Australian Journal of Basic and Applied Sciences, 3(2): 486-496, 2009
ISSN 1991-8178

Characteristics of Concentration Pollutant in Plume Dispersal: Probability Study

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Abstract: The instantaneous concentration fluctuation in pollutant plume dispersion in a neutral stratified atmospheric boundary layer previously measured experimentally in a wind tunnel experiment were used for the purpose of evaluating the probability of concentration distributions. The diffusion fields in the boundary layer were studied using an isolated building model. Instantaneous concentration fluctuations reported were measured along the mean plume centerline at various downwind distances from the source at different heights with the frequency of 1KHz. Probabilistic analysis was performed on the concentration fluctuation, and the probability density functions (PDF) of mean concentration, fluctuation intensity and crosswind mean-plume dispersion were developed. Furthermore, the effects of turbulence intensity on the statistical nature of concentration fluctuations were presented and discussed. Probability density functions of the concentration fluctuation data have shown a significant non-Gaussian behavior. The lognormal distribution appeared to be the best fit to the shape of probability density functions of fluctuating concentration measured in the boundary layer in the wind tunnel. It is also shown that the plume dispersion PDF near the source was shorter than that those far from the source.

Keywords: Atmospheric dispersion; Concentration fluctuation; Probability distribution; Wind tunnel

INTRODUCTION

The boundary layer of the atmosphere is characterized by relatively high turbulence, with fluctuations in one-second averages of variables such as wind speed typically having magnitudes roughly equal to 10 to 100% of the mean value. When pollutants are emitted into this boundary-layer velocity field, they are carried out by turbulent eddies and also are observed to exhibit fluctuations at the same order of magnitude as their mean value. Therefore, these fluctuations are of great practical importance when the pollutant is highly toxic or flammable material. Most dispersion models are capable of predicting the mean pollutant concentration, but provide no guidance on the probability of fluctuations from this mean value (Hanna and Insley, 1989).

The study of concentration fluctuations in dispersing plumes of pollutants in urban environment has resulted considerable advance in understanding the detailed structure of plumes in recent years. An understanding of concentration fluctuation is important for a number of practical applications. Several experiments have described tracer experiments using fast response concentration detectors. Those studies describe the turbulent fluctuations of concentrations at fixed points downstream of continuously emitting source. The results have given statistical descriptions of the concentration fluctuations under relatively simple atmospheric conditions in terms of, the standard deviation of concentration and the concentration probability density function (PDF).

Study of probability distribution of fluctuating concentration has been hampered by a lack of suitable instrumentation. Some of the initial attempts at both predicting and measuring concentration fluctuations in ground level plumes have again emphasized the need for thorough experimentation. Recently, several studies have been completed for the probability distribution of concentration fluctuations. Sykes (1984), Hanna (1984), Sawford *et al*. (1985), Sawford (1987). and Diner *et al.* (1988). have agreed that the distribution of concentration fluctuation is skewed towards higher values, but disagree on the exact form of optimum distribution function. Furthermore, they have suggested analytical expressions for the mean and

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the standard deviation of the concentration fluctuations and found that the fluctuation intensity varies with distance from the source, position within plume, average time, and the time scale of atmospheric turbulence. However, observations cannot provide any information on eddy size that causes the observed fluctuations. Sykes (1988). discussed how knowledge of concentration fluctuations may be used in the evaluation of dispersion models to give an estimate of inherent variability and errors in predictions. In addition, a few probability distributions with field and wind tunnel experiments have been completed in which series of pollutant concentrations have been observed (Hanna and Insley,1989; Fackrell and Robins, 1982). Yee and Biltoft (2004) have presented a detailed picture of the behavior of concentration fluctuation statistics such as concentration standard deviation ratio, probability density function, power spectra and so on the domination motions in the array plume.

The probability density function of concentration in an atmospheric plume is an important quantity used to describe environmental diffusion. The plume concentration PDF forms the basis for the definition and computation of a number of relevant parameters intervening in various practical problems. It has many applications. Yee and Chan (1997). have assessed the level of harm from toxic materials that requires the frequency of concentration peaks that exceed the critical threshold. Weil *et al.* (2002). have proposed a number of very different probability density function forms and they have great efforts to measure, the required quantities for representation and understanding the concentration distribution of the probability density function. However, despite this enormous effort, there are still no general mechanisms of the PDF that provides the best fit to plume concentration data over a wide range of experimental conditions.

This paper reports the analysis of probability characteristics of concentration fluctuations in plume dispersion in the atmospheric boundary layer in the wind tunnel experiments under neutral conditions. With this in mind, the probability density function of the instantaneous plume concentration are evaluated and used to analyze data at various downwind distances from the source for a number of different heights. The aim of this paper is to improve the understanding of the mechanisms of concentration fluctuations in plume dispersion emitted from a continuously steady source at fixed point in an urban Environment. For better understanding the modeling of data, the experimental technique and the data reported can be elsewhere (Yassin *et al.,* 2008).

