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VELOCITY AND CONCENTRATION MEASUREMENTS WITHIN ARRAYS OF OBSTACLES

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ABSTRACT

Field experiments have been conducted to investigate flow and dispersion through obstacle arrays. Model obstacles which represent real structures at a nominal scale between 1/10 and 1/20 were used. The main purpose of the experiments was to examine flow and dispersion of contaminants in the vicinity of individual obstacles embedded in an array of cubes. Two array configurations were used, namely the in-line and staggered array configurations. The field experiments were supported by flow visualisation trials performed in the wind tunnel. In the light of the results of these wind tunnel trials, the field experiments were carried out using an array spacing S/H = 1.5 (where S is the space between two consecutive array elements). Dispersion around an isolated model building has already been investigated in the field (Mavroidis and Griffiths, 1996). Thus comparison is allowed between dispersion around an isolated obstacle and around the same obstacle embedded in an array of cubes.

KEY WORDS: buildings, plan area density, flow regime, pollutant dispersion, wake

INTRODUCTION

Increased concern over the problem of atmospheric pollution in urban areas has highlighted the need for detailed investigations of atmospheric flow and dispersion of contaminants in the vicinity of buildings. Examination of flow and dispersion in the wake of isolated obstacles is very useful in identifying the effect of a building or any other construction on the behaviour of plumes released in their vicinity. However, in real situations occurring in urban areas there is a complex interaction between plumes of pollutants and groups of buildings and other obstacles. At relatively large distances from the source, where the plume cross-section becomes large enough in comparison to individual obstacles, the individual building form and layout becomes less important and dispersion rates are defined mainly by the overall drag. In this region computational models are used to simulate the flow and dispersion patterns. However, closer to the discharge, where the interaction between the plume and single structures dominates the plume path and its dispersion, detailed experiments are required to provide the necessary information on the flow patterns and the dispersion characteristics. Such information may be used in the development of an urban dispersion model in order to describe the region of impact between the plume and the group of buildings. Hosker (1984) described the main characteristics of flow and dispersion around individual obstacles and small obstacle arrays. Hall *et* *al*. (1996) presented an up-to-date review of the literature on urban dispersion, dividing the "urban area" into three regions of increasing scale, for which different types of urban dispersion models are required.

Several techniques have been used to investigate flow and dispersion around obstacles. Wind tunnel investigations have been proved very valuable in assessing the general behaviour of emissions, but they do not give a complete picture of the flow, since they eliminate the large-scale horizontal meandering of the wind direction that occurs in the atmosphere. Thus field experiments are required to validate wind tunnel experiments and numerical modelling studies. However, only a limited number of field trials examining dispersion around buildings have been conducted due to difficulties encountered in the field, such as the changes in wind direction occurring in the atmosphere. Davidson *et al*. investigated flow and dispersion through large groups of obstacles, both in the field (1995) and in the wind tunnel (1996). Their main findings were that the plume followed a Gaussian distribution both laterally and vertically and that it was initially deflected upwards. Increased vertical mixing was induced around individual obstacles by the presence of horseshoe vortices. Field and wind tunnel experiments by Macdonald *et al*. (1997) confirmed the above findings and also showed that the plume meandering was reduced within a built-up area due to the blocking effect of the buildings. Furthermore, they showed that at short distances from the pollutant source, concentration profiles in the obstacle arrays were quite variable, while at distances beyond approximately two rows concentration profiles were well approximated by a Gaussian distribution. Baechlin *et al*. (1991) and Theurer *et al*. (1996) suggested a general method of predicting short-range dispersion, based on a semi-empirical approach. They indicated that for irregular arrays of buildings, with aspect ratios greater than one, the near-field profiles were not Gaussian but were dominated by local building effects, which often caused a lateral displacement of the plume.

Most of the above investigations concentrated on the general effects of the urban array on the dispersion patterns and did not look carefully on the complex interactions occurring between the obstacles and the pollutant plume. The work presented here concentrates more on the region close to the discharge, where the cross-section of the dispersing plume is not very large. In this region local effects of flow around the obstacles dominate the plume path, and dispersion is influenced by the effect of the obstacle shape and distribution on local dispersion patterns.

