WIND TUNNEL MODELLING OF VENTILATION AROUND AN URBAN SQUARE

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ABSTRACT

During this research, a small-scale model of the quarter surrounding József Nádor Square (JNS) in downtown Budapest was prepared and with this 1:350 scale model flow field measurements were carried out in the Large Horizontal Wind Tunnel (LHWT) of the Department of Fluid Mechanics at the Budapest University of Technology and Economics (BME) using Laser-Doppler Anemometry (LDA).

A large amount of information about the flow characteristics could be obtained, for instance turbulent kinetic energy and velocity distributions on certain horizontal planes were determined. Moreover, vertical velocity profiles were also investigated. The results show the evidence of low air exchange between the square and the neighboring areas as well the atmospheric boundary layer, which accounts for the bad air quality observed on-site. Mean flow structures responsible for the complex airflow in the square could be identified. The results of the measurements could later be used as reference data set for validation of urban wind field models.

INTRODUCTION

The air quality of our environment is significantly deteriorated by traffic pollution. Dispersion of air pollutants is determined by various flow phenomena. These flow phenomena take place in the atmospheric boundary layer, so the characteristics of the atmospheric boundary layer play an important role in air pollutant dispersion. The parameters of the boundary layer are measurably affected by the terrain conditions, vegetation and buildings. In urban areas, surrounding buildings have the most significant effect on flow characteristics.

Concentration of contaminants increases dramatically in the vicinity of the emission of pollutants, so busy roads and nearby squares could be the most contaminated areas. The relevant studies in connection with microscale air pollution research focused mainly on the investigation of urban street canyons, street intersections and regular arrangements of building blocks. Air pollution and flow phenomena at urban squares were much less dealt with. Only a few papers [1, 2] paid attention to flow and dispersion specifically at urban squares. The study of wind and concentration fields at squares is also included in larger scale investigations of whole districts [3]. During a recent research [4] of the Department of Fluid Mechanics at the

BME, CFD simulations were performed to analyze pollutant dispersion and flow phenomena around József Nádor Square.

JNS in downtown Budapest is located next to the extremely busy József Attila Street; moreover, the square is surrounded by buildings from all sides. In case the square has favorable ventilation, the pollutants do not enter the square or the entered pollutants disperse quickly and the air quality complies with the requirements. However, measurements at the nearby Erzsébet Square have proven very high pollutant concentrations, indicating similar situation at the József Nádor Square.

During this research, the ventilation around JNS was investigated with wind tunnel measurements. A small-scale (1:350) model was created and Laser-Doppler Anemometry (LDA) was used for the measurements.

The model was placed in an urban-type boundary layer, which was modelled in the wind tunnel and checked by vertical profile measurements.

The fiber-optic LDA probe accessed to the flow from below through a pane of glass. With the applied method the flow was absolutely not disturbed by the probe. A two-component LDA system was applied, so with the mentioned arrangement the *u* and *v* velocity components could be determined.

EXPERIMENTAL DETAILS

Modeling an urban-type atmospheric boundary layer

Experiments were carried out in a 3.8 m long open test section with a diameter of 2.6 m of the LHWT at the BME. This Göttingen-type wind tunnel is operable in a closed circuit mode with a suction configuration. In order to model an urban-type boundary layer, vortex generators, crossbars and roughness elements were placed into the preparatory section of the wind tunnel in an appropriate arrangement. The measurement layout can be seen in Fig. 1.