Probability Model:

The instantaneous concentration reported was used to calculate the PDF. It is worth while mentioning, the experimental data reported were conducted on the Atmospheric Diffusion Simulation Wind Tunnel. The obstacles used in the flow and diffusion fields was isolated building model with height 200 mm, width 100 mm and length 100mm. A simulated atmospheric boundary layer was developed. For more details of the simulated turbulent boundary layer in the wind tunnel, measurement devices can be in Yassin *et al.* (2008). Because of the extended area in the source and the wind speed which was found to be log-normally distributed. The log-normal distribution was widely used to represent long-term urban air quality statistics. The PDF of the lognormal distribution for concentration fluctuations is given by equation (Li *et al.,* 1999).

$$f(c) = \frac{\exp(-0.5((\ln(|c| + \hat{c}) - \mu)/\sigma)^2)}{\sqrt{2\pi\sigma}(|c| + \hat{c})} \tag{1}$$

where; the parameters, σ and μ can be determined conveniently by calculating the mean and standard deviations of the natural logarithms of the data, and $\hat{c}$ is the positive crest factor.

$$\hat{c} = \max(c - \bar{c}) / \sigma_c \tag{2}$$

On the other hand, the negative crest factors is as $\check{c} = \min(c - \bar{c}) / \sigma_c$ (3)

The shape of a probability density function of the concentration fluctuation (c) can be characterized by its third and fourth central moments (μ_3 and μ_4) relative to the standard deviation value (σ_c). The skewness coefficient, S_k, and the kurtosis coefficient, K_u, are defined, respectively, as

$$S_k = \mu_3 / \sigma_c^3 \tag{4}$$

$$K_u = \mu_4 / \sigma_c^4 \tag{5}$$

Where

$$\sigma_c^2 = \sum (c_i - \bar{c})^2 / n \tag{5}$$

$$\mu_3 = \sum (c_i - \bar{c})^3 / n \tag{6}$$

$$\mu_4 = \sum (c_i - \bar{c})^4 / n \tag{7}$$

In which c_i is instantaneous concentration, $\bar{c}$ s the time mean concentration and n is total number of samples.

For a normal or Gaussian distribution, skewness and kurtosis coefficient are equal to 0 and 3, respectively. $S_k < 0$ corresponds to skewness to the left, while $S_k > 0$ to the right. $K_u > 3$ represents distributions more peaked than the Gaussian and $K_u < 3$ characteristics distributions flatter than Gaussian.

It is usually more convenient to use the following reduced variety of fluctuation intensity I when dealing with probability distribution, defined as

$$I = \sigma_c / \bar{c} \tag{8}$$

The crosswind mean-plume dispersion, σ_y was determined by Gaussian plume width, calculated from the measured turbulence statistics using the formula (Mylne *et al.,* 1992).

$$\sigma_y = \sigma_v \frac{cf(x)}{U} \tag{9}$$

where $f(x)$ is a correction factor whose is taken from Pasquill and smith[17] and is close to 1.0 for $x \sim$ 100 -300 m, σ_v is the standard deviation of the wind velocity in the lateral direction and U is mean wind velocity in the longitudinal direction.

RESULTS AND DISCUSSION

As mentioned earlier, the previously reported data were used to evaluate the PDF for mean concentration, fluctuation intensity and crosswind mean-plume dispersion.

Probability Distribution of Mean Concentration:

The basic concentrations measured (Li *et al.,* 1999). along the mean plume centerline in the wake region of the building model with various downwind distances *X/H* from the source at different relative heights *Z/H* through a vertical plume cross-section with the frequency of 0.5 KHz for 120 seconds. The non- dimensional downwind distances *X/H* = 0.375, 0.625 and 1.125 for different heights *Z/H* = 0.1, 0.25, 0.375 and 0.75 were selected in order to illustrate the change in the PDF with downwind distance from the source and height above the ground. The flow obstacle model was located at *X/H* =0. The ground source was located at *X/H* = 0.125 that has an inner diameter of 4 mm. The plume is non-buoyant with exit velocity less than the wind velocity. Fig. 1 illustrates the time series with the instantaneous concentration and fluctuation intensity, taken at *X/H* = 0.375 and Z/H = 0.1. It was seen that the fluctuation intensity falls abruptly to a constant zero within 120 s of some largest peaks recorded, indicating that the edge of the meandering plume is quite well defined relative to the scale of the meandering. The time series of instantaneous concentration meandering motions is similar in behavior to the onset of the peaks fluctuation intensity. However, the instantaneous concentration becomes more constant with the stronger fluctuation.

The probability distribution is an important character of the concentration fluctuations; because it might happen that the exceeded level of toxic gasses might be found at a given location and point at time where toxic level is exceeded, no matter what the mean value at that location is. Histograms of the instantaneous concentration fluctuation c normalized by the mean concentration $\bar{c}$ vere complied. Figs 2 to 4 display the measured PDF of c/ $\bar{c}$ along the mean plume centerline at various non-dimensional downwind distances *X/H* = 0.375,

