# Gaseous pollutant dispersion around urban-canopy elements: wind-tunnel case studies

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**ABSTRACT**: There is an evident lack of reliable and detailed *in situ* measurement data for verifying numerical predictions of atmospheric dispersion in the urban environment on sub-meso scales. Wind-tunnel studies of dispersion around typical elements of the urban canopy (isolated buildings, groups of buildings, street canyons) could provide valuable substitutes for field data sets. They can achieve a high resolution of the measured concentration fields, and may be used for evaluation of numerical models and for expert estimates of air quality in the urban environment.
This paper presents results of several case studies of gaseous pollutant dispersion in a neutrally stratified wind-tunnel flow. The following cases have been investigated: (1) Point source: (a) isolated rectangular building, and (b) isolated U-shape building; (2) Line source in a street canyon: effects of the upwind building configuration and the roof shape; (3) Line source in a city quarter (four blocks separated by two perpendicular canyons with rectangular cross-sections). For the case of a line source in a street canyon, the wind-tunnel results are compared with numerical model calculations.

**Keywords**: gaseous pollutant, atmospheric dispersion, concentration, isolated building, street canyon, street intersection, wind-tunnel modelling.

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## 1 Introduction

Dispersion of pollutants on the urban-canopy scales takes place in the close vicinity of pollutant sources and pollution impact targets. The main sources of pollutants in the urban environment are emissions from smoke and ventilation stacks (they may be regarded as point sources), and car exhausts (they may be represented by linear sources stretched along streets). Typical impact targets are pedestrian zones and living areas. Arrangement of sources and targets in urban areas is extremely variable, and formulation of a general approach for investigation of pollutant dispersion in the urban canopy is a very hard task. Lack of generalization is an obvious deficiency of all canopy-scale dispersion studies carried out so far. This is especially characteristic of experimental studies in the nature and, to a smaller extent, of laboratory studies. Data from both can hardly be used to draw general conclusions although they furnish essential insights on particular flow and dispersion regimes in the urban canopy (Mestayer and Anquetin 1995).

The canopy-scale dispersion is driven by three principal mechanisms, namely by dynamic, thermal, and chemical forcings. The experimental knowledge about the first of these mechanisms and about their interaction originates mainly from laboratory studies in wind tunnels. In order to enable verification of numerical model predictions against data of wind-tunnel experiments, one has to outline a group of basic urban-canopy elements, for which comparisons could be performed. These elements should include typical building shapes and characteristic urban-canopy configurations. In the present paper, isolated buildings of two typical shapes, rectangular and U-shape, are considered. With respect to the urban-canopy configurations, the study addresses an urban street canyon, either isolated or preceded by other canyons, and a perpendicular intersection of two rectangular street canyons separating four city blocks. Thus, we provide dispersion data sets for a range of increasingly complicated urban-canopy configurations.

There is a multitude of wind-tunnel studies of flow and dispersion around isolated buildings, see, for instance, Robins and Castro (1977), Li and Meroney (1983), and Ogawa et al. (1983). Of the variety of building shapes, cubic and rectangular ones have been studied extensively. In our study, mean concentration fields were measured around a rectangular building with two positions of a point source, and three building orientations with respect to the approach flow (Case 1a). The case of the rectangular building was used as reference for the study of pollutant dispersion around a U-shape building. For this more complicated case, the measured data sets include mean concentration fields for three building heights, three point-source positions, and five approach-flow directions (Case 1b).

Flow and dispersion fields inside and in the vicinity of an urban street canyon are other typical objects of laboratory (Wedding et al. 1977, Leisen et al. 1982, Hoydysh and Dabberdt 1988, 1994) and numerical (Yamartino and Wiegand 1986, Lévi Alvarès and Sini 1992, Johnson and Hunter 1995) model studies. The street-canyon studies carried out in the nature are much fewer. To be mentioned here are investigations by Chock (1977) and Rotach (1995). Due to obvious technical problems, most of these studies failed to achieve resolution of flow and dispersion measurements sufficiently high for tuning numerical models. Below we will present wind-tunnel data on dispersion from a line source placed between two rows of buildings (classic street canyon). The corresponding data set (Case 2) includes results of concentration measurements with different wind directions, canyon aspect ratios, source positions against the axis of the canyon, roof shapes, and for situations where one or two additional rows of buildings are located upwind of the street canyon. The case of a line source placed in front or behind one building row (one may consider this as a case of degenerate street canyon) was studied as well.

