AIVC 12,525

MINIMISING THE INGRESS OF EXTERNAL POLLUTION INTO URBAN BUILDINGS

Vina Kukadia, David Hall, Steven Walker, Angela Spanton

Building Research Establishment Ltd, Garston, Watford, WD2 7JR

To develop guidance on effective ventilation strategies for buildings located in urban areas, it is necessary to have an understanding of the processes involved in the ingress of external pollution into buildings and its effect on indoor air quality. For naturally ventilated buildings, the combination of pressure forces and contaminant levels around the building is important in generating the level of internal contamination. Thus regions of high external pressures combined with high external pollutant concentrations will give regions of high probable ingress of contaminants and hence lead to greater internal pollutant concentrations.

In this paper, results are given of the wind tunnel studies carried out at BRE to determine common regions of high contaminant levels and pressures on the surfaces of buildings, both in isolation and within arrays of urban structures. The implication of the measurements in developing low-energy ventilation strategies for buildings in urban areas are briefly discussed.

1. INTRODUCTION

Careful design of buildings is required in order to minimise the combined effects of contaminants from internal and external sources while at the same time providing adequate ventilation for the occupants. At present this process is rarely carried out with any thoroughness in buildings on sites where external contamination levels are high. The main reason for this is that there is limited formal advice, and little research data, on ventilation design to avoid or minimise the effects of external contaminants. Although, there is a growing interest in this subject and some work has been carried out (1, 2, 3), there is still a lack of fundamental understanding of the processes involved in the ingress of externally contaminated air and its interactions with ventilation requirements.

Internal contamination of buildings from external pollution sources depends upon both the ventilation strategy and the pollutant dispersion processes around the building. For naturally ventilated buildings, the combined distribution of both pressure differences between the inside and outside of the building and contaminant levels around the building is important in generating the internal contamination levels. Regions of high pressure differences combined with high external pollutant concentrations will give regions of high probable ingress of contaminants and hence lead to greater internal pollutant concentrations. These areas would therefore need to be avoided when siting 'fresh' air inlets for all types of ventilation systems.

Although both wind pressures and pollutant levels around buildings have been the subject of previous investigation, much of this has been concerned with isolated structures (4). The behaviour of buildings in urban areas, where they are closely surrounded by other buildings, has received far less attention, especially with regard to the dispersion of contaminants around buildings. Most work of this sort has been mainly concerned with specific applications and there are relatively few generic studies (5, 6, 7). In addition, almost no consideration has been given to the combined effects of pressure and concentration distributions on the surfaces of buildings, which is required for the present programme.

In this paper, results are given from wind tunnel studies, carried out at BRE to determine contaminant levels and pressures on the surfaces of buildings, both in isolation and within arrays of urban structures (8). This is the first investigation of these two parameters simultaneously known to the authors and forms part of a wider programme whose overall objective is to develop guidelines for effectively ventilating buildings in urban areas using low energy technology.

2. THEORY

2.1 Surface Wind Pressures

All pressures on building surfaces quoted here are given as pressure coefficients, C_p, in the usual format,

$$C_p = \frac{p - p_{ref}}{1/2\rho u_H^2}, \qquad (1)$$

where,
p is the surface pressure, p_{ref} is a reference pressure, usually the free stream static pressure, u_H is the reference windspeed and Δ is the density of air.

For the present work, due to the presence of the upwind building array, the reference pressure was taken as the static reading from a pitot static tube at a height of 2H. The reference dynamic head was taken as the undisturbed pitot-static pressure at the building height, H. In practice this could not be measured close to the array, so a reference pressure at height 2H above the buildings was used in the experiments. This was then corrected to an equivalent value at the reference height using the values for the undisturbed wind profile. The correction was of the order of 10%.

2.2 Pollutant Concentrations

All concentrations on building faces quoted here are given as a dimensionless concentration K, which is defined as

$$K = \frac{c u_H H^2}{Q} \qquad (2)$$

where,
c is the trace gas concentration, u_H is the reference windspeed (at the building height, H), H is the reference scale length, taken as the building height and Q is the rate of discharge of the tracer. Values of concentration from any scale of pollutant discharge, building height or windspeed can then be determined from the value of K from the model.

