COMPARISON OF WIND TUNNEL MEASUREMENT AND NUMERICAL SIMULATION OF DISPERSION OF POLLUTANTS IN URBAN ENVIRONMENT

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ABSTRACT: Air quality in the urban environment has become one of the most significant issues of environmental protection. Methods and experiments concerning wind tunnel investigations are reported in the paper, that are carried out on a 1:500 scale model of the planned new Millennium City Centre in Budapest. Simultaneously, flow field and pollutant dispersion simulations are performed using CFD codes as FLUENT®6.1 and MISKAM®. A comparison of the concentration distributions obtained from model experiments and numerical simulations is presented and discussed. Sand erosion method is used for prediction and evaluation of the impact of new buildings on the ventilation of the next district.

1 INTRODUCTION

Obviously, the architectural city-planning measures, new building design and the presence of other planned obstacles have influence on the ground level pollutant concentration caused by vehicle emission and on the pollutant loading originated from changing in traffic. Moreover, purposive prediction of the change in living conditions in regarding to wind comfort or the best available fresh air transport in the city is needed when city-planning are considered and the variations have to be evaluated. In the cases when control measures on atmospheric pollutant transport are needed for prediction, the field measurement tests can not be used. Wind tunnel investigations and numerical simulation are the tools that can be applied in planning and licensing procedures.

Recently, wind tunnel investigation became to be regarded as the most reliable tool for predicting pollutant transport. It is confirmed by several investigation reported, e.g., in Plate [1], Schatzmann and Leitl [2], Ketzel et al. [3]: if the modelling criteria are ensured then the pollutant transport in the atmospheric boundary layer /ABL/ can be modelled and properly determined in a wind tunnel. Application limits of numerical codes are broadening through the extensive development in CFD: the codes are more and more suitable for solution of complex flow problems in the fields of turbulent transport modelling.

Both of the applied CFD codes for general use (e.g. FLUENT®) and codes developed for calculation of pollutant dispersion in urban environment (e.g. MISKAM®) are more and more reliable tools for this purpose, see in Schatzmann and Leitl [2], Ketzel et al. [3].

A new Millennium City Centre is planned in the southern part of Budapest, parallel and close to the bank of the river Danube, limited by two bridges. The City Centre will include a row of relatively large buildings: a conference centre, museums, concert hall, hotels and residences. Since these buildings are planned to be built on the riverside of a busy (60000 vehicles/day) main street that is between the Danube and a district of Budapest, the possibility of an adverse effect from these buildings on the air quality in the neighbouring district has been supposed.

2 EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experiments have been carried out in the horizontal wind tunnel of the Department of Fluid Mechanics at the Budapest University of Technology and Economics. It is a low-speed closes circuit tunnel with an open test section with the length of 5.7 *m* and 2.6 *m* in diameter.

The ground was situated 0.8 *m* below the jet centre and was made aerodynamically rough by covering it with uniformly spaced roughness elements to simulate the lower part of an urban atmospheric boundary layer. In order to produce a thicker boundary layer, a differently spaced horizontal grid was placed at the beginning of the test section (Figure 1.). The combination of the grid and the surface roughness is resulted in simulation of an urban neutral boundary layer (VDI 3783 Part12 [4]) those properties are shown in Figure 1.

The vertical velocity distribution in fully developed boundary layer can be described by the power law:

$$\frac{u(z)}{u_{ref}} = \left(\frac{z \quad d_0}{z_{ref} - d_0} \right)^{\alpha} \tag{1}$$

Values of $\alpha = 0.29$ and $d_0 = 30mm$ are used as the profile exponent and the displacement height referred to the middle of the turntable, respectively. Since the transport of pollutants takes place between buildings, in street canyons, i.e. in the part of the atmosphere where the characteristics of flow field and turbulent transport are affected mainly by the flow past buildings, the role of the stability of the atmosphere can be neglected.

