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WIND TUNNEL AND FIELD INVESTIGATIONS INTO PLUME DISPERSION THROUGH AN ARRAY OF OBSTACLES

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ABSTRACT

In this paper we present the results of a wind tunnel and a field investigation into plume dispersion through a large array of equally sized obstacles. The agreement between the scaled results is satisfactory. Measurements in the flow field indicate that there is a significant reduction in the mean velocity (to ~50% of the upstream value), however, there is little effect on the transverse eddy diffusivities within the obstacle array. Concentration profiles indicate that the plume remains Gaussian as it passes through the obstacle array. The obstacle array has little effect on the lateral spread and decay of mean concentration of the plume with downstream distance, but the vertical extent and internal structure of the plume are altered by the presence of the obstacles.

INTRODUCTION

The transportation and storage of toxic substances presents a potential hazard to nearby populated areas and therefore some assessment of the risk associated with such activities is required. A vehicle accident or a fire at a storage site may result in the release of a toxic plume, the behaviour of which is often complex and difficult to predict. The properties of the gases involved, the prevailing atmospheric conditions and the nature of the release play a major role in determining the behaviour of the plume. Additional complexity is introduced by an irregular local topography, which may include a number of buildings. We may be required to not only predict the behaviour of the mean plume under a variety of conditions, but also to give some indication of the structure of the plume and hence the nature of the concentration fluctuations. Many aspects of this type of problem have been studied in the past and it is often possible to use Gaussian plume models to predict the behaviour of the mean plume. Reviews have been given by Hosker(1981), Hosker & Pendergrass (1987) and Fackrell (1984). One area that has received little attention is the behaviour of a plume passing through a large group of approximately equally sized obstacles such as those found in an industrial or housing estate. In suburban areas such as these the buildings are often sufficiently spaced that secondary flows (street canyon effects) are not present and thus the studies of urban areas, where street canyon effects are significant (Chaudry & Cermak (1971) and Cermak et al.(1974)) may not be relevant. There have been a number of field and wind tunnel investigations into plume dispersion at nuclear installations where one or two large structures are surrounded by a number of small buildings and hence these results are more relevant to the study of single and small groups of buildings. In the past researchers have concentrated their efforts in this area and there have been a number of wind tunnel investigations (Castro & Robins (1977), Castro & Snyder (1982)) and theoretical studies (Hunt & Mulhearn (1973), Puttock & Hunt (1979), Turfus (1986). Fung & Hunt (1992) attempted to extend the ideas developed for single obstacles to a large group of obstacle in a building block approach, however they were unable to produce any general formulae. The purpose of this investigation was to develop some general concepts for the flow and dispersion around a large group of obstacles from wind tunnel and field investigations. As with investigations of dispersion around single obstacles we have focused on an idealised problem, with arrays of simple pattern (equally spaced and sized obstacles), as these studies are the best way to develop a general understanding of plume behaviour.

EXPERIMENTAL DETAILS

Two sets of experiments where conducted, one in the field and one in a wind tunnel. A number of source positions and array configurations were considered in each of these studies, but in this paper we will present the results from a single configuration and a limited number of source positions. Details of the remaining results can be found in Davidson et al. (-). The obstacle array consisted of 39 obstacles positioned in a staggered configuration (figure 1). The obstacles in each array were identical with height (h), width (w) and breath (b). The spacing *between* the obstacles was twice the relevant obstacle dimension; that is $2w$ in the y direction and $2b$ in the x direction.

The field study was conducted at the United Kingdom Meteorological Office's field site at Cardington. It is a flat terrain site. The wind profile can be characterised by the friction velocity (U_*) divided by the mean velocity ($<U>$) which has a value of 0.07 and a roughness height (z_o) of 5mm (estimated from stress measurements at a height of 4m). The dimensions of the obstacles were w=2.2m, b=2.45m and h=2.3m. The experiments were conducted in two phases. Phase I consisted of a number of flow visualisation experiments where smoke was released from grenades for a period of 15 minutes and the behaviour of the plume was recorded on VHS and 35mm cameras. A video and still camera were mounted on a tethered balloon approximately 500m above the obstacle array to give a plan view of the experiments. In each experiment a second plume (the control plume) was released alongside the array experiment as a control experiment for comparison. In Phase II a hydrocarbon tracer system based around the TIP detector (Mylne & Mason (1991)) was used to obtain quantitative information. This detector is sensitive to 0.1ppm with a frequency response of 1Hz. A point source of propylene (C_3H_6) gas was released for 15 minutes for each experiment and although propylene is heavier than air, with wind speeds of ~6m/s buoyancy effects were negligible. Source positions at $x_a=1b$ and $x_a=4b$ were considered (figure 1). The experiments were conducted in near neutral conditions when the wind direction was approximately perpendicular to the front face of the obstacle array.