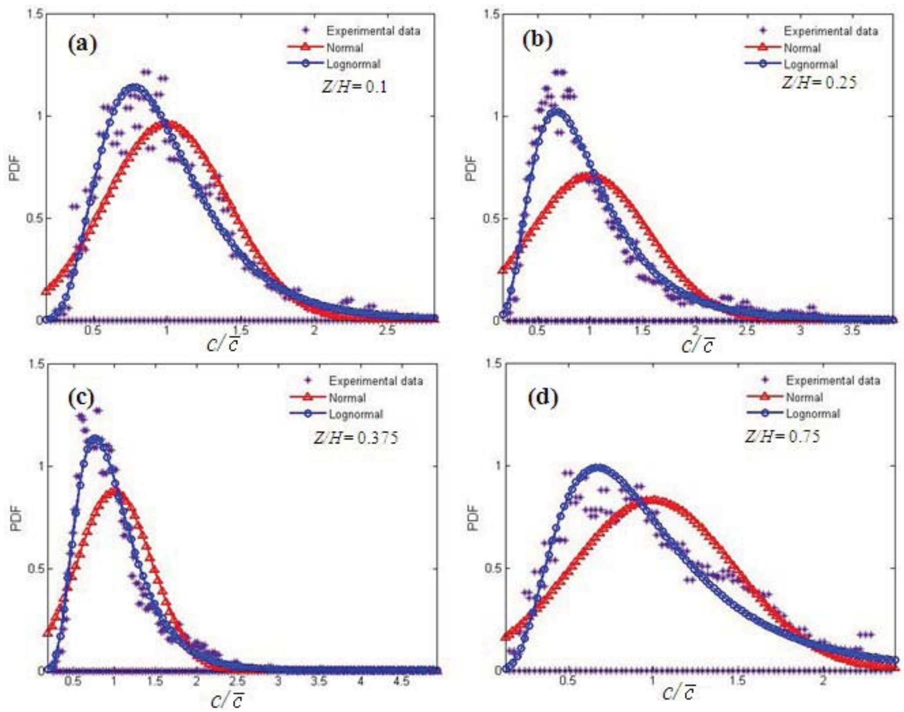

Fig. 1: Probability density for mean concentration measured at X/H = 0.375

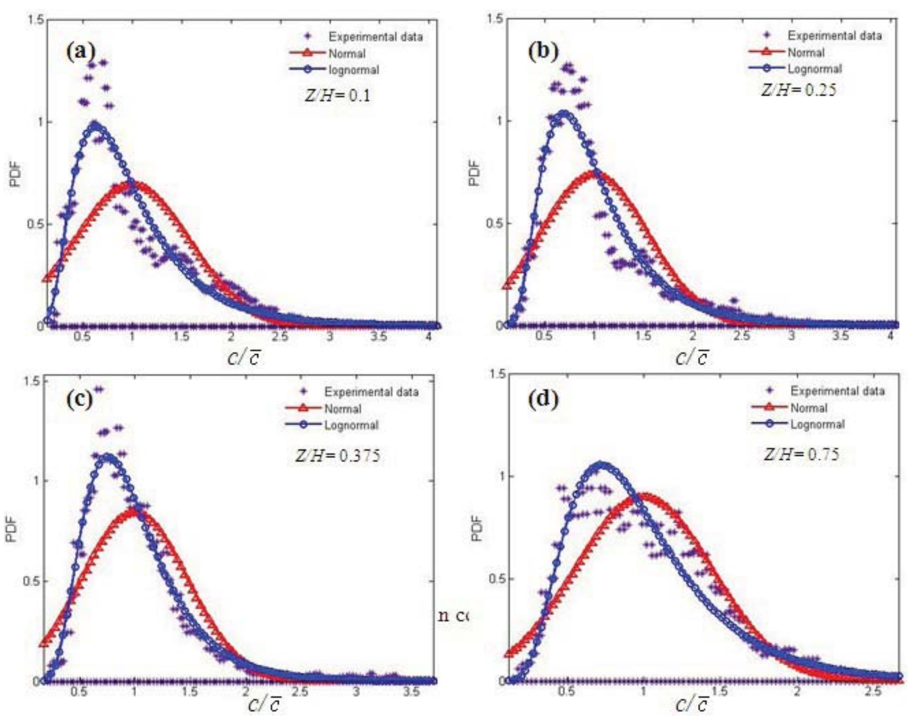

Fig. 2: Probability density for mean concentration measured at X/H = 0.375.

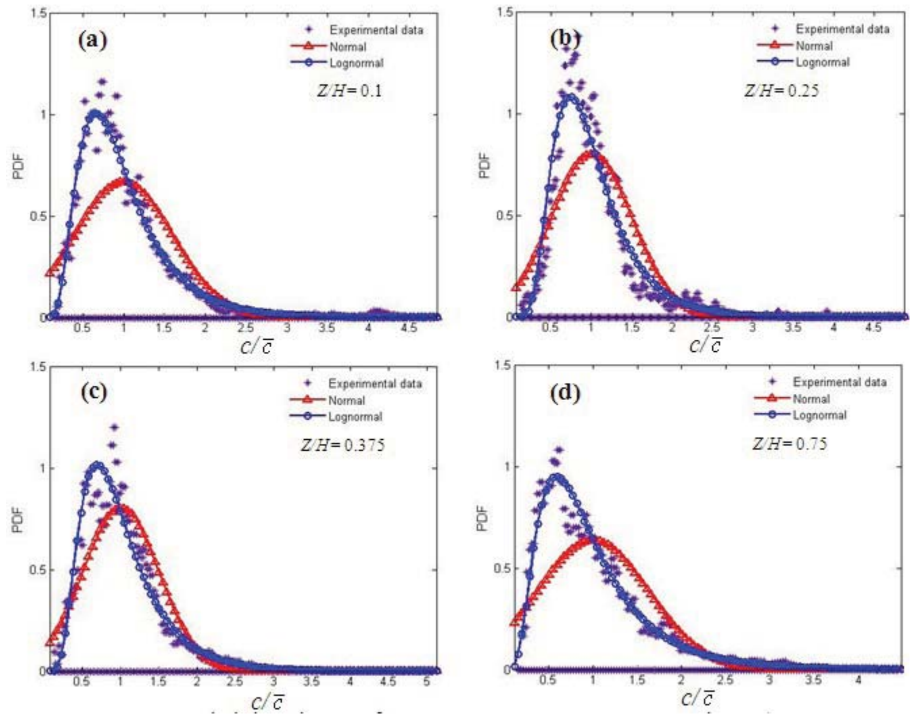

Fig. 3: Probability density for mean concentration measured at X/H = 0.625.

