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APPLICATION OF TWO COMPONENT HOT-WIRE ANEMOMETRY TECHNIQUE FOR FLOW MEASUREMENT INSIDE STREET CANYONS

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1. 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 [1]. 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 of the building blocks and the width of the streets are equal. 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, Fig. 1,). with height of 100 mm and with width of 1250 mm.

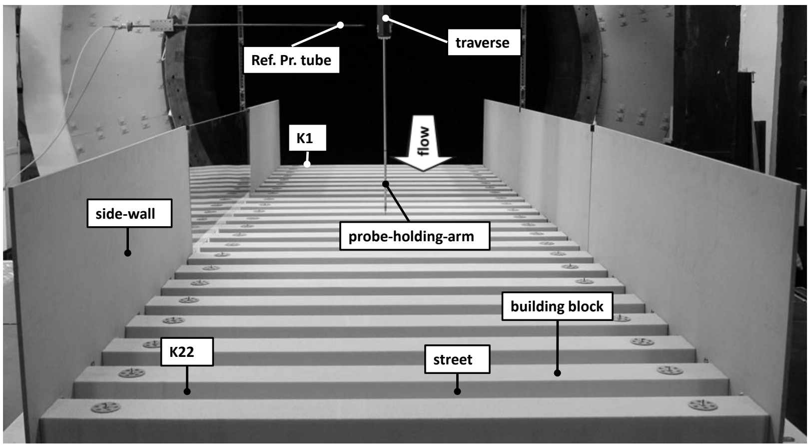

Fig. 1
Model of street canyons at the test section of the Large Wind Tunnel

In case of a single selected canyon from the row of street-canyons, three main region can be distinguished from viewpoint of flow structures ([2], Fig. 2). Inside the canyon the so called street-canyon flow (or vortex) evolves. The flow direction at the street level is opposite relative to the main wind, points upwards

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near the upwind building-block wall and downward in the vicinity the upwind wall. At the top wind vectors are mostly parallel to the main flow, but the absolute values are increasing according to a very high spatial gradient in vertical direction, this region is called shear layer, the thickness of which is slightly grows towards the downwind wall. Above the canyon, in the region of external flow, the velocity is growing according to an atmospheric boundary layer. The pollutant emission takes place at the street level (exhaust gas of vehicles in reality, tracer gas in experiments) and the street canyon flow transports it towards the shear layer which is characterised by intense turbulent mixing. Significant amount of pollutants diffuse into the external flow through the shear layer, leaving the street canyon vortex. The remaining quantity, mixed-up with some “clean” air, drifted back air to the street level near the downwind wall. If a constant pollutant emission flux level is given, it can be assumed, that turbulent properties of the shear layer has an essential effect of the time-averaged concentration inside the canyon.

In case of higher level of turbulence, the mixing is intensifies, more pollutant escape to the external flow, and more “clean” air enters to the canyon vortex.

Besides the mass transfer, a turbulent impulse transfer process also takes place in the shear layer. The increased impulse transfer raise velocities in the canyon flow, transporting more amount of air to the shear layer corresponding to a single time unit.

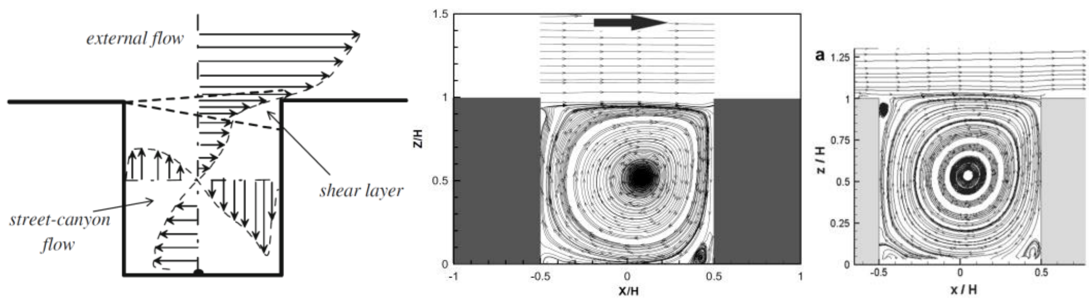


Fig. 2
Left: main flow regions in the vicinity of a single street canyon according to [2]; centre and right: time-averaged measured streamlines inside a canyon from [4], [3]

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 ([2], [3], [4]). 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 this paper a more traditional measurement technique (two-component hot wire anemometry) was used to map the flow in the vicinity of the shear-layer. First, the calibration method is discussed, than some measurement results concerning on the whole wind-tunnel model is shown. Than the limitations of this technique (unable two detect backflow) and a possible treatment method is explained. At the end the measurement results concerning of turbulent quantities concerning on a single chosen canyon is briefly interpreted.