We have not found any references in the literature concerning experimental or model studies of the dispersion of pollutants near a street-canyon intersection surrounded by four city blocks. The simplest case of this kind with two perpendicular street canyons of the same rectangular geometry was investigated in the wind-tunnel and will be considered below (Case 3). Dispersion of pollutants from a line source placed in one of the canyons was simulated. The corresponding data set contains mean concentration fields for thirteen flow directions.

For Case 1b and for some basic street-canyon configurations from Case 2, results of wind-tunnel simulations have been compared with available numerical model data (Röckle and Richter 1995, Schädler et al. 1996). A comparison example for one street-canyon configuration is shown in Section 3.

## 2 Experimental setup

The experiments were performed in the boundary-layer wind tunnel of the Institute of Hydrology and Water Resources (IHW), University of Karlsruhe. The wind tunnel has a test section 10.5 m long, 2 m wide and 1 m high. A thick boundary layer is generated along the floor of the tunnel by vortex generators at the entrance of the test section, and by roughness elements of the test-section floor. The parameters of the flow velocity profile and the turbulence intensity are set similar to those in the atmospheric boundary layer according to the methodology given in Plate (1982). The vertical profile of the velocity in the approach flow is described by the power law

$$u / u_r = (z / z_r)^{\alpha} .$$

The values of the exponent $\alpha$, and the reference wind speed $u_r$ at the reference height $z_r$ varied for the different cases studied. They are given below within setup descriptions of the cases. The pollutant emission was simulated by air mixed with a tracer gas ($SF_6$). Concentration values were measured with a leak detector.

Diagrams of the investigated building configurations are presented in Figs. 1-3. The experimental program for the Case 1 (see Fig. 1) incorporated concentration measurements in the vicinity of an isolated building. Dispersion from point sources was studied. Setup parameters for this case were as follows: model to prototype scale $M$=1:200, $z_r$ =10 m (in the nature), $u_r$=$u_{10}$=5 m/s, and $\alpha$=0.28. In the rectangular-building option, (Case 1a), the building height $H$ was 14 cm, source positions were A and C, and wind directions were 0°, 120°, and 180°, as shown in the plot. In the U-shape option (Case 1b), building heights were 8, 14, and 20 cm, sources were located in positions A, B, and C, and the wind was blowing from directions 0°, 45°, 90°, 120°, 135°, and 180°. More detailed information about the experimental setup for the Case 1 is given in Klein et al. (1994).

In the street-canyon configuration, (Case 2), dispersion from a line source was investigated. The corresponding setup is schematized in Fig. 2. Model scale $M$ was 1:150, and the wind profile was represented by $z_r$ =100 m (in the nature), $u_r$=$u_{100}$=7.7 m/s, and $\alpha$=0.23. Line sources were placed in position A, which is at 35 mm distance from building I (see the plot), and in position B (85 mm from building I). Geometrical parameters of the buildings were as follows: $H$ =12 cm; $L$ = 60, 120, and 180 cm; $B1$=6, 12, 18, and 24 cm; $B2$ = $B3$ = $B4$ = 6 and 12 cm, $D$ = 12 and 18 cm (see Fig. 2 for notation). Concentration values were measured for wind directions 0°, 15°, 30°, 45°, 60°, 75° 90°. Number of building rows upwind the street canyon was varied, as well as roof shapes of buildings forming the canyon.

For the configuration of the street-canyon intersection, (Case 3), the model scale and parameters of the wind profile were the same as in Case 2. Building blocks were of the uniform height $H$ = 12 cm. Source A was placed at 35 mm, and source B at 85 mm distances from the walls of buildings I and II, see Fig. 3. Dispersion patterns were obtained for wind directions of -90°, -75°, -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60°, 75°, and 90°. Cases with different roof shapes of the buildings were investigated.

Technical details of experiments with street-canyon and street-intersection configurations are given in Kastner-Klein and Plate (1996).