The wind tunnel study was conducted in the United States Environmental Protection Agency's atmospheric boundary layer wind tunnel in the Research Triangle Park, North Carolina. This wind tunnel has a working section that is 2.1m high, 3.7m wide and 18m long. The atmospheric boundary layer was simulated using the Counihan (1969) system of a fence, vortex generators and downstream gravel roughness. The obstacles were cubes with $w=b=h=0.12$m and this is a scale of approximately 1:20 when compared to the field study. The statistics of the upstream profile at a reference height of $2h$ were $U_*/\langle U\rangle=0.06$, $z_o=0.3$mm and the height of the boundary layer was 0.8m. Flow field measurements were made with cross-wire and pulse wire anemometers and the tracer measurements were made with low (1Hz) and high (150Hz) frequency response Flame Ionisation Detectors. The tracer gas was ethane (with wind speeds of 4m/s this was effectively neutrally buoyant in air) and this was released from a point source at $x_a=10b$ (figure 1). The source height for all of the experiments was $h/2$.

FLOW FIELD

The flow field around sharp edge obstacles is relatively simple to model in a wind tunnel as the sharp edges define where the flow will separate and hence, providing the ambient flow is fully turbulent (the Reynolds number is sufficiently high), similarity is maintained. There are however limitations as it is not possible to simulate large scale atmospheric motions in a wind tunnel. Whereas a plume in the atmosphere meanders because there are always eddy motions larger than its width, a plume in a wind tunnel eventually becomes larger than the largest scales of turbulence and ceases to meander. This is not a serious limitation and much can be gained from studying the simplified wind tunnel version of the atmospheric problem. In this case the wind tunnel experiments enabled us to gain valuable information about the flow field in and around a large group of obstacles.

There are two mechanisms that are likely to alter the behaviour of a plume as it passes through the obstacle array. These are the divergence and convergence of streamlines and changes to the scale and intensity of the turbulent eddies. Lateral and vertical velocity profiles were measured in and around the obstacle array. A temporal and spatial (y direction) average of the u component of the mean velocity at $z=h/2$ is shown in figure 2. Clearly there is a significant reduction in the flow through the obstacle array and therefore by continuity there must be a significant flow around the obstacle array as a whole. Near the front of the obstacle array we would expect the streamlines to diverge and near the downstream end they will converge as the flow field recovers. With an obstacle array that presents a low wide aspect to the oncoming wind we would expect most of the diverted flow to pass over the array as opposed to passing around it. There will be a dividing streamline above which material passes over the obstacle array and below which material passes through the obstacle array. Streamlines will diverge and converge within the obstacle array as the flow passes around individual obstacles, but as this occurs on a relatively small scale when compared to the global changes described above, we would not expect it to significantly influence the plume behaviour.

Measurements were also made of the transverse and longitudinal turbulence scales (l_x, l_y, l_z) and intensities ($\sigma_u/\langle U\rangle$, $\sigma_v/\langle U\rangle$, $\sigma_w/\langle U\rangle$) at the source height ($z=h/2$). The method of estimating these quantities is outlined in Davidson et al. [-]. Eddy diffusivities were then calculated as the product of the turbulent length scales and fluctuation strengths (σ_u, σ_v, σ_w). Despite a reduction in the scale and increase in the strength of the fluctuations, the net effect on the transverse diffusivities was small. Thus for a continuous release the dilution of the plume with downstream distance will resemble that of the control plume. However, the structure of the plume may be quite different as the high intensity small scale turbulence within the obstacle array will thoroughly mix the plume. It appears then that changes to the nature of turbulence have little effect on the mean plume, but that they may affect the structure of fluctuations in the plume and that divergence and convergence of streamlines near the upstream and downstream ends of the obstacle array will influence the behaviour of the plume.

The size of the plume relative to the obstacles in the array will determine the significance of these effects. If the plume is small relative to the obstacles in the array then we expect the presence of the obstacle array to dominate the behaviour of the plume. If the plume is large relative to the obstacles in the array then the effects on the mean plume will be negligible and changes to the plume structure will be local to the obstacle array. The size of the plume is dependent on the position of the source with reference to the obstacle array and in these experiments the source positions were such that the plume was of a similar order or smaller than the obstacles in the array.

