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GAS DISPERSION NEAR A CUBICAL MODEL BUILDING

PART II: CONCENTRATION FLUCTUATION MEASUREMENTS

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Summary

A wind-tunnel study of the concentration fluctuation measurements in the near wake region ($1.0 \leqq x/H \leqq 5.0$) of a cubical model building was performed in a simulated neutrally-stratified shear layer. The contaminants were released at a central roof vent for buildings with 0° and 45° orientations, and at a downwind roof vent for building with 0° orientation.

The log-normal concentration probability model was found appropriate for measurements in the building wake and the concentration fluctuation intensity was found to be reduced by the presence of the model building in an obstructed flow. A simple algorithm, based on the relation of the peak-to-mean concentration ratio to the local intensity, suggested an upper limit to the peak-to-mean concentration ratios near the ground centerline.

Introduction

When an exhaust gas contains toxic, flammable, bacteriological or odorous material one is interested not only in the average levels of concentration but in their instantaneous magnitudes and associated probability distributions.

Although Hinds (1) reported that no detectable difference existed between peak-to-mean concentration ratios measured in an unobstructed

flow and in the lee of a building, data presented by Fackrell (2) indicated that the peak-to-mean concentration ratios were affected by the presence of a model in the near wake region behind the building. It was suspected that the release of Hinds was located at the forward stagnation point of a building oriented 45° to the wind, thus the gas may have swept around the building and not participated significantly in the wake motion.

Ramsdell and Hinds (3) examined concentration fluctuations and peak-to-mean concentration ratios in plumes from a ground-level continuous point source. It was found that near the edge of the plume the standard deviation of the short-term concentration is more than triple the mean. The absolute intensity of the concentration fluctuation is relatively constant near the center of the mean plume and decreases rapidly near the edge of the plume. Csanady (4) proposed that concentration fluctuations are log-normally distributed about the mean for a continuous ground-level point source and, further, that the distribution is a function of the logarithmic standard deviation only. Wilson (5) measured concentration fluctuations on a sharp-edged building surface for a source released from different roof vent locations. He reported that the concentration statistics are in good agreement with the log-normal probability distribution and the fluctuation intensity decreases as distance from the vent increases.

Meroney (6) examined Wilson's and Ramsdell's data and proposed an approximate asymptotic emperical formula for the relation between local concentration intensity, I_c, and downwind distance from the source, as $s/\sqrt{A_c}$,

$$(I_c)_{CL} = (I_c)_{CL\infty} + (4 - (I_c)_{CL\infty}) \exp(-2\, s/\sqrt{A_c})$$

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Netcoons (6) examined Wilson's and Ramsdell's data and proposed an approximate asymptotic empirical formula for the relation between local concentration intensity, i_c, and downwind distance from the source, as given,

$$(i_c)_s = (i_c)_{bm} + ((i_c)_0 - (i_c)_{bm}) \exp(-2\, s/\sqrt{A})$$

where s is the distance from vent to inlet found by stretching the shortest possible string between the two points. Based on this algorithm the concentrations do not exceed their mean value by more than a factor of 2 for more than 10 percent of the time at any reasonable distance from the vent.

Fackrell and Robins (7) measured concentration fluctuations and turbulent fluxes for two isolated possive plumes from an elevated and a ground-level source in a simulated neutral, rural, atmospheric boundary layer. The mean square concentrations were found to decrease near the ground and to have a maximum near 0.75 of the mean concentration field half width height. Probability density functions were found to follow an exponential distribution for elevated plumes, become log-normal as the plume approached the ground, and near the ground the distributions are very close to Gaussian. The distribution function is thus strongly affected by the degree of mixing and the presence of a surface.

The purpose of this study is to examine the instantaneous concentration fluctuations in a model building wake and the resultant probabilities of exceeding various peak-to-mean concentration ratio values.

Experimental Facilities and Measurements

Wind-Tunnel Facility and the Boundary Layer

The facility used was the Meteorological Wind Tunnel of the Fluid Dynamics and Diffusion Laboratory at Colorado State University. The meteorological wind tunnel was designed specifically to model atmospheric boundary-layer flow. The tunnel is a closed circuit facility with a 9:1 contraction ratio driven by a 400 hp variable-pitch, variable-speed propeller. The test section is 27 m in length and nominally 1.8 square. The wind speed in the test section can be adjusted continuously from 0.3 to 37 mps and does not deviate from the set speed by more than 0.5 percent. A detailed description of the meteorological wind tunnel is given by Cermak (8).

Figure 1 shows the mean velocity and local turbulence intensity profile as a function of non-dimensional height in the boundary layer. The height in the plot is normalized with respect to the boundary-layer thickness. Two different effluent velocities were employed, $U_e/U_H = 0.46$ for the central roof vent and $U_e/U_H \doteq 0.64$ for the downwind roof vent. The vent diameter was 1.25 cm. The downwind vent was located on the roof centerline 2.5 cm away from the edge. A velocity profile power law exponent of $n = 0.2$ existed for the approach flow. Pure argon gas released from a Plexiglas cubical model (15 cm x 15 cm x 15 cm) at various roof locations to simulate released from a flush vent on a rectangular building.

Concentration Measurements

A hot-film aspirating probe was employed to measure concentration fluctuations. The film was operated in a constant temperature mode at a temperature above that of the ambient air temperature. A feedback amplifer maintained a constant overheat resistance through adjustment of the heating current. A change in output voltage from this sensor circuit corresponds to a change in heat transfer between the hot-wire and the sample environment. For a fixed probe geometry and film temperature, the heat transfer rate, or the related voltage drop across the film, is a function of only the gas composition (under isothermal flow situation).

Calibration was made by passing the known argon-air mixtures through a preheat exchanger to condition the gas to the tunnel temperature environment. An overheat ratio (temperature of film/ambient temperature) of 1.75 was found to provide a variation between the voltage drop and the argon concentration and to provide a maximum sensitivity. A more detailed description of the hot-film aspirating probe is given by Wilson and Netterville (9).

The concentration data obtained by the aspirated probe were recorded for 3 minutes sample periods. A probability density function was established for each sampling location, and zero concentration reading were eliminated from the processing of the data. The peak concentration is that value of the concentration which is not exceeded more than a given percentage of the cumulative probability density function. Three values of the "peak" concentration were examined in this study, i.e., those which were not exceeded for 90 percent, 95 percent, or 99 percent of the cumulative probability density function.

Error in Concentration Measurement

The effective sampling area of the probe inlet is a function of the probe's aspiration rate and the distribution of approach velocities of the gas to be sampled. The effective sampling area was always less than the area of the probe's inlet, 1.88 cm^2.

The aspirated probe is expected to have a 1000 Hz upper frequency response, but to improve signal to noise characteristics, the signal was filtered at 200 Hz. This is well above the frequencies of concentration fluctuations that were expected to occur.

The errors caused by a linearity assumption in the reduction of concentration data are approximately the component value (percent argon) ±0.75 percent. The error caused by calibration change due to temperature drift is approximately 0.1 percent of the component value per degree centigrade. The cumulative error in this experiment would be less than 1.2 percent of the component value.

Results and Discussions

The concentration fluctuations observed in this study were normalized with mean concentration magnitudes into local intensity and absolute intensity. The local intensity, I_c, is defined as the ratio of rms value of the fluctuating concentration to the mean concentration at that point. The absolute intensity, $(I_c)_{1G}$, is the rms value of fluctuating concentration normalized by the ground-level mean concentration at $x/H = 1$.

Figure 2 displays measurements in the near wake region for the relation between peak-to-mean concentration not exceeded by 99 percent of the cumulative probability density function as a function of the logarithmic standard deviation. It is implied that the log-normal probability model is a reasonable approximation even in a building wake flow regime (it is assumed that the intermittency factor $\gamma = 1$ for every location in the wake).

The local intensities were found to be less than 1 for most of the data in the near wake region behind a model building (see Figures 3, 4, and 5). When compared with data (Ramsdell and Hind) reported for continuous plumes in unobstructed flow, it was found that the fluctuation intensities appeared lower in the obstructed flow than in the unobstructed flow (ranging from 1.0 to 2.0 on the plume centerline). As expected, the presence of a building evens mixing which reduced local variations and results in a decrease of the flucutation intensities rather than an increase.