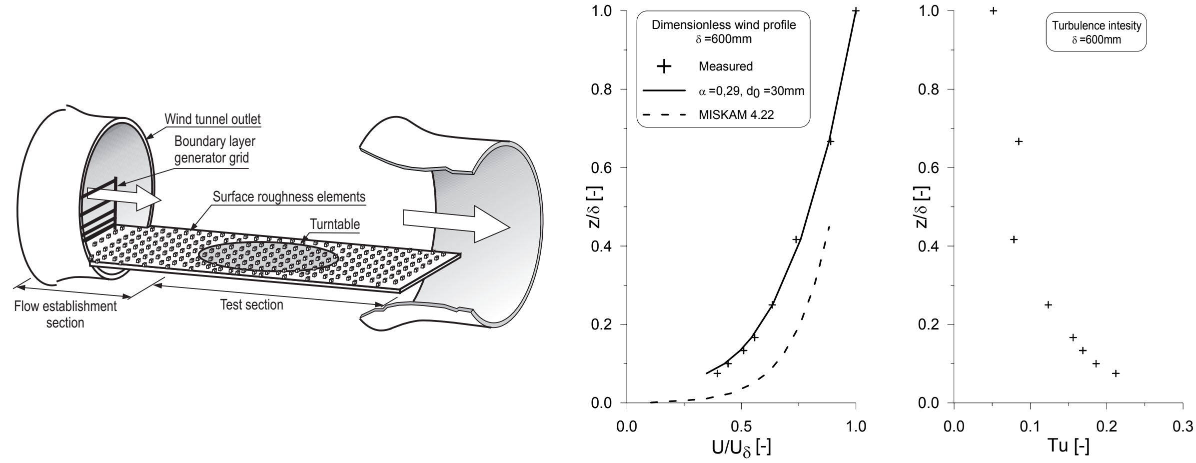

Figure 1. Test section of the wind tunnel (left), properties of the modelled urban boundary layer flow (right)

Five dominant wind directions were taking into account in dispersion tests. The sum of the annual incidence of these wind directions was 71 percent. Figure 2 shows the relative incidence of wind directions. The dark-grey area represents the data of the nearest meteorological base in front of the investigated area, at the opposite bank of Danube. The light-grey one corresponds to the data of the main meteorological station of Budapest. The selected wind directions represent the most frequent wind directions and those which could cause high concentration in the area of investigation (E and W).

The model is built to a 1:500 scale. Besides buildings, where relevant, trees and hedges are also modelled. The photo on the right in Figure 3 shows the model of the planned City Centre in the test section of the wind tunnel: the row of light coloured buildings on the right side, near to the Danube, the existing district (dark buildings on the left side), the busy road between them and the models of two bridges. The traffic emission is simulated by introducing tracer gas (methane) through line source elements that are placed in the middle of road surfaces (dotted lines, see Figure 3, on the left). These elements are designed after Meroney et al. [5] and covered by a canopy reducing the vertical momentum of jets and turning the tracer gas flow into the horizontal direction. The tracer gas flow rate corresponds to the present and predicted traffic data for the individual streets and also for the bridges.

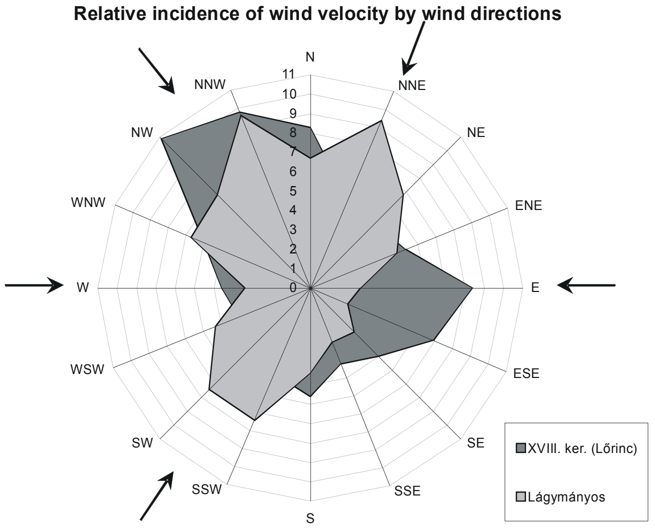

Figure 2. The main wind directions for the dispersion tests

In all tests, the emissions are determined by analyzing samples simultaneously collected from 24 measuring points of the model. 16 points of that are situated in the district (among existing buildings) and the rest 8 points is located in planned area. Figure 3 shows the position of the line sources (dotted lines) and numbered sampling points. The traffic density in the street nearly parallel to the river (in the following busy street) is about four times higher than that of the street perpendicular to the river. The height of the tracer gas sampling tubes is 3*mm*, corresponding to 1.5*m* in full scale. The tracer gas concentration of the collected samples is measured by a flame ionization detector. The reference velocity is measured 600mm above the ground in model scale (z = 300*m* in full scale) by using a Pitot-static-tube and a pressure transducer.

