Study of Near-field Dispersion through Large Groups of Obstacles

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Abstract
The flow and dispersion around the obstacles is important to understand the pollution problem in the urban areas. This study presents the preliminary results of the experiment carried out at Dugway Proving Ground, Utah. It shows that the presence of obstacles has a significant effect on the structure of the plume. Both horizontal plume spread ($\sigma_y$) and vertical plume spread ($\sigma_z$) are higher in arrays of obstacles compared to without obstacle configuration. It is also observed that the concentrations in arrays of obstacles are generally lower than those without obstacles. The modeling results show that the Gaussian plume model for the time-averaged concentration in the near-field can provide important information with few input parameters. The information obtained from the controlled conditions of the model canopy can be useful for interpreting data from real urban areas.

Keywords: atmospheric dispersion; urban canopy; obstacle array; gaussian plume; plume spread

1. Introduction
Recently dispersion of gases in urban environment has become a subject of great importance. The increased pollutants concentrations and threats of chemical and biological contaminants release during accidental release or terrorist attack have increased the need for comprehensive studies of flow around buildings and near-field dispersion. The flows in the urban area are strongly influenced by the presence of an obstacle or groups of obstacles. Meroney (1982) and Hosker (1984) provided excellent reviews on the main characteristics of flow and dispersion around single or small groups of obstacles. Flow and dispersion around an isolated building was also studied extensively by Murakami (1990). These studies have motivated several researchers to study the problem of dispersion around the obstacles and on short-range dispersion more systematically.

Several experiments have been carried out in model and real urban canopies and wind tunnel using tracer gases (Davidson et al., 1995; Davidson et al., 1996; Theurer et al., 1996; MacDonald et al., 1997; Mavroidis et al., 1999; Venkatram et al., 2002; Bentham and Britter, 2003). Oikawa and Meng (1997) investigated diffusion around a building in field experiment in suburban area in Sapporo. They found that high concentrations were observed both upwind and downwind of the source on the roof. Field and wind tunnel experiments by MacDonald et al. (1998) confirmed that at short distances from the source, concentration profiles in the obstacle arrays are quite variable. Mavroidis and Griffiths (2001) examined the flow and dispersion through arrays of obstacles. The results suggested that enhanced mixing and dispersion occur within array. Recently, dispersion of atmospheric pollutants in the vicinity of isolated obstacles of different shape and orientation with respect to the mean wind direction has been examined in scaled field and wind tunnel experiments (Mavroidis et al., 2003). It has been found that the presence of taller obstacles results in a reduction of ground level concentrations.

It is now widely acknowledged that the greatest damage to human health is caused in the near-field of toxic releases from sources within the urban canopy. Complex flows around the obstacles in urban canopy pose difficult challenges to researchers and modelers. Thus, it is essential to address these challenges and develop methods to model the impact of contaminants at short distance from the source within urban canopy. In the present study, preliminary analysis of results from a tracer experiment is presented. The experiment has been carried out to understand the dispersion through arrays of obstacles in model urban canopy.

2. Experimental Details
The small-scale experiment was conducted at Dugway Proving Ground, Utah from 12th July 2001 to 26th July 2001. The urban canopy was simulated with a 5 x 9
rectangular array of 45 barrels with height $H=0.91\text{m}$ and diameter $d=0.57\text{m}$, and a center-to-center spacing $S=1.8\text{m}$. The experiment corresponds roughly to a model length scale ratio of $1:10$ and plan area density of $16\%$, which is typical of an urban canopy. Figure 1 shows a photograph of the experimental site at Utah.

Propylene ($C_3H_6$), a tracer, was released through a 25.4mm diameter pipe, both upstream and within the barrel array. The release rate was 15 standard liters/minute. The tracer was sampled on receptor arcs at 1.5S, 2.5S, and 4.5S from the source. Each arc contained 11 photo-ionization detectors (PIDs), $5^\circ$ apart at 0.23H. The furthest distance of 4.5S scales up to approximately 100 meters in a real urban area. One PID was placed at 0.5S to sample the cavity region of the obstacle where the source is located. At 4.5S, two PIDs were placed at 0.5H and 1.5H, where H is the height of the obstacle. The vertical array of three PIDs at 4.5S provided information to construct the vertical profile of concentrations. Figure 2 illustrates a schematic view of the experimental arrangement.