The model building has the effect of adding turbulence to the wake, but at scales smaller than the boundary layer scales. The scales are appreciably smaller close to the model than further downstream in the wake (Peterka and Cermak (10)). If the concentration variance can be treated as a transportable, quantity, then it can be transferred and dissipated in the same way as turbulence kinetic energy (Csanady, 1973). The energy dissipation rates are higher in the building wake than in the boundary layer since they increase with decreasing turbulent length and time scales. Consequently, the fluctuation intensities observed in the near wake region dissipate faster than in the unobstructed boundary layer. This is the reason why lower fluctuation intensities were observed in the building wake during the present study.

The large eddies in a turbulent boundary layer are broken into many small eddies in the near wak region behind a model building. Near the edge of a building wake the smaller eddies recover to the boundary values rather quickly. In the inner building wake, $x/H < 4$, $y/H < 1$, $z/H < 1$, one would anticipate a small eddy size of the oroder of a characteristic dimension of the building. On the fringe of a building wake the mechanism of transition of eddy size is rather complicated. The absolute intensities were found to vary magnitudes proportional to the mean concentration profiles as shown in Figures 3, 4, and 5. The maximum absolute intensity occurred where the maximum mean concentration occurred. The local intensity has its minimum value near the ground centerline as noted by Fackrell and Robins (7) for elevated releases with no building. The 90 to 99 percent peak-to-mean concentration ratios remained 1 and 2 as seen in Figure 6.

An empirical formula $R_r \leqq 0.75 \cdot M_r^{1.2}$ was found to provide an upper limit to the rms concentrations observed in the inner building wake, where M_r is a percentage of the observed mean concentration normalized by the source strength and R_r is the percentage of the observed rms concentration normalized by the source strength. This simple formula only holds for the region where the dispersion process is dominated by small eddies. In the relation $R_r \leqq 0.75 \cdot M_r^{1.2}$, it is implied that the absolute fluctuating concentration increases as the mean concentration increases in the inner building wake. If a simple transformation is performed, this equation also shows that $I_c \leqq f(Q.U.A) \cdot K$ where $f(Q.U.A)$ is a constant which depends on the flow configuration. In present study, the constant was found to be 0.57. This upper limit algorithm relates the maximum values of the centerline concentration fluctuation to the mean concentration distribution. It is restricted to the inner wake region for a specified flow situation. The algorithm provides an alternative approach to the relation predicted by Wilson for the concentration intensity on the building and to the relation predicted by Meroney for the centerline plume fluctuations. The rms concentrations are plotted versus the mean concentrations in Figure 7 to Figure 9. It can be seen in Figure 7 that the rms concentrations near the fringe of a building wake significantly exceed the value of the upper limit given by the simple algorithm. In Figure 8, $\theta = 0°$, downwind roof vent release, the deviation was not significant since most of the contaminants were entrained into the inner building wake by downwash. In Figure 9, $\theta = 45°$, roof central vent release, the building wake and the downwash effects were changed since a change in orientation of the building was made. However, the algorithm provides a reasonable upper limit of the rms concentrations in the inner building wake.

Figure 10 displays a cross-wind profile of local concentration intensity and absolute concentration intensity near the ground. The maximum local intensities were observed near the edge of the building wake ($y/H = 1.0$) on the ground level. The variation of fluctuation intensities at the ground level along the centerline is presented in Figure 11. By adopting $(I_c)_{1G} = 0.35$, the data support the prediction suggested by Meroney (6).

A fairly reliable estimation of the peak-to-mean concentration ratios in the near wake could be made by simply assuming it is some constant times I_c. Upper limits for the peak-to-mean concentration ratios in the inner building wake can be obtained by applying the empirical formula of rms concentration.

$$(\chi_p/\bar{\chi})_{99\%} = 3.75\ M_r^{0.2}$$

$$(\chi_p/\bar{\chi})_{95\%} = 3.0\ M_r^{0.2}$$

$$(\chi_p/\bar{\chi})_{90\%} = 2.25\ M_r^{0.2}$$

Conservative estimates for the peak-to-mean concentration ratios near the ground level are:

$$(\chi_p/\bar{\chi})_{99\%} < 3.0$$

$$(\chi_p/\bar{\chi})_{95\%} < 2.5$$

$$(\chi_p/\bar{\chi})_{90\%} < 2.0$$

Conclusion

The log-normal concentration probability model was found appropriate for measurements in the building wake. The local intensity, I_c, tends to be reduced by the presence of a building over that for sources released in an unobstructed flow reported by other authors.

The local intensities on the ground centerline were found in good agreement with Meroney's prediction. The absolute intensity, $(I_c)_{1G}$, has its maximum value at the same location where the maximum mean concentration exists.

Data presented in this study suggest that near the ground centerline behind the model building upper limits to the peak-to-mean concentration ratios are

$$(\chi_p/\bar{\chi})_{99\%} < 3.0$$

$$(\chi_p/\bar{\chi})_{95\%} < 2.5, \text{ and}$$

$$(\chi_p/\bar{\chi})_{90\%} < 2.0.$$

<u>Nomenclature</u>

A_c	reference building area
H	height of building
I_c	rms value of the fluctuating concentration to the men concentration at that point
$(I_c)_{1G}$	rms value of the fluctuating concentration normalized by the ground level mean concentration at x/H = 1.0
$(I_c)_{Ł}$	local intensity at ground centerline
M_r	The percentage of the observed mean concentration normalized by the source concentration
R_r	the percentage of the observed rms concentration normalized by the source concentration
s	string distance from vent to inlet
U	mean velocity
θ	building orientation
$\bar{\chi}$	mean concentration
$\bar{\chi}_p$	peak concentration
γ	intermittency factor
x,y,z	coordinates (origin is ground level under the center of the roof
δ	boundary layer thickness
U_∞	free stream velocity

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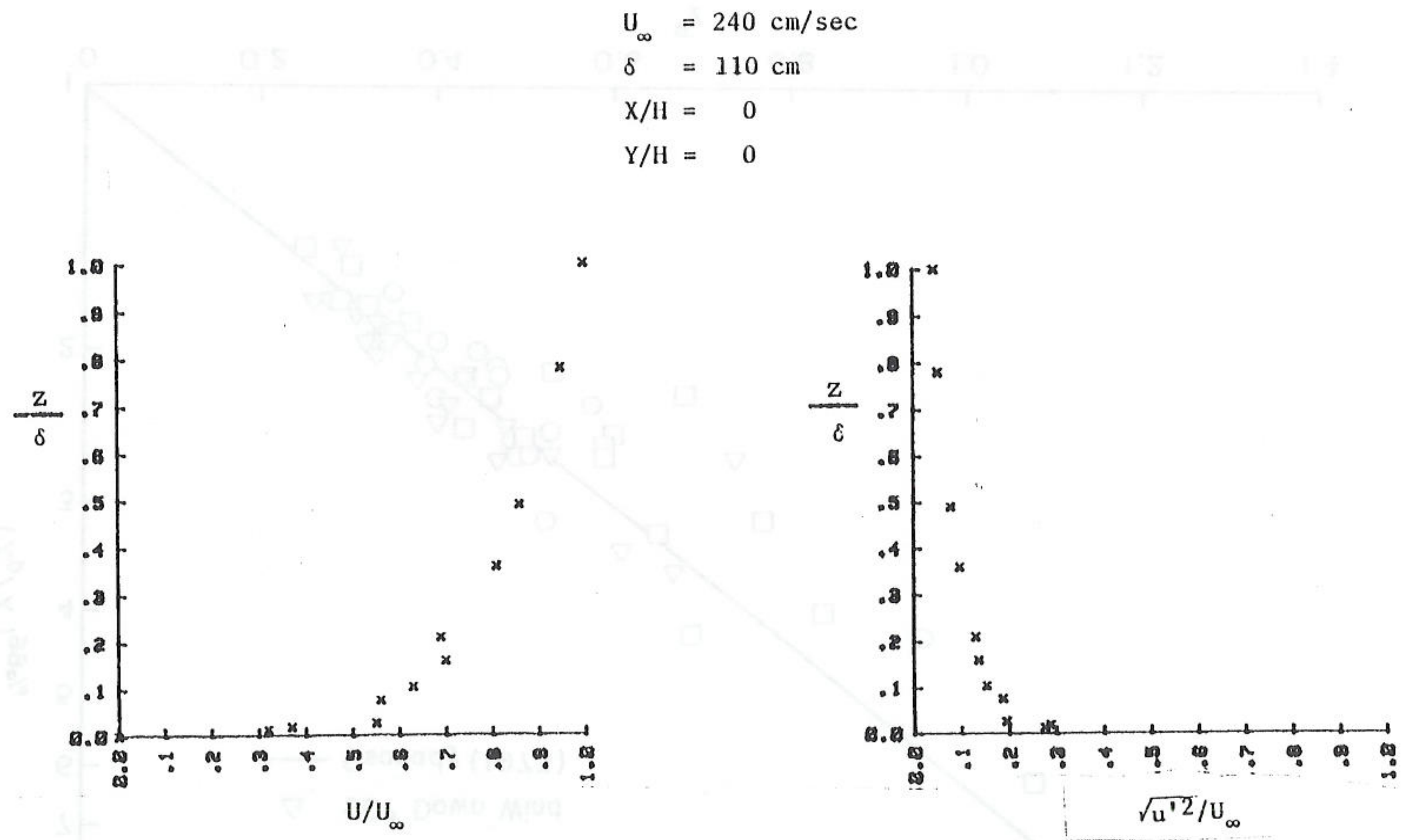


Figure 1. Mean velocity and turbulent intensity profile upwind of building.