The measurements are conducted with the Reynolds number, based on the velocity u_{ref} and the reference height H = 0.05*m* (25 *m* in full scale) higher than 10^4.

$$Re_{mod\,ell} = \frac{u_{ref} \cdot H}{\nu} \geq 10^4 \qquad (2)$$

This setting ensures of the similarity of the dispersion processes (VDI 3783 Part12 [4]). In this case the following equation applies for dimensionless concentration c^* in model and full scale:

$$\left[c^* = \frac{K \cdot u_{ref} \cdot H}{Q/L} \right]_{\text{model}} = \left[c^* = \frac{K \cdot u_{ref} \cdot H}{Q/L} \right]_{\text{full scale}} \qquad (3)$$

The concentration at 24 sampling points is measured for the five dominant wind directions (Figure 2, 3) with and without the model of the new City Centre. Calculating of the dimensionless concentration $c*$ at a given sampling point for the all wind directions, the frequency of different wind directions and wind velocities, the daily (and rush-hour) number of vehicles and the emission of a given pollutant (e.g., CO) for a vehicle-kilometre, the annual (and rush-hour) mean concentration value K [$\mu g/m^3$] can be calculated.

Further factors investigated are the influence of the City Centre on the ventilation of the neighbouring district as well as its effect on the wind comfort. For both purposes, the sand erosion test is used.

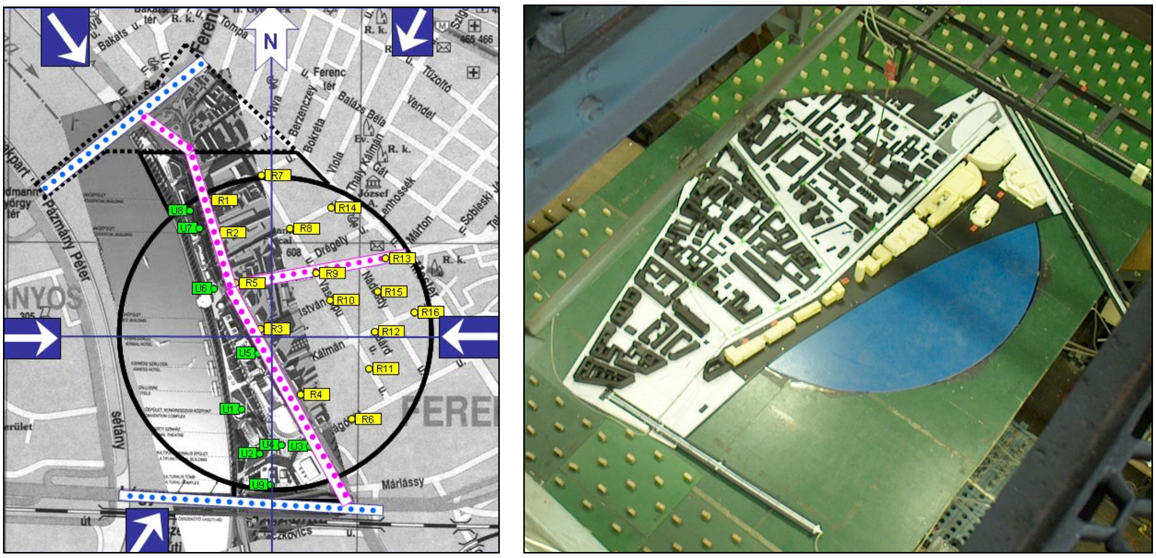

Figure 3. Modelled part of the city with line sources (dotted line) and sampling points (numbered)

A following method is developed to determine the average ventilation of the district under consideration. The sand erosion experiments are carried out at a given wind direction with and without City Centre. For different wind velocity values, the areas of sand erosion were summarized by digital post-processing of the pictures and comparing to the total area of streets and squares of the district model. The change of average ventilation for the district at a given wind direction as a consequence of the planned buildings can be predicted by comparing the wind velocity values with and without City Centre belonging to the same relative area of sand erosion.

3 *NUMERICAL SIMULATION OF FLOW AND POLLUTANT TRANSPORT*

Numerical simulation of the flow field and concentration distribution is performed with two different codes: MISKAM® 4.22 (with and without City Centre) and FLUENT® 6.1. (with City Centre only).

The micro scale prognostic flow and dispersion model of MISKAM® solves the 3D equations of motion with K-ε turbulence closure and the Eulerian dispersion equation for the flow and concentration field in a non-uniform Cartesian grid. The simplified geometrical model of the City Centre is taking the orthogonal grid system into consideration and neglecting the accurate modelling of roofs was built up using WinMISKAM® 1.94, the user interface of MISKAM® (Schatzmann and Leitl [2]) (Figure 4). The size of the model domain is 1250*m* x 1660*m* x 140*m* (129 x 172 x 40 = 887 500 cells). Neutral atmosphere is supposed. Wind speed is set to 3.1 *m/s* at 25*m* height. Near the ground logarithmic wind profile is used by MISKAM (See Figure 1). The computational time for one wind direction case is about 6 hours on a 2.4 GHz PC.

The flow and dispersion in City Centre and neighbouring district is also modelled using commercial multipurpose finite volume CFD code FLUENT® 6.1. Detailed geometry model of the area is prepared (Figure 4).