3. EXPERIMENTAL DETAILS

3.1 Wind Tunnel Experiments

The contaminant dispersion and wind pressure studies were carried out in BRE's Dispersion Modelling Wind Tunnel. This has a working section 1.5m high, 4.3m wide and 22m long and is primarily designed and equipped for contaminant dispersion modelling using methane trace gas. However, for the current study the wind tunnel was also set up to carry out pressure measurements. A single reference wind speed of $1.5 ms^{-1}$ at the height of the obstacles (H = 0.1m) was used for the dispersion experiments. A wind speed of $3ms^{-1}$ was used for the wind pressure measurements, in the interests of obtaining larger and more readily measurable pressure differences. The equivalent wind speed at the top of the boundary layer was 2.2ms^{-1} in the former case and 4.4 ms^{-1} in the latter case.

3.2 Range of Experiments

Arrays of cubes (0.1x0.1x0.1m) and rectangular blocks (4x1x1 cubes resulting in dimensions 0.4x0.1x0.1m) simulating urban building arrays, as described in previous wind tunnel experiments (7) were used in the present study. Investigations were carried out for arrays of three area densities, D (the proportion of the surface covered by buildings of 0% (that is, in isolation), 16% and 44%). Area densities around 16% are very common for UK housing estates and city suburbs generally. The higher area densities around 44% occur commonly in city centres.

Diagrams of the building layouts for the two area densities, 16% and 44%, and the two shapes are shown in Figure 1. The spacing between the buildings and other details are given in Table 1. The lateral extent of the array was 20 building heights.

Table 1. Dimensions of Building Arrays

Building Type	Area Density D(%)	Spacing Between Building Faces		Spacing Between Building Centres		Number of Upwind Rows in Array
		x	y	X	Y	
Cube	16%	1.5H	1.5H	2.5H	2.5H	9
	44%	0.5H	0.5H	1.5H	1.5H	13
4x1	16%	2.75H	2.75H	3.75H	6.75H	6
	11%	0.9H	0.9H	1.9H	4.9H	9

Pressure and concentration measurements were made on tapped models situated in the last but one row of the array. The presence of a single row of buildings behind the tapped model ensured the correct wake behaviour around the measurement area. The tappings either measured the building face pressure via connection to a pressure transducer or measured the trace gas concentration using samples sucked continuously through the tappings and passed to the gas concentration measuring equipment.

The experiments were carried out at a number of wind directions (0° 15° 30° and 45°) and contaminant source positions. For each of the test cases it was only necessary to measure a single pressure distribution on the building. However, there were a large number of possible pollution source positions, so that a relatively large number of these needed to be studied for each test case. For each test case, concentration patterns on the building were measured from a range of upwind and lateral source positions. The upwind limits of interest were the distances beyond which concentration contours on the building became largely uniform. The lateral and downwind limits of interest were where the dispersing plume no longer contacted the tapped building. All the source positions studied produced measurable concentrations on the tapped building.

4. RESULTS

The results presented here are only examples of the findings from the full study reported in Reference 7.

4.1 Pressure Measurements.

Figures 2 and 3 show the effects of area density and wind direction respectively on the pressure distributions for the 4x1x1 building. The building is shown in plan with the walls folded outwards. The contours are of the pressure coefficient, C_p as given by Equation 1. The shaded areas are of the approximate areas above the 75%ile (the grey shading) and below the 25%ile (the hatching) of the surface pressures. These areas are those of relatively high and low pressure respectively which would be expected to act as the regions of ingress and egress of ventilated air. In wind driven ventilation, it is the pressure difference between the high and low pressure regions on the building surface, which drives ventilation processes and are therefore of interest in the present study. This varies with wind direction and the area density of the building array. The 75%ile and 25%ile values of C_p and the difference between them are also shown on the plots.

