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INVESTIGATION OF VENTILATION AND AIR QUALITY IN URBAN SQUARES

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Abstract: To understand the flow structures which influence the flow and dispersion fields on urban squares, a simplified and a complex square geometry with rectangular layout was investigated by wind tunnel tests applying sand erosion technique, Laser Doppler velocimetry (LDV) and tracer gas concentration measurements at various wind directions. The obstacle-resolving MISKAM model was used to simulate flow and dispersion in the same square geometries. Numerical results agreed well with the experimental ones, which allowed the use of a vortex core detection method on the numerical results to identify the flow structures appearing on the square. The interaction of these structures gives an explanation for the observed inhomogeneous wind speed distribution in the square. The observations made about the square's flow field were summarised at each wind direction in a schematic figures.

One of the important observations was that separation zones of buildings located on the upstream side of the square cause low local wind speeds and strong vertical pollutant transport. Separation zones (horseshoe vortices) in front of building blocks located on the downstream side of the square induce higher local wind speeds and improve the removal of pollutants. At slanted wind direction, a large helical vortex dominates the square, transporting pollutants in a direction perpendicular to the incident wind.

The representation of velocity vector time-series as wind roses was used to further improve the understanding of the instantaneous flow field in the square. This way, locations with periodic wind direction change or flow switching could be identified.

Key words: *Urban square, flow field, ventilation, wind tunnel, CFD, dispersion.*

INTRODUCTION

Urban squares play an important role in the life of a city. Both wind conditions and the dispersion of pollutants in and around them is thus of specific interest. Previous studies of Gadilhe et al. (1993), Parra et al. (2010) and Bastigkeit (2011) provide valuable data about flow and dispersion in closed urban squares bordered by building blocks. Our study aims to provide high resolution data from the flow field in urban squares and to identify the major flow structures appearing in them, which influence the pollutant dispersion and wind comfort of the area.

INVESTIGATION METHODS

We investigated a simplified and a complex urban square with an approximate length to width ratio of 2 (Fig. 1). The complex square is József Nádor Square located in central Budapest. Wind tunnel tests were performed in 1:650 scale for the simplified, geometry applying the sand erosion technique for the estimation of ground level wind velocity magnitude v_{MD} (Livesey et al., 1990). The complex geometry was measured in a large Göttingen type wind tunnel in 1:350 scale, and LDV measurements of the horizontal u and v velocity components at various horizontal planes in the square and in connecting streets were performed.

Numerical simulations of the simplified geometry were performed using the MISKAM obstacle resolving microscale meteorological model (Eichhorn and Kniffka, 2010) which was successfully applied earlier in street canyon-scale investigations, e.g. Balczó et al. (2009). The model solves the Reynolds-averaged Navier-Stokes equation using a modified k-ε turbulence closure on a non-equidistant Cartesian grid. In this study, grid resolution was $1.25 \times 1.25 \times 0.7$ m in the square. As our aim was to identify flow structures, 3D streamlines and vortex cores were extracted from the 3D quasi-steady flow field.

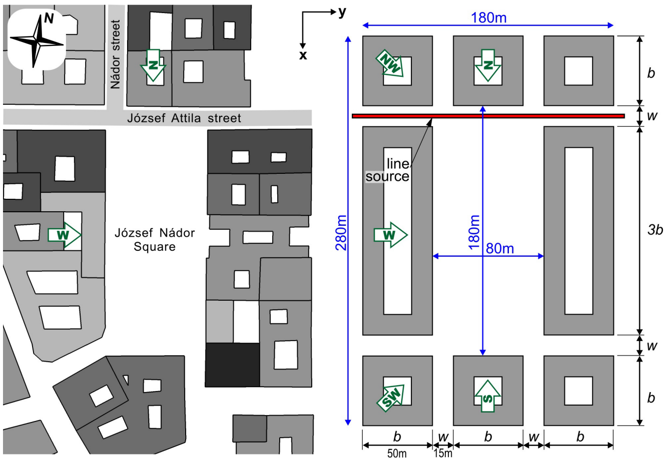

Figure 1. The urban square geometries investigated. Buildings are coloured by height. Left: real geometry of József Nádor Square, Budapest; right: simplified square.

