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ANALYSIS OF CONCENTRATION FLUCTUATION AND STEP-UP TENDENCY OF TRACER GAS DISPERSED ON A RECREATED URBAN MODEL IN A WIND TUNNEL.

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ABSTRACT

The concentration fluctuation is an indispensable element in studies on risk assessment of toxic gas dispersion in urban areas. Wind velocity fluctuation occurs through the nonlinear feature of flow, as well as concentration fluctuations. In the case of urban areas with a variable scale of eddies and a wide range of turbulence length scales, wind randomly flows in and out of open metropolitan spaces. Thus, fluctuation features are influenced by urban geometry, such as the density or height of buildings. Because of these fluctuations, some peak concentrations have much higher values than the average concentration. This means that pedestrians could be exposed to a potentially fatal dose within a split second. Therefore, simply building up a database of average concentrations is inadequate for the assessment of accidental pollutant dispersion. It is necessary to analyze the characteristics of fluctuations in urban areas, and this is the objective of our report. In order to measure the fluctuation data, a wind tunnel experiment was conducted using a finely recreated model of an actual residential area in Japan. In the model, six source points of toxic gas were located in characteristic places, such as the spaces between high-rise buildings or from a highway. Four measurement points were positioned between high-rise buildings, corresponding to the location of the inlet ducts of the building. In this research, the vacant space between the buildings is described as a 'void'. Such voids comprise the main component of ventilation in urban areas, so research about the efficiency of ventilation via voids is now ongoing in our research process. In this document, the stochastic features of concentration, such as average concentration and standard deviation, and the feature of probability density distribution were related to the features of urban geometry, the distance between the source and measurement points, and related to specific characteristics near the source point.

KEYWORDS: GAS DISPERSION, PROBABILITY DENSITY DISTRIBUTION, UNSTEADY DISCHARGE CONDITION, URBAN AREA

Introduction

Recently, the demand for a database on concentration fluctuations to better assess the urban environment has been increasing. Nowadays, urban areas, especially major cities, are at increased risk of contamination from nuclear, biological and chemical-related (NBC) terrorism or accidental emission of radioactive substances or manufactured gases, and at such critical times, the evacuation procedure must be sufficiently effective to predict the hazardous area and avoid using such area as an escape route. But assessments of the wind environment only consider average concentrations, and fluctuations are not considered. Such assessments of average concentration cannot be applied when there is the danger of gust-induced high concentrations. In urban areas, the feature of fluctuation may be somewhat dependent on the complex terrain. So it is possible that in unexpected areas, pedestrians may intake unusually high concentrations of toxic gas transported by unpredictable fluctuations in the flow field. The motivation for this report is to show the time series for concentrations of a tracer gas under unsteady discharge conditions (Step-Up discharge) and the stochastic features in a recreated model of an actual residential area in Japan.

Experimental Setup

The experiment was conducted in the environmental wind tunnel at the Institute of Industrial Science at the University of Tokyo. The operational section has dimensions of 16,470 mm (length), 2,200 mm (width) and 1,800 mm (height). It was used as an open-circuit wind tunnel so that the tracer gas does not accumulate in a chamber. The turntable can be fully rotated through 360 degrees and has a diameter of 2,000 mm. The wind velocity ranges from 0.2 to 2.0 m/s. Tracer gas was discharged via a mass flow controller (Ohkura), which enabled a 1-cc/s fixed flow rate, and a valve system (DGMS6-48: Scanivalve) which enabled step-up discharging. In order to measure the concentration fluctuation, a fast flame ionization detector (THC-2A: Technica) with a frequency response of 50 Hz was utilized. The model area is the Iidabashi district in Tokyo, Japan. The model was on a scale of 1:500 (Fig. 1). The measurement points were placed alongside an office building located in the center of the model (Fig. 2). The measurement point M1 was 5-mm high (equivalent to 2.5 m at full scale), M2 was 60 mm (30 m at full scale), and M3 was 120 mm (60 m at full scale). Measurement