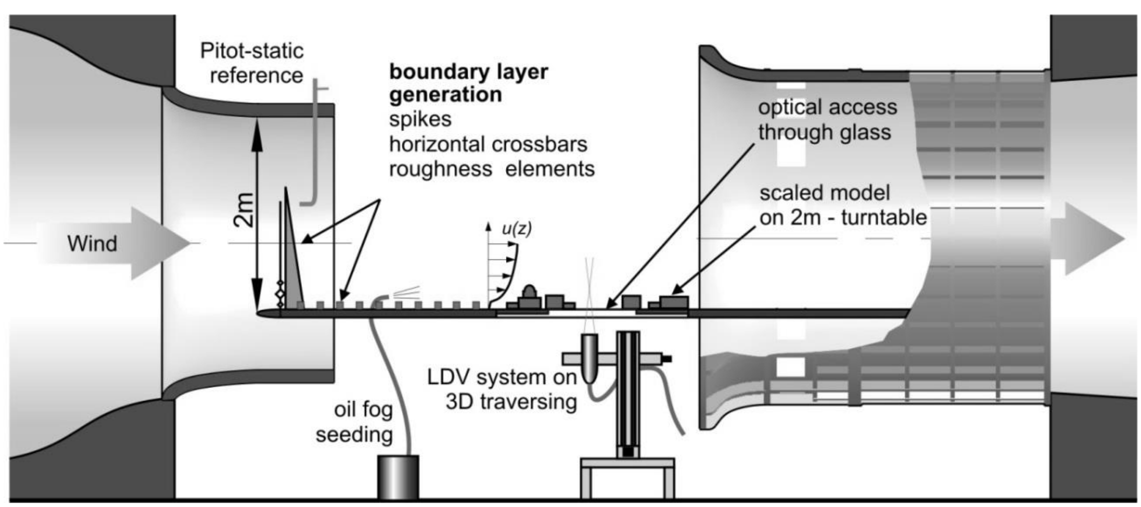

Fig. 1
The wind tunnel test section

The inlet profile of the modelled atmospheric boundary layer was checked by two-component LDA measurements.

The profile measurement results are shown in Fig. 2 and Fig 3. Fig. 2 shows mean velocity $\bar{u}$ into the main flow direction, as well as turbulence intensity determined for the mean and lateral flow directions.

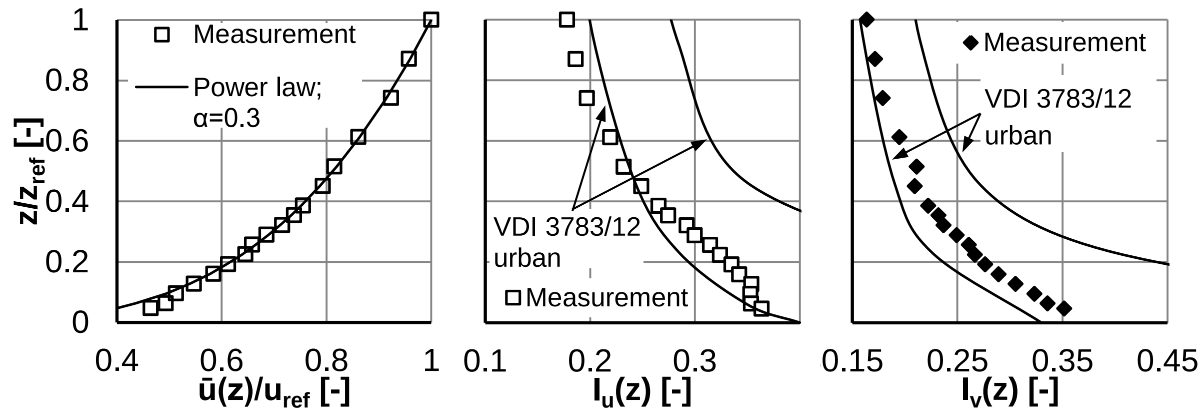

Fig. 2

Inlet profiles of dimensionless mean velocity and turbulence intensity

Height dependence of mean velocity $\bar{u}$ can be approximated with the following formula, so called power law [5]

$$\frac{\bar{u}(z)}{u_{ref}} = \left(\frac{z - d_0}{z_{ref} - d_0} \right)^{\alpha} \tag{4}$$

where α is the exponent, z is the height, z_{ref} is the reference height, u_{ref} is the mean velocity at the reference height and d_0 is the displacement height. In order to obtain dimensionless mean velocities, local velocities, $\bar{u}(z)$, were divided by the reference velocity u_{ref} = 4.60 m/s, which was measured at the reference height z_{ref} = 309.50 mm. Displacement height was considered to be zero in all cases. The longitudinal integral length scale of turbulence L_{ux} was also determined and found 0.2-0.23 m at building height and above (70-80 m in full scale).

The above parameters of an urban boundary layer are described in several guidelines and standards. According to ESDU 72026 [6], the power law exponent α = 0.3 can be accepted for the representation of the urban atmospheric boundary layer; thus the measured mean velocity profile was adequate. Turbulence intensity I_u profile shows some differences compared to VDI 3783/12 [7] data; however, turbulence intensity profiles such as the longitudinal integral length scale profile could be accepted, although the natural value of L_{ux} is larger, 100 to 190 m at 50 m height, below this level the agreement is perfect. Based on the profile measurements, the generated atmospheric boundary layer is considered to be applicable for the investigation of ventilation around an urban square.