The flow in the wind tunnel model with City Centre building models is calculated with FLUENT®. Because of the special geometrical requirements, a non-structured mesh is created containing of tetrahedral elements.

The computational domain includes one kilometre empty surrounding space around the model buildings to avoid direct forcing effects of the boundary conditions. The height of the computational domain is 600*mm* that corresponds to 300*m* in full scale. The total computational domain includes 978000 cells. The computational time on a 1.8GHz processor is around one and a half day.

At the inlet, the velocity and the turbulence distribution are specified. The profiles of the distributions are taken from the wind tunnel experiments. At the outlet of the domain, constant pressure is prescribed as a second order type boundary condition. The sky is represented by a symmetry boundary condition.

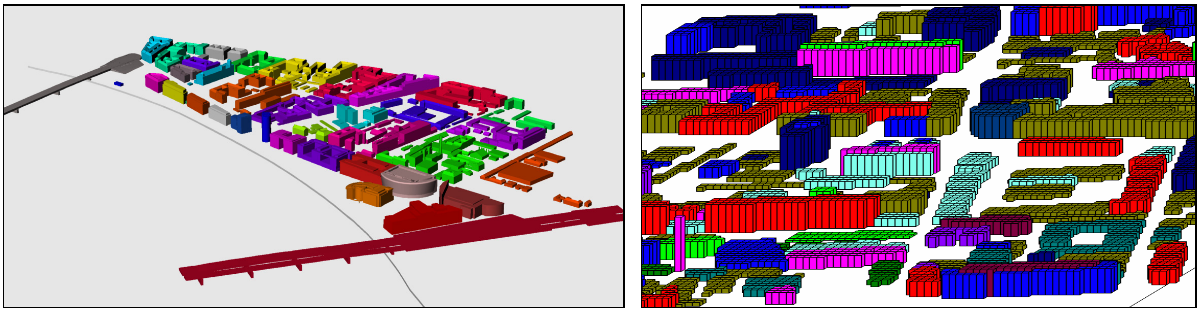

Figure 4. The geometry model of the area prepared for numerical simulation for FLUENT® (left) and MISKAM® (right)

„Realizable” k-ε model is used for modelling turbulence, which is a vortex viscosity model. The tracer gas is introduced through volume sources: cells above the given streets are separated from the others and the same amount of methane is introduced as it was at experiments. The details of introduction of tracer gas in the wind tunnel model through two gaps between ground and canopy covering the line source is not modelled at numerical simulations.

Detailed exposition of the numerical simulation can be found in Lajos et al. [6].

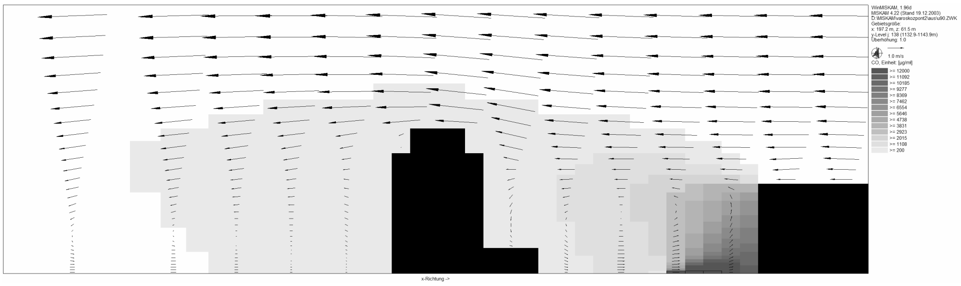

Figure 5. Wind speed and concentration distribution at E wind direction obtained by MISKAM® in the cross section of Soroksári street

4 *RESULTS AND DISCUSSION*

4.1 Results of concentration measurements

The main goal of the measurements is the determination of the modification in air pollutant loadings induced by architectural changing (effect of City Centre) and the increasing traffic caused by the novel role of the Danube bank.

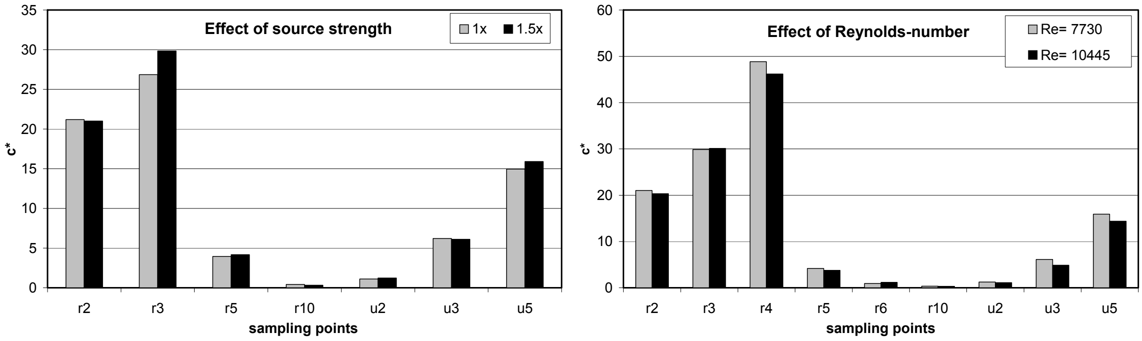

Figure 6. Effect of source strength (left) and Reynolds-number (right) on the measured concentration

