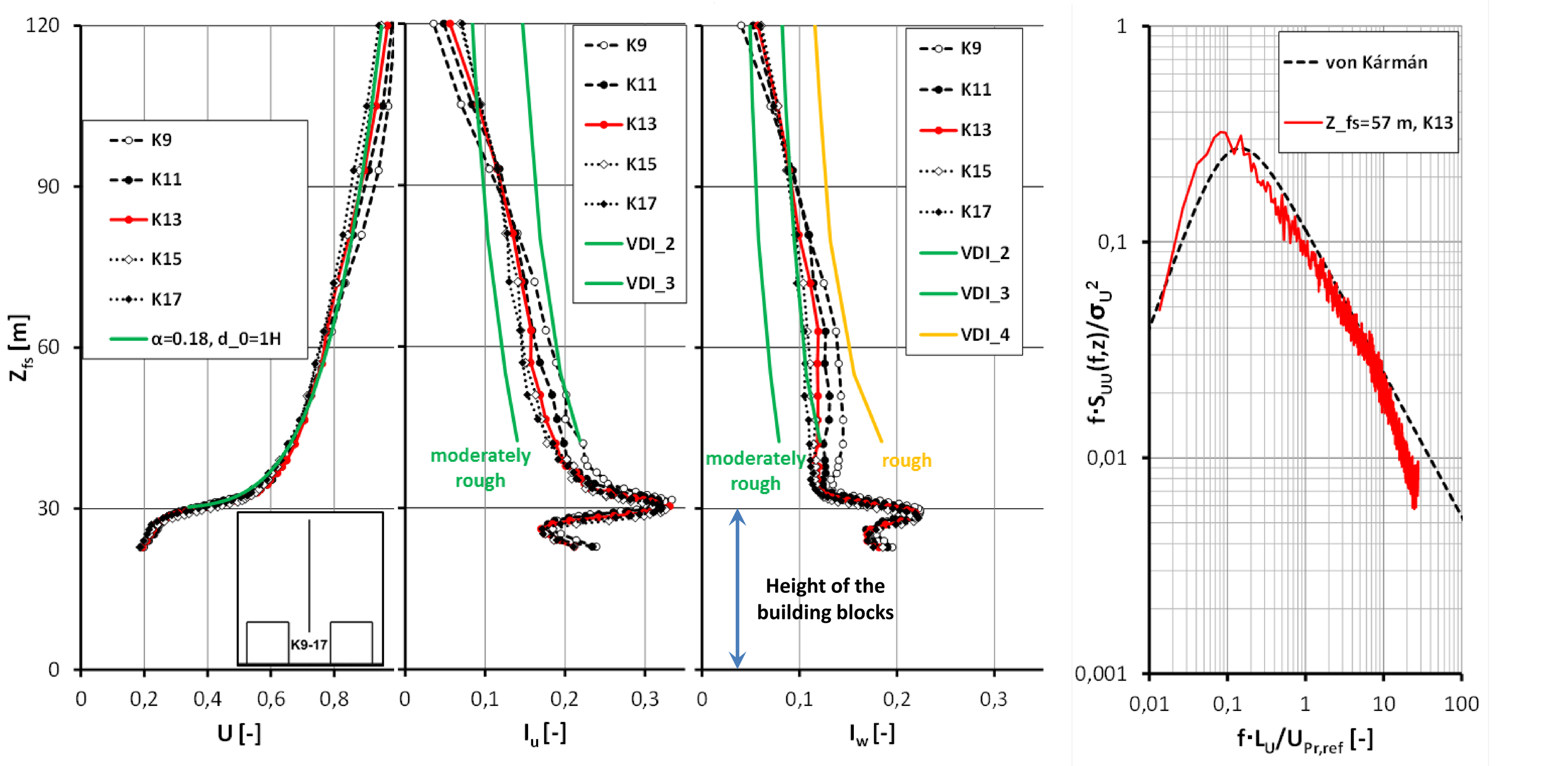




- 55P51 type two-component constant temperature hot-wire anemometer
- Calibration of the instrument was carried out in a blower-type open test section wind tunnel
- During the calibration process the velocity of the incoming flow measured by a Pitot-static tube as a reference. The flow angle was varied by rotating the probe support relative to the incoming flow. The voltages on the output of the two bridges (E1, E2) are measured in 525 individual calibrational points, then calibrational maps were plotted for the velocity and the angle
- During the measurement actual instantaneous value-pairs of E1 and E2 voltages were captured, the current value of the velocity and angle values were determined by second order interpolation based on the calibrational maps