2. CALIBRATION OF THE TWO.COMPONENT HOT-WIRE PROBE

During the measurements 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, arranged in "X" shape, suitable for measuring two velocity components in the plane, where the "X" lies (Fig. 3), if the flow angle does not exceeds +45° or -45°. Fast response electric control loops – so called hot-wire bridges (type 55M10, manufacturer: DISA): – are connected to each wire. 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 (dimensions: 0.35x0.35 m, flow inhomogeneity: below 3%, turbulence imtensity: 0.8% [5]). The flow angle (α) was varied by rotating the probe support relative to the incoming flow by the help of a stepper-motor driven turntable. During the calibration process the velocity of the incoming flow (U [m/s], measured by a TSI Prandtl-tube as a reference) varied between 1-16 m/s in 0.6 m/s steps and the flow angle between -40° to +40° in 4° steps. The voltages on the output of the two bridges (E1, E2) are measured in 525 individual calibrational points (3 s average), then calibrational maps were plotted for the velocity and the angle

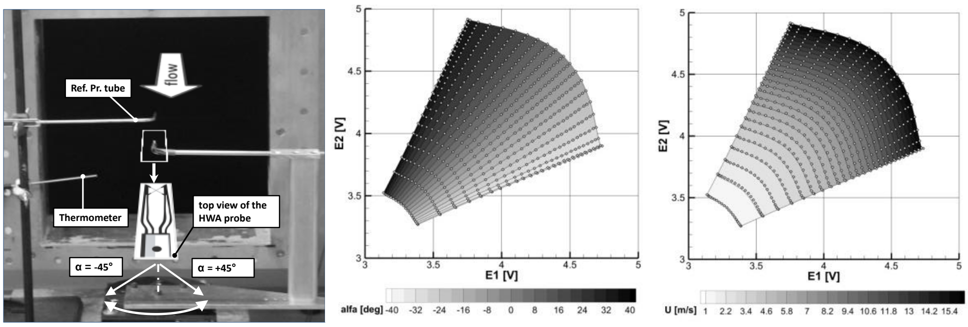


Fig. 3
Calibration rig of the two component HWA, flow-angle, α [°] and the flow-speed, U [m/s] in the function of the two measured bridge-voltages (calibrational maps)

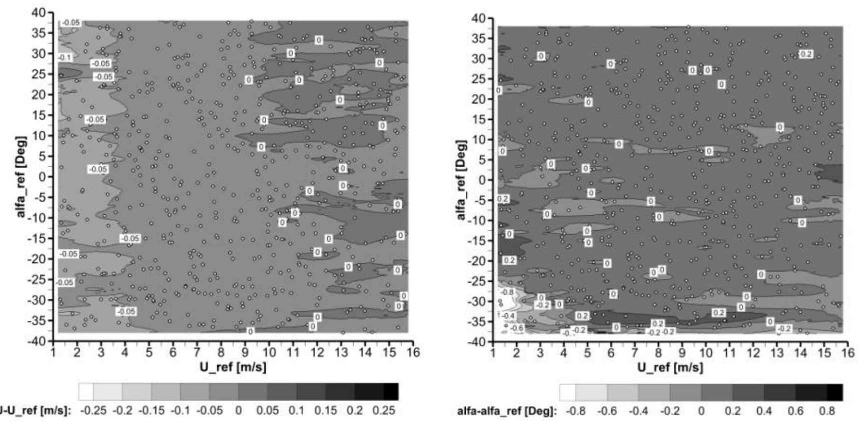


Fig. 4
Difference between the reference and measured flow angles and velocities

During the measurement actual instantaneous value-pairs of E1 and E2 voltages were captured (the sampling rate was 5000 Hz), the current value of the velocity and angle values were determined by second order interpolation based on the calibrational maps. To estimate the precision of the device and the interpolation method, the difference between the reference and measured velocity and angle values are determined in randomly spaced points in the whole calibrational domain (Fig. 4). The error for the velocity is less than 0.05 m/s and 0.8 ° for the angle.

After the calibration the support of the anemometer was rotated in vertical position and mounted on the probe holding arm of the traversing system [5], integrated into the test section of the Large Wind Tunnel (Fig 1).