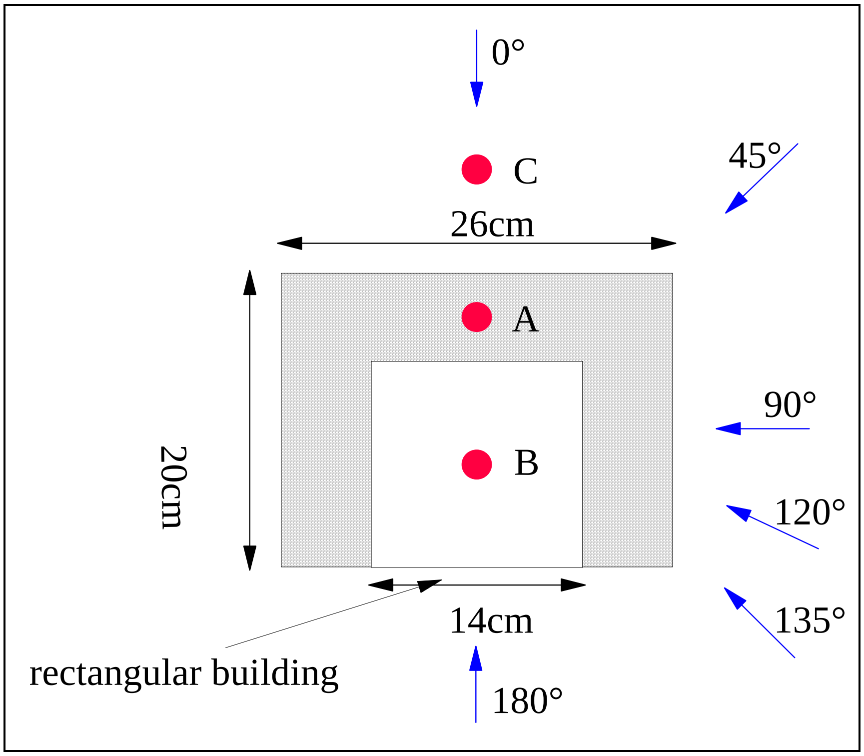


**Figure 1** Sketch of experimental setup for the Case 1a and Case 1b studies.

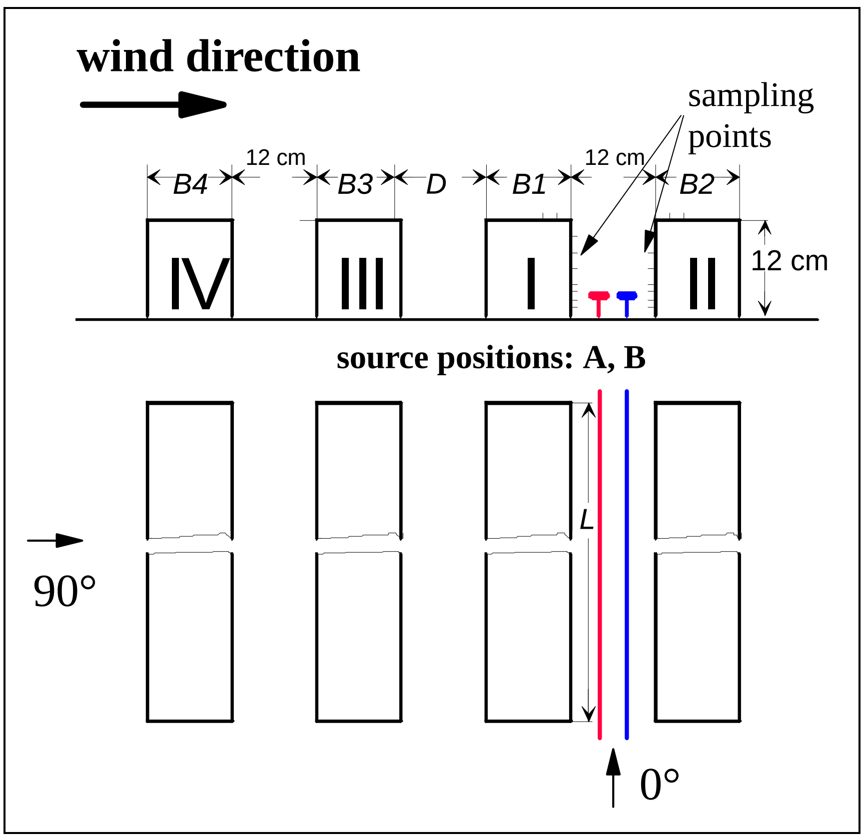


**Figure 2** Sketch of experimental setup for the Case 2 study.

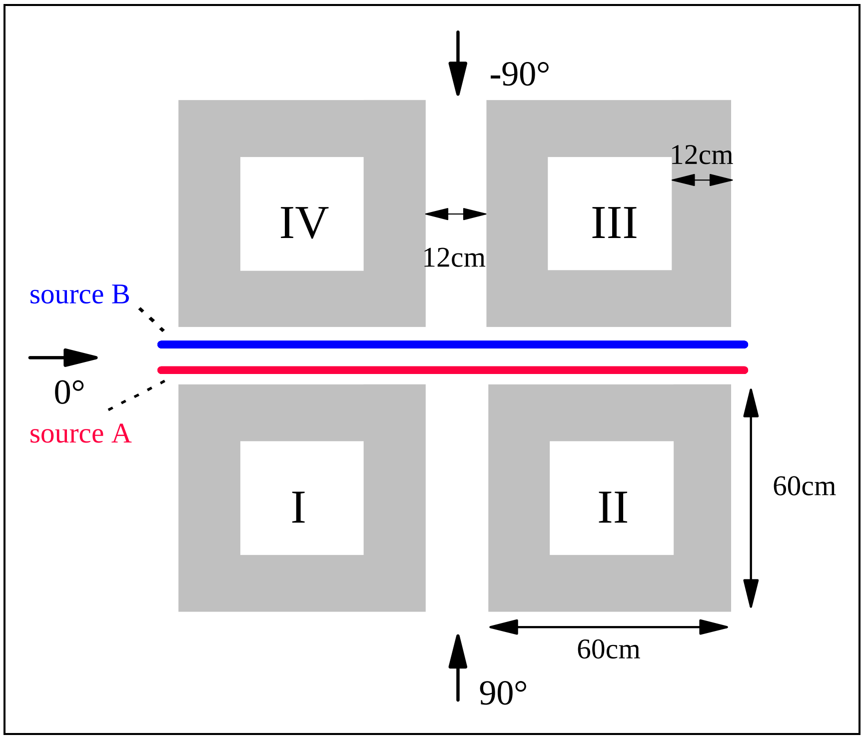


**Figure 3** Sketch of experimental setup for the Case 3 study.

## 3 Wind-tunnel results

*Case 1: Isolated building*

Two-dimensional distributions of mean concentrations in vertical planes *Y-Z* placed perpendicular to the flow at the distances $x$=20 cm, 40 cm, and 60 cm downwind the sources were measured during the wind-tunnel studies of dispersion around isolated rectangular and U-shape buildings. Figure 4 shows a comparison of the concentration patterns for these two building shapes, corresponding to source A, $x$=20 cm, building height 14 cm, and two wind directions, 0° and 180° (see also Fig. 1). Plotted concentration values are normalized: $c_n = c \cdot u_{10} / Q$, where $c$ is the tracer gas concentration in ppm, $u_{10}$ is the wind velocity of the approach flow at the height corresponding to 10 m in nature, and $Q$ is the source strength. The normalized concentration $c_n$ is given in $1/\text{m}^2$. For wind direction 0°, the peak concentration values and local gradients of the concentration field are larger in the case of a rectangular building. Nevertheless, concentration patterns for each building do not differ fundamentally at this wind direction. For wind direction 180°, the difference between concentration patterns for rectangular and U-shape buildings becomes substantial. The pattern for the rectangular building keeps an approximate vertical symmetry against the level of the source, while the pattern corresponding to the U-shape building is strongly shifted upwards. The observed differences display the strong effect of the courtyard of the U-shape building on the downwind flow configuration.