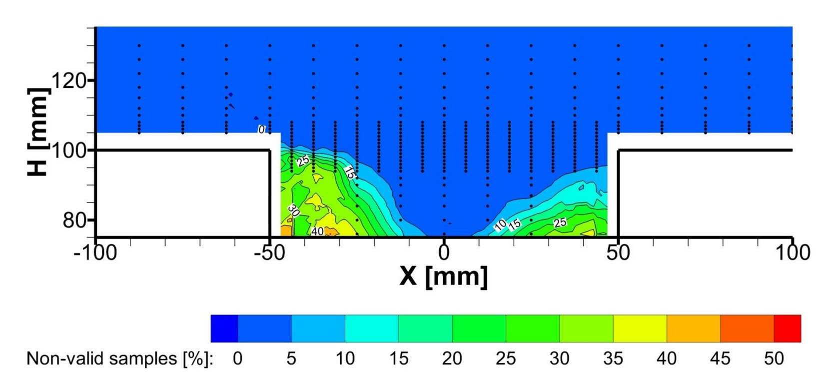
Nowadays, the optical methods (PIV: particle image velocimetry, LDA: laser-Doppler anemometry) are widely used to investigate the wind tunnel models of simplified street canyon geometries. However, these methods have some difficulties: they require optical accessibility and dispersion of optically diffuse particles (seeding), the data rate (the number of incoming samples per second) are strongly depends on the quality of the seeding.
In my investigations a more traditional measurement technique (two-component hot wire anemometry) was used to map the flow in the vicinity of the shear-layer.

4. BOUNDARY LAYER CHARACTERISTICS ABOVE THE WIND TUNNEL MODEL

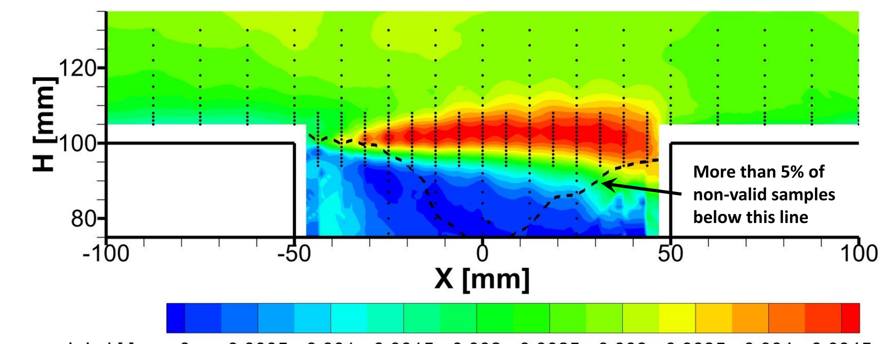


Dimensionless velocity (U), longitudinal (I_u) and vertical (I_w) turbulent intensity profiles at the centreline of canyons K9-17 (the height above the surface is expressed in full scale, therefore the top of the building blocks are at Z_{fs}=30 m). Left: dimensionless power spectral density of the longitudinal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

5. DEFFICIENCY OF THE HOT-WIRE TECHNIQUE AND A POSSIBLE TREATMENT METHOD

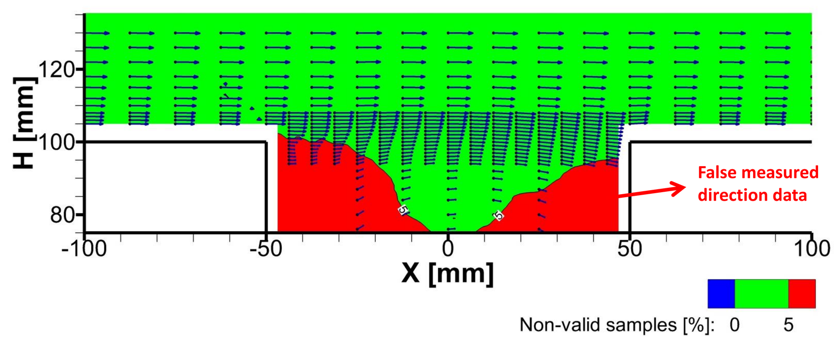


Proportion of non-valid samples (α > +35° or α < -35°) at the measurement points at the top of K13