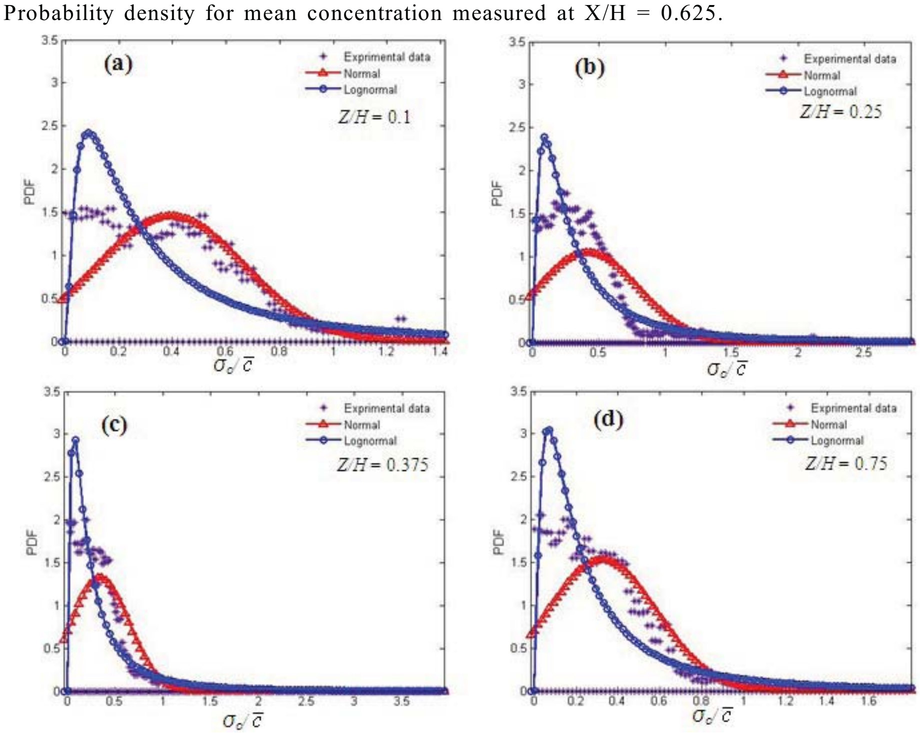

Fig. 4: Probability density for mean concentration measured at X/H = 0.625.

0.625 and 1.125 from the source for different heights *Z/H* = 0.1, 0.25, 0.375 and 0.75 in the near wake region of the building model. The non-dimensional downwind distances X/H for the different heights Z/H were selected in order to illustrate the change in the shape of the PDF with downwind distance from the source and with height above the ground. Normal and lognormal probability densities are also plotted in these figures for comparison purpose. The lognormal distribution appeared to be the best fit to the shape of the actual probability density functions of concentration measured in the boundary layer wind flows in the wind tunnel. It is shown that the peak value of concentration PDF at the mean plume centerline is close to the source at the downwind of *X/H* = 0.375 with heights *Z/H* = 0.1. This can be due to the higher turbulence mixing near the ground in the wake region. The longer tail of concentration PDF was observed at distance *X/H* = 1.125 with height *Z/H* = 0.375, while the shorter tail observed *X/H* = 0.375 for *Z/H* = 0.75. The tail of concentration PDF for heights far from the ground surface was observed at shorter distance than those heights near the ground surface except at *X/H* = 1.125. The wider shape of concentration PDF was observed for height *Z/H* = 0.75 at distance *X/H* = 0.375. In the wake region of the building model, at height *Z/H* = 0.375 at distance *X/H* = 0.375, the peak concentration PDF has a wide sharp. This can be attributed to the fact that the value of concentration was high. In addition, the concentration PDF narrow shape was observed far from the source. A higher probability was observed for concentrations close to c/= $\bar{c}$ 0.75. As can be seen in these figures, the slope of concentration PDF near to the source is much steeper than that near the source.

Probability distribution of Fluctuation Intensity:

Fluctuation intensity is an important parameter used to characterize the concentration fluctuation. Figs. 5 to 7 display the probability of density functions (PDF) of the normalized fluctuation intensity $\sigma_c / \bar{c}$ at various relative distances *X/H* = 0.375, 0.625 and 1.125 for different heights Z/H = 0.1, 0.25, 0.375 and 0.75, which was measured in the near wake region of the high rise building model. It was observed that the lognormal distribution fits the actual PDF in the centre region much better than the normal distribution. The fluctuation intensity PDF presented in these figures was clearly positively skewed. The fluctuation intensity PDF based on the experimental data are distinctly different from the normal distribution, particularly for both tails. The actual probability distributions have much longer positive tails. This indicates a much higher probability for the larger positive concentration than that predicted by a Gaussian PDF. However, the lognormal distribution represents a much better fit for the centre as well as the tails of the probability densities than the normal distribution. The probability distribution in the region of the tail has a significant effect on the estimation of peak concentration fluctuations. Therefore, it is important to give reasonably close representation of the actual probability distribution at the tail of the positive side. The experimental data exhibited a probability distribution with a higher peak at the centre than the Gaussian.