EXPERIMENTAL METHOD

The experiments were performed at Altcar Field Site on the northwest coast of England. The atmospheric stability ranged from moderately unstable to neutral. Detailed meteorological measurements that were conducted at the same site gave a mean roughness length of approximately 12 mm for the prevailing wind direction (Kourniotis, 1996). Two array configurations were used (in-line and staggered array configurations). The obstacles investigated were a cube (H=1.15 m), a cylinder (H=D=1.15 m) and two stacked cubes forming a taller obstacle with a height of 2.3 m. Flow visualisation trials were initially performed at the Environmental Wind Tunnel, Building Research Establishment, Cardington. In the light of the results of these wind tunnel trials, the field experiments were carried out using an array spacing S/H = 1.5 (where S is the space between two consecutive array elements).

Measurements of the flow characteristics within the array were conducted using an ultrasonic anemometer. Flow measurements, within the array, as well as concentration measurements, were supported by meteorological data collected by an ultrasonic anemometer which was continuously positioned upwind of the array of obstacles. The ultrasonic anemometers provided the three orthogonal components of the wind vector and the speed of sound in air, all of which were sampled at a frequency of 21 Hz.

In each field experiment, a single obstacle was embedded in the array of cubes. The main experimental configuration (for a cube normal to the flow) is presented in Figure 1 for the in-line and in Figure 2 for the staggered array configuration. The tracer gas used for the concentration measurements was propylene, and the instruments deployed in the trials were UVIC® detectors (Ultra-Violet Ion Collectors). The UVIC® detector is a fast-response photo-ionization detector that provides a useful calibratable range from about 0.01 to 1000 ppm by volume and has a

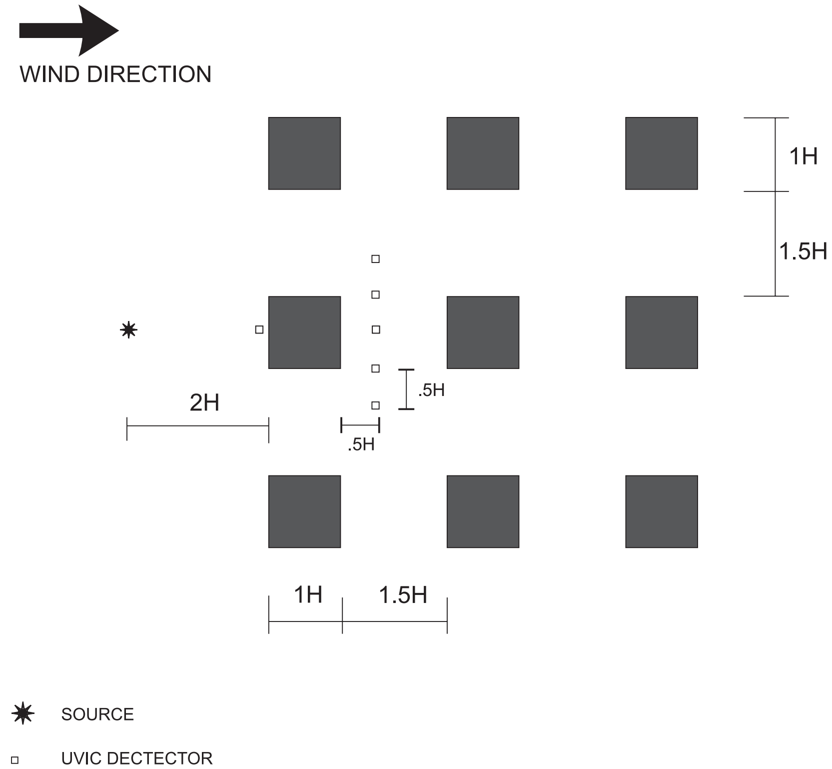

Figure 1. Plan view of the main experimental configuration for trials conducted in the in-line array (cube normal to the flow).