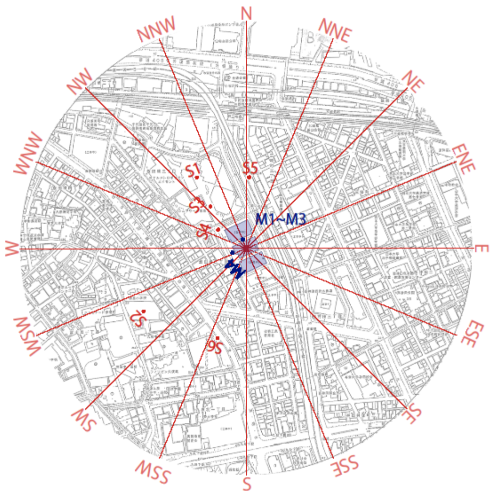


Fig. 1 The Model Area

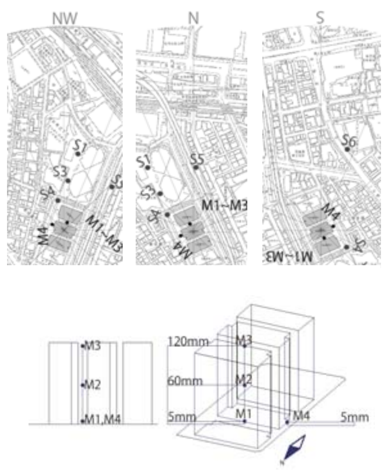
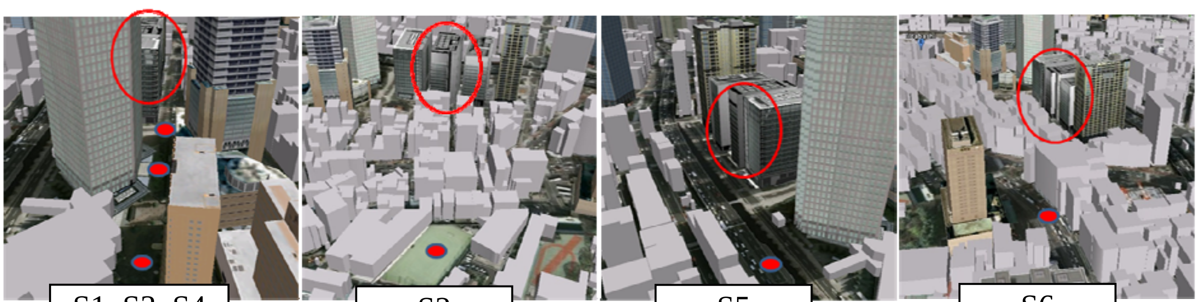


Fig. 2 Detail of Source and Measurement Points



S1, S3, S4
S2
S5
S6

Fig. 3 Details of the Source Points

point M4 was positioned in front of the office building entrance at a height of 5 mm (2.5 m at full scale). The source points were placed in six locations. S1, S3 and S4 were located between high- and mid-rise office buildings. S2 was located in a school ground, S6 was on a trunk road, and S5 was on a highway (the red rings in Fig. 3 represents the location of the void). At the top of the ejection hole, a baffle plate was positioned to discharge the tracer gas as a passive scalar. Figure 4 shows details of the experimental setup. Flame ionization detectors (FIDs) were set up both at the source and measurement points. These two data feeds were acquired at the same logger, and temporal sequences were synchronized. In the case of

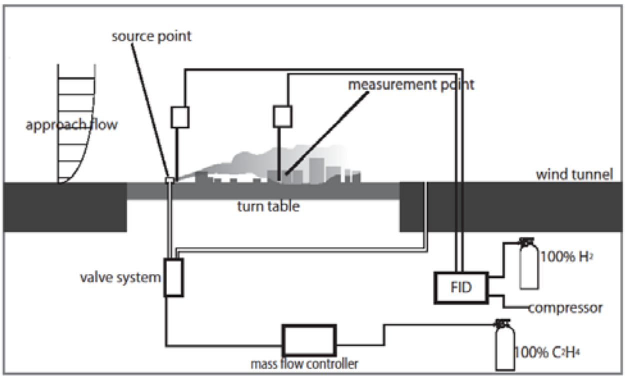


Fig. 4 Details of experimental setup

step-up, the concentrations were emitted and dispersed from the source point by switching on the valve system. The step-up time was identified by the fluctuation, which the FID at the source point itself has. The time at which the value exceeded 6σ was identified, where σ is the standard deviation before emitting the tracer gas. The tracer gas was dispersed by the wind flow in the urban area, and the concentration at the measurement points increased with time. The FID at the measurement point measured the time delay in the concentration rising. In terms of step down, the time delay and concentration reduction were measured in the same way. In the experiment, one-minute measurements were conducted and the step-up and step-down periods were achieved by switching the valve system. Thus the data included step-up and step-down tendencies. This report documents the step-up tendency.