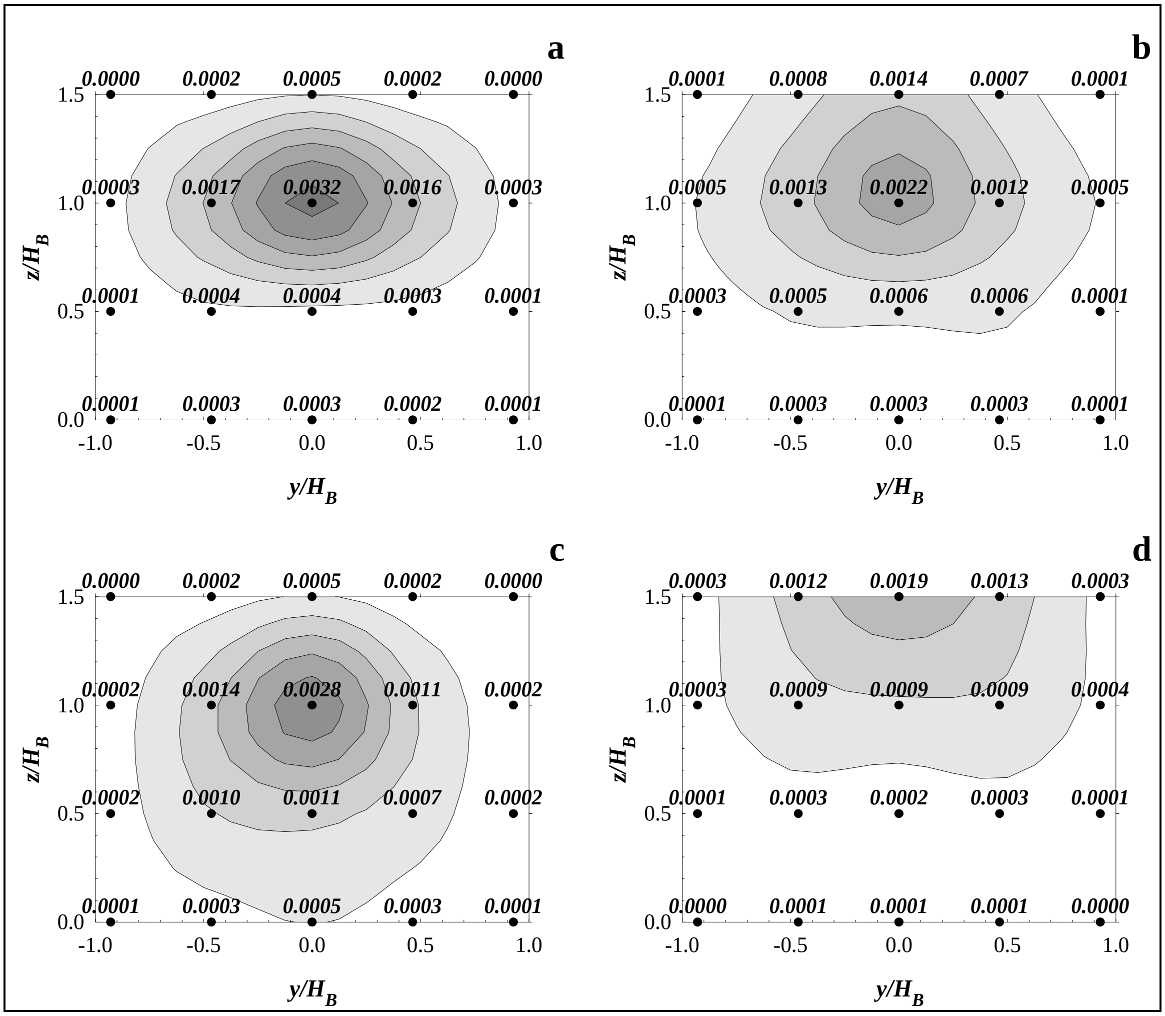


**Figure 4** Comparison of concentration patterns in the vicinities of rectangular (a: wind direction 0° and c: wind direction 180°) and U-shape buildings (b: wind direction 0° and d: wind direction 180°). Concentration isolines are given in a vertical plane *Y-Z* placed perpendicular to the flow at *x*=20 cm downwind source A. Both buildings are 14 cm high..

*Case 2: Street canyon*

In the street-canyon experiments, the mean concentration values were measured at the building walls. At least three near-wall vertical profiles in different horizontal positions were taken for all configurations shown in Fig. 2. Results for 180 cm-long buildings, placed perpendicular to the approach flow, are presented in Fig. 5. We consider this case as the two-dimensional one. Concentration profiles in Fig. 5 correspond to the building centre points ($y$=0). Two sampling points were situated on the roofs of buildings I and II as shown in Fig. 2. They are formally assigned to the elevations $z$=140 mm and $z$=160 mm in the plots referring to the reference case and situations 1 and 2, and they were both omitted in the experiments for situations 3 and 4. The reference case corresponds to a 12 cm-wide street canyon limited by two buildings with 12 cm×12 cm cross-sections. Concentration values in Fig. 5 are normalized as: $c \cdot u_{100} \cdot H \cdot L_q / Q$ , where $H$ is the building height, and $L_q$ is the source length, which was 144 cm in all street-canyon experiments.