Figure 2 shows that regions of high pressures occurred primarily on the upwind face of the building for all density areas studied. Pressure differences across the buildings reduced markedly as the area density, and hence the related degree of sheltering increased. In the 44% area density array the 75%ile to 25%ile pressure differences reduced to 5-15% of those on an openly exposed building (D=0). The significant reduction in pressure differences across the building with increasing area density implies reduced rates of wind driven natural ventilation and an increase in the critical wind speed that divides buoyancy and wind driven ventilation. This result is significant to the ingestion of external contaminants since the air flow patterns for the two modes of ventilation are different and hence the areas of ingestion are also different. The critical wind speed for wind driven flow in a 44% area density array is about $6ms^{-1}$. However, since this exceeds typical wind speeds ($3\text{-}4\ ms^{-1}$) the implication of this result is that for most of the time natural ventilation in dense urban areas is likely to be buoyancy driven.

Figure 3 shows that pressure distributions over the building were more arbitrary with variation in wind direction. At wind directions of 0° and 15° high pressures occurred primarily on the upwind face roof of the building. At wind directions of 45° and 90° high pressure regions were displaced to the downwind end of the upwind face and roof and the end walls. Pressure differences across the building gave little variation with wind direction.

4.2 Concentration Measurements.

Figures 4 and 5 show the effects of area density and wind direction respectively on contaminant concentration patterns for the 4x1x1 building with the pollutant source at ground level at a distance of x/H =0.45. Against each individual plot are values of the 75%ile and 25%ile of the concentrations and their difference. Also given is the absolute distance (x/H) of the source from the tapped building and the number of rows of buildings between the source and the tapped building. In this case there is only one row. The dominant effect on short-range plume dispersion patterns near the ground is due to the presence of surface obstacles, especially buildings. Thus it is usually the number of rows of buildings that is the most critical feature of upwind source distance, rather than the absolute distance.

Figure 4 shows that the highest concentrations occurred mainly on the upwind faces and on the roofs at all area densities studied. The positions of the lowest concentrations were less consistent, varying mainly between the side and downwind walls. A marked reduction with increasing source distance (not shown here) was seen both in the absolute surface concentrations and in the 75%ile to 25%ile differences. The reduction in surface concentrations from isolated buildings to those in a 16% area density array is due to enhanced turbulent mixing and hence increased dispersion. The increase in concentrations for the 44% area density is due to a combination of reduced dispersion and lower local wind speed caused by the additional buildings.

On the cubical building (not shown here, but may be found in Ref. 8), the highest concentrations occurred most often low down around the upwind and side faces and the lowest concentrations on the downwind faces. However, at the highest area density the highest concentrations occurred on the side faces for the more distant sources. The lowest concentrations on the cubical buildings occurred more variably, on the side and downwind walls and the roof under different circumstances.

Figure 5 shows that with a wind direction at 0°, the highest concentrations were distributed symmetrically over the upwind building face and the roof. For the other three wind directions, the highest concentrations are displaced to the downwind end of the front face and roof and the side walls. The considerable reduction in concentration on the building in the 45° and 90° wind directions is also notable. Despite the proximity of the source to the building, the bulk of the plume has passed along the adjacent 'street' having limited contact with the building. In the 90° wind direction the plume has also passed around the downwind face of the building and penetrated upwind to about half way up the other side.

4.3 Comparison between Concentration and Pressure Regions

Comparison of Figures 2 and 4 show that the most persistently recurring common region of high pressure and high contaminant concentrations was the upwind face of the building at all the area densities considered. This implies that under the conditions considered, this is the most likely area for ingress of ventilation air into the building coupled with relatively high pollutant concentrations leading to greater internal contamination. At 44% area density, there are also common regions of high pressures and concentrations on the roof and although pressure differences are small, some ingress is likely to occur.

Comparison of Figures 3 and 5 show that with a wind direction of 0° the common areas of high pressure and concentration are on the upwind face and roof of the building; potential regions for ingress of pollutants. With a wind direction of 15°, there are no common areas. For wind directions of 45° and 90°, common areas of high pressures and concentrations occurred on the upwind faces and downwind ends of the building, but since both pressure and concentration differences were small seems to imply that these areas are of limited importance to the ingestion of contaminants.

Thus the most frequent region of commonality of high pressures and concentrations seemed to be the upwind building face where sources were upwind. However, this was not a consistent result and a great variety of other pressure and concentration distributions also occurred, depending especially on source positions. In one case (not shown here, but may be found in Ref. 8) the downwind face of the building gave high pressure and concentration region and thus acted as an area of contaminant ingestion.