Distribution of dimensionless Reynolds shear-stress above K13

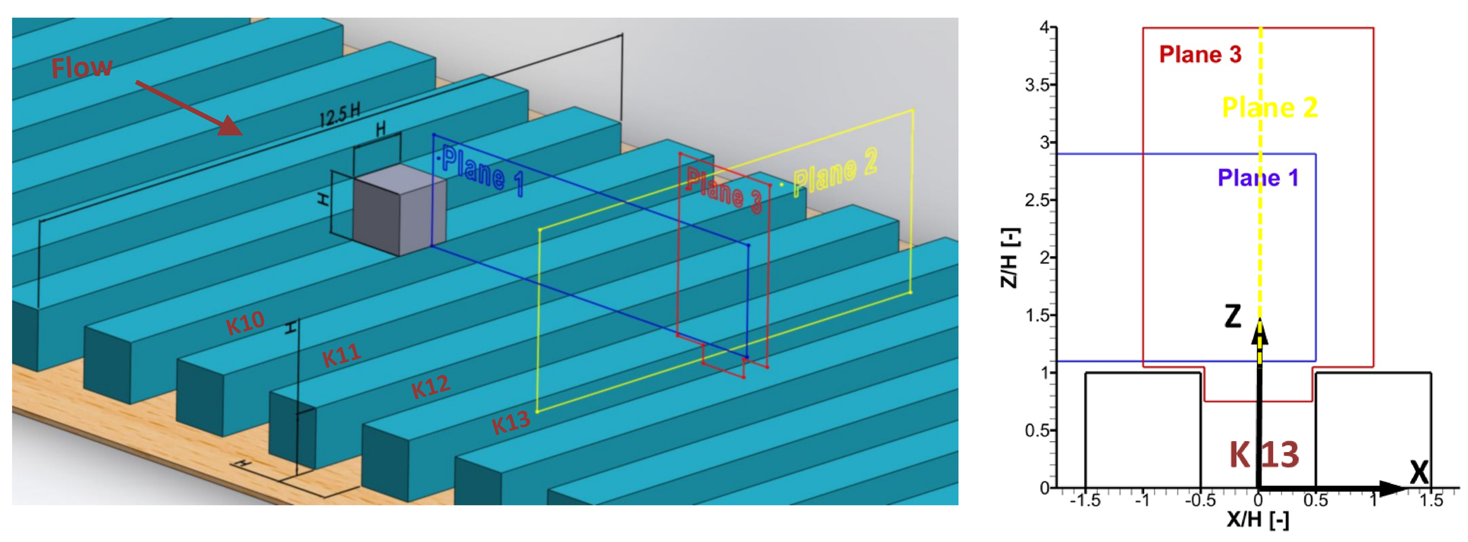
$$u'w'_d = \frac{\frac{1}{N}\sum(u_i - u_{mean})(w_i - w_{mean})}{U_{ref}^2}$$



Time-averaged velocity-vectors, at the measurement points at the top of K13. Points inside the red area contain more than 5% amount of non-valid samples