FLOW FIELD IN A SIMPLIFIED SQUARE

Fig. 2. shows the ground level wind velocity magnitude v_{md} (normalized by the rooftop level mean wind speed) at wind from north, northwest and west. The most important flow field features are beyond doubt (a) the high speed air jets in the street intersections close the upstream corners of the square and (b) the separation zones (horseshoe vortices) in front of building blocks located on the downstream side of the square. Both cause high local wind speeds $v_{md} > 1$. The latter vortices also induce a flow in the connecting side streets perpendicular to the incident wind direction. Besides these, the flow visualisation of the CFD results (Fig. 3) proves the existence of a strong helical vortex at slanted (northwest) wind direction, which is similar to street canyon vortices observed earlier by similar wind directions. The experimental and numerical results were summarized in simplified flow maps shown in Fig. 4.

FLOW FIELD IN A COMPLEX URBAN SQUARE

To answer the question whether the flow field – and subsequently the concentration field – is similar in a real urban square, we show the LDV measurement results in Fig. 5 at northern and western wind direction. In case of northern wind direction, comparing Fig. 2, left to Fig. 5 left, it is obvious that there are major differences between simplified and real geometry, caused by the inhomogeneity of building heights (see for example the large side separation vortex indicated by A in Fig 5, left) and by the asymmetry of the connecting streets. These cause an asymmetric flow field in the real urban square.

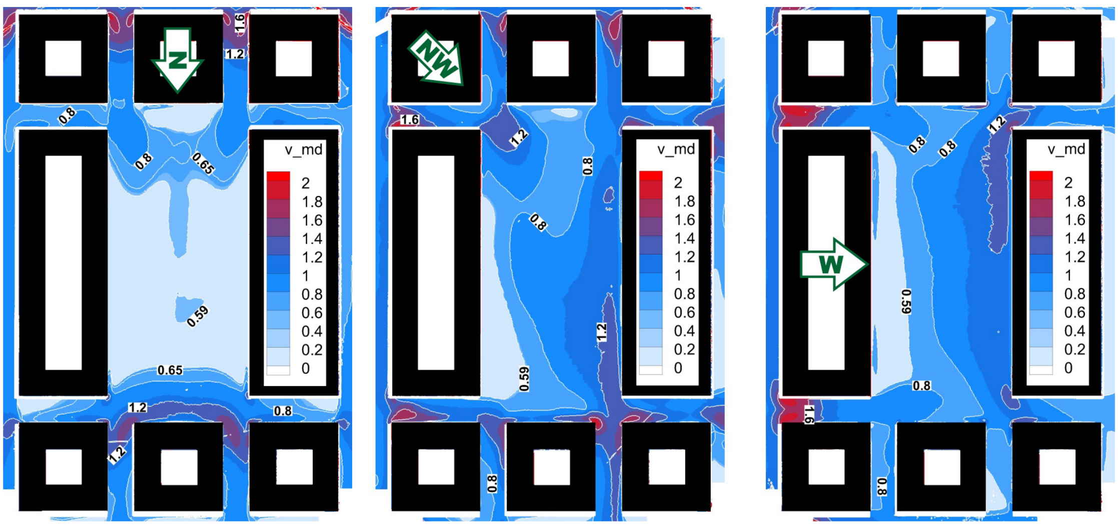

Figure 2. Sand erosion results for normalized mean wind speed at various wind directions.