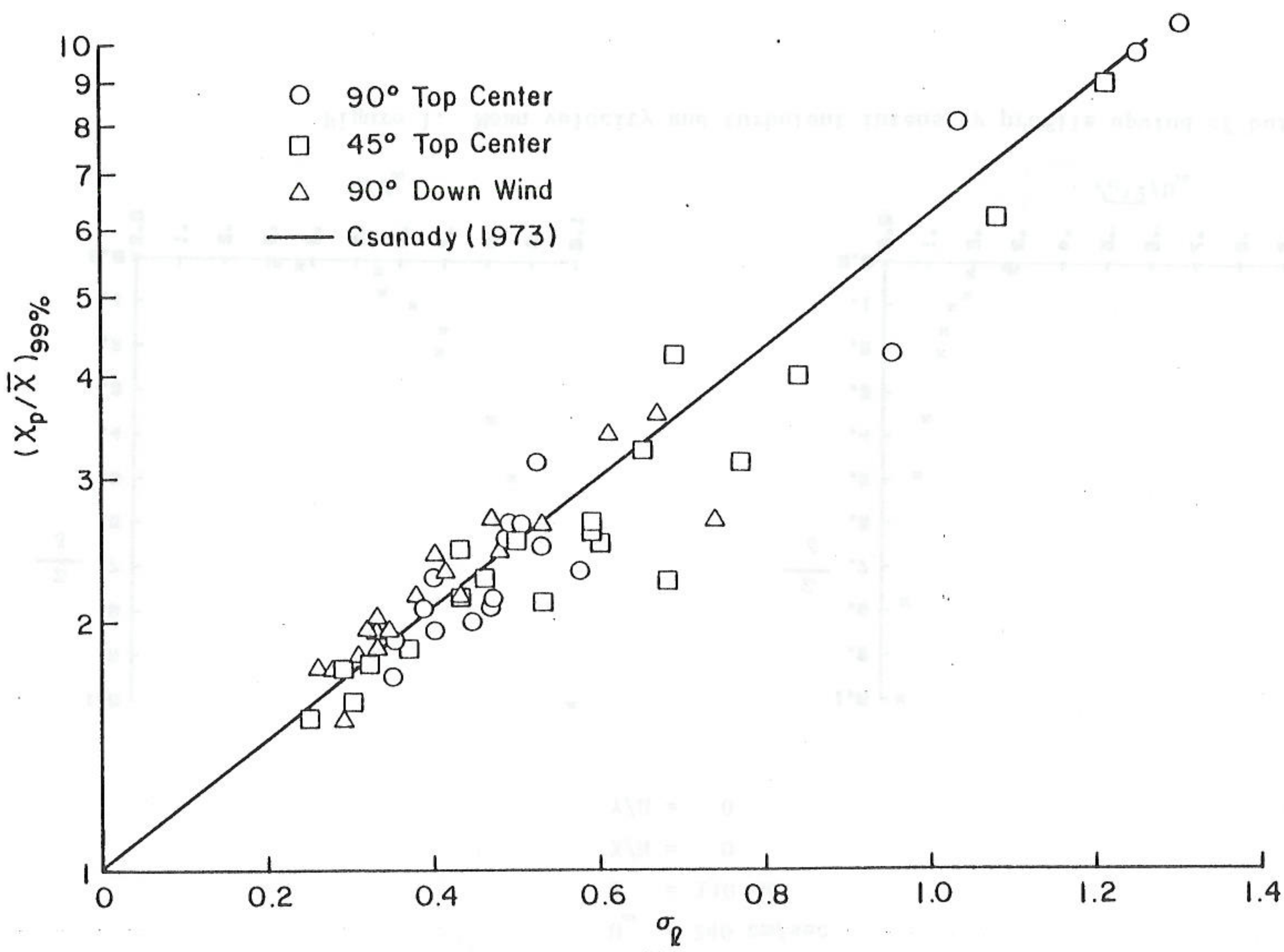


Figure 2. Peak-to-mean concentration ratios vs. logarithmic standard deviation.

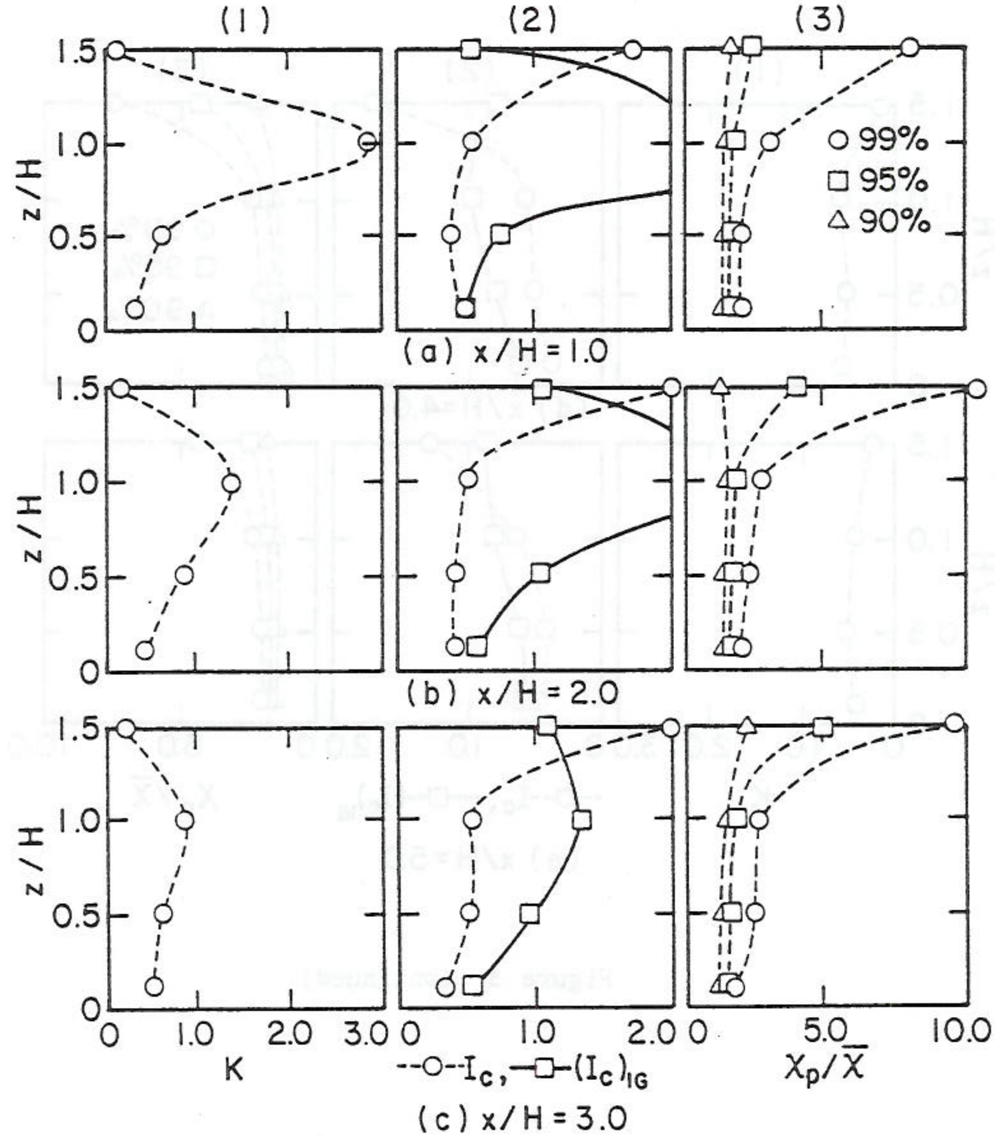
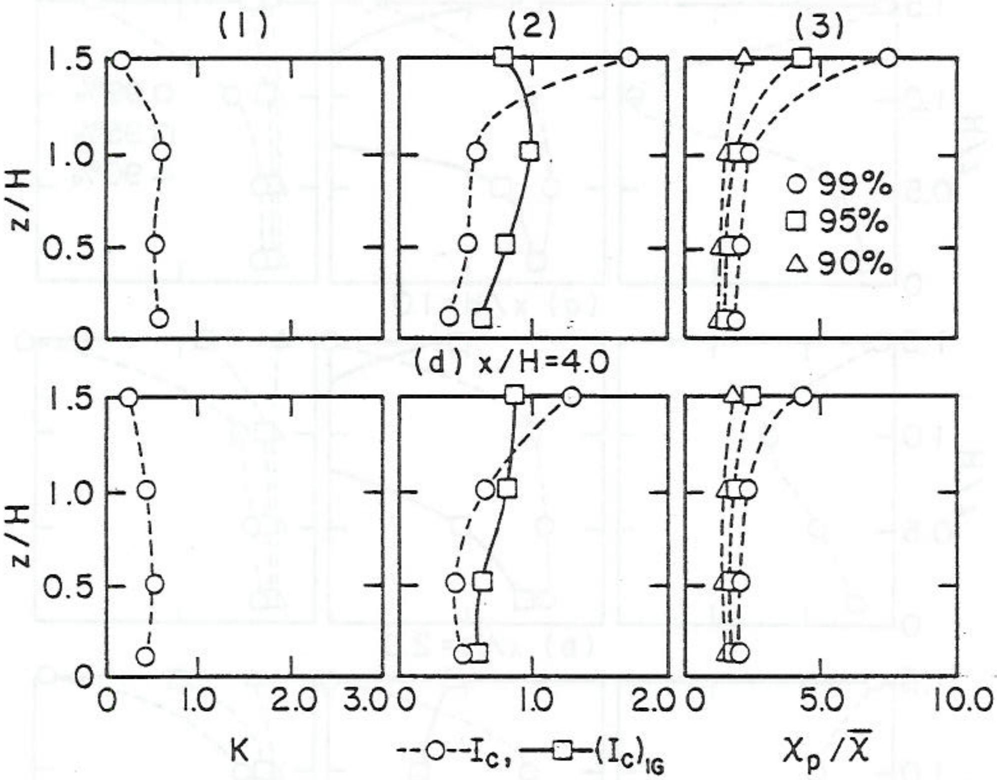