The evolution of skewness and kurtosis of the fluctuation intensity calculated based on the data obtained at *X/H* = 0.375, 0.625 and 1.125 for height Z/H = 0.1, 0.375 and 0.75 are shown in Table 1. The skewness and kurtosis of the concentration fluctuation position provides information on the distribution of the plume as transported by the large-scale turbulent motion. As pointed out by Luhar *et al.,* (2000), there are no currently available data to validate the evolution of the skewness and kurtosis. The coming discussion will discuss the data obtained in this work and its importance to validated the skewness and kurtosis. It can be seen that turbulence intensity in the longitudinal direction I_u decrease is associated with an increase in the magnitudes of skewness close to the source at *X/H* = 0.375. It means that the turbulence intensity increase with the decrease of skewness. Moreover, the shorter tail of fluctuation intensity appeared with the decrease in the magnitudes of skewness coefficient, while the longer tail appeared with skewness coefficient increase. The wind tunnel results provide an estimation of the downwind locations of the skewness which can be useful to drive a suitable parameterization. Close to the source, as the tail is the mean contribution to plume dispersion, the fluctuation Intensity PDF distribution is mainly affected by the large-scale motions. The value of kurtosis measured far from the source was observed much higher than those obtained close to t he source. The value of ĉ and č measured far the source at *X/H* = 1.125 was observed much higher than those obtained close to the source at *X/H* = 0.375 and 0.625. This illustrates that the concentration fluctuations close to the source shows a higher value of its peak. In comparison of the crest factor ĉ at location close to the source at *X/H* = 0.375 and far the source at *X/H* = 1.125 with the height at Z/H= 0.25 and 0.375 from *X/H* = 1.125. The value of crest factors of fluctuating intensity is low close to the gas source due to the increased longitudinal turbulence intensity I_u, which create strong meandering plume.

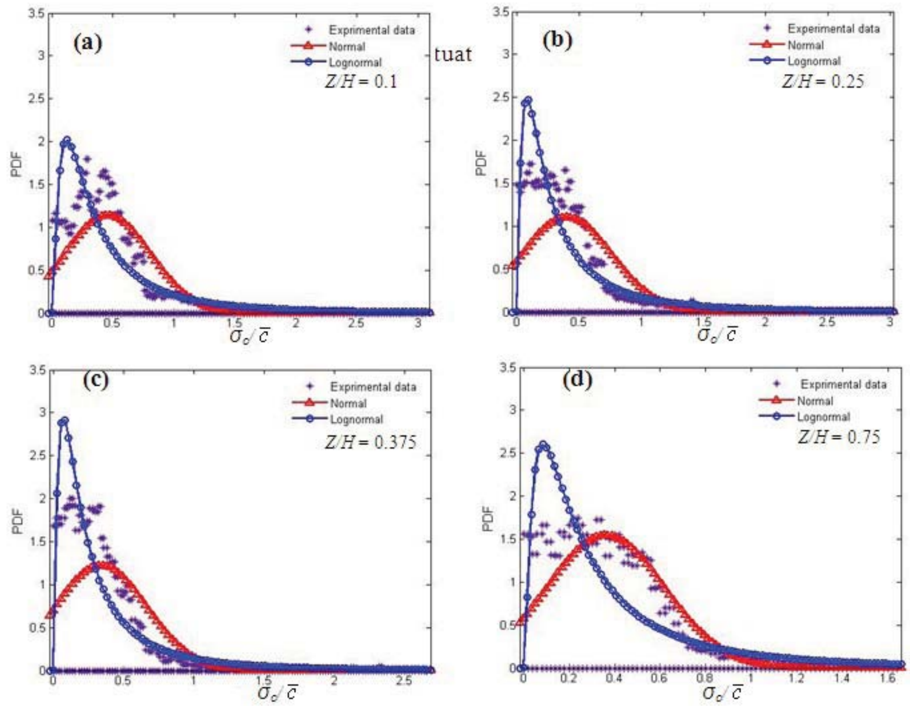

Fig. 5: Probability density for fluctuation intensity measured at X/H = 0.375.