Approach flow profile

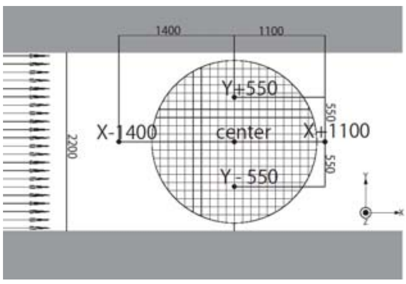


Fig. 5 Measurement points for approach flow velocity

An experiment to establish the approach flow profile was carried out. Atmospheric stability was set to neutral. The roughness was stabilized to realize the power law ($U \propto Z\alpha$; α: 0.25; U: velocity; Z: height). The velocity at the center of the turntable was stabilized at 2 m/s. For velocity measurement, a constant temperature anemometer (CTA) was utilized with a response frequency of 1,000 Hz. As shown in Fig. 5, the measurement points were set in the center of the turntable (center), 1,400 mm upwind of the center (X-1400), 1,100 mm downwind of the center (X+1100), 550 mm right of the center (Y+550) as viewed from downwind, and 550 mm left of the center as viewed from downwind (Y-550). Figure 6 shows the mean velocity profiles and turbulence intensity at each point.For the sake of conducting the experiment without loss of generality, a preliminary measurement was conducted. It was confirmed that the concentration is inversely proportional to the wind velocity, and verified

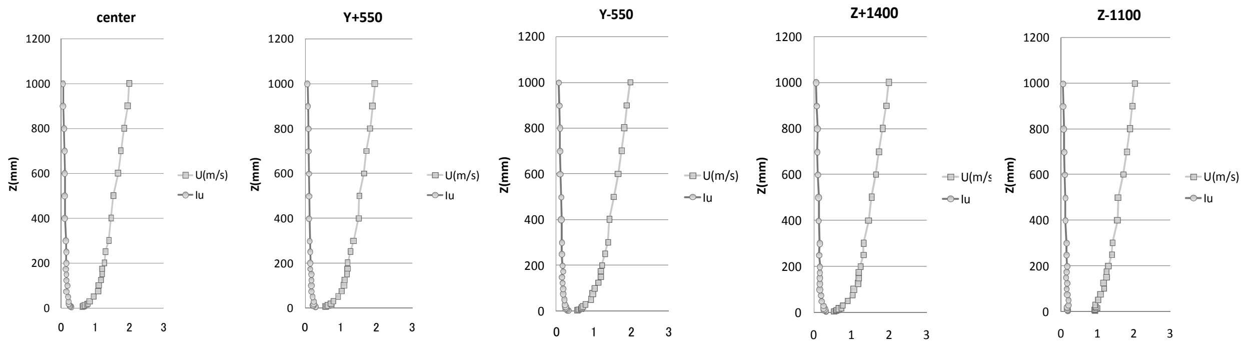


Fig. 6 Details of approach flow

that the concentration is proportional to the dosage of tracer gas. The time will be transformed to a dimensionless timescale t^* according to Equation (1), and the concentration will be transformed to a scaled concentration C^* according to Equation (2) (where C is the concentration, H is the height of the office building in the center [cm], u is the mean velocity at the height of the office building in the center [cm/s], and Q is the dosage of tracer gas [cc/s])

$$t^* = \frac{u}{H} t \qquad (1) \qquad\qquad C^* = \frac{CuH^2}{Q} \qquad (2)$$

Time series response

Table 1: Measurement case

1MINUTE

source point	wind direction	measurement pont
S1	NNW	M4
	NW	M2
	NW	M3
	NW	M4
S2	WSW	M4
	SW	M3
S3	NNW	M1
	NNW	M2
	WNW	M3
	W	M3
S5	NNE	M3
	N	M3
	NNW	M3
	NNW	M4
S6	SSW	M1

32ENSEMBLE

source point	wind direction	measurement pont
S2	SW	M1
	SW	M2
	SW	M4
S3	NNW	M4
	NW	M1
	NW	M2
	NW	M3
	NW	M4
S4	NNW	M4
	NW	M1
	NW	M2
	NW	M3
	NW	M4
	WNW	M1
	WNW	M2
	WNW	M4
	W	M1

