Modelling of air pollution on urban buildings: a wind tunnel study

A. M. Mfula[1,2], V. Kukadia[1], R. F. Griffiths[2] & D. J. Hall[3]
[1]Building Research Establishment Ltd (BRE), UK
[2]Environmental Technology Centre, University of Manchester Institute of Science and Technology (UMIST), UK
[3]Envirobods Ltd, UK

Abstract

Tools for predicting where areas of high ingress of external pollution occur on a building can be developed if information regarding wind flow, dispersion and infiltration processes is available. These tools can be used for developing effective ventilation strategies for improving indoor air quality in urban buildings. In deriving them, it is important to determine the region from which pollution sources affect the building and generate concentrations on its surface. To this end, the effects of the position of external pollution sources on the magnitude and spatial variation of concentrations on a building model were investigated in a boundary layer wind tunnel. The tests were carried out at a nominal building model scale of 1:100 and involved continuous releases of a tracer gas at different locations within generic arrays of buildings. The region of influence of sources around the test building was variable in shape and size depending on the area density of the building array and the incident wind direction. The region increased in size across the wind with increasing area density of the array and was progressively skewed in the direction of the approaching wind with progressive increments in wind angle. The spatial variation in concentrations on the test building decreased with increasing source distance from the building, with no apparent consistency between the different configurations. The region from which sources generated high variations in concentration on the test building extended a considerable distance upwind of the building in each array.

Keywords: pollutant ingress, ventilation, wind tunnel, urban, buildings.

Air Pollution XII, C. A. Brebbia (Editor)

1 Introduction

Minimising ingress of external pollution into buildings is an important part of providing good indoor air quality for occupants, especially in urban areas where external pollution levels can be high. Ingress of external pollution is dependent on both pressure and contaminant concentration distributions on the building. Areas on the building façade where there is a combination of high wind-induced pressure differential across the building, and high pollutant concentrations on its surface are ‘high risk’ areas for ingress of external pollution. Contamination of indoor air from external sources can be minimised by siting ventilation inlets away from these areas.

It is, at present, difficult to predict the occurrence of high risk areas because there are limited published data from which a direct correlation of pressure and concentration measurements can be made. A major problem is that existing pressure data have generally been collected in separate experiments to concentration data and under different experimental conditions. In comparison to pressure data, available concentration measurements are limited with the focus being on ventilation of street canyons (Hoydysh and Dabberdt [3], Rafailidis et al. [8], Rafailidis and Schatzmann [9], Meroney et al. [7] and Kastner-Klein et al. [4]).

A study by Kukadia et al [5] appears to have been the first in which both pressure and concentration data were collected in a common experiment and proved the effectiveness of this method in determining the occurrence of high risk areas. Additional information from a wider experimental range is however required for the development of prediction tools and their subsequent use in preparing effective ventilation guidance for buildings in urban areas.

To determine where high risk areas are likely to occur, it is necessary to understand, firstly, whether a pollution source in a given location affects a building at all and, secondly, the magnitude and distribution of concentrations that the source generates on the building. Until now, there have been no available experimental data that provide this information, taking into consideration the effects of the urban layout and the incident wind direction. The aims of the present research are therefore to determine:

1. The region around a building within which the pollutant plumes from sources are likely to interact with the building, and within it;
    - The region from which pollution sources generate relatively uniform concentrations on the building (in which case the ingress of external pollution is independent of the concentration distribution and hence the siting of ventilation inlets);
    - The region from which pollution sources generate high spatial variation in concentrations on the building (in which case the concentration distribution influences the ingress of external pollution and it is possible to site ventilation inlets to minimise this behaviour (Kukadia et al [5], Hall et al [2]).

Air Pollution XII, C. A. Brebbia (Editor)

2 Experimental detail

2.1 The BRE dispersion modelling wind tunnel

The experiments were carried out under neutrally stable atmospheric conditions in the Dispersion Modelling Wind Tunnel at BRE. The wind tunnel has a working section 22 m long, 1.5 m high and 4.3 m wide and is specially designed and equipped for dispersion modelling using tracer gases. The atmospheric boundary layer model was simulated using Counihan's [1] system of crenellated fence and vorticity generators and a long fetch of suitably roughened surface. A single wind speed of 1.5 ms^{-1} was used at the reference height of 0.1 m, which was also the height of the building models. This corresponds to a Reynolds number in the approaching flow of approximately 1.1×10^4. The boundary layer characteristics at the leading edge of the test section were as follows: boundary layer depth δ~0.75 m, wind speed at the top of the boundary layer U_{top}=2.1 ms^{-1} and aerodynamic roughness height z_0=2.3 mm.