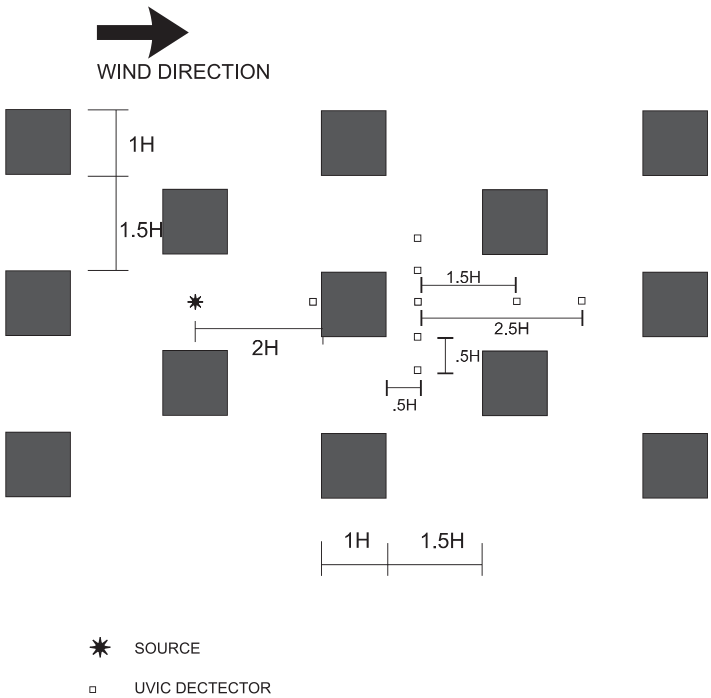

Figure 2. Plan view of the main experimental configuration for the trials conducted in the staggered array (cube normal to the flow).

response time of about 0.02 seconds. The development of the UVIC® detector is described by Griffiths *et al*. (1998). A number of UVIC® detectors were located downwind of the examined obstacle to investigate the local dispersion pattern around that obstacle and a further detector was located at the upwind face of the obstacle to monitor gas concentrations in the approaching flow. The array size for the in-line array configuration was 7x7 and for the staggered array configuration was 8x8, in order to account for the different array pattern. All detectors were located at a height of 0.5H. Concentration data were collected at a frequency of 50 Hz.

Reduced scale simulations, as the ones presented here, offer an attractive alternative to full-scale experiments, which are costly, time-consuming and often hazardous. However, they need to be correctly scaled. The general principles of setting up a reduced scale field experiment are similar to those used in scaling wind tunnel experiments, while placing some further constraints on the lowest scalable wind speed. Snyder (1972) suggests that the main non-dimensional parameters that have to be scaled are the Reynolds number and, in the case of buoyant plumes, the Froude number. It is generally accepted that for Reynolds numbers above a critical value - often quoted as 11000 - there is Reynolds number independence. The Reynolds number in the present experiments is approximately 16000 in the wind tunnel and of the order of 10^5 in the field. Therefore Reynolds number independence is guaranteed. Since the wind tunnel experiments were conducted in neutral conditions and most of the field trials in near-neutral conditions, the effect of atmospheric stability can be ignored. Detailed scaling considerations for field and wind tunnel experiments using isolated obstacles of the same dimensions with those used in the present work are presented by Mavroidis *et al.* (2000).

RESULTS AND DISCUSSION

Flow visualisation results

Flow visualisation trials were initially carried out in the wind tunnel, to investigate the effect of array spacing on dispersion and to provide guidance in choosing the array spacing for the field trials. For a regular array of cubes, the spacing (S) between two consecutive array elements (obstacles) is related to the plan area density (λ) of the obstacles by the following expression:

$$\lambda = \frac{1}{(1 + \frac{S}{H})^2} \tag{1}$$

The flow visualisation showed that there are three main flow regimes depending on the spacing between two consecutive cubical obstacles. These regimes are presented in Table 1.

The behaviour of the flow depending on the plan area density and the indicated transition between the three regimes are in agreement with the findings of Hussain and Lee (1980). A large increase in the lateral dispersion rate occurs at the transition from the skimming flow to the wake interference regime (at a spacing of S/H = 1.0-1.5), due to the transfer of plume material from one obstacle wake to another across the diagonal of the array. The findings of the flow visualization suggest that an array spacing of S/H=1.5 is appropriate to examine in the field, since at this spacing interference between consecutive obstacles is clearly occurring and a row-to-row plume interaction occurs. This spacing results in a large lateral spread of the dispersing plume. The visualized smoke dispersing through an in-line and a staggered array configuration with S/H=1.5 is presented in Figures 3 and 4 respectively. The lateral spread of the plume is somewhat larger for the staggered array than for the in-line array, since the smoke tends to follow the diagonal channels because of the positioning of alternate rows of obstacles.