Verification tests are also carried out to avoid the Reynolds-number effect and the source strength effect (Figure 6.). In case of NWNNW wind direction the reference velocity is chosen to u_{ref} = 3,13 - 2,32 *m/s* and the source strength is varied between Q=400-600 *l/h* thereby the values of dimensionless concentration, c* is in the range of ±2 percent. These tests are resulted in an acceptable accuracy when taking into account also the complex flow conditions. The left graph in Figure 6 shows the data of tests for source strength effect. No considerable effect is found in the case when one and half times higher gas release is applied. Correspondingly, the 1.35 times higher wind velocity has no effect on the dimensionless concentration.

Other important question is that how does the rather busy Petőfi Bridge (70.000 vehicle/day, see Figure 4, bridge on the north side of the area) the concentration distribution affect. The measurements are performed in case of NWNNW wind direction without City Centre. The graph on the left side in Figure 7 shows that taking into account also the release on the bridge, it causes only 5 percents increase in concentration. This indicates a quite rapid dilution of the pollutants due to the turbulent diffusion. In sampling points inside the district and the City Centre far from the traffic related emission (where the concentration is only few percent of that of sampling points in the busy street) the effect of the traffic on the bridge is quite considerable.

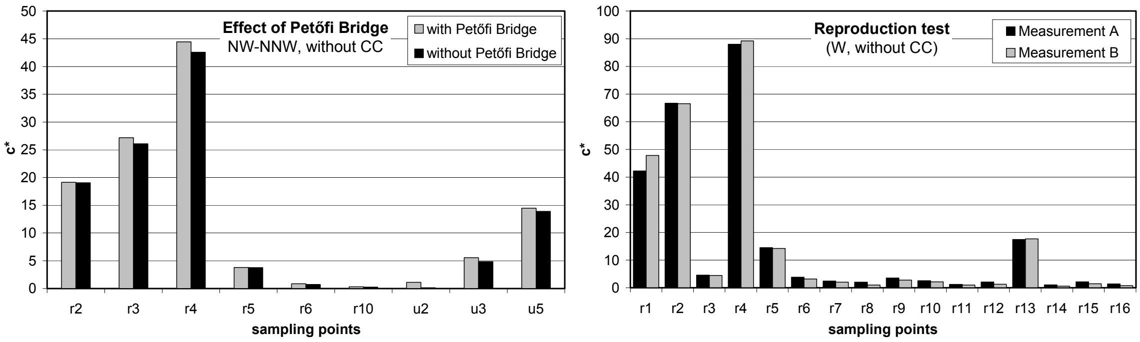

Figure 7. The effect of the emission released on the Petőfi Bridge (left) and the results of the reproduction measurements (right)

In case of W and NWNNW wind directions reproduction measurements are carried out. The results of measurements are conducted in same conditions, shown in Figure 7 on the right. No considerable change can be observed.

Beside of the main goal of the dispersion investigation, the classification of the pollutant transport is also aimed at. Several simple mechanisms can be observed like remote and near source, building flow, street channel, street vortex effects, etc. (See Figure 5). Detailed description of the classification of pollutant transport can be found in Lajos et al. [6].

Putting aside of the detailed description of every wind directions, only the summarized results are presented. The main goal of the measurements is to determine the effect of the City Centre on old district (inner part of the Ferencváros). In this respect summarized the results of the series of measurements some ascertainment can be taken.

In the inner part of district:

a) The pollutant concentration is generally low, the dimensionless concentration is varied between 0-3
b) Independently on the existence of City Centre in case of some wind directions the concentration is decreased while in others increased
c) Only in the Haller street (perpendicular to the busy street) exists high concentration value (c^{*}_{max} =14) caused by the considerable traffic

Eastern part of busy street (Soroksári street):

a) Very high concentrations exist without the City Centre (c^{*}_{max} =50-70)
b) In case of NNE wind direction the City Centre does not affect the concentration. In case of NWNNW wind direction just moderate while E wind direction considerable increasing can be experienced. For SWSSW and especially W wind direction significant decreasing can be observed.