2.2 Concentration measurements

The tracer gas used was a 47% by volume gas mixture of methane in argon, which produced a neutrally buoyant discharge. The discharge was continuous and with negligible momentum from a small diffusing plug, 10 mm in diameter. The tracer gas was released at different locations at the ground within the building arrays considered, and for each individual source position the concentrations generated on a test building were measured.

Air samples were drawn from the outside surface of the test building down sampling tubes, which were mounted from within the building and were attached to probes flush with the outside walls at each sampling point. The samples were drawn through 20-port sampling valves into Flame Ionisation Detectors (FIDs). The FID units measured the hydrocarbon content in each air sample and their output was an electrical signal proportional to the concentration of tracer gas (approximately 1 volt for every 1000 ppm of methane).

Individual concentration measurements were sampled over an effective sampling time of two minutes, which was deemed sufficient to obtain a stable average of the fluctuating concentration (Macdonald et al., [6]).

Three sets of sampling valves and three FID units were used to sequentially sample the building surface concentrations. A fourth FID unit continuously sampled background concentrations of the tracer gas from a point far upwind of the building array and the source. Background concentrations of the tracer gas were automatically subtracted from the measured concentrations. Concentrations were expressed non-dimensionally as:

$$K = \frac{CU_H H^2}{Q}, \qquad (1)$$

Air Pollution XII, C. A. Brebbia (Editor)

where, K is the dimensionless concentration, C is the measured concentration at the building surface, U_H is the wind speed at height H (taken as the height of the building models, 0.1 m) and Q is the volumetric rate of discharge of the tracer gas.

2.3 Experimental range and configuration

Figure 1 shows the basic arrangement adopted in the tracer dispersion experiments and Table 1 gives the experimental range and parameters used.

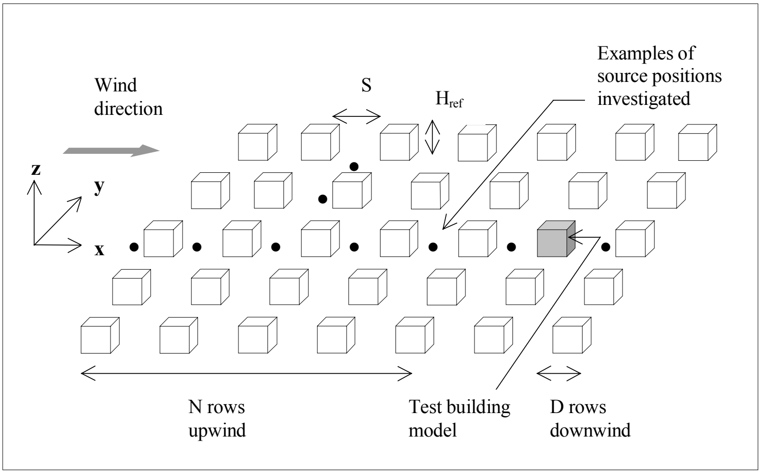

Figure 1: Schematic diagram of the basic experimental arrangement.

In Table 1, the distance between individual buildings, S, is normalised with respect to a reference height, H_{ref}, taken as the height of the building models.

Table 1: Range of experiments.

Building shape	Area density, A_d (%)	Spacing between faces (S/H_{ref})	Number of rows upwind (N)	Number of rows downwind (D)	Wind directions, θ (°)
Cubes	16	1.5	9	1	0, 15, 30, 45
	44	0.5	13	3	0, 15, 30, 45

Two area densities (proportion of surface covered by the obstacle) were considered, 16% and 44%. The effects of varying the incident wind direction on the region of influence of sources were studied to account for the range of wind directions that occur at full scale. In both configurations, the angle of skew of the building array to the incident wind was progressively increased from 0º (normal to the building array) in 15º intervals up to 45º (Table 1).