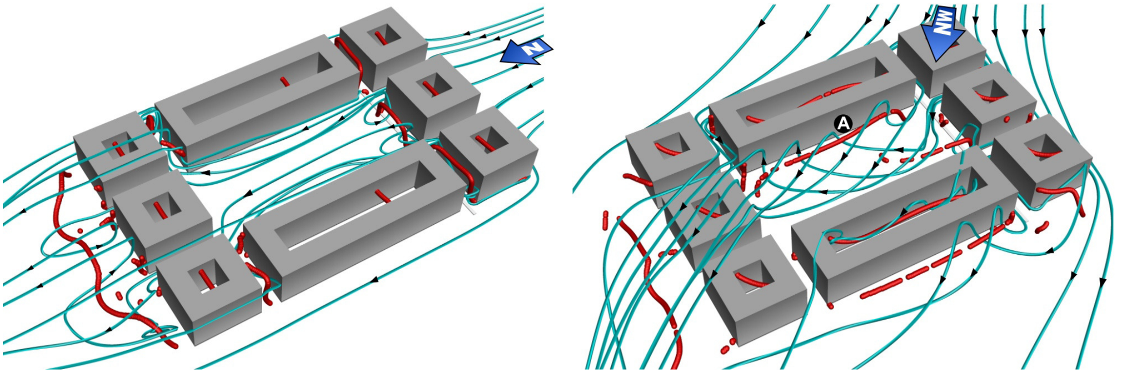

Figure 3. Flow structures at north and north-west wind direction. Note the large helical vortex dominating the square at north-western wind (marked by A)

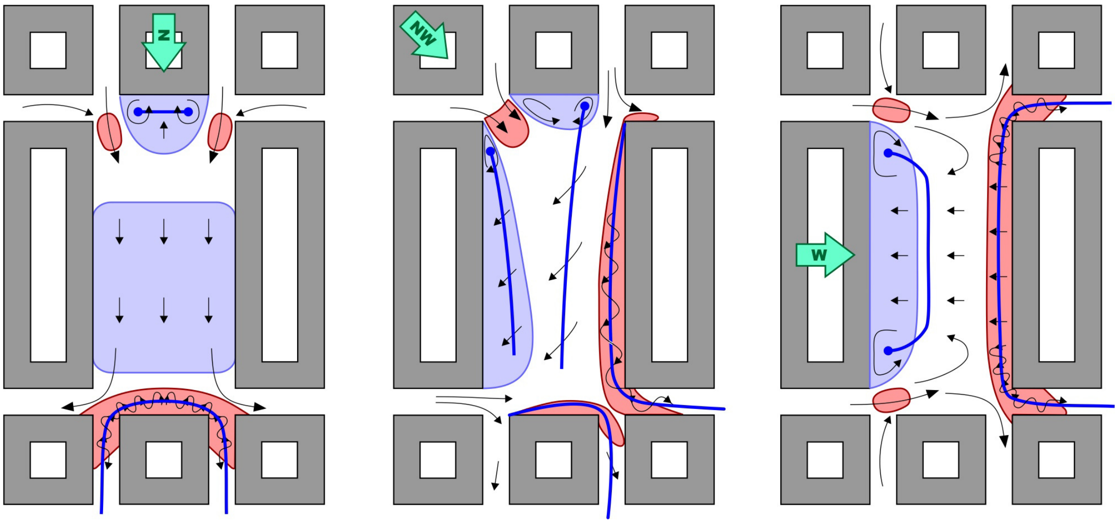

Figure 4. The schematic flow fields in the simplified square at various wind directions. Black arrows: pedestrian level wind directions, thick blue lines: vortex cores, purple areas: high wind speed zones near the ground; light blue areas: low wind speed zones near the ground.

Calculation of vertical flow component

Traditional 2D LDV probes can only access wind tunnel models of urban areas from above thus they are able to measure only the horizontal velocity components u and v. However, the measured mean horizontal flow field ($v_{Hor,\, d}$) let us calculate the vertical velocity gradient based on the continuity equation:

$$-\frac{\partial w}{\partial z} = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = div(\underline{v}_{hor}) \quad (1)$$

using the approximation that close the ground, where vertical velocity component should vanish, the velocity gradient can be approximated by the vertical velocity divided by the distance from the ground h, we can calculate the vertical velocity as follows:

$$\frac{\partial w}{\partial z} \approx \frac{w}{h} \Rightarrow w \approx -div(\underline{v}_{hor}) \cdot h \quad (2)$$

Using the 'divergence' method, we calculated vertical velocity components as well. Fig. 5, centre and right show the horizontal and vertical velocity field at western wind direction. Vertical velocity components indicate large updrafts and downdrafts, that prove the existence of a steady vortex with horizontal axis dominating the square. One can also observe street canyon vortices in the connecting streets (southwest and northeast corners of the square).