3. MEASURED TURBULENT QUANTITIES

The two component hot-wire anemometer supplies a captured time series for the absolute value of the flow velocity and angle, and the time series of the velocity components (u, w) can be determined, too. The dimensionless turbulent intensities into the u and w direction is the I_u and I_w: the standard deviations of the u and w velocities are divided by the time-averaged mean value of u. The dimensionless turbulent kinetic energy (TKE_d) is calculated from the standard deviation of the velocity absolute value U and the velocity measured by the reference Prandtl-tube above the model, placed in an undisturbed flow (Fig. 1).

$$I_u = \frac{\sigma_u}{u_{mean}};\; I_w = \frac{\sigma_w}{u_{mean}};\; TKE_d = \frac{1}{2}\left(\frac{\sigma_U}{U_{ref}}\right)^2;$$

The dimensionless virtual Reynolds stress $u'w'_d$ is derived by the using mean and captured instantaneous (u_i, w_i) values of the two velocity components, the reference velocity and the number of the samples N:

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

4. GLOBAL FOW QUALITY ABOVE THE STREET CANYON MODEL

Above the series of street canyons a boundary layer develops (the lower part of the external flow region), 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) from height H=75 mm to H=400 mm (H=0 mm represents the street level). The sampling time at each point was 25 s, the measurements were carried out at reference velocity 10.5-11.5 [m/s]. The dimensionless velocity 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 and in the lower part of the external flow region up to H=175 mm. In case of the I_u turbulent-intensity profiles the differences are larger, but the profiles are still nearly the same in the shear layer up to H≈115 mm. For further investigations the K13 was chosen, as the flow in the shear layer of this canyon is similar to any other subsequent canyons.

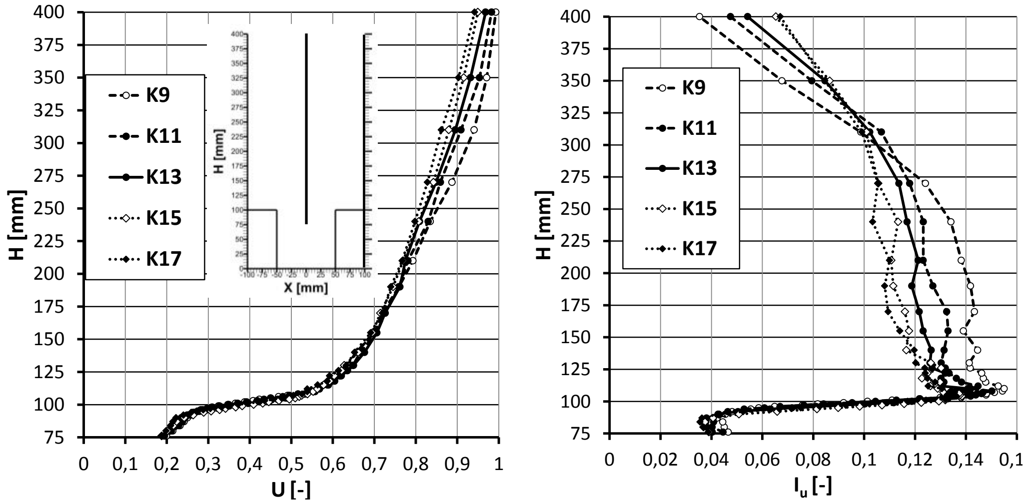


Fig. 5
Dimensionless velocity and turbulence intensity profiles in canyons K9-17

In case of idealized street-canyon geometry the streets are infinite or at least long enough so that the flow-field does not change in the direction of the streets. To approach this situation, side walls was use on the model, similarly to wind tunnel investigations of air foil-segments (Fig. 1). At K13 the flow field was scanned in a plane perpendicular to the main flow direction (Fig. 6). In the map of dimensionless velocity can be shown, that a boundary layer develops on side walls, the velocity decreases if the Y coordinate is smaller than -450 mm or larger than 450 mm. From viewpoint of turbulent kinetic energy the turbulence reducing effect of the walls is more appreciable, intense drop can be noticed on both side when absolute value of Y is exceed 250 mm. However, it can be stated that averaged and turbulent flow quantities are independent of the streetwise Y coordinate if the value of the Y is between -200 and 200 mm.