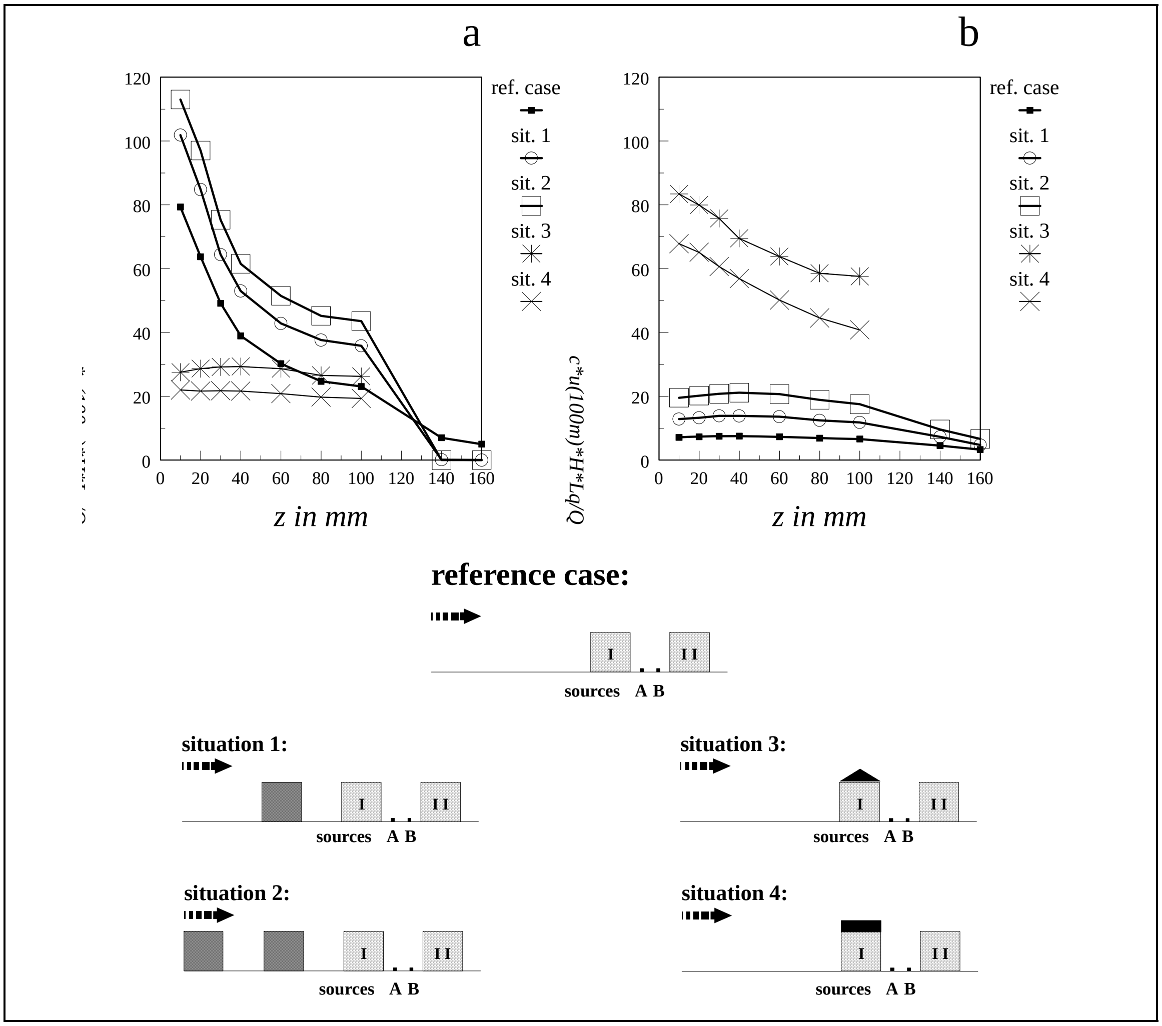


**Figure 5** Influence of upwind building configuration and roof shape on mean concentration values in a 180 cm-long (2D-case) street canyon for wind direction 90° and source position A. Concentration profiles were measured at the wall of building I (a), and at the wall of building II (b).

Effects of an additional upwind building, or two upwind buildings, on the concentration field in the canyon are modelled in situations 1 and 2, respectively. As seen from the plot, the presence of upwind buildings leads to an increase of mean concentration values inside the canyon which is higher when two buildings are placed upwind the canyon. Roof-level concentrations with additional buildings are smaller than in the reference case. Both of these features of the concentration field may be explained by the upward displacement of the flow, and impeding of air exchange between outer flow and canyon interior in situations when the flow field is affected by additional upwind obstacles.

Concentration measurements for situations 3 and 4 correspond to different roof shapes (rectangular and triangle ones) of the upwind building of the canyon. With both roof shapes, concentration values in the canyon decrease at the wall of building I, which is upwind, and increase at the wall of building II, the downwind one. The decrease is more pronounced for the rectangular-roof case, while the increase is larger for the triangular-roof configuration. The roof shape considerably alters the vorticity dynamics in the canyon and intensifies the transport of pollutant material towards the downwind side of the canyon.