Figure 3. Mean concentration, concentration fluctuation, peak-to-mean concentration ratio vs. Z/H for θ = 0°, central roof vent release.



(e) x/H=5.0

Figure 3 (continued).

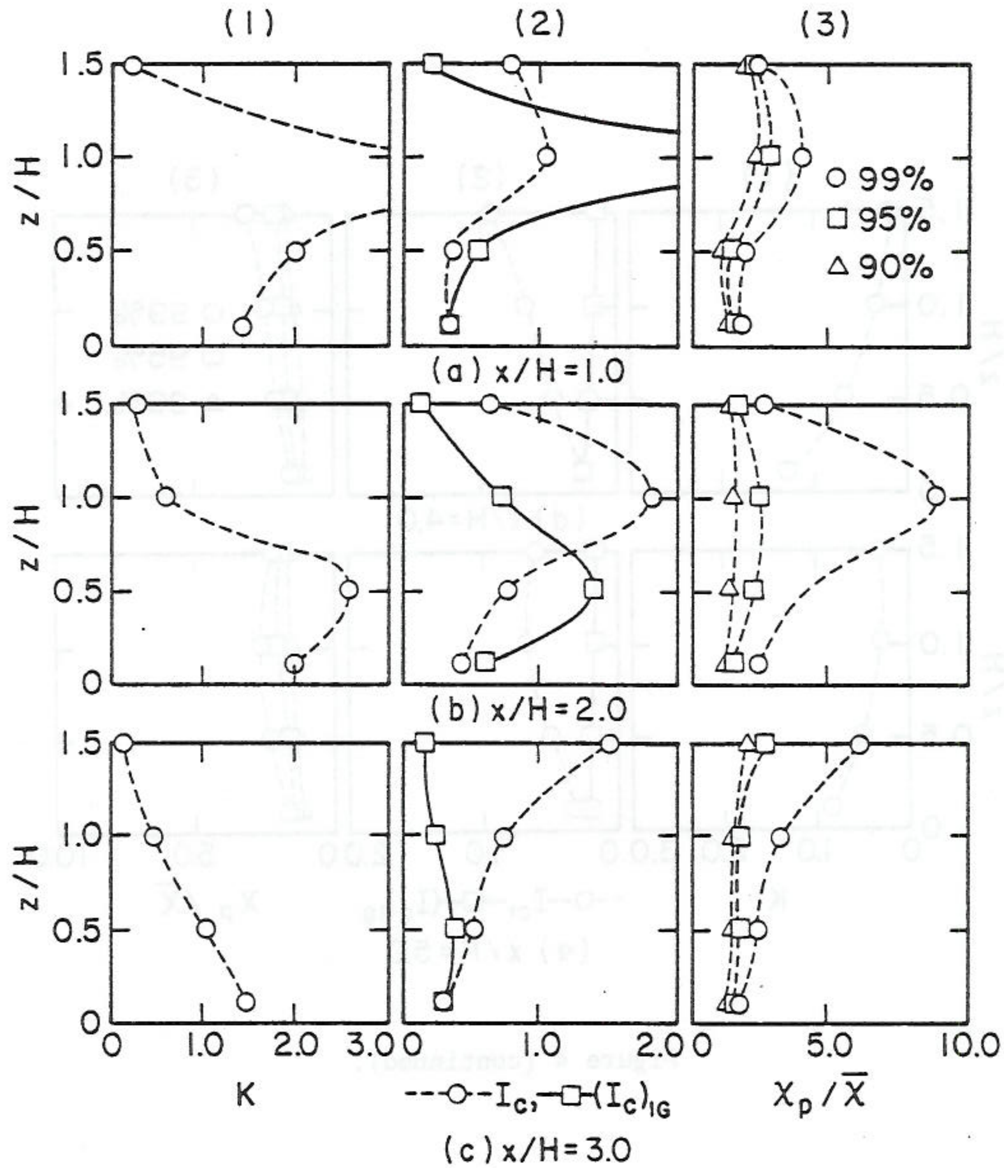


Figure 4. Mean concentration, concentration fluctuation, peak-to-mean concentration ratio vs. Z/H for θ = 45°, central roof vent release.

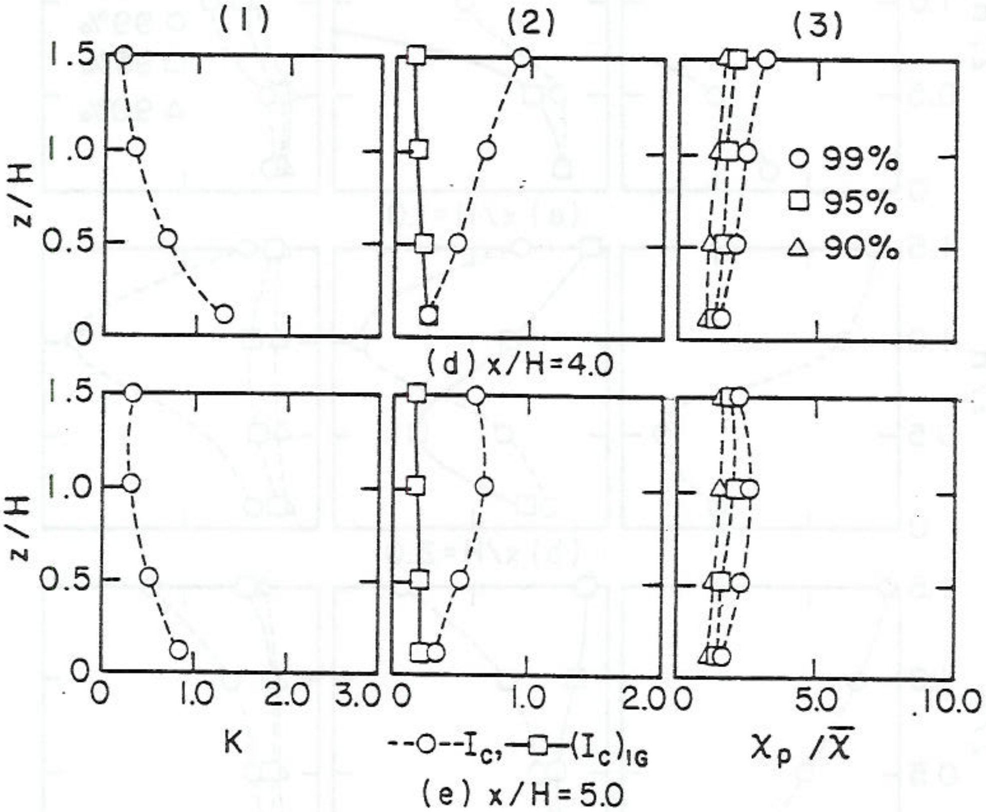


Figure 4 (continued).