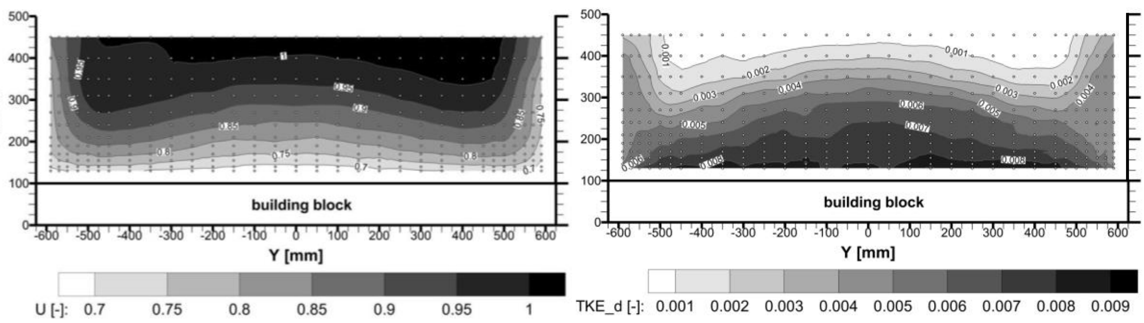
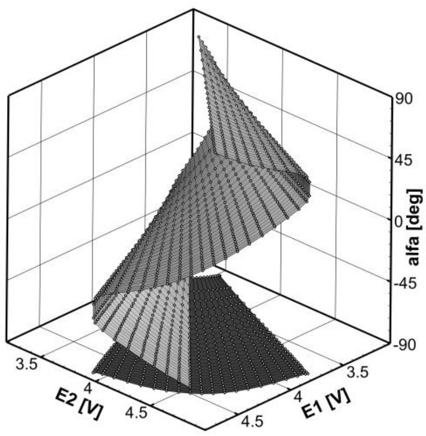


Fig. 6
Dimensionless velocity and turbulent kinetic energy at K13 in a plane perpendicular to the main direction, side walls are at Y= - 625 mm and at Y= 625 mm. up to H= 500 mm

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

If the calibration method, which was presented in chapter 2., continued for flow angles exceeding the +/-45° range, and the results are represented as a surface, a folded structure evolves (Fig. 7, right). The folded nature understandable by the help of the diagram on the left side: wire “2” produce the same output voltage (E2) in case of 0° and 90°, because the two angle position produce the same cooling effect from the viewpoint of the wire, the α(E2) function is mirrored to the horizontal line at α=45°. Since the street canyon vortex is characterized by backflow, the flow inside the canyon can’t be explored unambiguously.



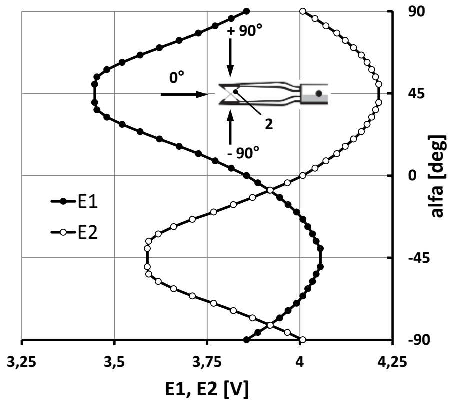


Fig. 7
Left: the three-dimensional calibration diagram, when the flow-angle larger than +45°, or smaller than -45°; right: the flow-angle in function of the two bridge voltages between -90°-+90° at U=5,2 m/s

Despite this known deficiency, it is worth to apply two component hot-wire technique in the shear layer, because it is mainly characterised 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 (the angle domain is chopped before the “mirroring” or “foldig” takes place at +/-45°) and defined as “non-valid samples”.

To test this concept, measurement series were carried out on the upper part (75 mm < H < 135 mm) of the K13 in the vertical symmetry plane at Y=0. The distribution of the measurement points was dense in the shear layer, and the sampling time was raised to 100 s to get statistically representative values for the turbulent quantities.

The proportion in percent of non-valid samples are calculated at each measurement point, and the spatial distribution of these statistical quantities are plotted (Fig 7, right). At the regions below the roof level near the upwind and downwind wall the proportion of non-valid samples are gradually increase towards the walls, as here the flow starts to turn upward and downward. 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. This line is marked with dashed curve on Fig. 8 right, where the time-averaged velocity vectors are presented. It can be seen, that the absolute-value is changing very rapidly through the shear layer, and it becomes thicker towards the flow direction. Velocity vectors near the upper corner on the upwind side located in the excluded zone, and they are points towards the main flow direction. PIV measurement result from [4] and [3] (Fig 1) here denote up flow with sharp turning, or a small vortex, so the exclusion of these domain was reasonable and justified.