The effect of City Centre on the annual daily and hourly mean CO concentration K [$\mu g/m^3$] is shown in Figure 8, determined from the measured dimensionless concentration c^* in sampling points belonging to different wind directions, the frequency of different wind directions and wind velocities, the daily number of vehicles and the CO emission for 1 vehicle-kilometre.

On the basis of the measurements, a reduction of the air pollution in the district under consideration (sampling points R1-R16) can be predicted. In the internal part of the district the change is negligible but in the busy street (sampling points R1-R4) the overall concentration reduction is 14%. These results include also the considerable (about 20%) increase of the traffic caused by the City Centre, too. In the area of the new City Centre the increase of concentration is significant (90%).

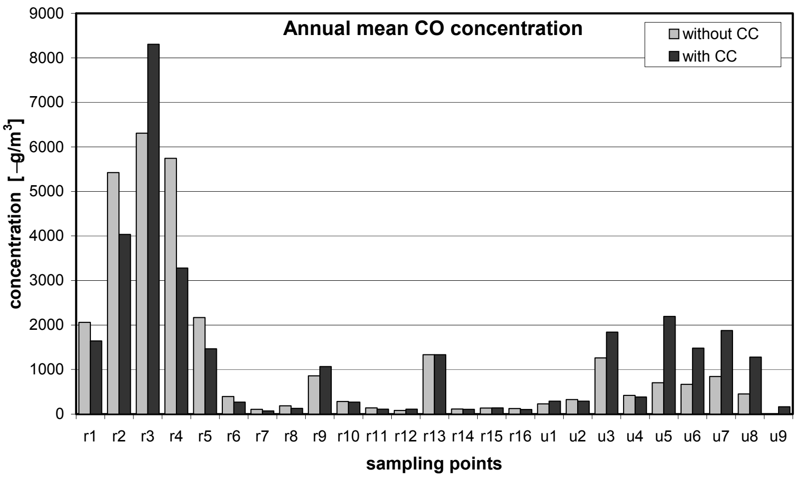

Figure 8. The effect of the City Centre on the annual mean CO concentration

4.2 Comparison of measurement and simulation

When comparing the results of simulation and measurements in the case of MISKAM® the concentration value belonging to the cell coinciding with the sampling point is taken. In the case of FLUENT® the spatial change of concentration has been substantial, particularly in points that are close to the emission source cells. That is why the results of FLUENT® simulation the concentration is determined differently. Concentration distribution has been plotted along the line of the cross section perpendicular to the street, including the sampling point, 1.5*m* over the ground. By taking the maximum and minimum values of this concentration distribution, a concentration interval is defined for all sampling points.

In order to compare the wind tunnel and CFD results the measured and calculated concentrations have been plotted as a function of wind direction. One example is shown for a sampling point near the busy street (Figure 9).

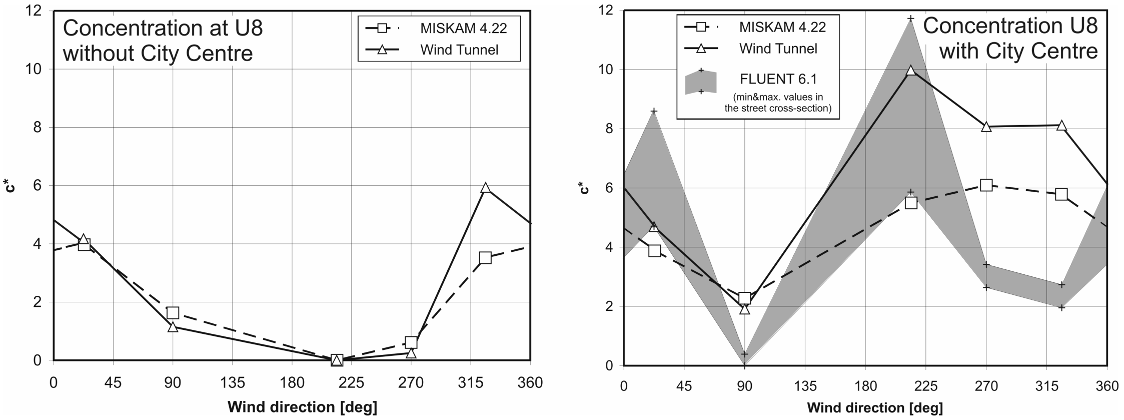

Figure 9. Measured and calculated dimensionless concentration plotted against wind direction for sampling point U8.

The concentration calculated with FLUENT® shows change across the street. There are considerable differences between measured and calculated concentration values but the trends of change reflected by both simulations are generally correct. Considering the sampling points close to the pollution source, the differences between measured and calculated values and the change of concentration across the street are in general larger. These differences can partly be explained by the inaccurate modelling of tracer gas release in case of the numerical simulation.

