Modelling of flow and pollutant dispersion in urban squares

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A short summary of the thesis submitted for the degree of doctor of philosophy

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2015
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Introduction

Urban squares can be defined as open spaces bordered by blocks of buildings. Squares often feature trees or shrubberies, and between the building blocks, streets connect the square to the neighbouring areas (Fig. 1). About 50 squares can be identified in the 30 km$^2$ area of the inner city core in Budapest. Squares fulfil important functions in urban life: they facilitate playing and sporting grounds, dining opportunities, markets and open-air events. In summary, they contribute to the quality of urban life and also to the attraction of a city to its visitors.

The motivation to study the wind conditions and pollutant dispersion in urban squares is further enhanced by the fact that the creation of new squares is a frequent part of urban redevelopment programmes. This is often based on the common assumption that squares improve ventilation and air quality; however the influence of such an action on the ventilation of an area is not documented in the literature. The flow and dispersion conditions in urban squares themselves have not been investigated thoroughly yet.

Fig. 1 Left: Eötvös Square and József Nádor Square in Budapest, with significant vegetation. Right: am Hof in Vienna, with underground car park.
The literature available on the ventilation in urban squares (Gadilhe et al., 1993, Parra et al., 2010, Bastigkeit, 2011, Fig. 2) made notable observations, and provided valuable measurement and simulation results about urban squares, but the analysis of wind conditions in squares, and a systematic assessment of squares from the ventilation and air quality point of view has not yet taken place. It is also obvious, that more detailed measurements and/or simulations are necessary to the successfully accomplish these tasks.

**Aim of the thesis**

The main direction of my research was thus the exploration of flow structures and pollutant transport mechanisms following the methodology often applied in the literature:

1. Investigation of an urban square with simplified geometry with the purpose to draw conclusions on the squares ventilation and air quality which are easy to generalise, and can be applied to other squares;
2. Investigation of a square with real, complex geometry to see if the observations made in the simplified case really apply;
3. The utilise the observations made about squares in practical applications and answer the questions:

   a. How does the creation of a new urban square in a built-up area influence ventilation and air quality of the neighbourhood?

   b. Are there techniques, methods to mitigate air pollution in urban squares?

**Investigation methods**

For my investigations, I applied wind tunnel testing, a traditional, established method of environmental aerodynamics, and computational flow simulation (CFD), a modelling method of ever growing importance since the 1990’s.

The wind tunnel tests were performed in the small, closed test section NPL type wind tunnel and the large, horizontal, Goettingen-type wind tunnel of the Theodore von Kármán Wind Tunnel Laboratory of the Department of Fluid Mechanics (Fig. 3). Model scale varied between 1:350 and 1:650, the measurement techniques included sand erosion technique (Livesey et al., 1990), laser-Doppler velocimetry (LDV) (Ruck, 1987), and dispersion measurements based on methan tracer release and sampling (Balczó et al., 2006). The parameters of the boundary layers generated in the wind tunnels were adjusted and checked according to the guideline VDI 3783/12 (VDI, 2004).

Fig. 3 Measurement arrangement of a square model in the large horizontal wind tunnel.
For my CFD simulations I applied the MISKAM model, which solves the Reynolds-averaged Navier-Stokes equation with a modified version of the Kato-Lauder $K-\varepsilon$ closure (Kato and Launder, 1993) on a non-equidistant Cartesian grid. The model is developed by Dr. Joachim Eichhorn at the Johannes-Gutenberg-University of Mainz (Eichhorn és Kniffka, 2010) specifically for urban flow and dispersion simulations. Due to its simple user interface, rapid solver, the model found widespread use in the environmental planning, air quality and regulatory field.

As a member of the European COST research Action 732 „Quality Assurance and Improvement of Micro-Scale Meteorological Models” (Britter and Schatzmann, 2007) I had the opportunity to validate the MISKAM model using the Mock Urban Setting Test (Leitl et al. 2007) wind tunnel data set. Based on the outcome of the validation, the MISKAM model can be seen a state-of-the-art model for microscale urban dispersion studies.