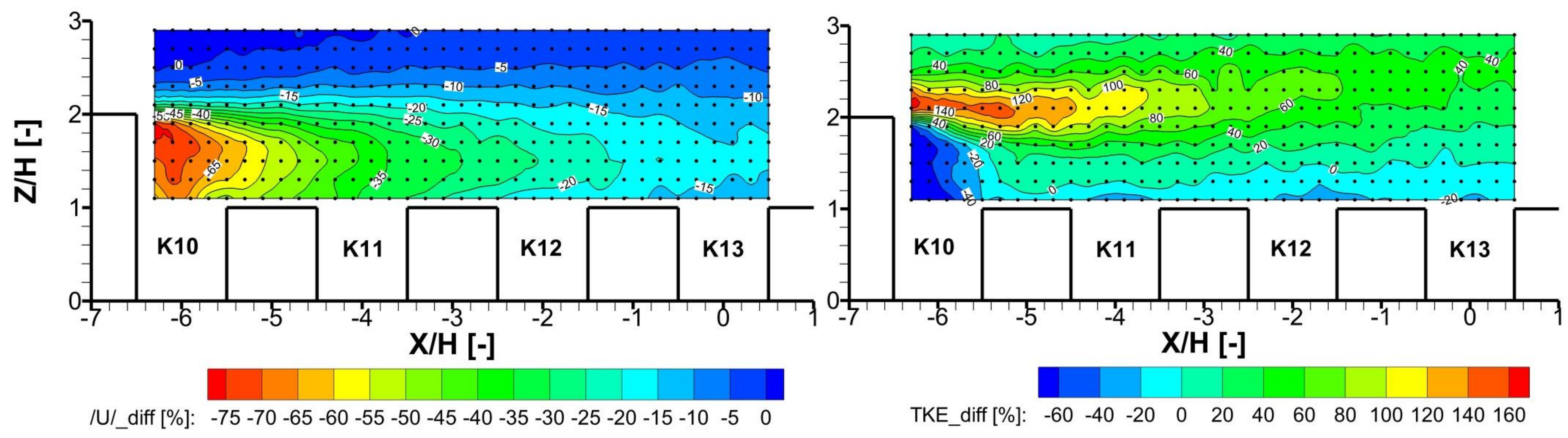
The two-component hot wire anemometry gives non-unambiguous direction values if the angle of the incoming flow exceeds the initial +/-45° measurement range. Since the street canyon vortex is characterized by backflow, the flow inside the canyon can't be explored unambiguously.
Despite this known deficiency, it is worth to apply two component hot-wire technique in the shear layer, because it is mainly characterized by velocities perpendicular to the main flow. The question is that, how to separate or exclude regions where the incoming data may result wrong values corresponding to the flow direction. The samples in the time series of flow-angles are marked if they are out of the +/-35° range and defined as "non-valid samples".
The proportion in percent of non-valid samples are calculated at each measurement point, and the spatial distribution of these statistical quantities are plotted. Arbitrarily, the non-valid samples = 5% iso-line is chosen as a border, which separates the regions with reliable and less reliable hot-wire results.

6. GLOBAL EFFECTS OF AN OBSTACLE ON A FLOW FIELD ABOVE THE URBAN CANOPY I.: LOCATION OF THE MEASUREMENT PLANES



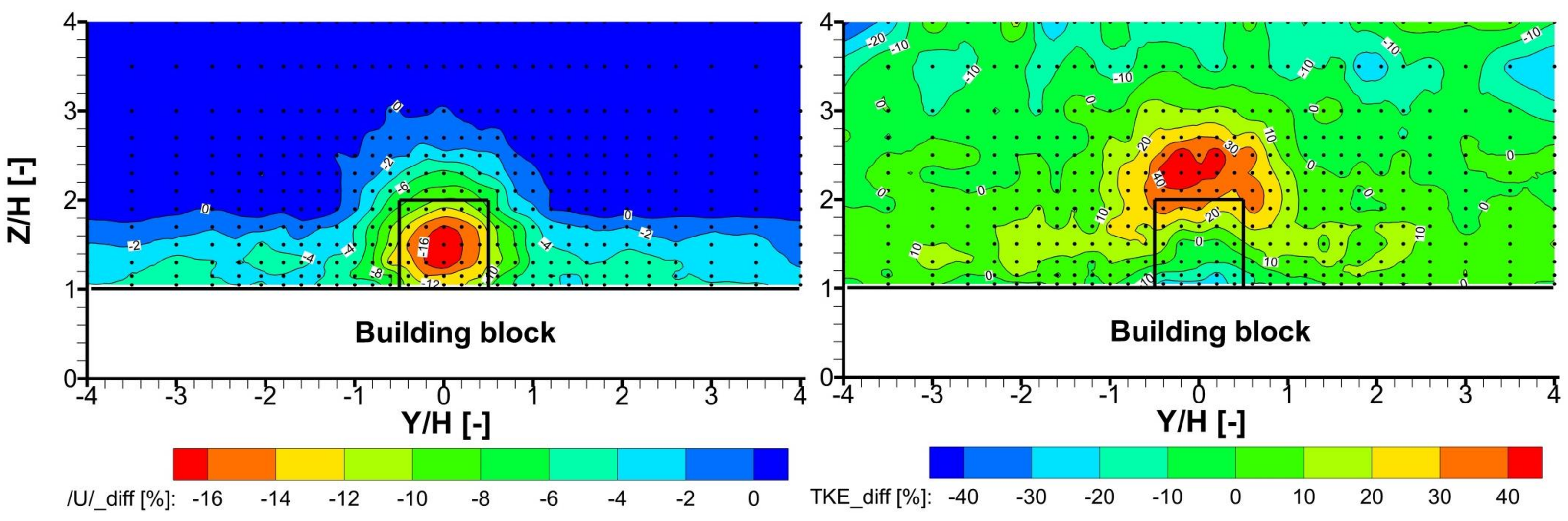
To simulate the effect of a tall building on the flow above the idealized urban canopy a cubic body was mounted at the top of the building block located directly in front of K10. The height, width and the length of the body was 1 H, the total height of the obstacle therefore was 2H. Then measurements were carried out in measurement Planes 1, 2 and 3. 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.