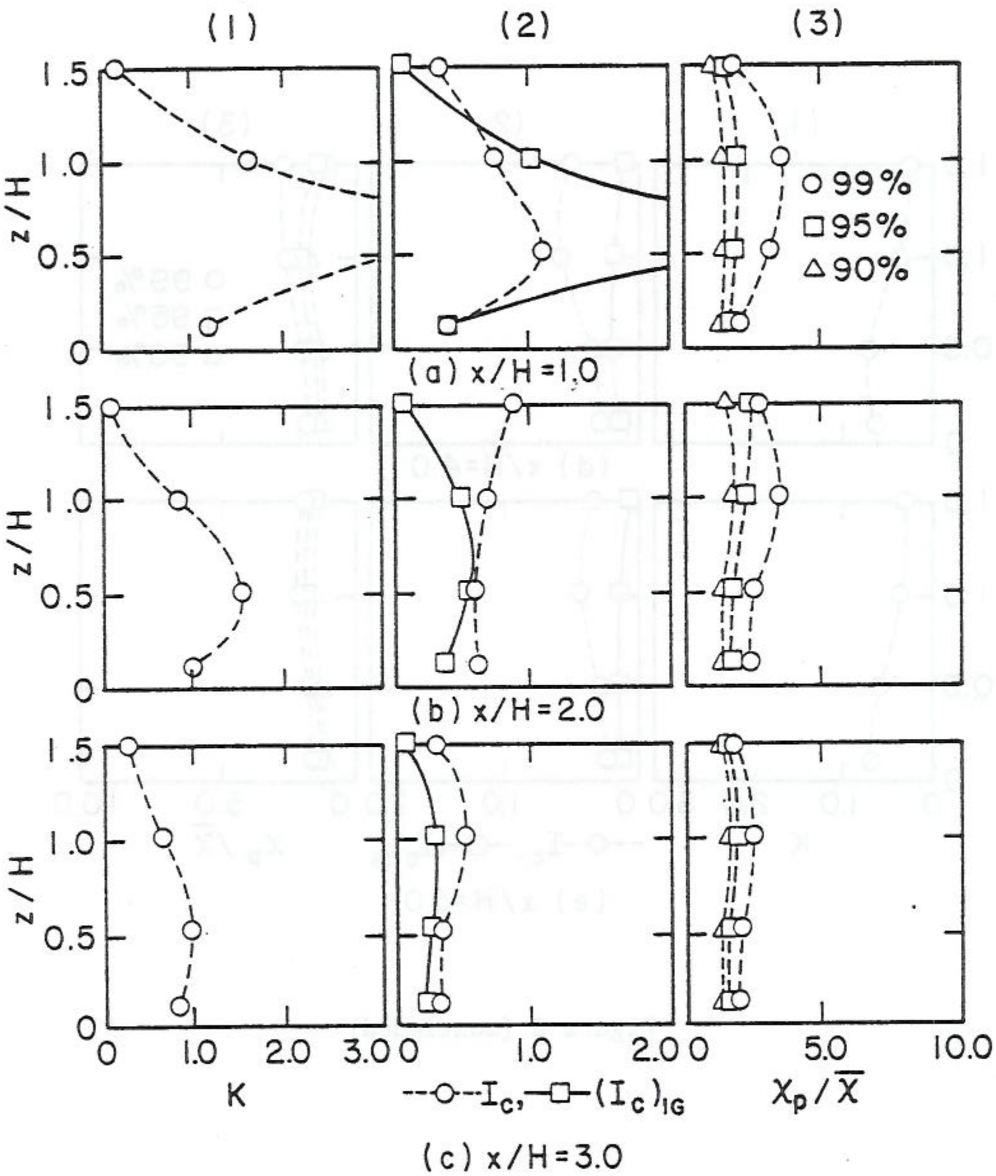


Figure 5. Mean concentration, concentration fluctuation, peak-to-mean concentration ratio vs. Z/H for θ = 0°, downwind roof vent release.

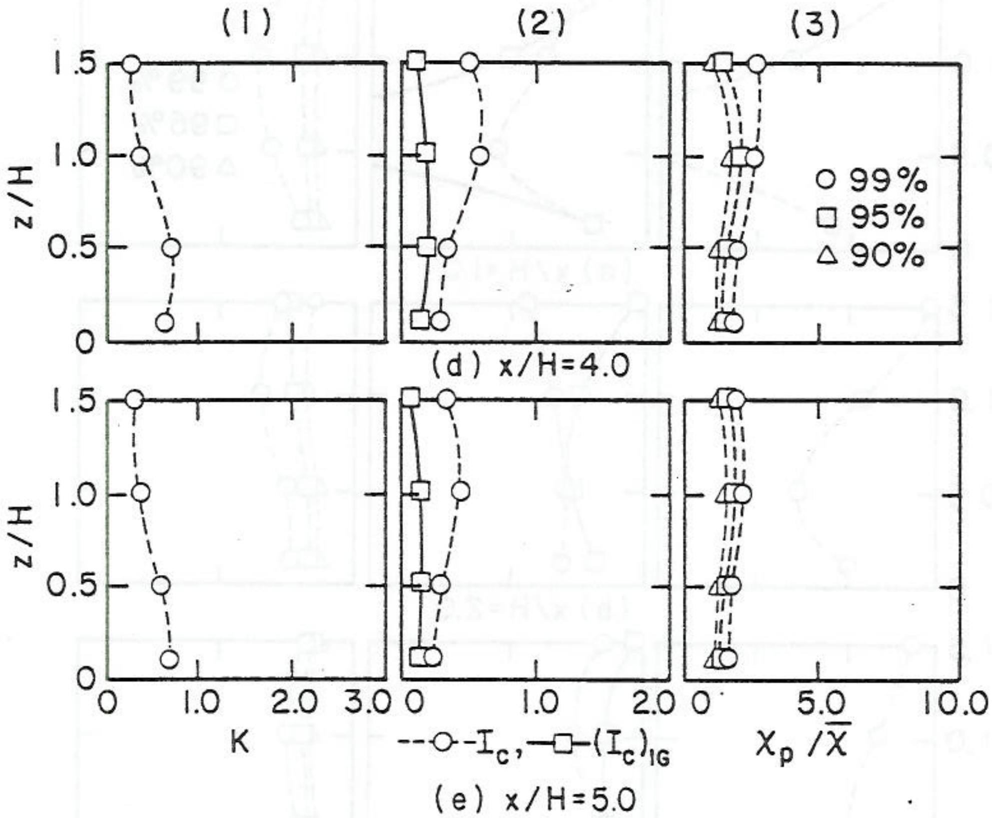


Figure 5 (continued).