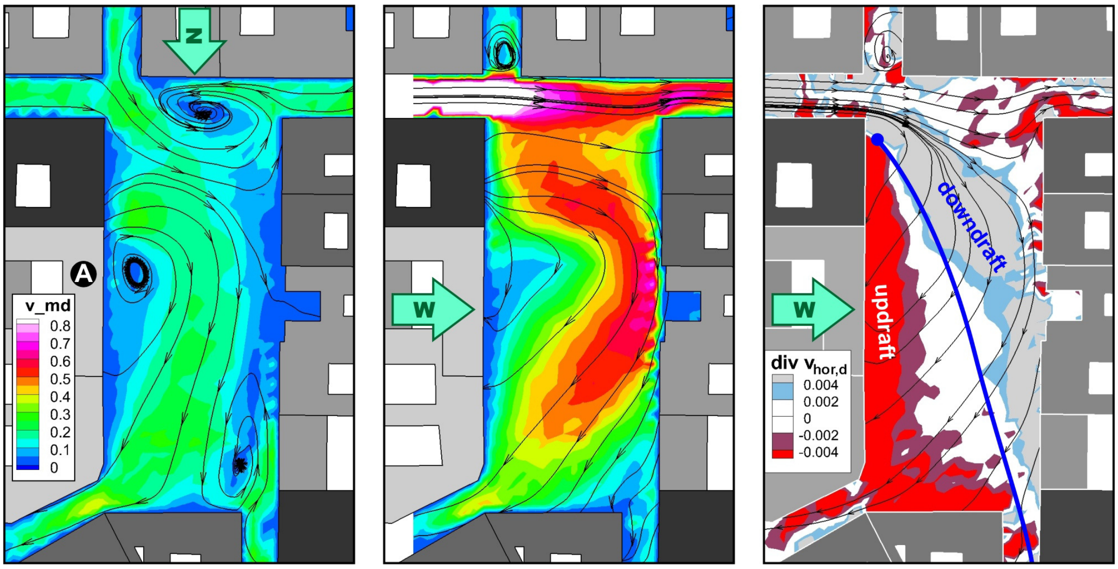

Figure 5. Left: LDV flow field results at 0.5*h* height in the complex square at north wind direction; centre: at west wind; right: calculated vertical velocity using the divergence method. Note the strong helical vortex

In Fig. 6, the schematic flow maps of the real urban geometry, based on the LDV results are shown. Notable is the similarity of the map shown on the right (western wind direction) to the flow field observed at northwest wind direction in the simplified square (Fig. 4, centre).

Representation using wind roses

Simultaneous *u* and *v* time series captures by LDV can be visualised by wind roses (polar area diagrams). In Fig. 7., one can identify several locations, in which wind roses show strong turbulence anisotropy, and double or even triple peaks. Such a flow behaviour can be caused by periodic or mode-locking flow changes, and have a large impact on the pollutant dispersion, too (see e.g. the observations of Klein et al. (2011) made at smoke plume dispersion visualisation in an urban area). The typical locations where such wind roses were found are: (a) streets, in which flow direction is changing by 180° (wind rose No. 3); (b) street intersections where flow comes either from one or from the other connecting street (wind roses 26, 27); (c) near the core of quasi-steady vortices, the slight movement of which can cause a full flow reversal (wind roses 5, 11).

The results of our investigation are analysed in more detail in the papers of Balczó and Lajos (2015) and Balczó and Tomor (2016).