7. GLOBAL EFFECTS OF AN OBSTACLE ON A FLOW FIELD ABOVE THE URBAN CANOPY II.: PLANE 1



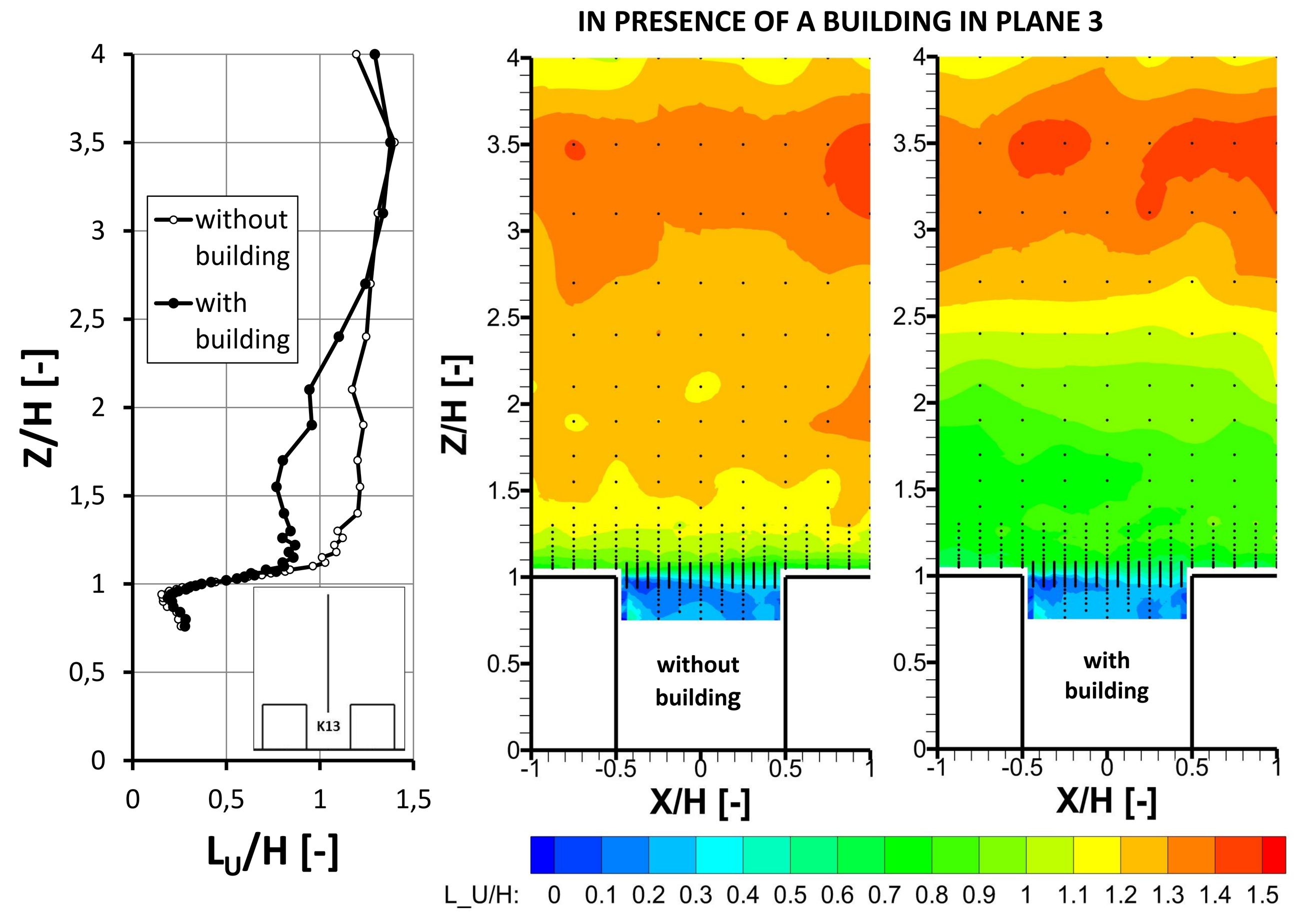
Distribution of the velocity-absolute value and turbulent kinetic energy (TKE) *difference* between the reference case and the arrangement with the obstacle, relative to the initial state (in percent) in Plane 1 .
The velocity deficit caused by the building model is the largest directly behind the obstacle (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%.