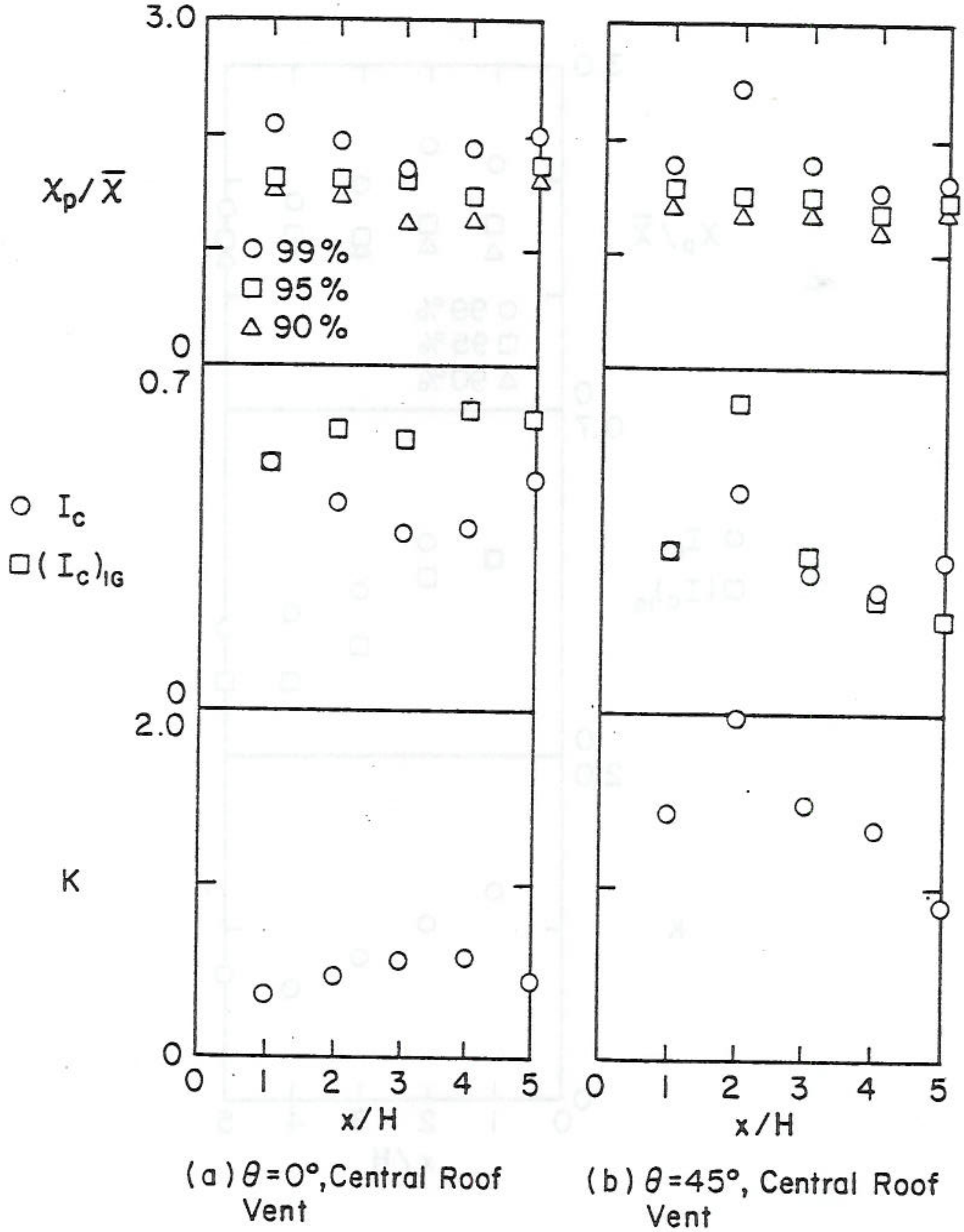
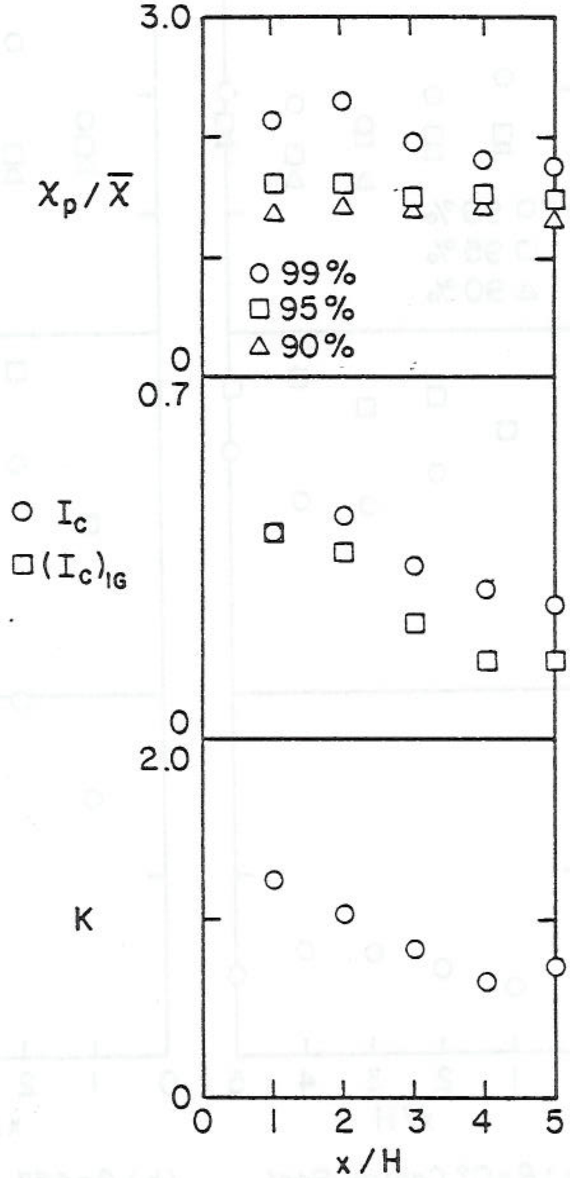


Figure 6. Longitudinal ground-level profile of mean concentration, concentration fluctuation, peak-to-mean concentration at Y/H = 0, Z/H = 0.1.



(c) θ = 0°, Downwind Roof
Figure 6 (continued).

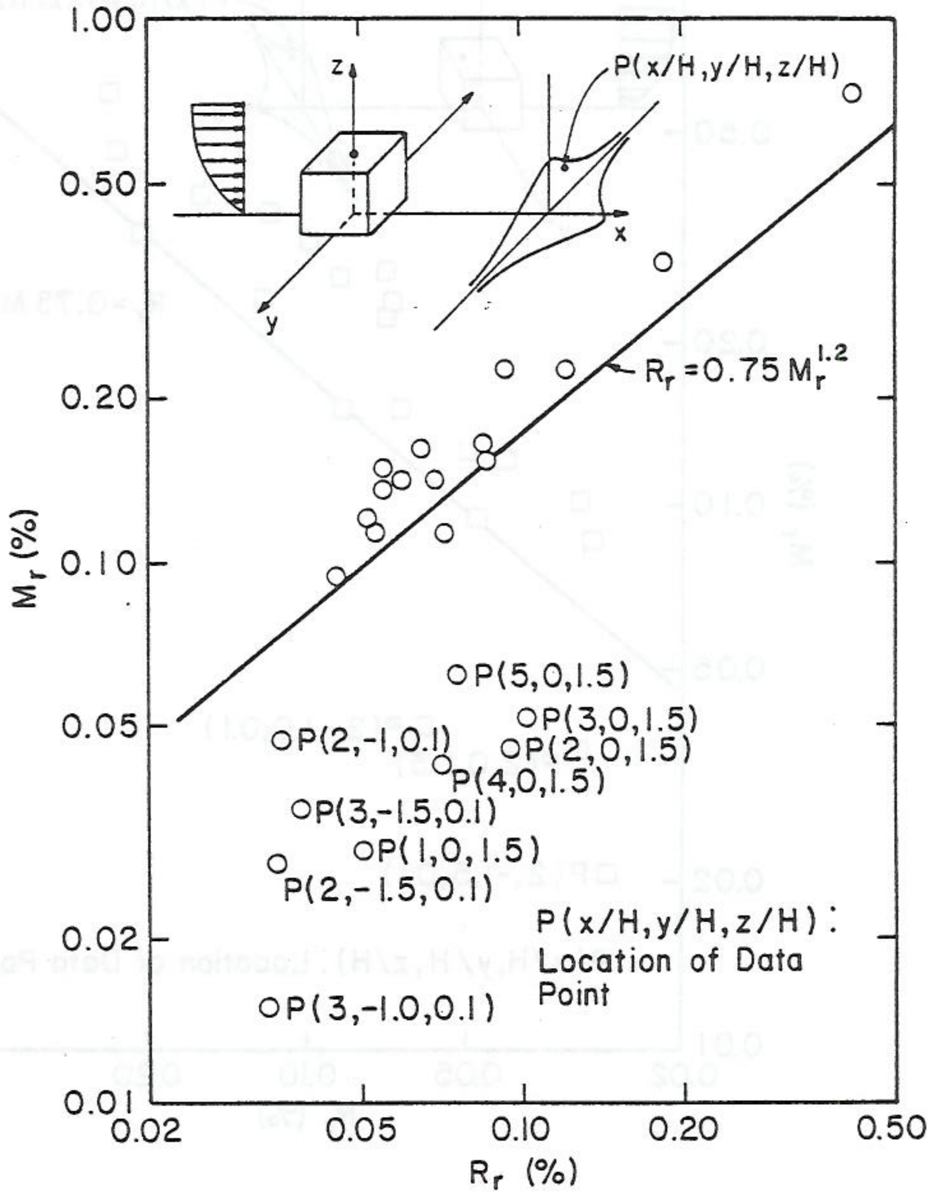


Figure 7. Normalized rms concentration vs. normalized mean concentration in the near wake region for $\theta = 0°$, central roof vent release.