The generic building shape used was a cube with a basic dimension of 0.1 m. There was no formally defined building model scale for the present study. If however the 0.1 m height building models used in the wind tunnel were considered as 10 m height buildings at full scale (a typical height of buildings in urban areas), then nominally the scale used was 1:100. Figure 2 shows the location of sampling points on the test building which is shown in plan with the walls folded outwards.

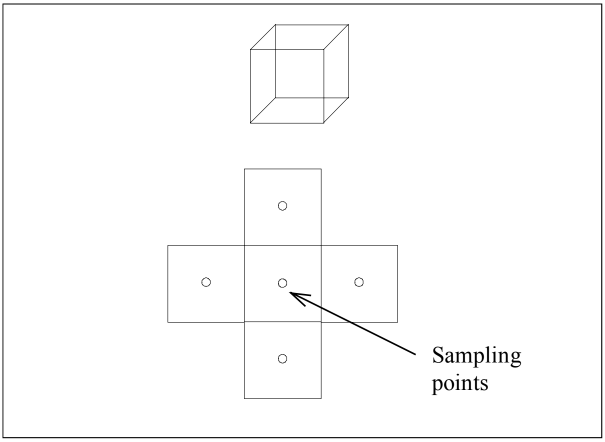

Figure 2: Location of sampling points on the test building model.

3 Results and discussion

The results of the experiments confirm the dependency of the size and shape of the region of influence of sources on the area density of the array and also show the effects of the incident wind direction on the region.

In both the 16% and 44% area density arrays of cubes the region of influence is progressively skewed in the direction of the approaching wind with progressive increments in the incident wind angle relative to the building array. Figure 3 illustrates this behaviour in both 16% and 44% area density arrays of cubes.

The values on the contour maps in Figure 3 represent the spatial mean of concentrations measured on the test building (shaded grey) and these are generated by ground level sources within the contoured areas. The concentrations are non-dimensional, scaled using Equation 1. In each contour map (a to d), the outer-most contour is the boundary of the region of influence of sources, within which the pollutant plumes from sources interact with the test building.

Air Pollution XII, C. A. Brebbia (Editor)