5. CONCLUSIONS.

The current study appears to have been the first in which the variations in both pressure and concentration on building faces, have been measured in a common experiment with buildings both in isolation and in urban arrays. This is an essential requirement for estimating the regions of ingestion of pollutants by natural ventilation and for the placement of ventilation inlets for all types of ventilation systems. For the range of experiments carried out, this study has identified areas where high pressures and pollutant concentrations occur simultaneously on a building and thus have a high potential for the ingress of external pollutants leading to high internal contamination levels. It is important therefore that these areas are avoided when developing a ventilation strategy such as the siting of ventilation inlets. The implication is that inlets need to be located in areas where pressures are high but concentrations are low. In addition, the study has shown that the mechanisms, which govern the ingress of external pollutants into buildings in urban areas are complex. Variables such as, building geometry, orientation to the wind, wind speed and pollutant source position need to be taken into account when developing ventilation guidelines for buildings located in urban areas.

The following specific conclusions may be drawn:

- Pressure differences across building faces reduced markedly as the surrounding array density increased. In the 44% area density array of the present experiments pressure differences reduced to 5-15% of those on an isolated building. This increases the critical wind speeds dividing buoyancy-driven from wind-driven ventilation in dense urban arrays, to the extent that buoyancy-driven ventilation is probably the most common occurrence.
- Concentration distributions and concentration differences around buildings in urban arrays show more complex patterns than pressures, depending on both array density and source position. Generally, regions of high concentration on building faces tend to be those closest to the source.

However, this result was not universal and dispersion patterns from sources within two rows of the building can show complex concentration distributions. With sources at greater distances, both concentrations and concentration differences diminished. For a given source position concentrations on the building face tended to increase with increasing array area density, although this behaviour was not consistent.

- Concentration differences across building faces showed a minimum for an array area density of 16% due to the high levels of turbulent mixing and dispersion at these conditions. Concentration differences increased markedly in the 44% area density array due to a combination of low local wind speed and low rates of dispersion within the narrow sheltered spaces of the array.
- Varying wind direction across buildings in the array modified the pressure distributions, but resulted in relatively limited variations in either pressures or pressure differences on building faces. However, there were greater variations in both concentration and concentration differences. There was pronounced lateral translation of plumes along streets of wide buildings for quite small angles of skew in the wind direction across the array.