An important feature of urban squares is the vegetation planted on them, the influence of which on flow and pollutant dispersion cannot be neglected. These effects are (1) the aerodynamic drag acting on leaves, decelerating the flow; (2) the decrease of turbulence and its length scale (large vortices of the incoming flow are broken up by branches and leaves); (3) the increase of turbulence on smaller scale (caused by separating vortices from branches). These affects are taken account of by vegetation parametrisations, extending the model equations in CFD models. The parametrisation proposed by Green (1992) was implemented in the MISKAM model by Ries and Eichhorn (2001).

I validated the vegetation module of MISKAM using the CODASC data base of Gromke and Ruck (2008). The database contains numerous sets of flow and tracer concentration data in various street canyon configurations including tree plantings of different density. I found that the CFD model overpredicts the concentrations by about 30% at wind direction perpendicular to the street canyon, however, the concentration change caused by the presence of vegetation is well predicted.
Fig. 4 Flow structures in a street canyon with vegetation at slanted incident flow angle. Thick red lines indicate vortex cores, cyan coloured stripes are streamlines.

Besides of the validation of the vegetation parameterisation, I also applied a vortex core detection method to visualise the influence of tree plantings on the flow structures (Fig. 4). Using this, I could show that the displacement of flow structures, vortex cores due to vegetation – clearly observable in both the wind tunnel results of Gromke (2008) and the MISKAM simulations I performed – plays a role in the disproportional change of pollutant concentrations observed in some parts of the street canyon.

**Results and discussion**

The sand erosion tests, tracer concentration measurements I performed on the simplified square model, and the CFD simulations showed excellent agreement in most locations of the square. Notable disagreement was only found near the windward building block, where measurements indicate the presence of a horseshoe vortex, while simulation failed to predict it.

I summarized the experimental and numerical results in schematic figures for each investigated wind direction, which indicate the areas of low and high local wind speed, the ground-level wind direction and the location of major vortices.
(see e.g. Fig. 5, left). One of the important observations was that the flow in the square influences the ventilation of connecting streets as well: the horseshoe vortex mentioned in front of the windward building block increases local wind speeds, but also induces air movements in the streets perpendicular to the incident wind direction.

Fig. 5   Schematics of the flow at northerly wind direction. Left: simplified square geometry; right: real square geometry (Budapest, József Nádor Square).

A real, complex urban square geometry was measured using LDV technique (see Fig. 3). The horizontal $u$ and $v$ velocity components were measured in the square at horizontal planes with high spatial and temporal resolution.

The vertical $w$ velocity component could not be measured using a traditional 2D LDV optics due to the lack of side access. To estimate the vertical velocity component in a horizontal plane close to the ground surface, I introduced a simple method, based on the continuity equation, using which one can determine the locations of major up-and downdrafts in the model of an urban area from the horizontal $u$ and $v$ velocity components measured in the same horizontal plane:
\[
\frac{\partial w}{\partial z} \approx \frac{w}{z_{\text{plane}}} \Rightarrow w \approx -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \cdot z_{\text{plane}} - \text{div}(v_{\text{hor}}) \cdot z_{\text{plane}}
\]

with \(z_{\text{plane}}\) - the height of the measurement plane above ground, \(v_{\text{hor}}\) is the horizontal velocity vector \((u,v)\).

The results from the measurement in a real urban square suggest that the asymmetry of connecting side streets and the varying height of the buildings bordering the square modify the flow structures observed in the simplified square geometry. When comparing the two schematic figures in **Fig. 5**, the difference in ground-level wind speed and direction becomes obvious.

![Fig. 6](image-url)  
**Fig. 6** Wind roses and mean wind field in the southern part of József Nádor Square, at half building height (14 m).

The simultaneously measured \(u\) and \(v\) horizontal velocity component time-series allowed the analysis of flow intermittency in the square. I introduced wind roses, known from meteorology, but not used in microscale wind tunnel studies, to visualise wind speed and direction occurrence frequency (**Fig. 6**).