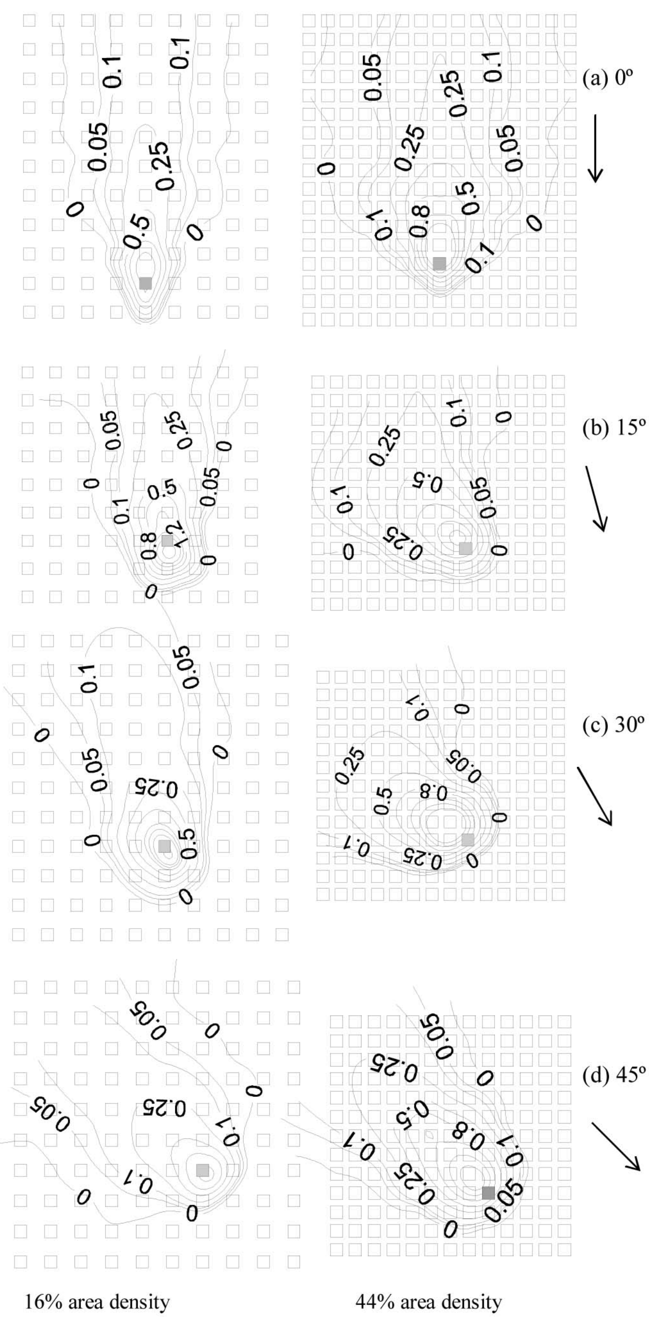

Figure 3: Mean concentrations, K, on the test building (shaded grey) from sources within the contoured areas in 0º to 45º incident wind directions (a to d).

Air Pollution XII, C. A. Brebbia (Editor)

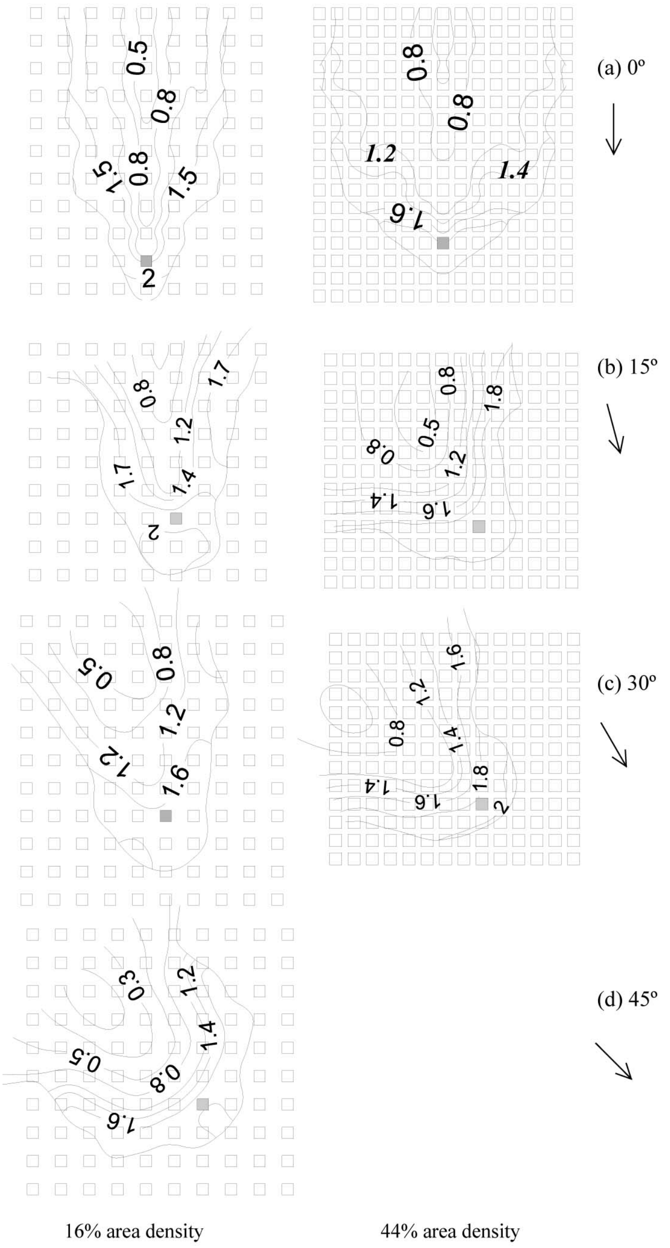

Figure 4: Spatial variation in concentrations, K_{diff}, on the test building (shaded grey) from sources within the contoured areas in 0º to 45º incident wind directions (a to d).

Figure 3 shows that the region of influence of sources across the wind increased in size, in terms of the number of streets covered adjacent to the test building, with an increment in area density of the array from 16% to 44% in each wind configuration. The regions from which sources generated given mean concentrations on the test building also increased in size with increasing area density of the array.

The diagram also shows that the incident wind direction strongly influenced the shape of the region of influence of sources in both the 16% and 44% arrays. In each contour map, the region extended a considerable distance upwind of the test building in the direction of the approaching wind. Variations in wind direction did not however appear to significantly affect the size of the region of influence or that of the contoured regions within it.