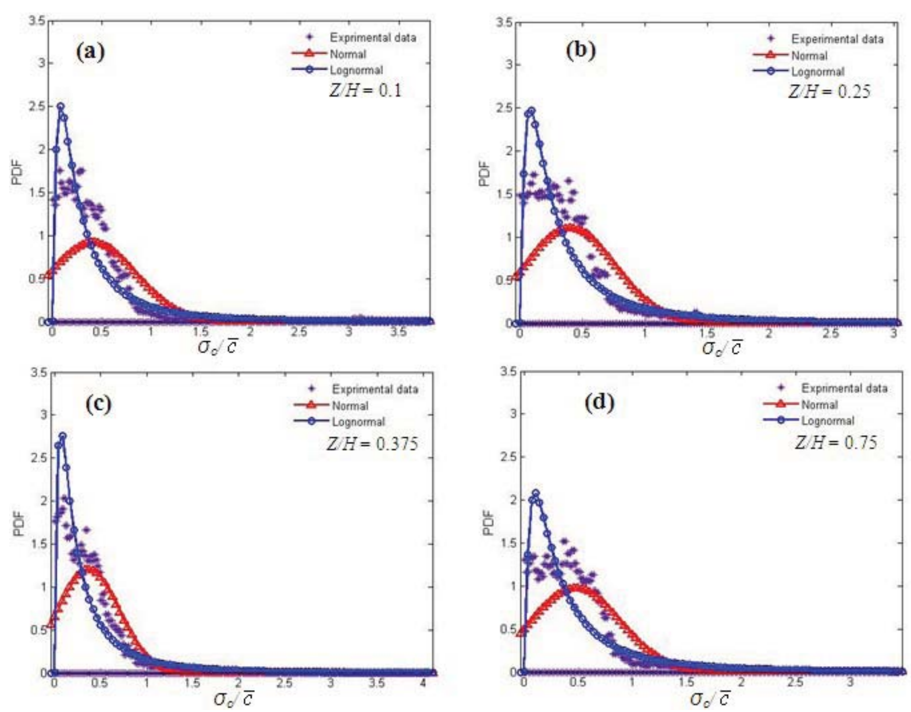

Fig. 6: Probability density for fluctuation intensity measured at X/H = 0.625.

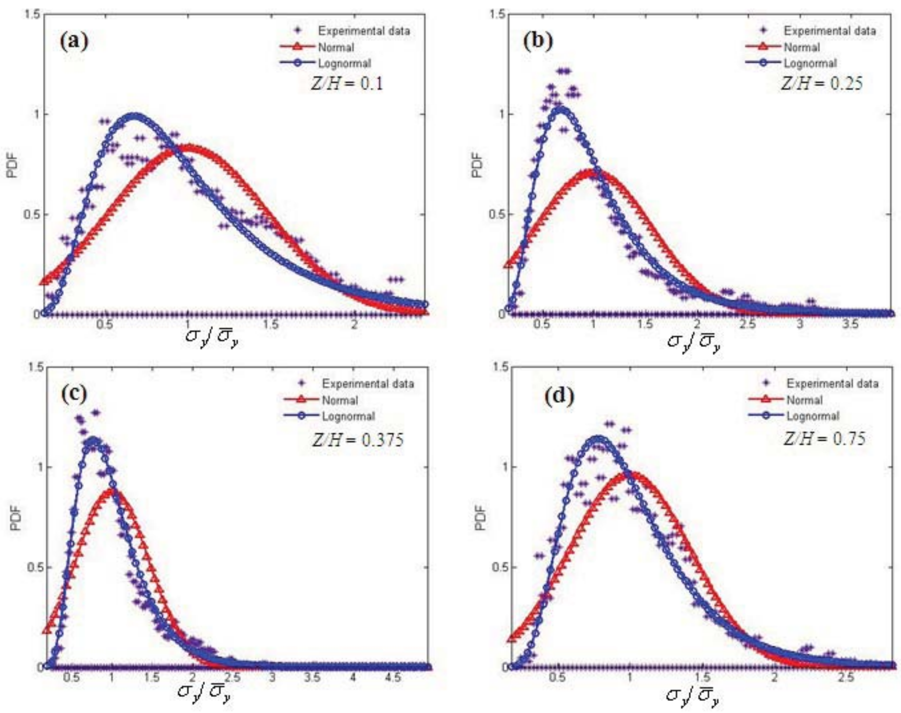

Fig. 7: Probability density for fluctuation intensity measured at X/H = 1.125.

Probability Distribution of Crosswind-Plume Dispersion:

The concentrations of pollutant were measured and the corresponding PDF of the normalized crosswind plume dispersion are calculated. Figs. 8 to 10 show the probability density functions (PDF) of normalizedcrosswind plume dispersion $\sigma_y/\bar{\sigma}_y$ at various distances *X/H* = 0.375, 0.625 and 1.125 with various heights Z/H = 0.1, 0.25, 0.375 and 0.75. From these figures, the distributions obtained for the plume dispersion PDF shows a tendency towards a lognormal distribution of all cases and also positively skewed. The tail of plume dispersion PDF close to the source at distance *X/H* = 0.375 for height near the ground surface *Z/H* = 0.1 was observed to be shorter than those of other tails at different Z/H because the tail of plume is the main contribution to the plume motion. The tail of plume dispersion PDF becomes longer further from the source. Moreover, wider sharp plume dispersion PDF was observed near the source distance *X/H* = 0.375 for height *Z/H* = 0.1, while the narrow sharp PDF was observed gradually further up the source. This phenomenon agrees with previous observations (Hanna and Insley, 1989). They reported that when the plume size is smaller near the gas source, the plume meanders back and forth more due to the advection of atmospheric eddies, resulting in higher intermittency. When the plume is farther away from the gas source and becomes larger than the eddies, they do not meander the whole plume as much but merely cause minor fluctuations deep within the plume, resulting in lower intermittency (Cheung and melbourne, 2000).

Table 2 gives coefficient of skewness and kurtosis, which were calculated based on the data obtained from the crosswind plume dispersion at *X/H* = 0.375, 0.625 and 1.125 with height Z/H = 0.1, 0.25, 0.375 and 0.75. It can be seen that turbulence intensity in the lateral direction I_v increase with decrease in skewness for all cases. It is also clear that minimum value of skewness was observed with the shorter tail of the plume dispersion PDF at distance *X/H* = 0.375 with Z/H = 0.1. The value of positive crest factor ĉ and kurtosis measured far from the source at *X/H* = 0.625 and 1.125 were appeared to be higher than those obtained near the source at *X/H* = 0.375.