8. GLOBAL EFFECTS OF AN OBSTACLE ON A FLOW FIELD ABOVE THE URBAN CANOPY II.: PLANE 2



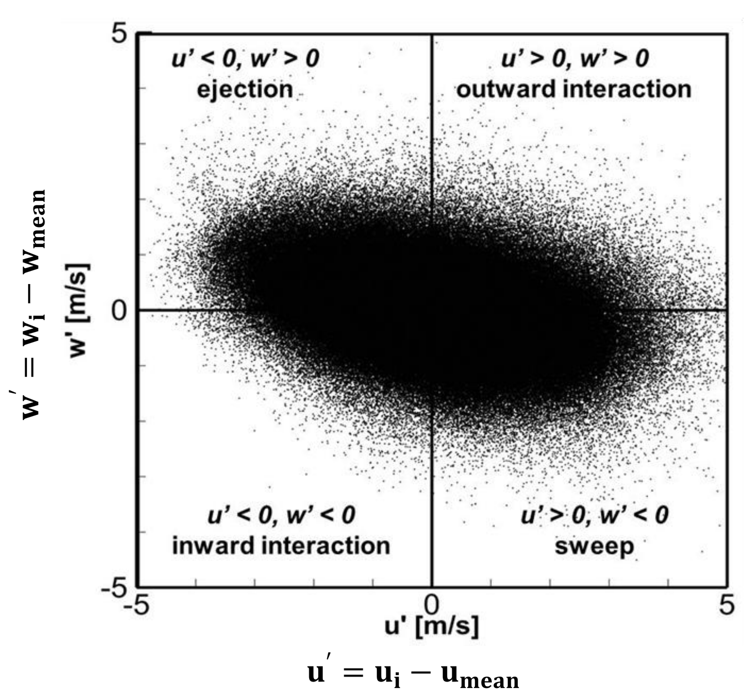
Distribution of the velocity-absolute value and turbulent kinetic energy difference between the reference case and the arrangement with the obstacle, relative to the initial state (in percent) in Plane 2.
The "shading" effect of the high-rise building is the strongest behind the projection of its contour 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%).

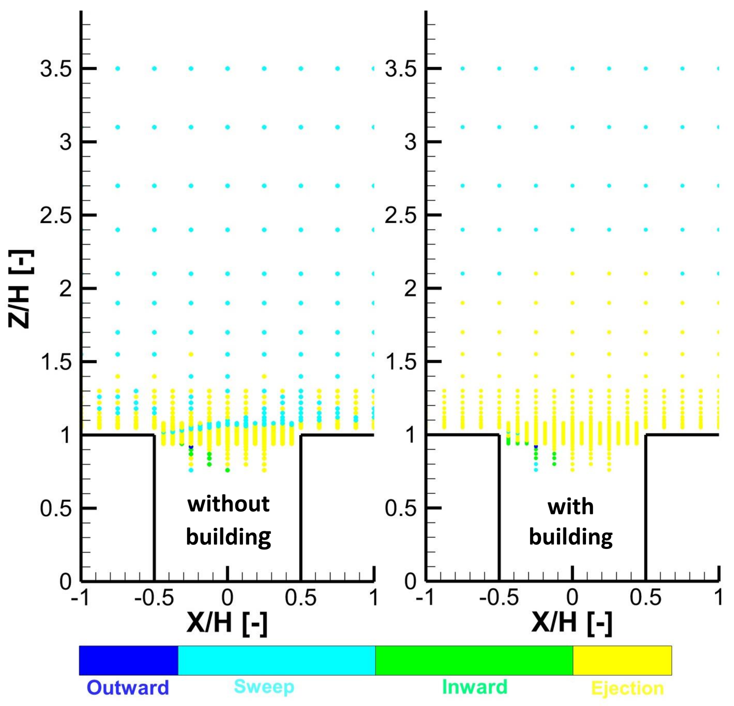
9. GLOBAL EFFECTS OF AN OBSTACLE ON A FLOW FIELD ABOVE THE URBAN CANOPY III.: VARIATION OF THE TURBULENT LENGTH SCALES IN PRESENCE OF A BUILDING IN PLANE 3