Considering the probabilities of wind directions, the annual mean dimensionless concentration can be calculated for every sampling point. Figure 10 shows the measured and calculated change of annual mean dimensionless concentration caused by the City Centre. It can be seen that the agreement between the measured and calculated mean values is quite acceptable in most cases and the trends of change caused by City Centre are correctly predicted in the 85% of the sampling points.

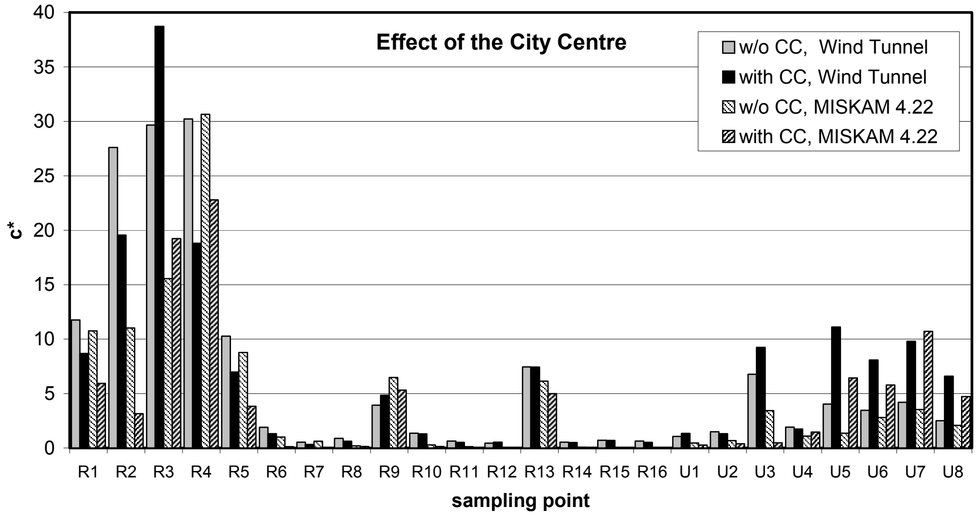

Figure 10. Annual mean concentration change measured in wind tunnel tests and calculated by MISKAM®.

In Figure 11 the annual mean dimensionless concentrations obtained from wind tunnel measurements and calculation with MISKAM® code as well as with FLUENT® (concentration interval) can be seen in logarithmic scale. The differences between measured and calculated values are considerable again, although 3/4 of the sampling points can the calculated concentration values be regarded as acceptable predictions of the measured ones.

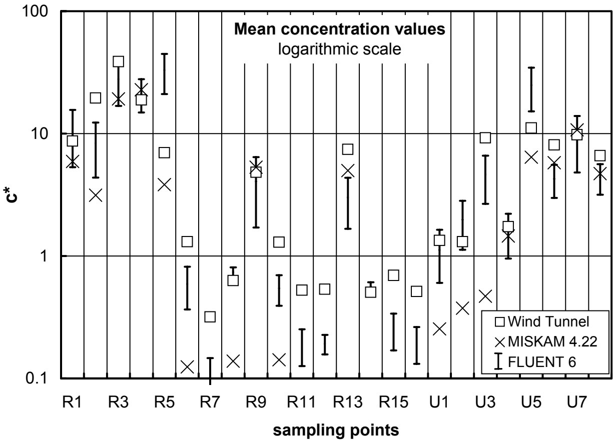

Figure 11. Comparison of MISKAM®, FLUENT® and wind tunnel test data: annual mean concentrations with City Centre.

4.3 Results of sand erosion test

A simple method is developed to determine the average ventilation of the interested area of this district.

A flat plate covered by a uniform thin layer of sand particles screened to size class of 0.2÷0.3*mm* is fixed to the turntable in the test section and the threshold velocity v_0 =3.4*m/s* (at the height of the mean buildings height) is determined where the erosion of the sand particles starts. The whole area of the model is painted previously to black. The streets and squares of the model are covered by a sand layer and gradually increasing wind velocity is set. For each wind velocity setting (v [*m/s*]) the areas of sand erosion (where the sand particles are removed from the black surfaces) are determined by taking photographs after 5 min. blowing.

For areas where sand erosion occurs at given v velocity, the v_0/v ratio (called as discomfort parameter, sometimes given in percent) indicates the local influence of the buildings on accelerating ($v_0/v < 1$) or decelerating ($v_0/v > 1$) of the wind.

a *b* *c* *d* *e*

Figure 12. Modified images of sand erosion tests (for SWSSW wind direction). Wind velocity increases from (12*a*) to (12*e*). Note, that negative images are shown.