Table 1. Characteristic regimes of the flow.

Flow regime	Array spacing	Plan area density (%)
'Isolated Roughness Flow'	S/H>2.0-2.5	λ<8-11
'Wake Interference Flow'	1.0-1.5<S/H<2.0-2.5	8-11<λ<16-25
'Skimming Flow'	S/H<1.0-1.5	16-25<λ

Flow Characteristics within the Array of Cubes

The mean wind speed within an array of obstacles has been found to decrease with distance from the perimeter of the array, until a near-asymptotic mean flow condition is reached (Davidson *et al.*, 1995; Macdonald *et al.*, 1997). Measurements of the mean wind velocity within the array of cubes were carried out to obtain some information on the overall array effect and on the location where the near-asymptotic condition is reached. This is important for the interpretation of the concentration measurements, since if measurements are made downwind of the location where the near-asymptotic condition is reached, these measurements will be representative of an infinite array. Velocity measurements were made within the two array configurations, for an array spacing of S/H=1.5.

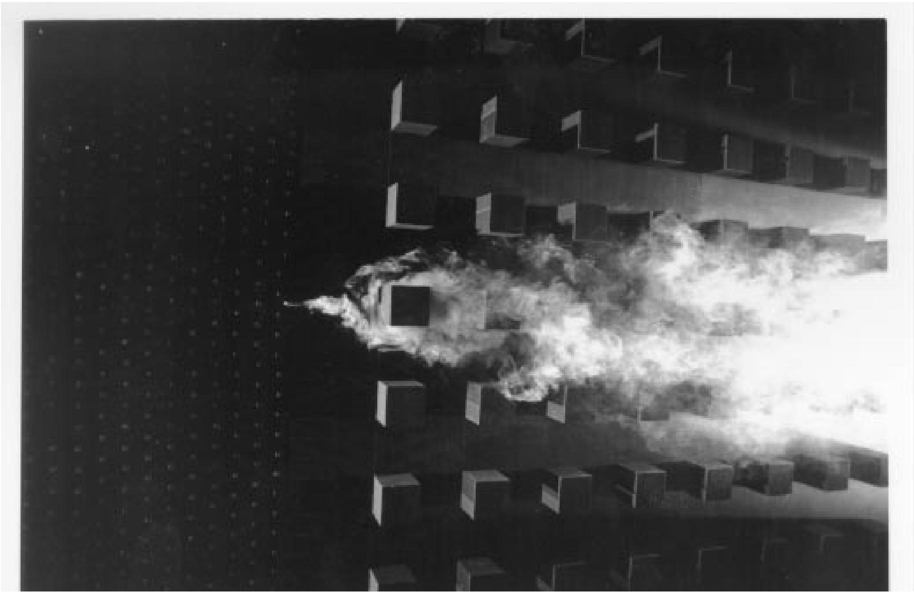

Figure 3. Smoke dispersing through an array with an in-line configuration and a spacing of S/H=1.5 (from the DERA Porton Down Urban Dispersion Archive).