In Figure 4, each contour map shows the effects of source position on the spatial variation in concentrations across the faces of the test building for the same conditions as in Figure 3. The values on the contours represent the largest normalised difference in concentration across any two faces of the test building from sources within the contoured areas, defined by:

$$K_{diff} = \frac{K_{\max} - K_{\min}}{\left(K_{\max} + K_{\min}\right)/2} \tag{2}$$

where $K_{\max}$ and $K_{\min}$ are the maximum and minimum non-dimensional concentrations respectively on individual building faces.

K_{diff} has a scale of 0 to 2, with the upper limit representing high spatial variation in concentrations on the test building, resulting from one face having zero concentration, and the lower limit representing perfectly uniform concentrations on the faces of the building.

The outer-most contour in each map shows the boundary of the region of influence of sources from Figure 3. Sources closest to the test building generated the highest differences in concentration across its faces. Figure 3 shows however that the region from which sources generated high values of K_{diff} extended a considerable distance from the test building, generally in the upwind and across-wind directions. The regions from which sources generated a given value of K_{diff} on the test building were also skewed in the direction of the approaching wind with progressive increments in wind angle.

4 Summary

The effects of the incident wind direction on the size and shape of the region of influence of sources have been investigated in a wind tunnel study. The experiments covered a range of ground level point sources in 16% and 44% arrays of cubes with incident wind directions ranging from 0° (normal to the building array) to 45°. The results showed that the shape (and perhaps to a lesser extent the size) of the region of influence and the sub-regions within it, is influenced by the incident wind direction. The region of influence is skewed in the direction of the approaching wind with increments in wind angle from 0°.

Using the contour maps, the mean concentration and the spatial variation in concentrations likely to be generated on a building can be estimated for sources at any location within the arrays considered. The results of the present study will play an important part in providing information on building exposure to urban pollution sources for use by ventilation strategists and designers.

Acknowledgements

The authors wish to acknowledge the support of the Foundation for the Built Environment (FBE) as sponsors of this project. The authors would also like to thank Mr Steven Walker (formerly at BRE) now at DSTL Porton Down, Mr Stuart Upton and Dr Sani Dimitroulopoulou at BRE for their assistance during the wind tunnel experiments.

References

[1] Counihan, J., An improved method for simulating an atmospheric boundary layer in the wind tunnel. *Atmospheric Environment 3, p197-214*, 1969.

[2] Hall, D.J., Walker, S., Mfula, A. M., Spanton, A.M., Kukadia, V., Pressure and Concentration Patterns on Buildings in Urban Arrays and the Ingestion of Contaminants. *6th Annual George Mason University Transport and Dispersion Modelling Workshop*, Virginia, USA, 2002.

[3] Hoydysh, W.G. and Dabberdt, W.F., Concentration fields at urban intersections: fluid modelling studies. *Atmospheric Environment 28, p1849-1860*, 1994.

[4] Kastner-Klein, P., Fedorovich, E., Rotach, M.W., A wind tunnel study of organised and turbulent air motions in urban street canyons. Journal of Wind Engineering and Industrial Aerodynamics 89, p849-861, 2001.

[5] Kukadia V., Hall D. J., Walker S. C., Spanton A. M., The Effect of Wind Pressure and Pollutant Concentration on Ventilation of Urban Buildings. *Indoor Air' 99 Conference,* Edinburgh, 1999.

[6] Macdonald, R., Griffiths, R. F, Hall, D. J., A comparison of results from scaled field and wind tunnel modelling of dispersion in arrays of obstacles. Atmospheric Environment 32, p3845-3862, 1998.

[7] Meroney, R., Pavageau, M., Rafailidis, S., Schatzmann, M., Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons. *Journal of Wind Engineering and Industrial Aerodynamics 62, p37-56,* 1996.

[8] Rafailidis, S., Pavageau, M., Schatzmann, M., Wind tunnel simulation of car emission dispersion in urban street canyons. *Annalen der Meteorlogische 31, p287-288,* 1995.

[9] Rafailidis, S. and Schatzmann, M., Physical modelling of car exhaust dispersion in urban street canyons-The effect of slanted roofs. 21st NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, p170-171, Baltimore, 1995.

Air Pollution XII, C. A. Brebbia (Editor)