The recorded timeseries in case of Plane 3 were long enough for determining the turbulent length scale belonging to the longitudinal velocity. (L_U) .The dimensionless values (corresponding to the building-block height H) of the turbulent length scale were compared for the reference and the „disturbed" case (with building) at K13. When the building was located in front of K13, the length scale values above K13 were significantly smaller. As the length scale value in a given point gives information about the temporally averaged vortex dimension, it can be assumed that the obstacle behind itself changes the original vortex structure and reduce the extension of the large eddies above the canopy.

10. QUADRANT ANALYSIS : POSSIBLE METHOD TO STUDY THE TURBULENT MASS AND IMPULSE EXCHANGE PROCESS BETWEEN THE LOWER AND UPPER REGIONS OF THE URBAN CANOPY





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

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. 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. 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.
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 favorable, 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.

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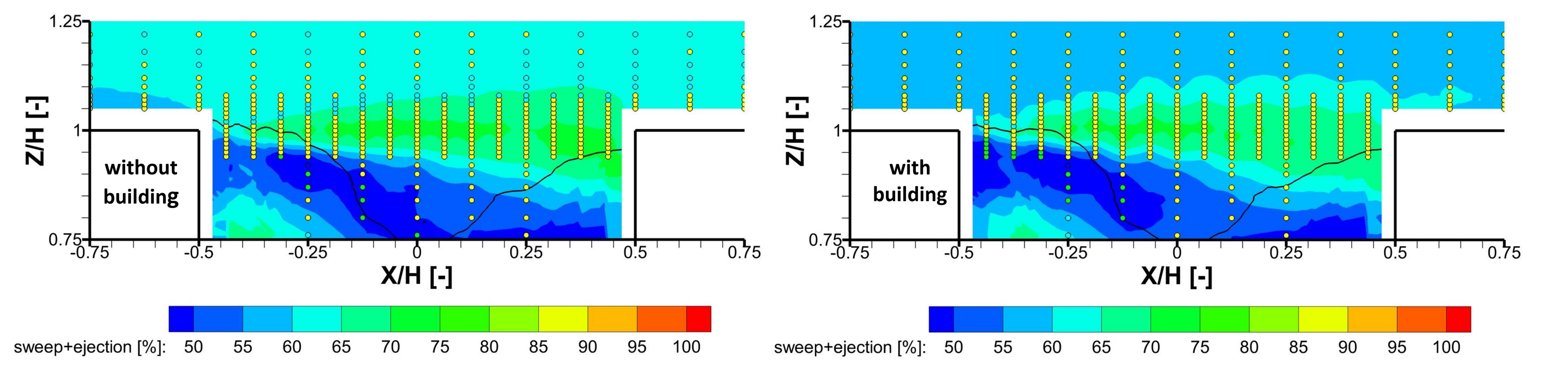
11. VARIATION IN SWEEP AND EJECTION EVENTS PROBABILITY IN PRESENCE OF A BUILDING IN THE VICINITY OF SHEAR LAYER ABOVE K13



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 point 10. Below the solid black line the proportion of out-of-range incoming hot-wire-probe samples (flow angle is larger than 35° or smaller than -35°) were larger than 5%.
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. 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%).

12. 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, and reduces the average vortex length above the canopy. 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.