Model construction

A 1:350 scale model of the quarter around JNS in downtown Budapest (Fig. 4) was prepared of rigid foam and the whole model was placed on a wooden circular plate with a diameter of 2 m. There was an 800x800 mm opening in the middle of the plate covered by a pane of glass. This pane provided optical access to the flow from beneath the model. Every building was modelled as a block with a flat roof and with classified heights in 1.5 m steps. Although roof shape has a certain influence on the flow, for the cause of a simple CFD model / mesh generation, this effect is neglected similarly to the effect of urban vegetation.

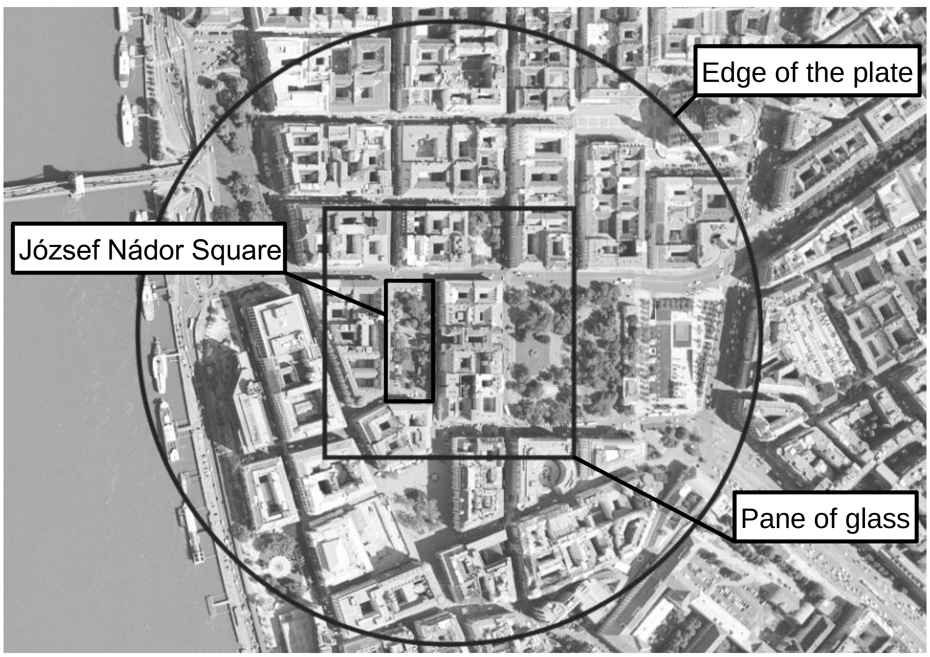

Fig. 4
József Nádor Square and the surrounding quarter; the edge of the wooden plate and the pane of glass are also marked

RESULTS AND DISCUSSION

Measurements were carried out on the model of JNS with only one wind direction (northern wind).

Dimensionless mean velocity and turbulent kinetic energy distributions were determined in vertical profiles in 10 locations, and on three horizontal planes of 568 measurement points at z = 20 mm (0.25h), z = 40 mm (0.5h) and z = 80 mm (h). The results of the profile measurements and investigation of planes can be seen in Fig. 6 and Fig. 7, respectively.