DISPERSION

Plate 1 is an example of a smoke release through the obstacle array. This photograph indicates that, when compared to the control plume, the lateral spread of the array plume is significantly greater and that the concentration of smoke in the array plume is lower. However, it must be noted that this is an instantaneous photograph. As the instantaneous array plume is relatively large and the obstacles reduce the scale of the turbulence, the array plume will be less susceptible to meandering than the control plume. What is being observed is a difference in the plume structure and not necessarily a difference in the mean quantities of the plume. Further evidence of the changes to the structure of the array plume can be seen in figure 3. In this figure portions of two time series recorded simultaneously in the array and control plumes (at position E in figure 1) are shown. The control plume signal is typical of a plume released in a neutral boundary layer. The signal is intermittent with strong bursts in the level of concentration. In contrast the detector in an equivalent position in the array plume receives a continuous low level signal. The presence of the obstacles therefore reduces the meandering of the array plume and at the same time increases the internal mixing of the plume. This results in a dramatic change to the nature of the concentration fluctuations.

The tracer systems were used to obtain detailed vertical and horizontal mean concentration profiles in the field and wind tunnel experiments. These profiles show that the plume remains Gaussian as it passes through the obstacle array (figure 4). It was therefore possible to fit Gaussian profiles to the array and control plumes and to characterise the mean plume with the mean centre line concentration ($\langle C\rangle$), the lateral spread (σ_y), the vertical spread (σ_z) and the height to the centre line of the plume (h_{cl}). The total height of the plume (σ_{zT}) is the sum of σ_z and h_{cl}. To compare the behaviour of the plumes in the atmosphere and in the wind tunnel and be certain that our wind tunnel results are relevant to full scale scenarios we need to scale the results from each of the experiments. As we are primarily interested in deviations from the behaviour of the control plume, it is important to consider scaling in the absence of obstacles. In this case the relevant scaling parameters are the upstream turbulence scales and intensities (at the source height). These values have been used to scale the data presented in figures 5, 6 and 7. Data from a Gaussian plume model of the control plume have been added for comparison. The agreement between the data from the two sets of experiments is satisfactory. It is interesting to note that the array plume data has scaled effectively with the upstream turbulence parameters. This is rather surprising as we would expect the obstacles' scales to dominate in the region of the array. However with a low wide obstacle array such as this a significant portion of the plume passes over the top of the array and continues to interact with the upstream scales and hence they are relevant for scaling purposes. Figures 5 and 6 show that the obstacle array has little effect on the lateral spread and decay of mean concentration of the plume with downstream distance. This is expected as the obstacle array has little effect on the transverse eddy diffusivities. The obstacle array does however have a significant effect on the vertical extent of the plume (figure 7) and this can be explained by considering changes to the mean flow field. With a single source and no sinks we expect the flux of tracer to be conserved downstream of the source. As the streamlines diverge (the mean velocity decays) near the upstream end of the obstacle array the plume must spread to maintain a constant tracer flux. This occurs predominantly in the vertical plane as streamline divergence occurs principally in the vertical plane (as the obstacle array presents a low wide aspect to the oncoming wind). Conversely as the streamlines converge near the downstream end of the obstacle array the opposite will occur. However, as the streamlines converge gradually over a considerable distance this effect is not as noticeable at the downstream end of the obstacle array.

CONCLUSIONS

The Gaussian properties of the mean concentration profiles of the array plume suggest that a modified Gaussian plume model may be appropriate for modelling the changes in the behaviour of the mean plume. This particular obstacle array has little effect on the transverse eddy diffusivities and hence the dilution of the plume. However, obstacles of a different dimension may alter the diffusivities up or down depending on the relative changes to the scale and fluctuation strength of the turbulent eddies. The reduction of the mean flow through the obstacle array alters the behaviour of the plume. The overall shape of the array (low and wide or tall and thin) determines whether the flow is primarily diverted over or around the obstacle array and hence whether the changes to the plume are predominantly in the vertical or horizontal planes. The density of the obstacles within the array will determine how much flow is diverted around the obstacle array and hence the magnitude of the changes to the extent of the plume. Clearly further detailed investigation is required before we can predict the behaviour of a plume passing through a given array of obstacles. However, we have been able to develop some general concepts of the behaviour of a plume passing through a large array of obstacles.

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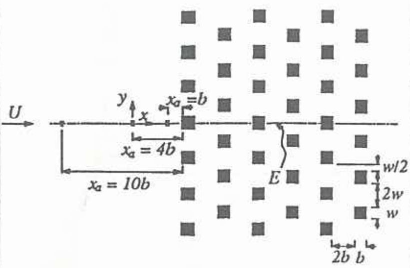
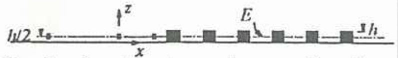


Plan view of the staggered array configuration



Elevation view of the staggered array configuration

Figure 1. A schematic diagram of the array configuration. Note x_a is the distance from the source to the front face of the array.