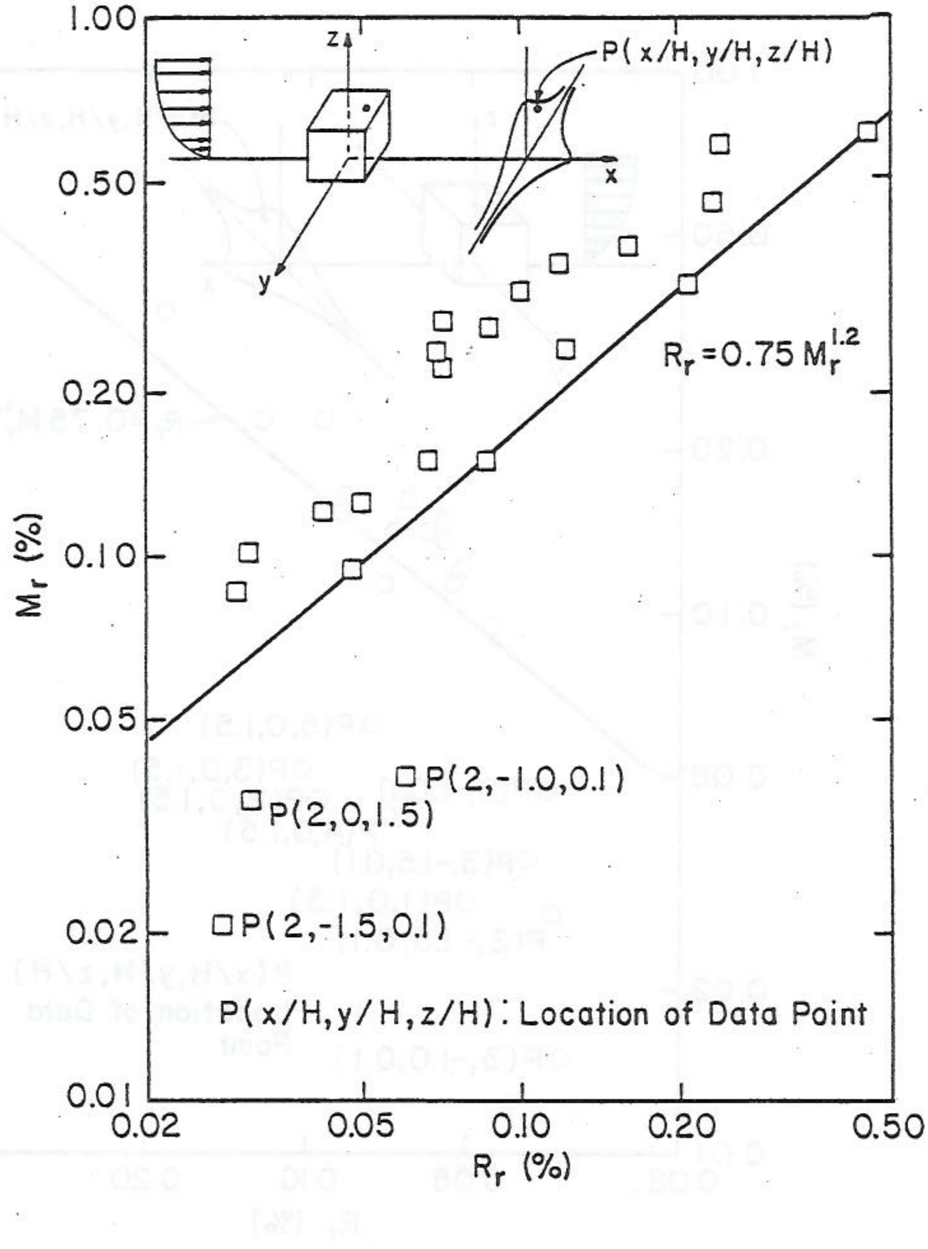


Figure 8. RMS concentration vs. mean concentration in the near wake region for $\theta = 0°$, downwind roof vent release.

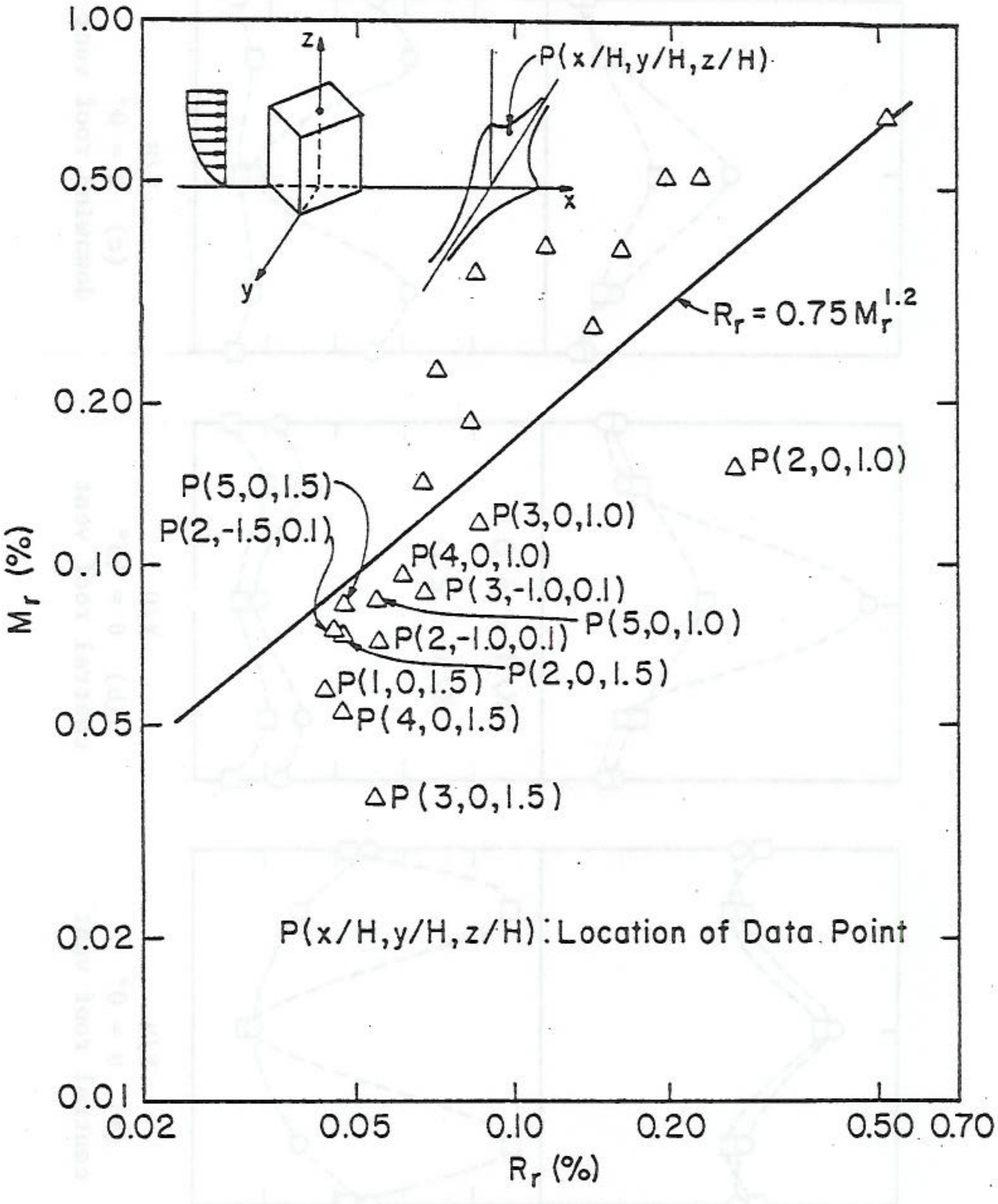


Figure 9. RMS concentration vs. mean concentration in the near wake region for θ = 45°, central roof vent release.