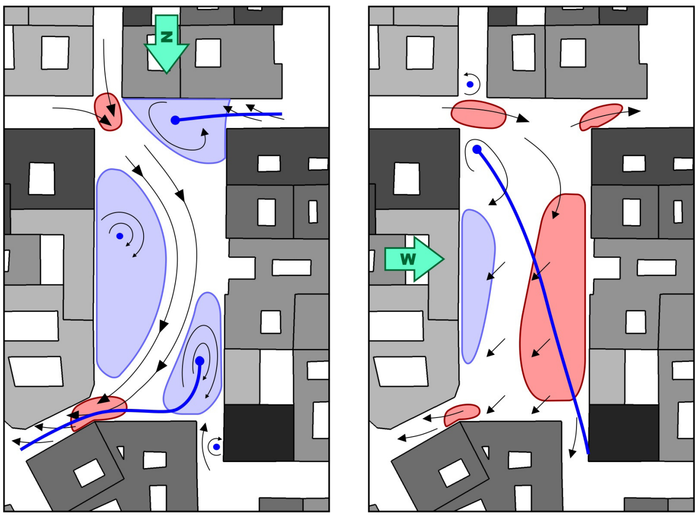

Figure 6. The schematic flow fields in the complex urban square at various wind directions

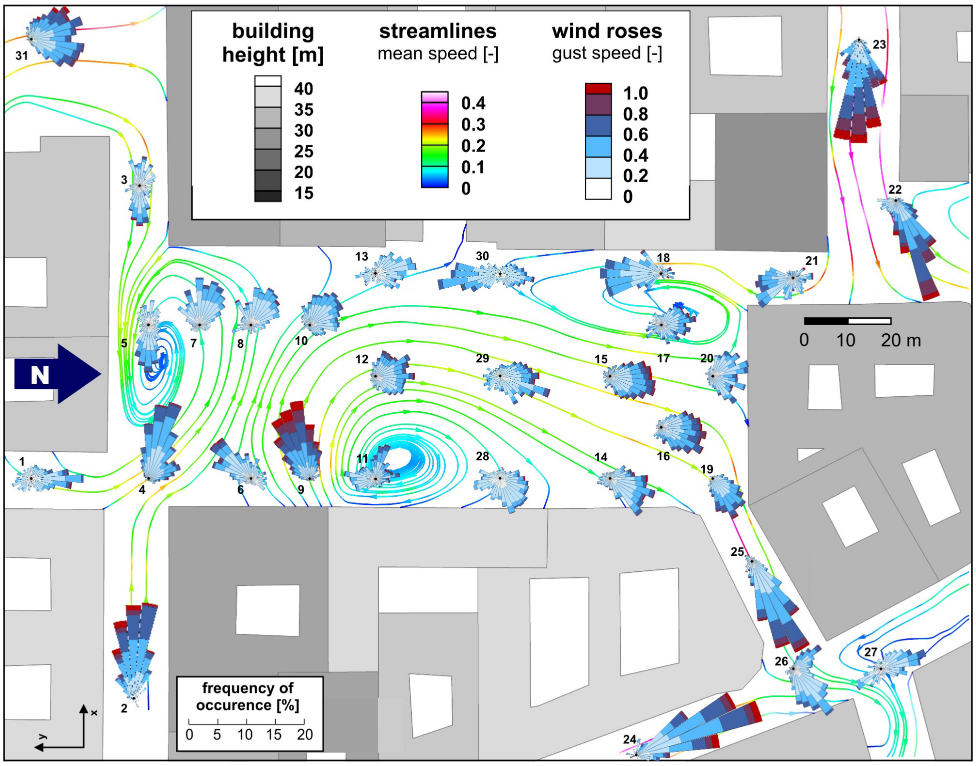

Figure 7. Flow field and wind roses at northern wind direction at 0.5 h height. Streamlines are coloured by average velocity magnitude v_{md}, and wind roses by the magnitude of the instantaneous wind vectors

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