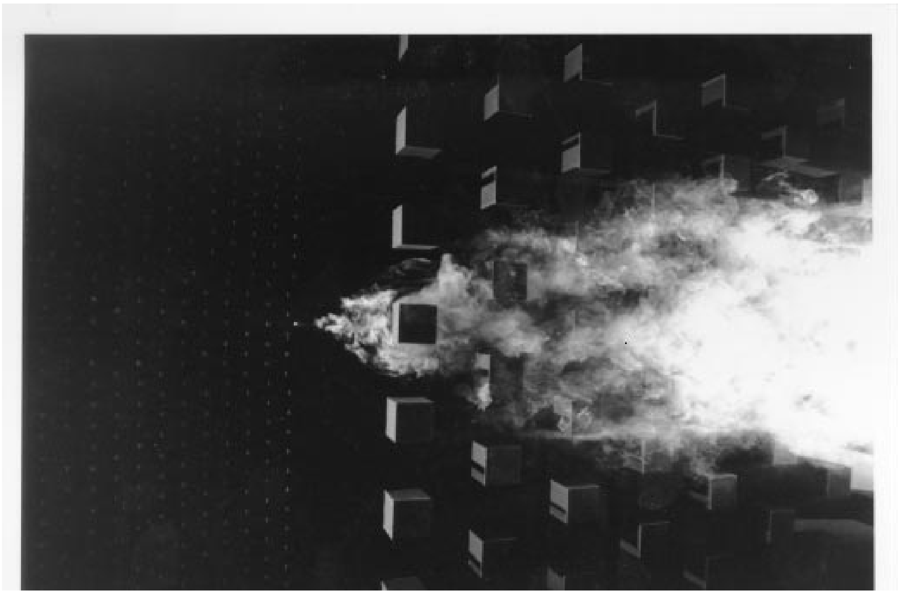

Figure 4. Smoke dispersing through an array with a staggered configuration and a spacing of S/H=1.5 (from the DERA Porton Down Urban Dispersion Archive).

Figure 5 presents the results from the wind velocity measurements inside the in-line array configuration. The measurements were conducted 0.5H downwind of each row, behind an obstacle and at a height of 1.0H. The wind velocity is normalised with simultaneous measurements from an anemometer that was located upwind of the array to measure the wind velocity in the approaching flow. There is a sudden decrease in the mean wind velocity after the impingement of the wind on the first row of cubes, and then the wind velocity (at 1.0H) is gradually reduced to a near-asymptotic value, which is approximately 35% of the free-stream wind velocity. Since the near-asymptotic value is reached behind the 5th row of the array, concentration measurements conducted behind an obstacle located in this row (or deeper) can be considered as representative of measurements conducted in an infinite array of cubes. The mean velocity pattern is very similar in the staggered array configuration, when measurements are made behind an obstacle. However, the mean velocity deficit behind a gap in the staggered array configuration is much less than that observed behind a cube. This is expected since this location is outside the immediate region influenced by the cube, where the recirculating flow results in a large velocity deficit.

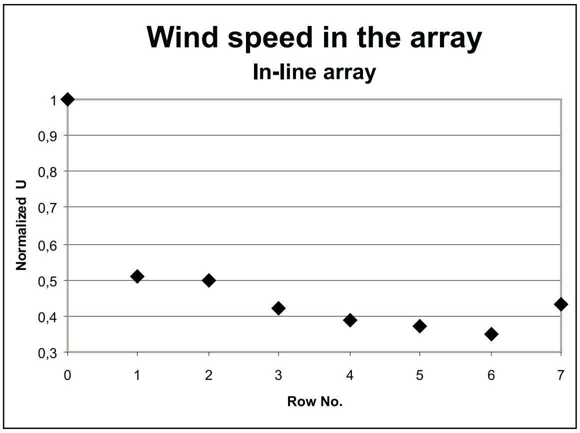

Figure 5. Velocity measurements within an array of obstacles (in-line configuration).

Since a typical wind speed during the field trials was about 5 m s^{-1}, the time scales in the near-wake were of the order of H/U, i.e. typically 0.2 seconds. To obtain stable averages of these scales, an averaging time of 3 minutes is used for the mean concentration data. To investigate the effect of averaging time on mean concentrations, average concentrations may be calculated for different averaging periods by breaking up the time series of concentration into shorter time intervals. The peak-to-mean ratio is then defined as the ratio between the maximum mean concentration for a shorter averaging time and the maximum mean concentration for a longer averaging time. In general, it is observed that as the averaging time increases the maximum mean concentration is decreasing. Various formulations have been developed to express the dependence of the ratio of maximum average concentrations on the ratio of averaging times. For plume dispersion in open terrain concentration ratio is usually given by a power law function of the time ratio (Strom, 1976):

$$\frac{C_1}{C_2} = \left(\frac{t_1}{t_2}\right)^p \qquad (3)$$

Values of p in open terrain have been found to vary between -1 and 0 and many authors agree on a value of -0.2 (Strom, 1976). Macdonald *et al.* (1997) examined the effect of averaging time on concentrations within an array of cubes and found an average value of p=-0.23, which is in agreement with the value of p observed in open terrain. However, Yersel *et al.* (1983) investigated disper-