6. FUTURE WORK

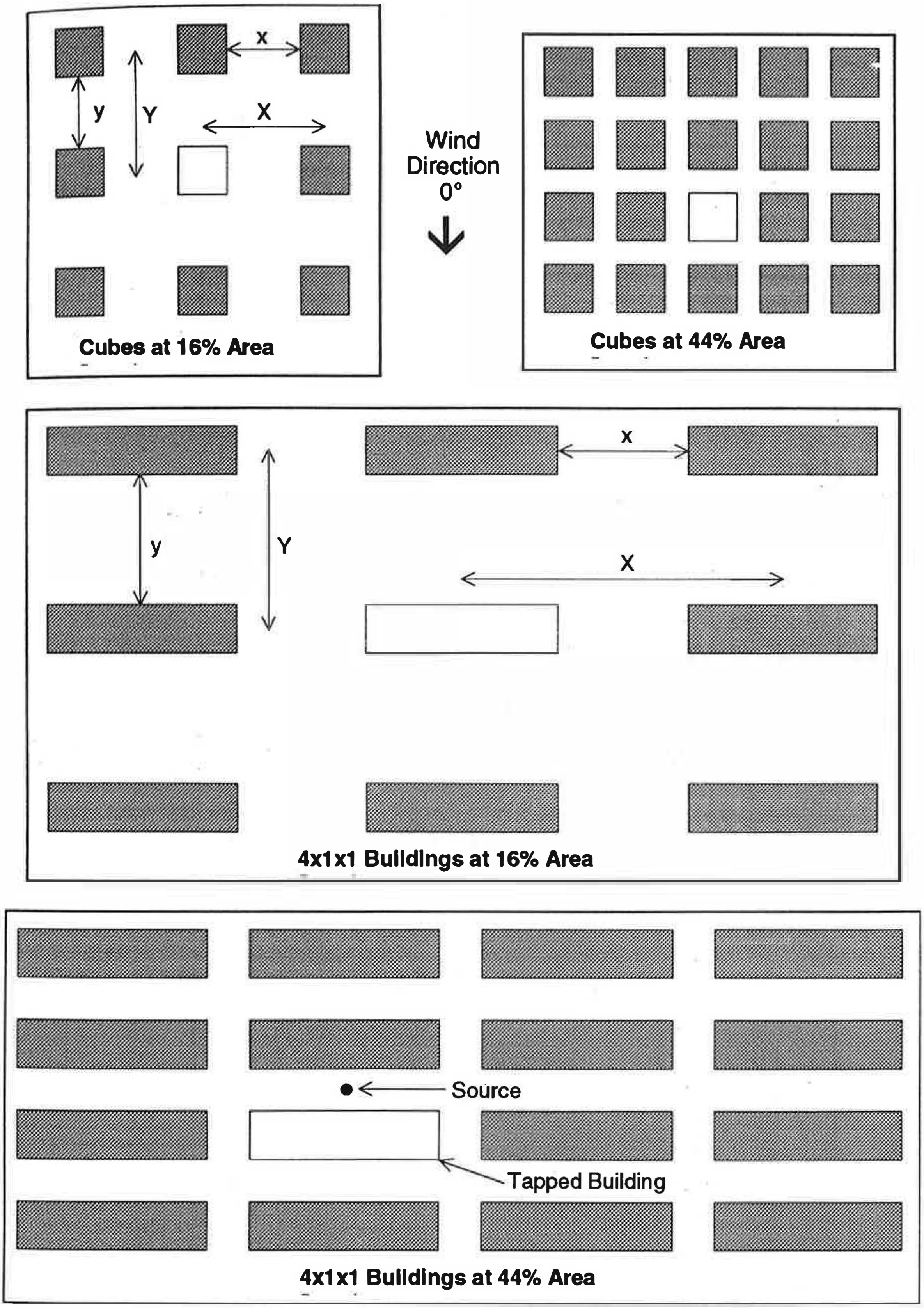
To enable effective ventilation guidelines to be developed for buildings in urban areas where external pollution levels are high, it is important to further understand the processes involved. The work in this area is being continued with building monitoring also being carried out. The results of the current study will be combined with those of the building monitoring results to formulate ventilation guidelines taking into consideration varying wind directions, density of urban buildings and local pollution sources.

7. ACKNOWLEDGEMENTS

Many thanks are due to the Department of the Environment, Transport and the Regions (DETR) for funding the research described here. Thanks are also extended to Peter Tily who assisted in the setting up of the pressure measuring equipment in the wind tunnel.

8. REFERENCES

1. Philips J L, Field R, Goldstone M, Reynolds L, Lester J N, Perry R (1993). Relationships Between Indoor and Outdoor Air Quality in Four Naturally Ventilated Offices in the United Kingdom. Atmospheric Environment, Vol 27A, No. 11, pp 1743.
2. Kukadia V, Pike J, White M (1997). Air pollution and Natural Ventilation in an Urban Building: A Case Study. Proceedings of CIBSE National Conference, Alexandra Palace, London.
3. CIBSE Technical Memoranda TM21: 1999, 'Minimising Pollution at Air Intakes'.
4. Akins RE, Peterka JA, Cermak JE (1979). Averaged Pressure Coefficients for Rectangular Buildings. Wind Engineering, Proc. of 5th International Conference, Fort Collins Colorado 1979.
5. Kukadia V, Hall DJ, Walker S (1998). Building Ventilation and Indoor Air Quality: The Impact of Urban Air Pollution – A Review. BRE Report No. CR 243/98.
6. Ho TC, Surrey D, Davenport AG (1990). The variability of Low Building Loads Due to Surrounding Obstructions. Journal of Wind Engineering and Industrial Aerodynamics, Vol 36 pp161-170
7. Hall DJ, Macdonald R, Walker S, Spanton AM (1998). Measurements of Dispersion Within Simulated Urban Arrays – A Small Scale Wind Tunnel Study. BRE Report No. CR244/98.
8. Hall DJ, Walker S, Spanton AM, Kukadia V (1999). Pressure and Concentration Patterns on Building Forms in Urban Arrays. BRE Report No. 125/99.