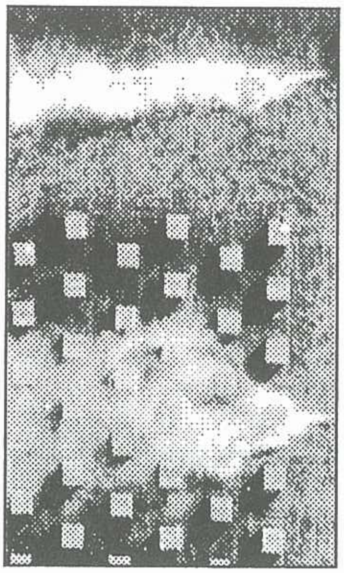


Plate 1. An instantaneous plan view of the array and control plumes. The wind direction is perpendicular to the front face of the array and the mean wind speed at a height of 4m was 6m/s (recorded over a 15 minute period).

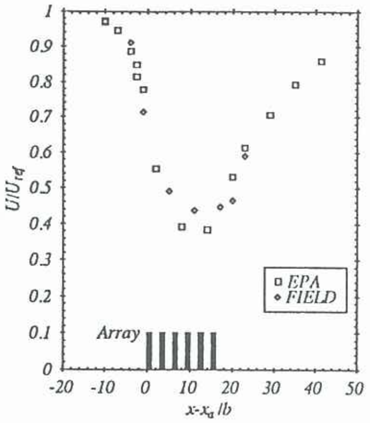


Figure 2. Mean velocity measurements in the region of the array, at $z=h/2$. U_{ref} is the upstream mean velocity at $z=h/2$.

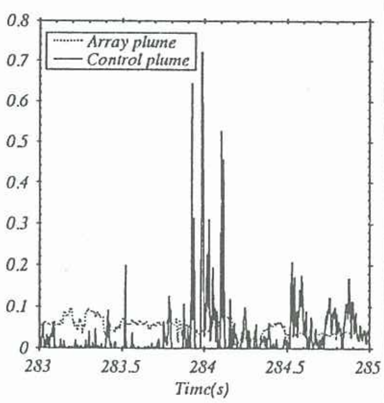
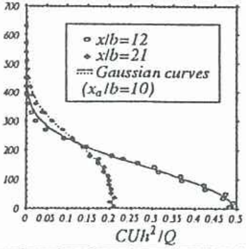
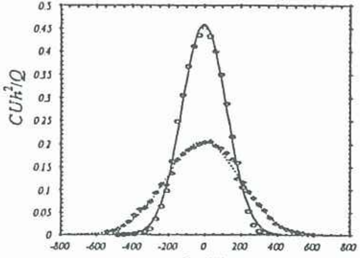


Figure 3. Concentration time series recorded at position E in figure 1.



Vertical mean concentration profiles



Horizontal mean concentration profiles

Figure 4. Mean concentration profiles

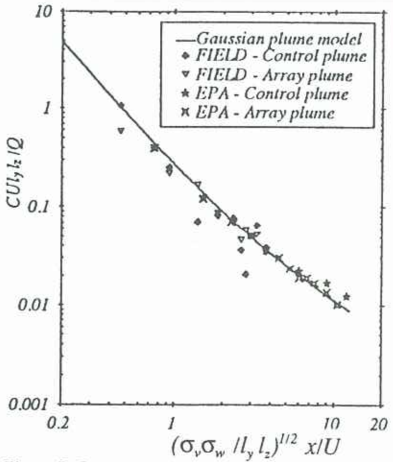


Figure 5. Centre line mean concentration (at $z=h/2$) against downstream distance.

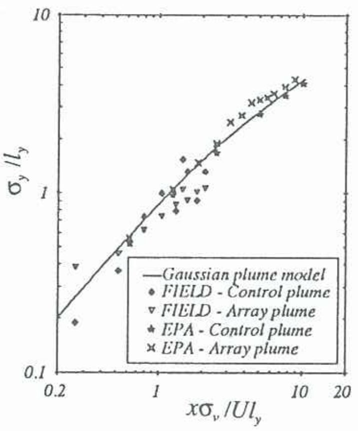


Figure 6. Lateral spread (at $z=h/2$) against downstream distance.

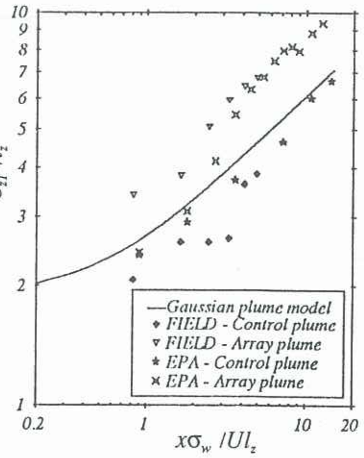


Figure 7. Vertical extent of plume against downstream distance.