![Fig.1. Photograph of experimental site at Dugway in Utah](image1)

Turbulence, velocity, and temperature measurements were made with sonic anemometers at three locations. Three sonics at 0.5H, 1.0H, and 2.0H on an upwind tower provided information on the approach flow. One sonic at 0.5H, behind the source obstacle, provided flow and turbulence information in the cavity region of the source. Two sonics at 0.5H and 1.5H located at 4.5S from the source provided information on the fully developed flow in the urban canopy. The tracer source was located at either ground-level or at 1H.

3. Results and Discussion

The data collected from the Dugway experiment was analyzed to obtain estimates of the plume parameters for two cases: (i) without obstacle (flat terrain) and (ii) with obstacles (barrel array). These plume parameters were obtained by averaging over all experiments for each case. The horizontal plume spread, $\sigma_y$, was estimated by fitting Gaussian profile to the concentrations in each arc. Vertical plume spread, $\sigma_z$, was obtained from ground-level concentration (Venkatram et al., 2002).

Figure 3 depicts the effect of the obstacles on the $\sigma_y$. It can be seen that the growth of $\sigma_y$ is linear with distance in both without obstacle and with obstacles configurations. But the rate of growth of horizontal plume is much higher in the arrays of obstacles compared to flat terrain. This corresponds to the increase in $\sigma_y/u$ from about 0.14 in without obstacle configuration to about 0.5 within the array measured just behind the source at height of 0.5H. In the downwind $\sigma_y/u$ within the array of obstacles is found to be 0.26, this value is more consistent with the $\sigma_y$ growth (Figure 3). This suggests that the behavior of $\sigma_y$ depends on the turbulent intensity within the urban canopy rather than that in the cavity of the source.

The effect of obstacles is more apparent in case of $\sigma_z$ with distance. It can be noticed in Figure 4 that in absence of obstacle, $\sigma_z$ increases rapidly with distance and growth is linear. When the arrays of obstacles are introduced, the plume grows linearly near the source, and then the
growth rate decreases beyond $x/H=5$. This same behavior was similar to that observed with source at release height $1H$.

Figures 5 and 6 show the variation of normalized concentration, $C/Q$ with distance for source release height at ground-level and $1H$, respectively. It can be seen that $C/Q$ is showing a decreasing trend with distance. It is further observed that the concentrations for both ground-level and elevated releases are 3-5 times lower in barrel array than that of flat terrain. It was expected that the concentration was higher in the wake of obstacle in both ground-level and elevated releases. The lower concentration in arrays of obstacles may be due to the enhancement of vertical diffusion by the array that result in effective lifting of the center of mass of plume. However, it is still uncertain, a more detailed analysis of data might provide the fact.

The effects of the obstacles on the plume dispersion were examined further by testing the model predicted concentrations with the observed concentrations for source release at ground-level. The model expression for concentrations associated with ground-level release is given by (Venkatram et al., 2002):

\[
C(x, y, z) = \frac{Q}{\sqrt{2\pi \sigma_y \sigma_z}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{b\left(\frac{z}{\bar{z}}\right)^s}{\sigma_z^2}\right)
\]

(1)

where $\bar{z}$ is the mean height of the plume, $u_e$ is the effective wind speed and $s$ and $b$ are parameters depend on atmospheric conditions. The further details on these parameters can be found in Du and Venkatram (1997). The model estimates is done with concentration observations at $z=0.23H$, the height of PID. The concentrations corresponded to five-minute averages. Figure 7 (a) shows the comparison of the model prediction with the observed concentrations in flat terrain for source at ground-level. It is found that the estimated concentrations in arcs 1 and 2 compare well and are within “factor of two” of the observed concentrations. Here “factor of two” means the predicted concentrations are within two-fold of the observed concentrations. But the model is underpredicting the concentrations in arc 3. The comparison of the model estimates with observations from experiments with arrays of obstacles is shown in Figure 7 (b). It is noticed that the model predictions are within “factor of two” in arcs 1 and 2 but there is slight underprediction in arc 3. But note that concentrations with obstacles are generally lower than those without obstacles.

4. Conclusion

The study presented in this paper shows the preliminary investigation of dispersion in the model urban canopy of the experiment conducted at Dugway Proving Ground, Utah. The results show that the obstacle
array has a significant effect on the structure of the plume. The horizontal plume spread ($\sigma_y$) is much higher in arrays of obstacles compared to without obstacle case. The vertical plume structure ($\sigma_z$) is also showing a growing trend. It is also observed that the concentrations in arrays of obstacles are generally lower than those without obstacles. From the modeling perspective, the present results show that the Gaussian plume model can provide quite important information in the present regime. But still it needs to make use of dispersion parameters that are sensitive to the obstacle dimensions and their different configurations.

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