Cubes at 16% Area

Cubes at 44% Area

4x1x1 Buildings at 16% Area

4x1x1 Buildings at 44% Area

Figure 1. Building Model Layouts for 16% and 44% Area Densities

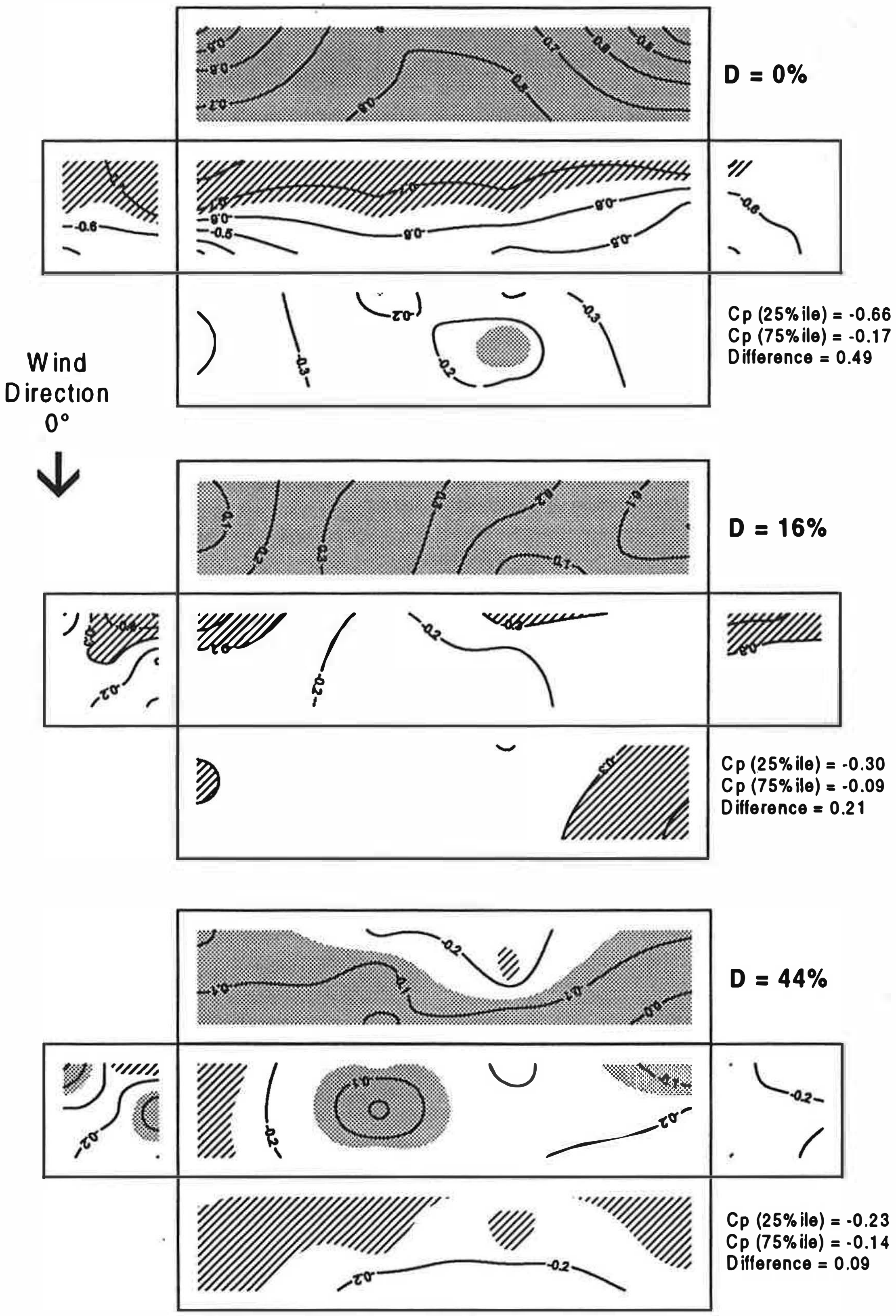


Figure 2. Pressure Distributions Around a 4x1x1 Building in Different Area Densities, Wind Direction 0°.