32ENSEMBLE

source point	wind direction	measurement pont
S4	W	M2
	W	M4
	WSW	M1
S5	NNE	M1
	NNE	M2
	NNE	M4
	N	M1
	N	M2
	N	M4
	NNW	M1
	NNW	M2
S6	SSW	M4
	S	M1
	S	M2
	S	M3
	S	M4

Table 1 shows the cases where the data was measured. In the “32 ENSEMBLE” case, unsteady discharge measurements were conducted 32 times. In the “1 MINUTE” case, only the case for 1-minute continuous discharge was measured because the 1-minute average concentration was no more than 30 ppm. For example, 32 measurements were conducted at the source point “S2” in the wind direction “SW” at the measurement points “M1”, “M2” and “M4” (hereafter, these cases will be written as “S2-SW-M1”, “S2-SW-M2”, and “S2-SW-M4”), and 1-minute constant measurements were carried out at M3 (“S2-SW-M3”). This report presents the information for cases S2-SW, S3-NW, S4-NW, S5-N, and S6-S. The average concentration and standard deviation is shown in Fig. 7. The time series responses are shown in Fig. 8. The zero time reference for the x-axis is set at the time that the tracer gas was initially discharged. Frequencies exceeding 12.5 Hz were cut off. The center plot of one graph is the ensemble-averaged value. The upper and lower plots are the t-test values with a 95% credibility interval.