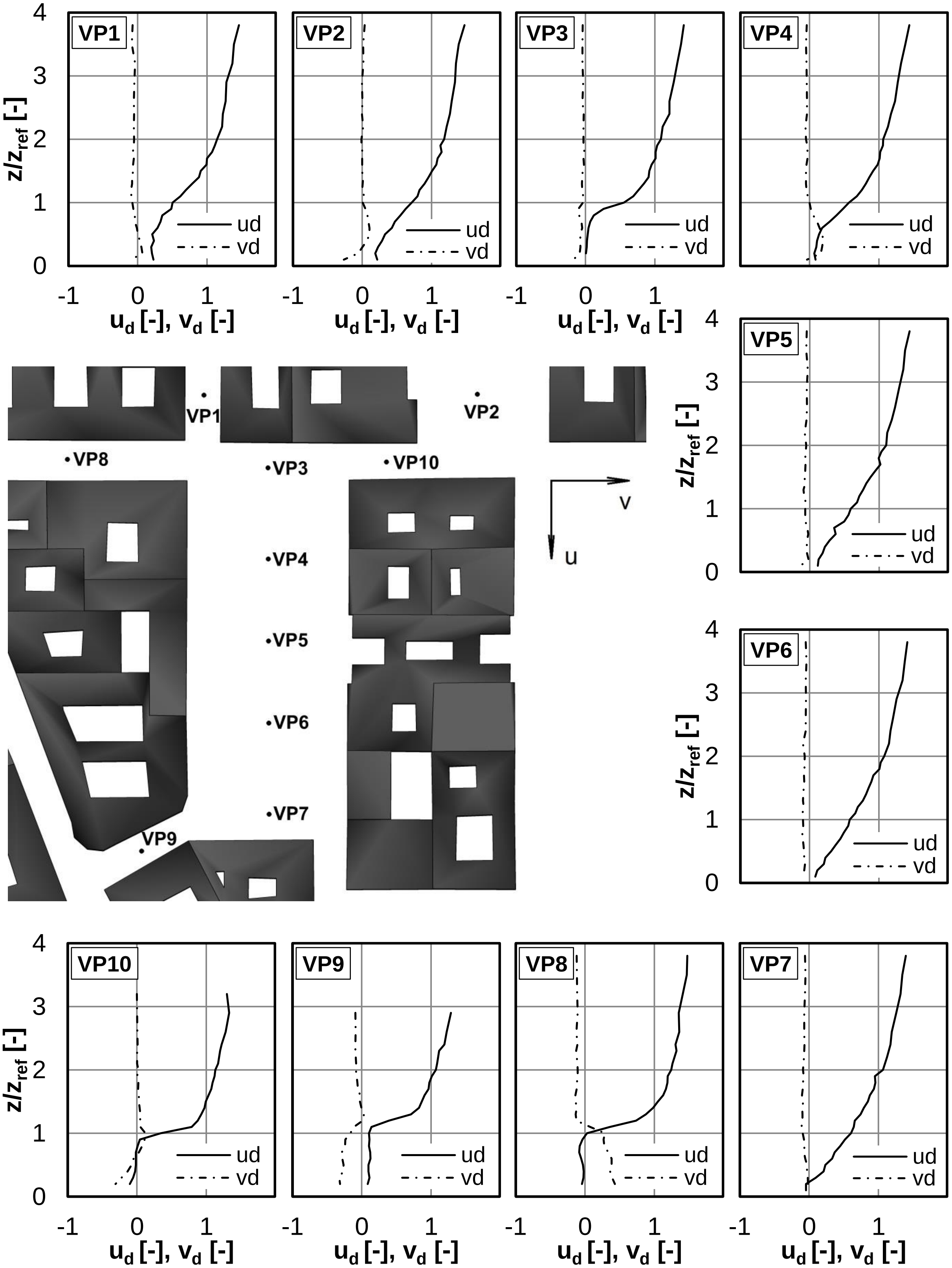

Fig. 6

Mean velocity profiles (u_d, v_d: normalized horizontal velocity components)