The images of sand erosion test at given v wind velocity and the reference image (taken from the same covered by sand at zero wind velocity) are used for quantitative evaluation. Each image has to be taken from the same position with the same size and resolution. Post-processing and masking of the images are done by suitable way that the investigated (recent) area of the district is transparent and the outer regions are black (colour code: I_{cc}= 0). In the differential image of the reference one and one other taken at given wind velocity, buildings and the area covered by sand is black. The streets and other surfaces where the sand particles are removed became white (I_{cc}= 255). Therefore, areas in the modified image are black except the area where the sand is removed at the given wind velocity, see in Figure 12. but note, that in the paper negative images are shown. It can be seen that in case of low wind velocity (DP is high) the area of black part (white in Fig.12. negative image) is large (Figure 12. a,) and when the wind velocity is high (Figure 12*e*) the white (black in negative image) area is grown.

After post-processing of the images the mean intensity ($\overline{I_{DP}}$) of a differential image can be calculated the following way:

$$\overline{I_{DP}} = \frac{\sum_{i=1}^{N_{pixel}} I_{cc_i}}{N_{pixel}} \tag{4}$$

For the reference image the mean intensity ($\overline{I_{ref}}$) can be calculated the same way. The relative mean intensity (RMI) represents the efficiency of wind comfort and can be calculated as the ratio of the mean intensities of reference and another images belonging to a given DP (5).

$$RMI = \frac{\overline{I_{DP}}}{\overline{I_{ref}}} \tag{5}$$

Equal relative mean intensity means equal wind comfort (equal area covered by sand). For comparing the effect of various building allocations on wind comfort, the discomfort parameters at constant relative mean intensity and wind direction has to be determined.

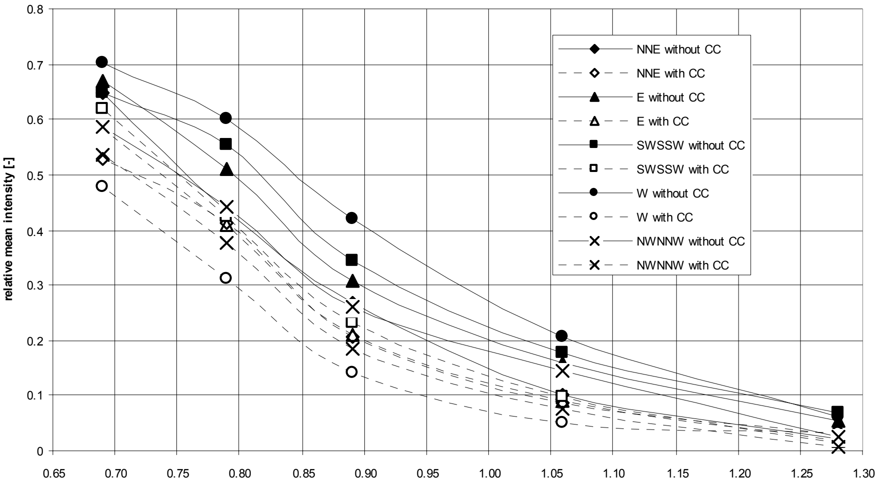

Figure 13. Relative mean intensity representing the wind comfort as a function of discomfort parameter.

In Figure 13 the relative mean intensity representing the wind comfort as a function of discomfort parameter can be seen. The continuous line denotes intensity values without the new City Centre and the dashed ones correspond to case with the new City Centre. If the value of mean intensity is 0,5 or 0,3 the variation of wind velocity so the wind comfort can be calculated (the curves run almost parallel in wide range of discomfort parameter).

Wind direction	Annual incidence of wind direction	Variation of wind velocity
NWNNW	19 %	-4.5 %
NNE	16 %	-2.7 %
E	14 %	-6.4 %
SWSSW	13 %	-8.5 %
W	9 %	-19 %
Annual mean		**-7 %**

Table 1. The effect of the new City Centre on the wind comfort

Table 1. contains of the variation of wind velocity as a function of the five most frequent wind direction. In case of W wind direction, the decreasing is considerable. The annual mean value takes into account the annual incidence of wind direction thereby the effect of City Centre is countable. The decrease in wind velocity is about seven percent.

5 CONCLUSIONS

a) Wind tunnel investigations are proved to be reliable tools for simulating the ventilation and pollutant dispersion in urban environment.
b) A simple approximation method for designating the effect of architectural change on wind comfort is developed.
c) Numerical simulation of the flow and the dispersion processes is a promising method for prediction of air pollution. The necessary increase in accuracy needs further improvement, particularly in proper modelling of pollutant emissions.

6 ACKNOWLEDGEMENTS

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