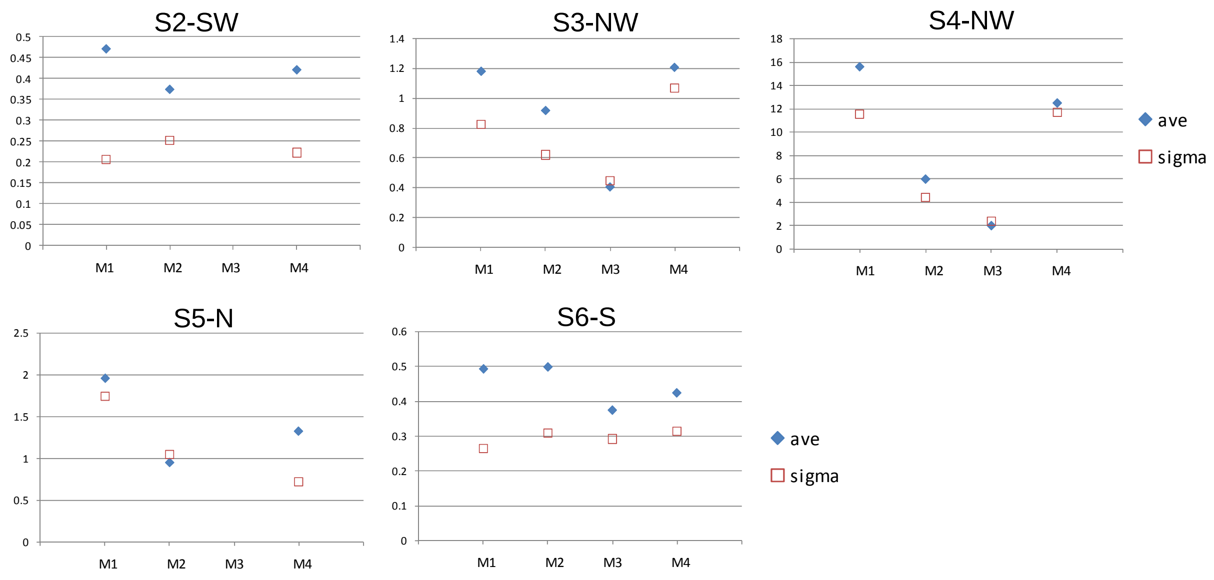


Fig.7 The Average Concentration and Standard deviation

In the case of S4-NW, which was the nearest source point to a measured void, the highest average concentration was measured at M1. The time delay was almost the same for M1, M2 and M4. Each stochastic value was quite different in each measurement point. But the tendencies of the average concentration and standard deviation were similar to each other. This trait was evident not only in the S4 case, but in almost all cases. In the case of S3-NW, which was the second nearest source point to a measured void, the average concentration was almost the same in M1 and M4. According to the time delay, the tracer gas reached M4 more quickly, and the other point showed a larger time lag. This tendency is different to the S4 cases. In the S3 cases, the source was located in the space between high-rise buildings, so that the tracer gas should drift through the narrow space with the flow passage expanding in the southern edge of the high-rise building. Accordingly, tracer gas spread across a wider open volume in front of source point S4. Vertical dispersion was more evident in case S3, with little difference in arrival times at M1, M2, and M3.In the case of S5-N, the source was located on a highway some 2.5 cm above ground level (GL). According to these cases, the tendencies for average concentration and standard deviation were dissimilar in the case of M4, which was at the southern side of the building. In other cases shown in the report, M4 was basically located in a windswept position. But in this case, the wind was blocked by the building. The concentration was still higher than M2 and M3 because of the wind passage through the narrow space between buildings, but the fluctuation was decayed and weak.In the case of S6-S, which was the second furthest place and located on a trunk road, the stochastic differences for each measurement point were smaller, as was the time delay. In the case of S2-SW, which was the furthest place to the measured void and located in a school ground, the stochastic value of each place showed quite similar tendencies and time delays. However, according to the time delay, a faster arrival at the measured void than in case S6 can be observed. From a distance aspect, the arrival time at S2 should take longer than S6. This can be considered to demonstrate the influence of the difference in source point conditions. S6 was located on a trunk road and there are somewhat higher buildings near the source. As a result, the gas has initially drifted upward or drifted along the trunk road (whose direction does not correspond to the measured void), and it took some time before it was carried on the approaching wind. By contrast, in the case of S2, there were no obstacles around the source point, because of its location in a school ground. Furthermore, the surrounding buildings were not that high. So the tracer gas easily drifted upward and rode the approaching wind.

According to cases S2 and S6, the stochastic value was not particularly influenced by the
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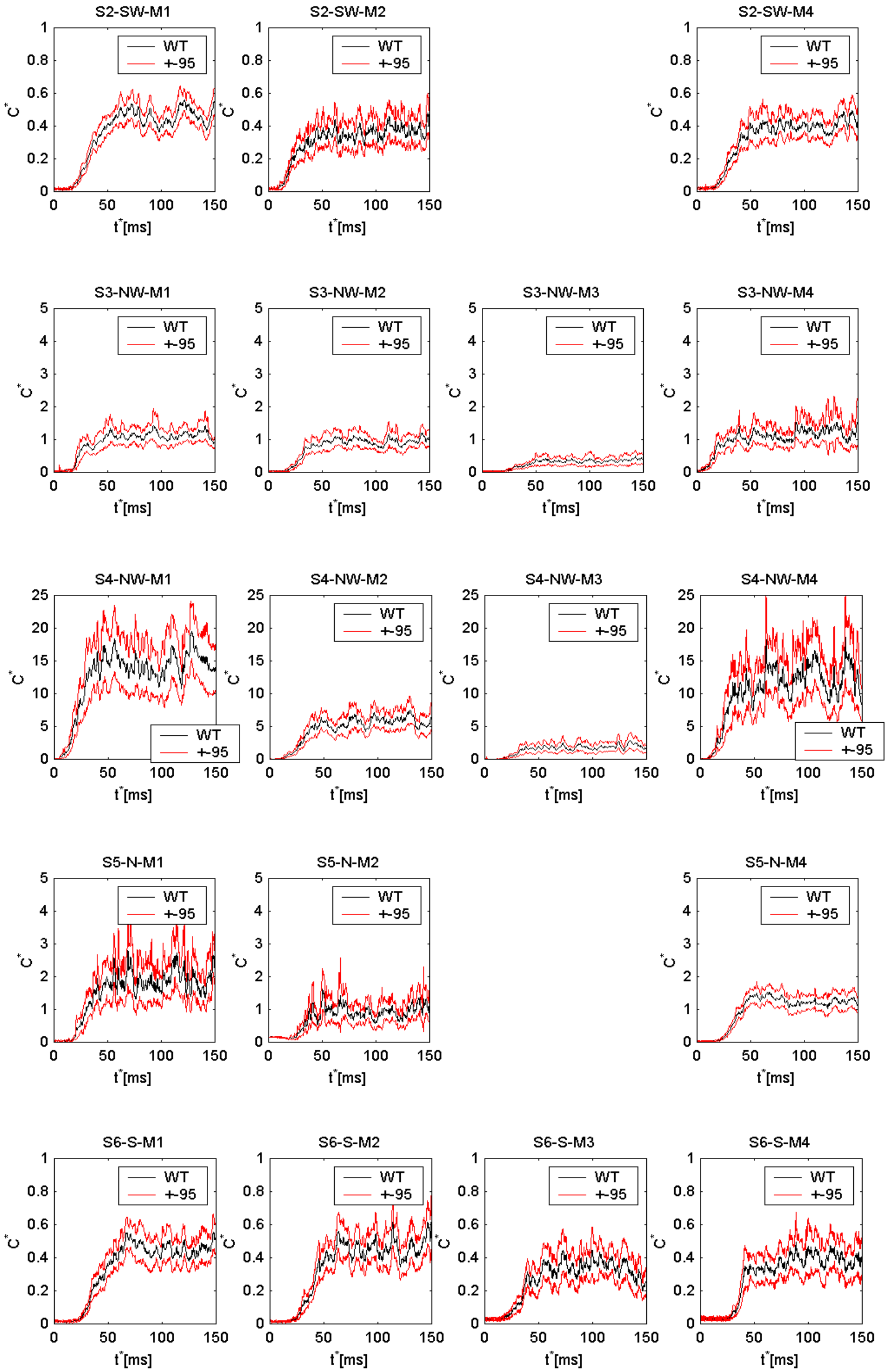