In Fig. 6 wind-tunnel concentration measurements in the street canyon are compared with predictions by two numerical models. Both models, called MISKAM and ABC, are used in Germany for regulatory purposes. MISKAM is a prognostic model, ABC is a diagnostic one. Brief model descriptions and corresponding references are given in Röckle and Richter (1995). The case of a street canyon with two 120 cm-long buildings (3D-case) was used as standard for comparison, and the concentrations were compared for different wind directions varying over the semicircle. Before plotting, data for source positions A and B were superimposed to provide for comparability with results of other experimental and numerical studies, in which dispersion from a linear source placed in the centre of the canyon is considered. Concentration values in the plot refer to the point on the wall in the centre of building I ($y$=0), at $z$=10 mm.

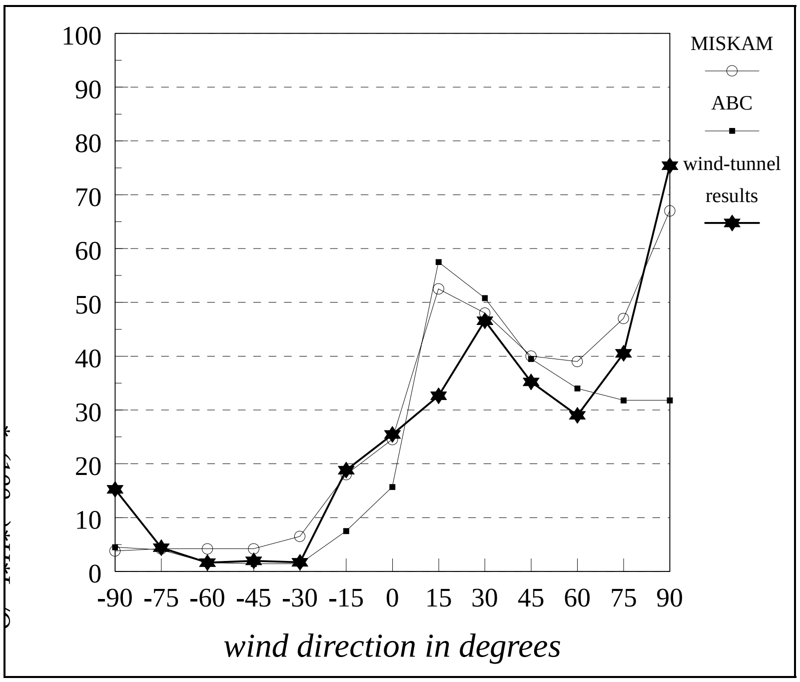


**Figure 6** Concentration in a 120 cm-long (3D-case) street canyon at building I ($z$=10 mm) as a function of wind direction. Numerical calculations by MISKAM and ABC models compared with wind-tunnel results.

Predictions by both models agree reasonable well with wind-tunnel measurements, but some principal differences exist. In the wind-tunnel study, the maximum concentration was found for wind direction 90°, (when the reference point is located at the upwind wall of the canyon). Wind-direction change from perpendicular to oblique leads to a concentration decrease which continues up to wind direction 60°, and then the concentration reaches the second maximum at 30°. Calculations with the MISKAM give a similar curve, but the second maximum is observed at the angle of 15°. The ABC results show a slight concentration growth with the wind direction decreasing from 90°, and predict only one concentration maximum at 15°. Thus, both models considerably exaggerate the concentration value for wind direction 15° as compared with the wind-tunnel results, and the ABC model underestimates concentrations for wind direction 90°. With wind approaching the canyon from the opposite side (wind direction -90°), both numerical models predict very low concentration values at the reference point which are much smaller than those measured in the tunnel.

*Case 3: Street-canyon intersection*

We conclude with first results from the wind-tunnel study of concentration fields around a street-canyon intersection. This study has been initiated quite recently, and so far measurements only cover the reference model configuration consisting of two perpendicular street canyons separating four building blocks of the same geometry. All model buildings were of the same height, *H*=12 cm, and had flat roofs. Figure 7 illustrates the experimental setup and presents concentration measurement data for wind direction 90°, and for source position A. The areas of the circles placed in the measurement points are proportional to the concentration values registered. These values are normalized in the same way as in the street-canyon study: $c \cdot u_{100} \cdot H \cdot L_q / Q$. At some points, the actual values of the normalized concentration are also indicated. Interpolated concentrations are presented by different extents of shading along the building contours.