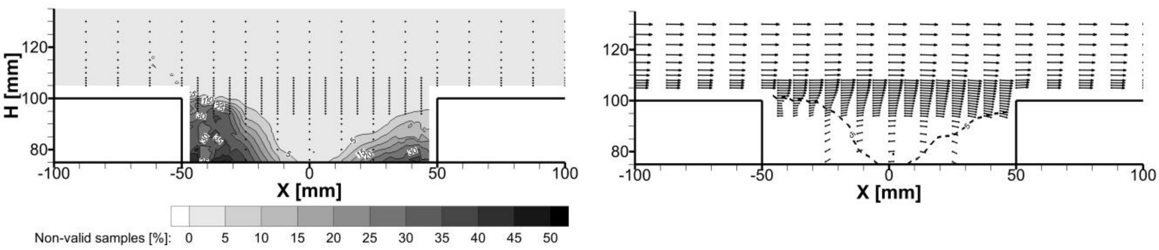


Fig. 8
Left: the proportion of non-valid samples (α > +35° or α < -35°) at the measurement points; right: velocity-vectors, the measurement points below the dashed line contains more than 5% amount of non-valid samples

6. MEASURED TURBULENT QUANTITIES IN THE VICINITY OF THE SHEAR LAYER

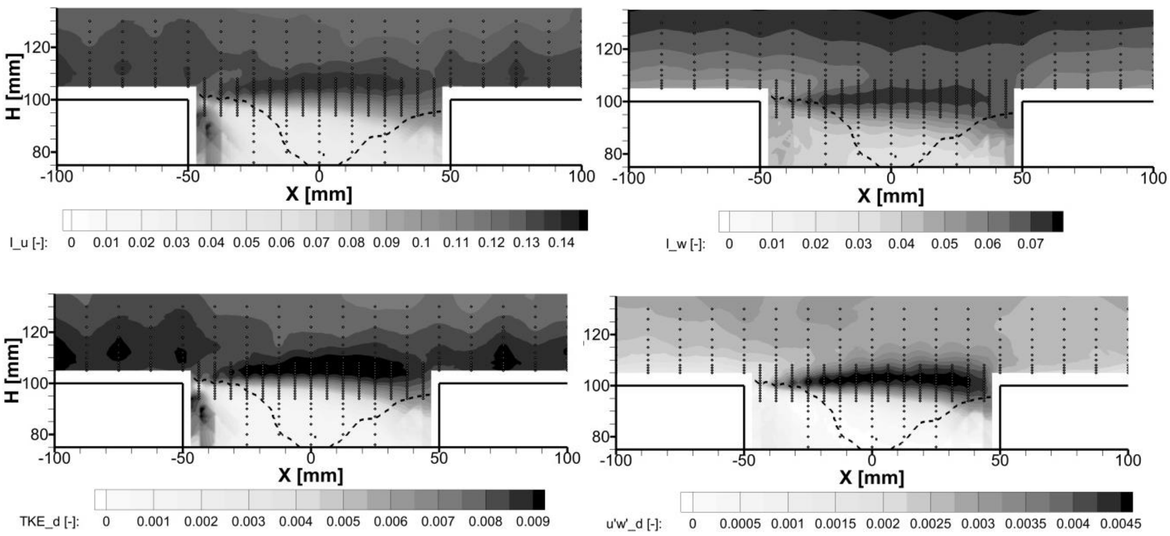


Fig. 9
Results of the shear-layer measurements, the role of the dashed line is the same as on Fig. 8 right

The distribution of the turbulent quantities is plotted on Fig. 9. In case of the turbulent intensities I_u I_w and the turbulent kinetic energy the values are higher above the canyon in the external flow, relative to the areas, located below the roof level. Despite that, the Reynolds shear-stress has moderated values both above and below the line of the roof (H = 100 mm), and these two parts divided by a clearly distinguishable stripe in the region of the shear layer. It can be assumed, that in this region takes place the impulse transfer from the external flow towards the canyon vortex. The maximal values of the turbulent intensity to the vertical direction (I_w) is about a half of the maximal values to the stream wise direction (I_u). The turbulent kinetic energy- and intensities also have a little bit less more recognizable stripe in the region of the shear layer, the regions of the intense mixing and the impulse transfer are in good overlap

CONCLUSION AND FUTURE OUTLOOK, ACKNOWELEDGEMENTS

The suitability of two component hot wire anemometry technique is proven for mapping the distribution of turbulent quantities in the shear layer of street canyons, considering the limitations of this method. In our future experiments a cubic body will be mounted at the top of the building block located directly in front of K10 to simulate the effect of a tall building on the flow above the idealized urban canopy and on the turbulent shear layer at K13.

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