Investigation of the Effect of Averaging time on Mean Concentrations

Concentration results are presented in the form of the non-dimensional concentration K_c:

$$K_c = \frac{CUH^2}{Q} \qquad (2)$$

where C is the measured mean concentration in ppm (volume) multiplied by 10^{-6} (i.e. for pure undiluted gas C=1), U is the mean wind speed at height H in m sec^{-1}, H is the height of a single cube in m and Q is the volumetric flow rate of the gas source in m^3 sec^{-1}. In the presentation of the experimental results, the height of a single cube (or cylinder) is used for non-dimensionalizing concentration data from the wake of all the examined obstacles, including the taller obstacle (two stacked cubes). This methodology of non-dimensionalization emphasizes the absolute differences of concentrations measured in the wake of different obstacles.

sion in an urban area and observed power law exponents ranging between 0 and -0.18 (for averaging times between 4 and 20 minutes), with a mean value of -0.07, which is considerably less (in absolute terms) than the -0.2 exponent quoted above. It is also suggested (Strom, 1976), that for longer averaging times there should be no difference in the dependence of mean concentrations on averaging time between open terrain and building wake dispersion, since the larger period components of the unobstructed flow will tend to dominate and to reduce the effect of building induced turbulence.

The effect of averaging time on concentrations measured in the wake of a cube located in the 5th row of a staggered array configuration has been investigated in the present experiments. The maximum mean concentration for different averaging times (ranging between 10 s and 15 min) was normalised by the maximum concentration for the 5-minute averaging time. The results are presented in a logarithmic plot in Figure 6. The source was located 2.0H upwind of the cube and at a height of 0.5H, with the downwind distance of the detectors varying from 0.5H to 3.0H and with one detector located at the upwind face of the cube. Equation 3 gives a very good fit on the results. Values of p range from -0.16 (0.5H downwind) to -0.06. These values are lower (in absolute terms) than the values observed by Macdonald *et al.* (1997) within an array of obstacles. This difference may be attributed to the effect of source location, since in the experiments described by Macdonald *et al.* the source was located upwind of the array. This suggestion is supported by the fact that the values of p calculated here are in good agreement with those measured by Yersel *et al.* (1983) in the case of a pollutant source located at a parking lot within the urban area.

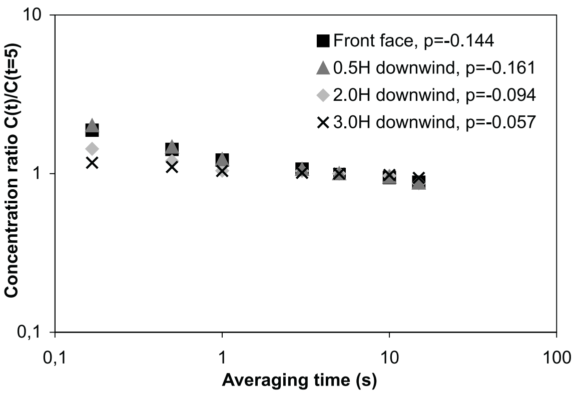

Figure 6. Effect of averaging time on concentrations measured at several locations in the vicinity of a cube located in the 5th row of a staggered array configuration.

Mean Concentration Results

Table 2 shows 3-minute mean concentrations measured in the wake of an obstacle located in the 5th row of an array with a staggered configuration. Concentrations were measured on the same axis with the source and the centre of the obstacle, and at distances 0.5H, 2.0H and 3.0H downwind of the downwind obstacle face. The pollutant source was located 2.0H upwind of the obstacle, at a height of 0.5H and at the centreline of the obstacle in respect to the mean wind direction. The location of the source and the detectors was selected to allow comparison between concentrations measured in the wake of isolated obstacles (Mavroidis and Griffiths, 1996) and obstacles embedded in an array of cubes.