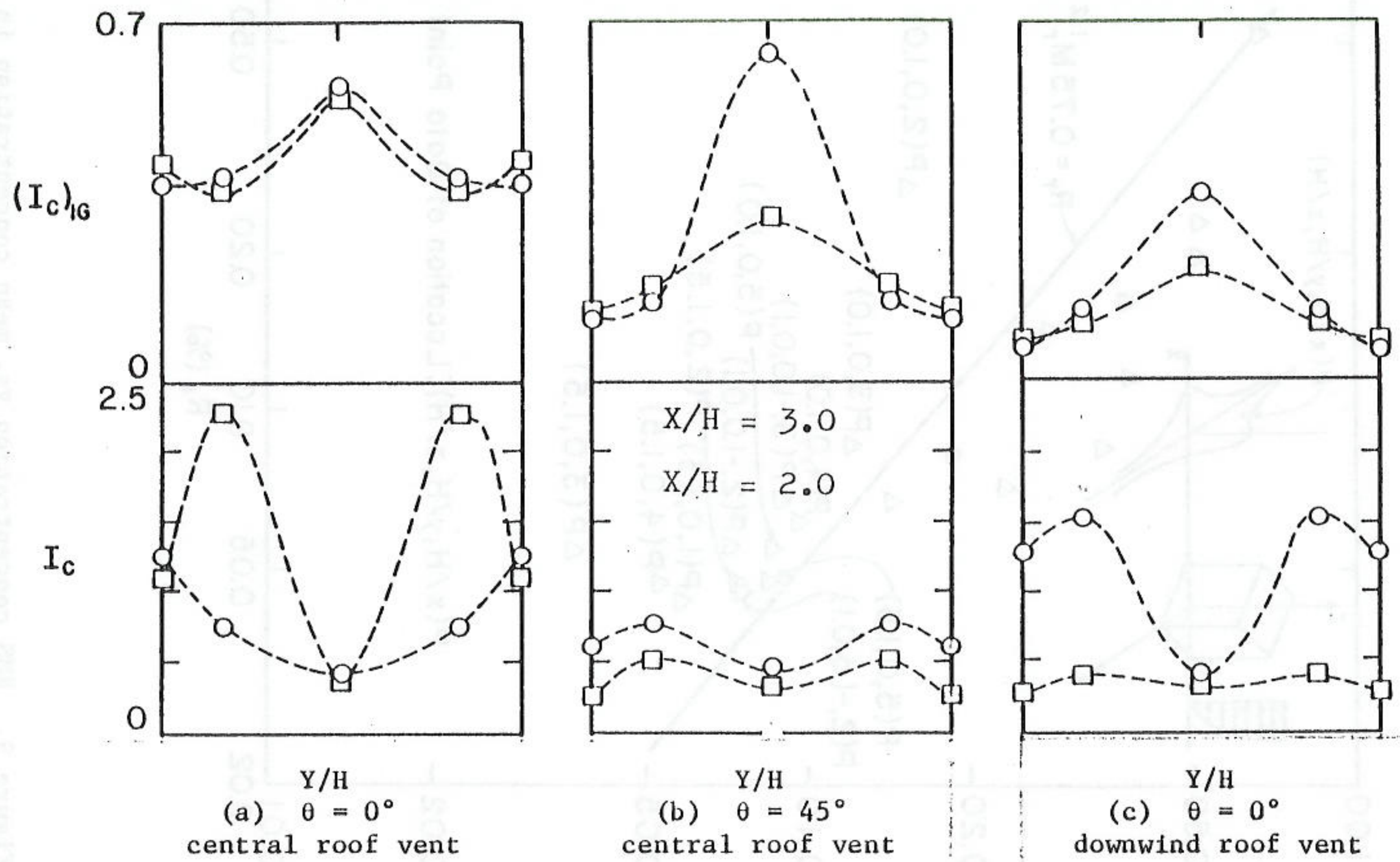


Figure 10. Crosswind profile of local intensity and absolute intensity on the ground.

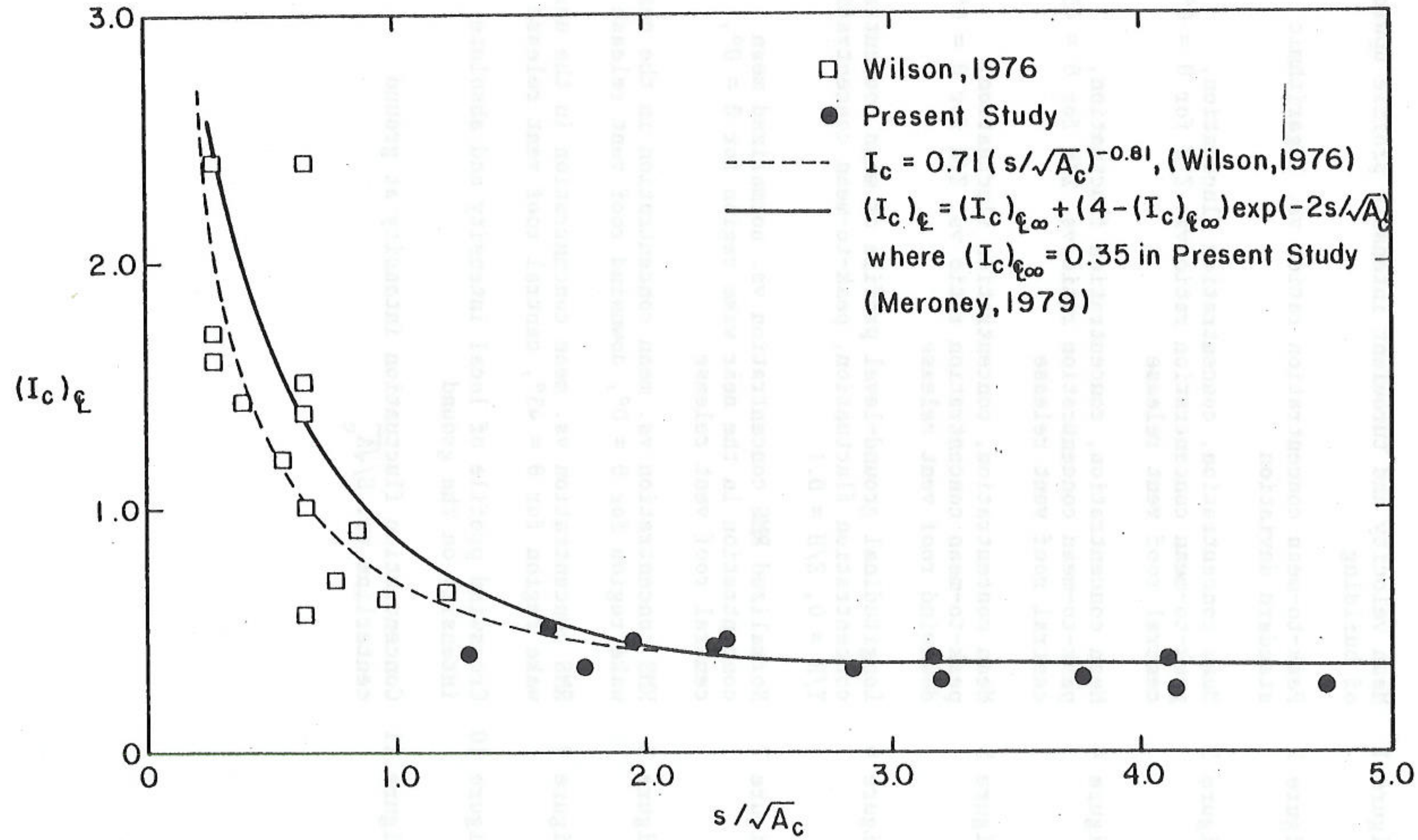


Figure 11. Concentration fluctuation intensity at ground centerline vs. $s/\sqrt{A_c}$.

LIST OF FIGURES