Based on this, I was able to identify locations in the square and the connecting streets where flow turbulence is non-isotropic, and I could determine the direction(s) of anisotropy. As opposed to the open space of the square, such locations can be found in streets, where flow fluctuations perpendicular to the
street axis are dampened by building walls (24, 25 in Fig. 6). In streets, street intersections, and near vortex cores, the flow is often switching between two or more flow directions (modes) indicated by wind roses with two or more distinct spokes (21, 26, 27).

![Diagram of urban square](image)

**Fig. 7** The urban square to be created by the removal of buildings as investigated in the *Boreas* project. Colour scale: change of rush hour NO\textsubscript{x} concentrations due to the removal of buildings in half building height (12 m) at southerly wind direction.

The flow structures and dispersion mechanisms observed in urban squares were also demonstrated in a case study at various wind directions. The *Boreas* project dealt with a built-up urban area on which some buildings were demolished thus a new square was created. Based on the CFD simulations for both cases (before and after demolition), wind speed increased in both the square and the connecting streets. In case of the wind direction shown in **Fig. 7** we see the change of air pollutant concentrations. While air quality improves on the windward side of the square, we see an increase in some connecting streets. Thus a general conclusion about the positive effect of urban squares on air quality cannot be drawn; a precise answer can only be given based on wind
tunnel tests or CFD simulations of the actual square performed for multiple wind directions.

Creation of a new square or transformation of an existing one is often accompanied by plans to construct an underground car park beneath it. Car emissions released in car parks and the powerful ventilation system needed to ventilate the car park can modify ventilation and air quality of a square. In the closing section of my thesis I presented a case study in József Nádor Square, in which I showed that with the proper design of a car park’s ventilation system, pollutant levels near the surface of the square can be decreased. Similar, active pollution mitigation principle was presented by Mirzaei and Haghighat (2010), however the utilisation of the considerable flow rate (~100,000 m³/h) of a car park ventilation system for this purpose is not mentioned in the literature.

Fig. 8 Ventilation concept of the underground car park planned underneath József Nádor Square. The colour scale indicates expected annual NOx concentration changes due to the operation of the car park.
In case of the planned car park, the ventilation air has to enter the car park through the exit ramps (blue arrows in Fig. 8), where the specific emission of vehicles is the highest. In this way polluted air in high concentration is removed from the square. The ventilation air passing through the car park must be released through a ventilation stack above rooftop level (red arrows), to avoid any concentration increase near the ground and at the buildings.

The method was checked using CFD simulations, and average annual pollutant concentrations were determined for the case before and after the construction of the car park. The colour scale in Fig. 8 shows the change of annual NOx concentration levels caused by the operation of the car park, and its ventilation system. An increase is only visible near the exit ramp and at road segments with increased traffic. In a large area of the square concentrations decline, the average improvement in air quality predicted by CFD is about 3–4% in the control points located on the square (black boxes).
Thesis statements

Statement 1.

I investigated flow and dispersion phenomena in urban squares using wind tunnel model experiments and CFD simulation. During this, I extensively validated the CFD model MISKAM and found fit for its purpose.

I concluded that in a square, bordered by buildings from all sides, air exchange is determined by in- and outflow through the connecting streets. This in-and outflow generates a unique combination of the flow structures already known from the flow around single buildings and in street canyons. This combination of flow structures determines wind speed, direction and turbulence near the surface of the square.

I observed that on the upstream side of the square, the inflow from connecting streets causes local high-speed jets near the ground. At perpendicular wind direction, the building block at the downstream side of the square generates a horseshoe vortex. This increases local wind speed near the ground, and forces a part of the flow coming from the square into the side streets in crosswind direction. At slanted wind direction, I observed a helical vortex with horizontal axis, covering the majority of the square, because of which flow direction near the ground is perpendicular to the incident flow direction.

I also observed that if the height of the buildings bordering the square is strongly different, the developing side separations modify the flow field in the square.