The experimental results presented in Table 2 show that non-dimensional concentrations in the wake of a cube are in general higher than those observed in the wake of any of the other examined obstacles. A similar behaviour was reported in the case of isolated obstacles by Mavroidis and Griffiths (1996). The difference in concentrations observed in the wake of the cube as compared to the taller obstacle is attributable to the fact that the gas is quite well mixed in the recirculation region up to the top of the obstacle not only behind the single cube but also behind the taller obstacle. As a result, approximately the same quantity of gas is dispersed behind the taller obstacle in a volume which is approximately twice that behind a single cube. The lower concentrations observed in the wake of the cylinder as compared to the cube are attributed to the differences in the flow pattern around the two obstacles, and mainly to the fact that in the case of the cylinder there are no sharp straight edges at which separation will occur, and the wake of the cylinder is somewhat narrower. A smaller proportion of the plume is entrained in the recirculation region of a

Table 2. Mean wake concentrations in the wake of an obstacle located in the 5th row of a staggered array configuration.

Obstacle (height)	K_c (0.5H downwind)	K_c (2.0H downwind)	K_c (3.0H downwind)
Cube (H)	1.266	0.604	0.480
Tall obstacle (2H)	1.098	0.447	0.343
Cylinder (H)	0.856	0.451	0.354

cylinder for an upwind source, and this is enhanced by the wind meandering occurring in the atmosphere, since the plume may more easily bypass the cylinder. However, the differences in concentrations measured for obstacles located within the array are not as great as in the case of isolated obstacles. For example, non-dimensional concentrations 0.5H downwind of a cube and a cylinder inside the array differ by a factor of 1.5, while in the case of isolated obstacles respective concentrations differ by a factor of 2.5. The apparent effect of the array is that it results in a reduction of the concentration differences in the wakes of different obstacles, mainly since the array spacing is such that interference between wakes of neighbouring obstacles is clearly occurring. Furthermore, within the urban array it is much more difficult for the plume to bypass an obstacle, as compared to a meandering plume in an open terrain.

The experimental results suggest that there are not any significant differences between non-dimensional concentrations measured in the wake of an obstacle placed in the 1st row of the two different types of arrays (in-line and staggered array). However, if a cube is located in the 5th row of the array, a source located 4.0H upwind of this cube results in higher non-dimensional recirculation region concentrations for a staggered array (K_c=0.666), than for an in-line array (K_c=0.408). As noted before the staggered array is more efficient in decelerating the flow, due to the increased blocking effect. Furthermore, these differences in concentrations may also be partly attributable to the fact that, for this source location, there is another cube located between the source and the obstacle under investigation in the in-line array configuration. It should be noted then that non-dimensional concentrations from sources located inside the array depend more on the relative position of the source with respect to other buildings in the array, which is different for the two types of arrays.

CONCLUSIONS

Atmospheric flow and dispersion through obstacle arrays was investigated in the field. Two typical array configurations were considered, namely the in-line and staggered configuration. Flow visualization trials were initially conducted in the wind tunnel. In the light of these trials field experiments were carried out using an array spacing of S/H = 1.5, which corresponds to a wake interference regime of the flow. This spacing results in a large lateral spread of the dispersing plume. Velocity measurements within the arrays of obstacles indicated that, for both array configurations, after the fifth row of the array a near-asymptotic condition is reached.

The effect of the averaging time on concentrations measured in the vicinity of a cube embedded within the urban array is examined for the staggered array configuration. Results suggested that a power law dependence exists between the concentrations and the averaging time, with the power law exponent ranging between -0.16 and -0.06. These values suggest that within the urban canopy the dependence of mean concentrations on averaging time is somewhat lower than in the unobstructed flow. Concentrations measured in the near-wake of different obstacles embedded within an array of cubes differ significantly, and these differences are attributed to the differences in the flow pattern and in the dimensions of the recirculation region for the examined obstacles. However, these differences are not as great as in the case of isolated obstacles. Deep in the array, local dispersion patterns are also determined by the relative location of the source as well as of the receptor with respect to neighbouring cubes, which may differ for different array configurations.

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