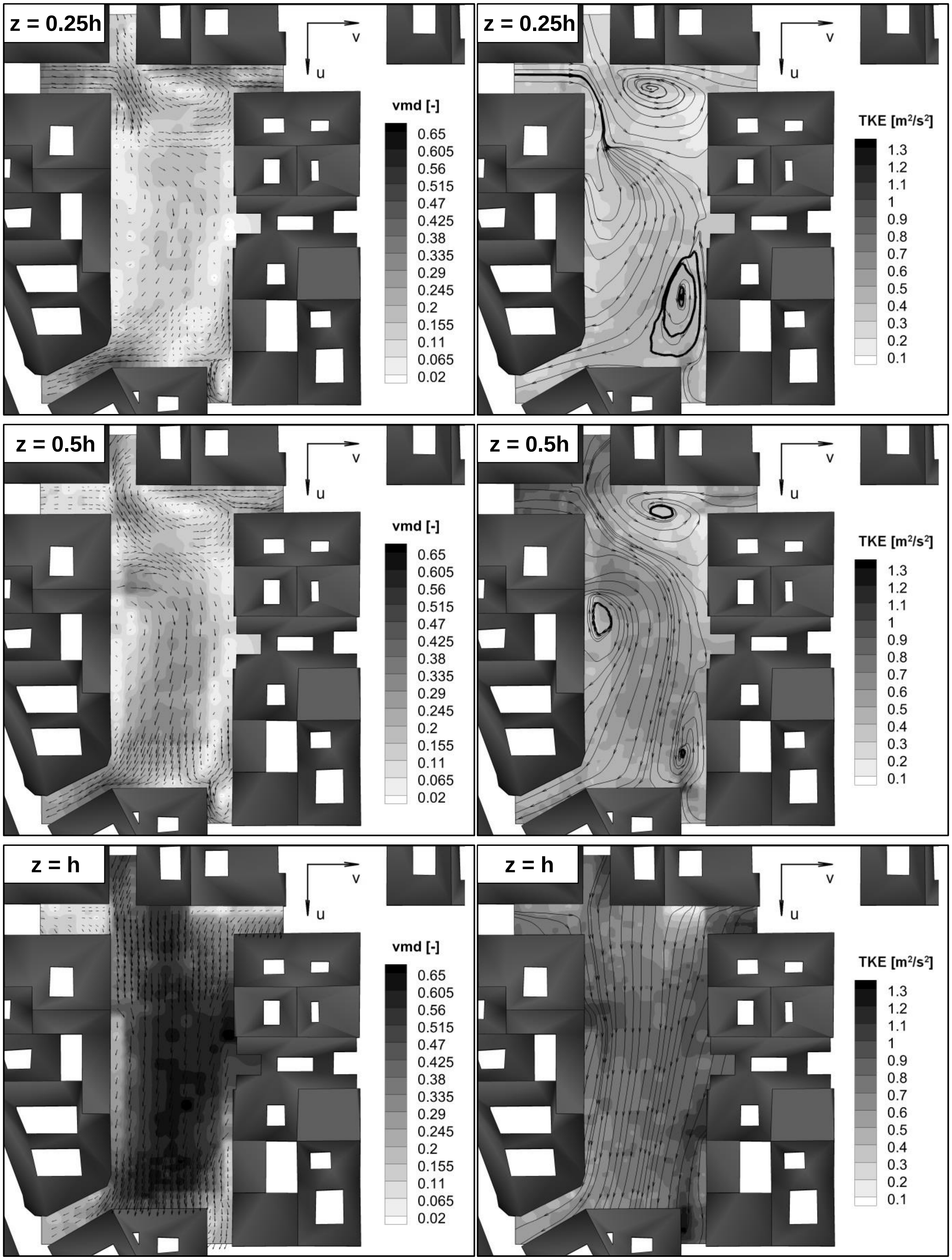

Fig. 7

Velocity and turbulent kinetic energy distributions on horizontal planes (*vmd*: dimensionless horizontal velocity magnitude)

Local velocities, $u(z)$ and $v(z)$, were normalized to the reference velocity u_{href} = 3.02 m/s, which was measured at the reference height z_{href} = 80 mm during the boundary layer measurements (mean building height of 28 m in full scale).

Analyzing the profiles above the square (VP3 to 7 in Fig. 6) a separation bubble evolved after the northern block can be clearly observed. The boundary layer after the middle of the square – at about 2-3*h* distance – penetrates the square and hit the southern block. The value of the *v* velocity component can differ from zero below the height of the buildings; this indicates remarkable cross-flow.

The VP1, VP8, VP9 and VP10 profiles are located in street canyons. The street in which profile VP1 can be found is parallel to the ambient wind direction; however, no significant velocities were measured here. In the streets perpendicular to the ambient wind direction the flow is parallel to the street axis. Although expected in VP8 and VP10, a clear street canyon vortex could not be observed.

Seeing the velocity fields on the horizontal planes (Fig. 7) it can be said that the highest velocity values were measured at $z = h$. No backflow is observable at this height. At lower heights, mean velocity values are also lower, at 0.25*h* less than 15% of the reference wind speed, with the exception of corners, where up to 30% can be observed.

Analyzing the streamlines, it can be stated that the flow forms three major vortices. Their vertical extension does not reach the reference height *h* but is clearly present at $z = 0.25h$ and $z = 0.5h$. The northern vortex is in the separation zone of the northern block, and the middle one is obviously caused by the second, taller building of the western building block.

Air enters the square from the northern streets and leaves it by passing through the southwestern connecting street. Interestingly, backflow is detected in the southeastern connecting street, so the outflow is blocked here. A stagnation point can be found in the front of the southern building. A significant proportion of the air, which arrives from northern connecting streets, is trapped into the first (northeastern) vortex of the square.

Studying the turbulent kinetic energy distributions (Fig. 7) it can be unequivocally stated that turbulent kinetic energy increases with the height and it has a maximum at the average building height (*h*). Values of the turbulent kinetic energy are usually smaller in the vicinity of the walls. This agrees well with the expectations, because both the mean velocity and standard deviation values are lower near to the walls.

CONCLUSIONS

The first round of wind tunnel measurements of a complex urban environment gave valuable insights into the flow phenomena of urban squares: Wind speeds near the ground are similarly low – or even lower - as in street canyons. Individual buildings can influence the flow structures developed on the square significantly. Highest wind speeds were observed at corner and intersection zones and not as expected, at the centre of the square.

The measured high-resolution flow data allows the validation of CFD wind field models, and will be extended to other wind directions and concentration measurements of tracer gas released from a line source representing the high traffic József Attila Street in the north of the square.

ACKNOWLEDGEMENTS

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