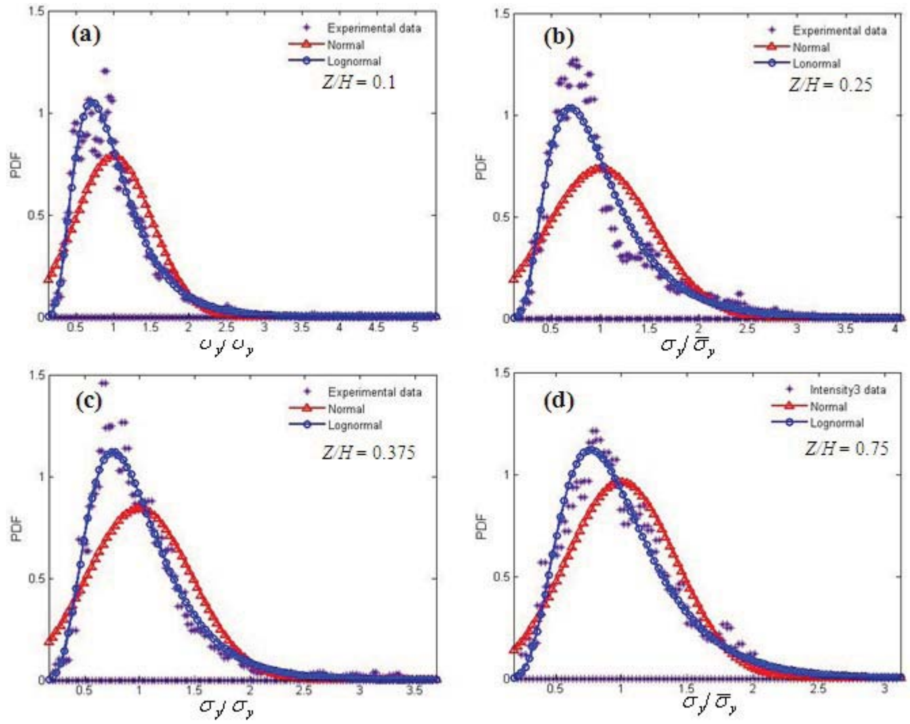

Fig. 8: Probability density for crosswind plume dispersion measured at X/H = 0.375.

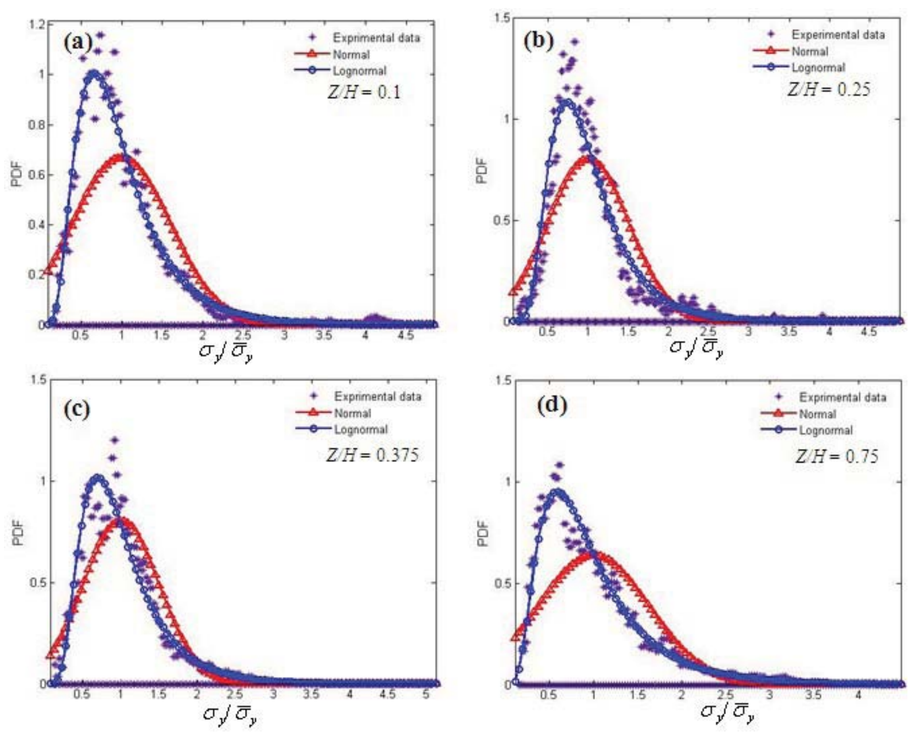

Fig. 9: Probability density for crosswind plume dispersion measured at X/H = 0.625.