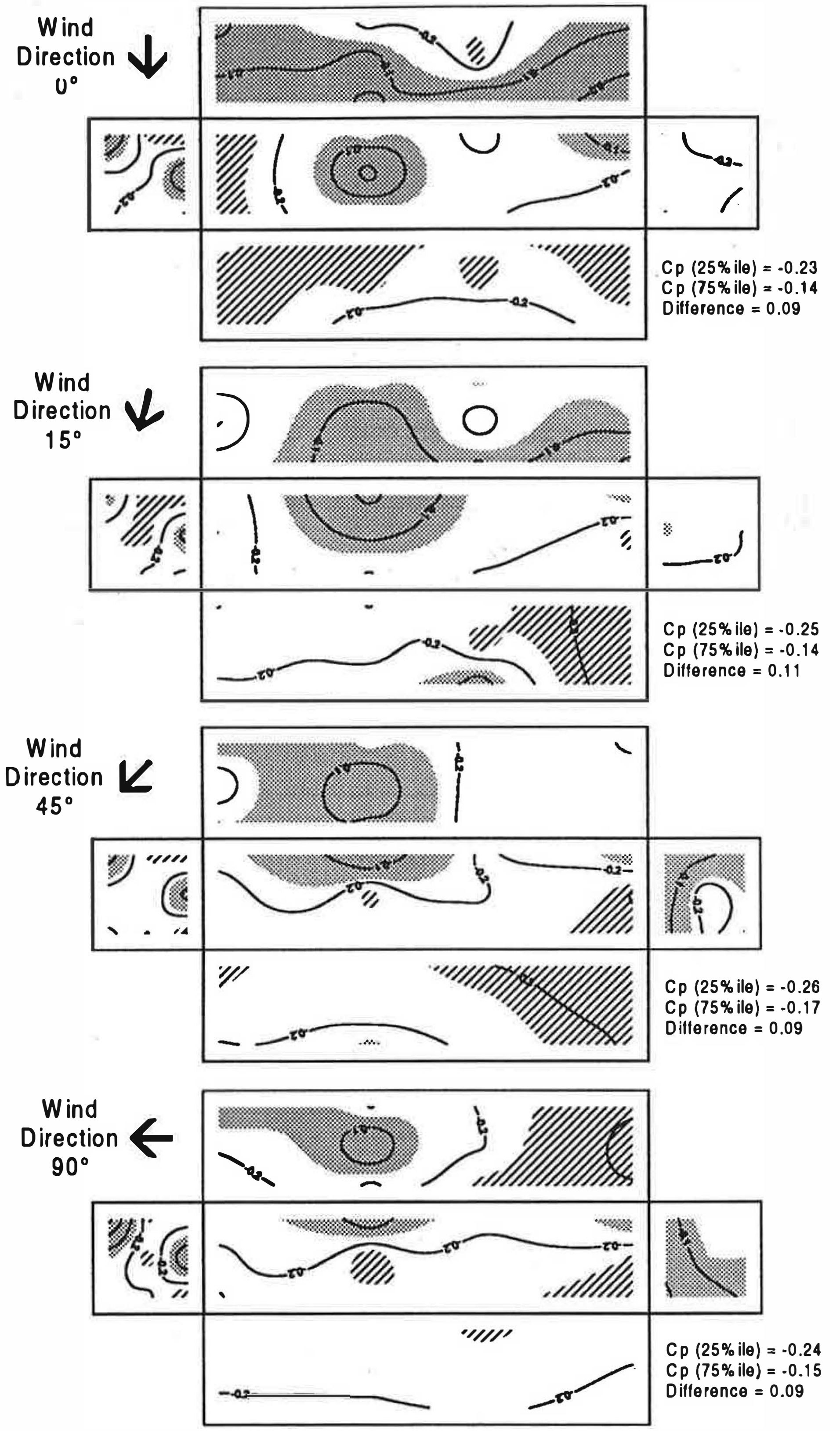
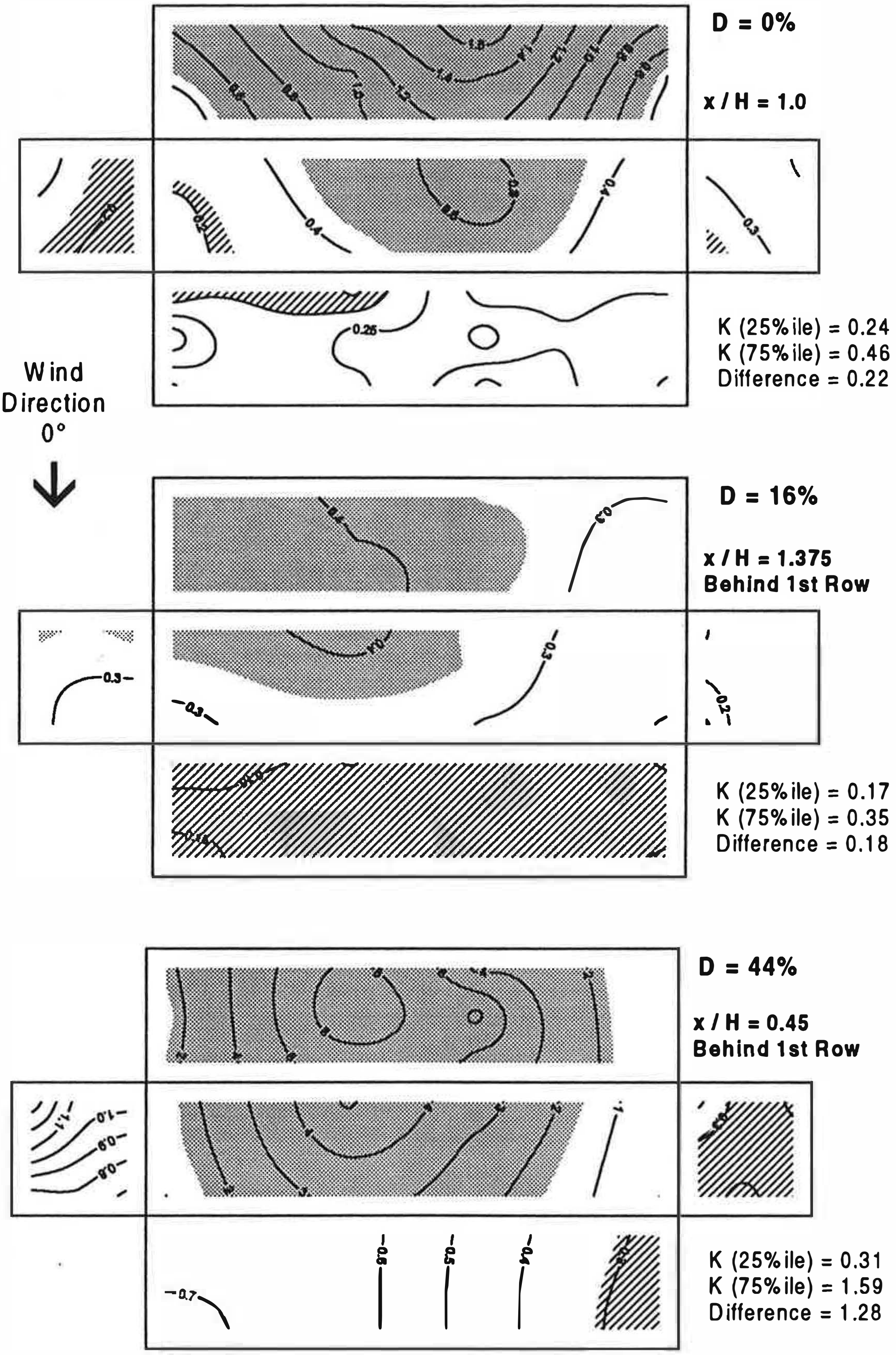


Figure 3. Pressure Distributions Around a 4x1x1 Building in Different Wind Directions, Area Density 44%.



D = 0%

x / H = 1.0

K (25%ile) = 0.24
K (75%ile) = 0.46
Difference = 0.22

D = 16%

x / H = 1.375
Behind 1st Row

K (25%ile) = 0.17
K (75%ile) = 0.35
Difference = 0.18

D = 44%

x / H = 0.45
Behind 1st Row

K (25%ile) = 0.31
K (75%ile) = 1.59
Difference = 1.28

Figure 4. Concentration Distributions Around a 4x1x1 Building for Different Area Densities, Wind Direction 0°.