As seen from the concentration pattern in Fig. 7, values of *c* measured at the walls of the buildings forming the source-containing canyon display considerable transverse variations in the vicinity of the intersection. These variations are apparently caused by local vortex motions with vertical axes created behind the upwind corners at the entrance of the source-free street canyon.

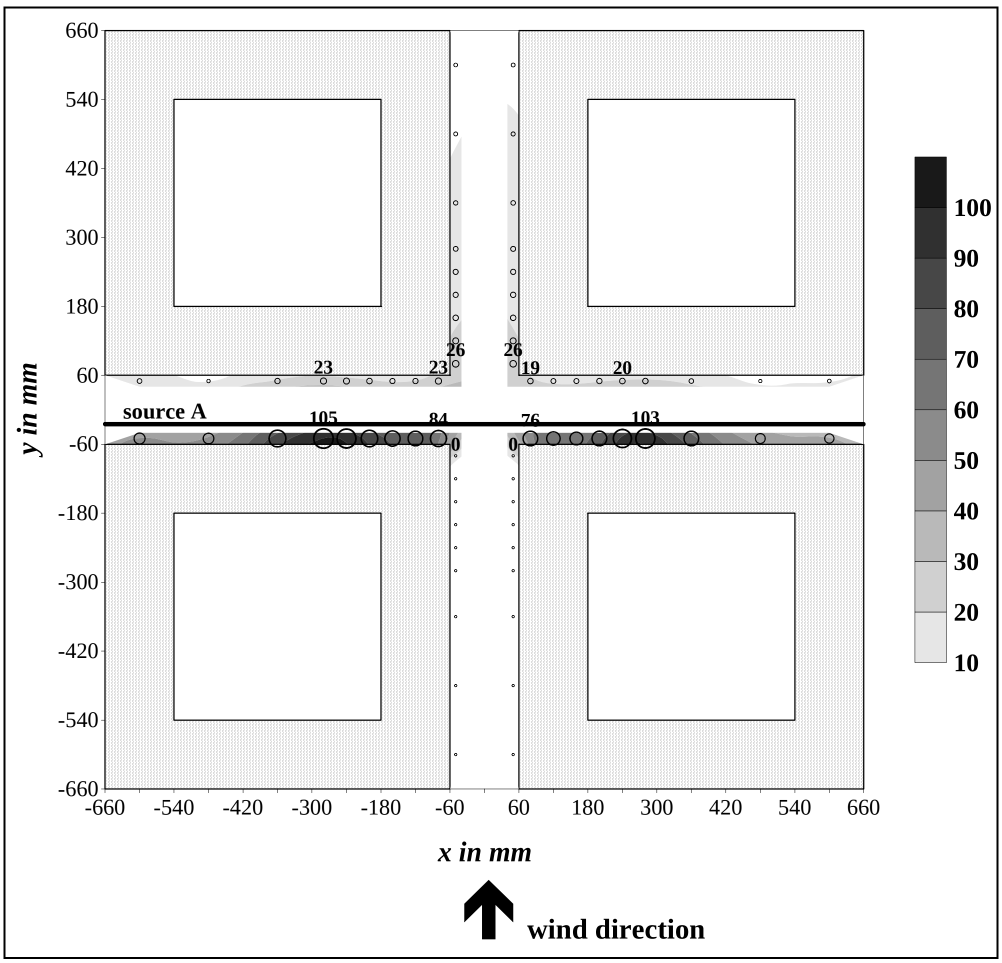


**Figure 7** Non-dimensional concentration values $c \cdot u_{100} \cdot H \cdot L_q / Q$ at building walls (*z*=10 mm) in the vicinity of a street-canyon intersection.

## 4 Conclusions

Results of modelling gaseous pollutant dispersion around typical urban-canopy elements have been presented. Wind-tunnel experimental configurations for the cases studied have been described. Several characteristic patterns of concentration distributions in the urban canopy have been analysed and discussed. Small-scale features of building design and composition (building shape, roof configuration, upwind building arrangement) were found to be important factors of concentration field modification. A comparison between wind-tunnel and numerical data for the street-canyon case has revealed general agreement of numerical predictions by two models with the concentration field measured in the tunnel. Nevertheless, for certain wind directions numerical results differed substantially from the experimental data.

Model data sets for the cases studied have been compiled. They are available for tuning numerical models and verification of their predictions.

## 5 Acknowledgements

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