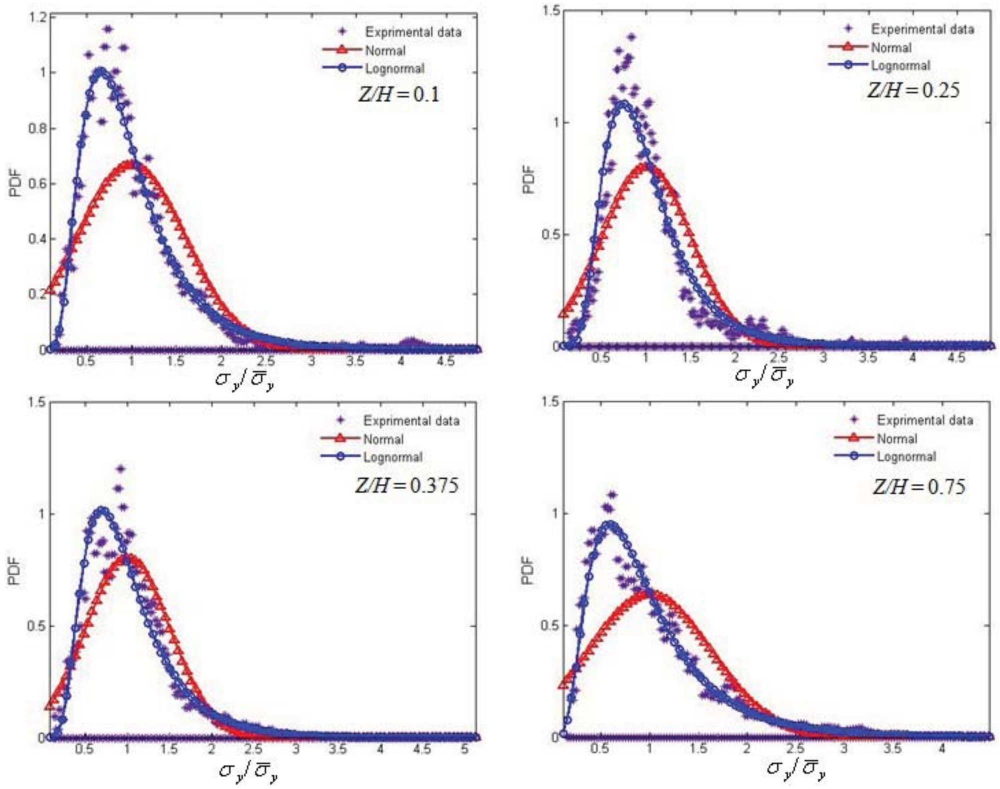

Fig. 10: Probability density for crosswind plume dispersion measured at X/H = 1.125.

Table 1: Skewness, Kurtosis and crest factors of fluctuating intensity

X/H	*Z/H*	Turbulence intensity, %			S_k	K_u	ĉ	č
		I_u	I_v	I_w				
0.375	0.1	16	19	12	0.8081	3.4906	1.3981	0.0001
	0.25	15	21	16	2.3347	10.0955	2.8158	0.0002
	0.375	15	17	17	2.5397	16.3599	3.8877	0.0002
	0.75	14	19	17	1.6799	7.3579	1.7775	0.0003
0.625	0.1	18	19	14	1.9073	9.3709	3.048	0.0003
	0.25	16	24	18	2.2044	9.9335	2.9957	0.0001
	0.375	15	20	18	2.8901	14.9268	2.6441	0.0001
	0.75	15	23	22	1.1867	5.1335	1.6389	0.0001
1.125	0.1	13	17	16	3.7517	22.1569	3.7791	0.0006
	0.25	14	20	17	3.3371	20.4092	3.8100	0.0003
	0.375	14	21	19	2.6463	14.9268	4.0595	0.0001
	0.75	16	21	21	2.2684	10.7149	3.4216	0.0007

Table 2: Skewness, Kurtosis and crest factors of crosswind plume dispersion

X/H	*Z/H*	Turbulence intensity, %			S_k	K_u	ĉ	č
		I_u	I_v	I_w				
0.375	0.1	16	19	12	0.5719	2.6323	2.3981	0.1529
	0.25	15	21	16	1.6278	5.9527	3.8158	0.2333
	0.375	15	17	17	1.5379	7.1068	4.8877	0.2437
	0.75	14	19	17	0.9784	4.2088	2.7775	0.2380
0.625	0.1	18	19	14	1.9539	11.3160	5.2132	0.1884
	0.25	16	24	18	1.5277	5.6582	3.9957	0.1763
	0.375	15	20	18	1.7928	7.8732	3.6441	0.2233
	0.75	15	23	22	0.8579	3.9232	3.0649	0.2193
1.125	0.1	13	17	16	2.3832	11.7587	4.7791	0.1678
	0.25	14	20	17	2.1318	10.7010	4.8058	0.1238
	0.375	14	21	19	1.4626	7.6333	5.0595	0.1238

0.75	16	21	21	1.4756	5.6194	4.4215	0.1768

Conclusions:

The data reported on instantaneous concentration were used to run statistical studies which were hindered for longtime due to the unavailability of these data. The corresponding PDF, skewness and kurtores factors were calculated. It has been observed that the peak concentration PDF has a wide sharp in the wake region of the building model. The peak value of concentration PDF was observed at the downwind near the ground in the wake region. The lognormal distribution appeared to be the best fit to the shape of the actual probability density functions of fluctuating concentration measured in the boundary layer wind flows in a wind tunnel. The tail of concentration PDF for heights far the ground surface was to be shorter than that those heights near the ground surface. The tail of concentration PDF for heights far from the ground surface was observed at shorter distance than those heights near the ground surface. The slope of concentration PDF near to the source is much steeper than that near the source. The fluctuation intensity PDF was clearly positively skewed. The actual probability distributions have much longer positive tails. The fluctuation intensity PDF based on the experimental data are distinctly different from the normal distribution, particularly for both tails. The skewness coefficient strongly affects of the tail of fluctuation intensity PDF. The wider sharp of the plume dispersion PDF was observed at distance near the source.

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