I introduced wind rose visualisation of two-component, time-resolved wind tunnel velocity measurement data. This method is known from meteorology but has not been applied in microscale wind tunnel measurements yet. The visualisation allowed drawing conclusions about the relationships between square geometry, the location of flow structures and the local anisotropy of turbulence.

Related publications: [1, 2, 5, 7-9].
Statement 2.

I investigated the dispersion patterns of the pollutants released along one of the tangential streets bordering an urban square using CFD simulations and wind tunnel tests. I determined the relationship between the concentration field and the flow structures described in Statement 1.

I observed that wind blows parallel to the longer axis of the rectangular square – in case the street emitting pollutants is on the leeward side of the square – the separation bubble of the leeward building block elevates the pollutants released at the surface, thus decreases concentration at ground level in the square. The inflow coming from the streets oriented parallel to the incident wind direction on the leeward side of the square cause local concentration peaks in the square at ground level.

At slanted wind direction – in case the street emitting pollutants is on the leeward side of the square – the helical vortex in the square and the front separation of the windward building blocks cause a remarkable concentration difference on the opposite sides of the square.

In case the incident wind direction is parallel to the pollutant emitting road segment bordering the square, there is no measurable concentration at the opposite half of the square. This phenomenon is in line with the properties of the flow structures identified in Statement 1.

Related publications: [7, 9].

Statement 3.

I proposed an active method to mitigate pollutants in the square using the modified ventilation system of the car park underneath the square, the effectiveness of which I checked using CFD simulations.

The required high ventilation flow rate of an underground car park is in the same order of magnitude as the airflow through a small urban square at low wind speed conditions.

Sucking the ventilation air needed from a highly polluted area in the square, one can remove significant amount of pollutants from the square. The proposed location is the exit ramp of the car park, where specific car emissions are the largest. This way the high local pollutant concentrations in a square can be decreased in comparison to the original situation without car park.
The ventilation air sucked into and passing through the car park must be exhausted through a ventilation stack above rooftop level to avoid any additional pollution in the square and its vicinity.

This pollutant mitigation method can be optimised knowing the influence of the identified flow structures on the concentration field.

Related publications: [6, 8]

Statement 4.

*Considering the frequent occurrence of vegetation in urban squares, I investigated the characteristics of the built-in vegetation parametrisation of the MISKAM CFD model regarding its influence on pollutant dispersion. I drew conclusions about the influence of urban vegetation on flow field and pollutant dispersion.*

I concluded that the MISKAM model, solving the Reynolds-averaged Navier-Stokes equation with a $K-\varepsilon$ turbulence closure and treating vegetation as a porous medium, predicts concentration distributions in a street canyon very similar to the wind tunnel measurement results of the CODASC database established by *Gromke and Ruck (2008).* I learned, however, that the model overpredicts concentration changes caused by the vegetation. The magnitude of overprediction can be reduced to a modest level when using the new, more sophisticated numeric schemes of MISKAM’s new version 6.

To visualise the complex influence of vegetation on the flow field, I first applied a vortex core detection method. I showed that the displacement of vortex cores due to the presence of vegetation indicates a disproportional change of pollutant concentrations in some parts of the street canyon.

Related publications: [3, 4].
Statement 5.

*I introduced a simple method to estimate the vertical velocity component w based on the continuity equation, if only the distribution of the horizontal velocity components u and v were measured in a horizontal x-y plane. Using this method, the up- and downdrafts can be identified in the model of an urban neighbourhood.*

The vertical gradient of vertical velocity component w near a horizontal ground surface can be approximated by the quotient of vertical velocity w and the height above ground. At the same time, the vertical gradient of w can be calculated from the divergence of the horizontal flow field (u, v) as well. Thus, knowing the distribution of the horizontal velocity vectors in a x-y plane near the ground, we can estimate the distribution of the vertical velocity w in the same plane.

Related publications: [9].
Publications related to thesis statements


Other publications of the author on the topic

In peer-reviewed journals


In conference proceedings


References