Fig. 8 Time Series Response

Probability density distribution

Fig. 9 shows the probability distribution and fluctuation concentration. The x-axis of the fluctuation concentration was the full-scale time [ms], and concentration was divided by the standard deviation. According to previous experiments, the probability distribution function can be modeled by exponential distribution, lognormal distribution and normal distribution. Generally speaking, the distribution profile near the source point can be approximated by the normal distribution. The exponential distribution agrees with cases where the marginal area of the plume and intermittency can be observed at a high rate (that is to say, at that point, much of the time the concentration is not transported, but once the tracer gas was carried, a spike-like response can be observed). According to the log normal distribution, a high affinity can be observed with the case of urban dispersion; that is to say, multiple sources exist. The distribution profile tendencies can be interpreted by the 4^{th} order momentum – the kurtosis. In terms of the S2-SW-M1 case, the experiment profile showed a good fit with the normal distribution. The value of kurtosis was 0.83, almost corresponding to the value of normal distribution (that is, zero).In terms of the S6-S-M1 case, a similar tendency to S2 can be observed (although there was some noise around the zero value). In these two cases, a lower concentration and small standard deviation were observed. That means the distance from the source to the measurement point was long enough for dispersal and mixing. The kurtosis value was 0.97.In terms of the S3-NW-M1 case, the profile is deflected to the left. The kurtosis showed a large value, 11.37. That means the peak concentration was much larger than the average concentration (even though the average concentration and peak concentration were both smaller than in case S4, the relative value was large). The fluctuation time series also shows the details of this tendency. The measured concentration was generally lower, but sometimes, extremely high values were plotted for short periods. The distribution profile was similar to the lognormal distribution. A similar tendency was observed in the S5-N-M1 case. The average concentration was lower compared to the max concentration. The distribution profile was similar to exponential distribution rather than lognormal distribution, with a kurtosis of 7.2. In terms of the S4-NW-M1 case, the distribution profile was similar to a lognormal distribution. The value of kurtosis was 2.93, it was larger than the value of normal distribution. The relative peak concentration compared to the average concentration was not as high as in the S3 and S5 cases; but crucially, the absolute peak value was large.

Conclusions

The time series of fluctuation concentrations dispersing in an urban area which is finely modeled in a wind tunnel was measured. The gas was dispersed under unsteady conditions and the arrival times were measured. The report documents the detail about time lags and probability density distribution. According to the step-up measurements, the stochastic tendency of each point correlated to the distance from the source point and the urban geometry. If the distance between the source and measurement point was small, the average concentration and peak concentration was large, but the relative size of the peak compared to the average was not as high as the medium distance value. The probability density distribution was similar to the profile for lognormal distribution. As the distance between the source and measurement point is reduced, the conditions of the measured location had a more prominent influence on each tendency. As the distance increased, the influence of urban geometry became remarkable (see cases S3 and S5, on the background of the high buildings or the abrupt expansion of a flow passage). The average concentration was small but the relative peak concentration was higher. In some geometrical cases, the probability distribution transited to an exponential distribution. This means that in some local area of the urban geometry, a typical distribution profile corresponding to the profile of the marginal area of the plume can be observed, and the location can exist in complicated urban geometry that is safe almost all of the time, but for a split second, a high density of toxic gas can influx. In addition, if the distance was wide enough, dispersion and mixing proceeded well and the blocking effect of buildings and flow field characteristics has little influence on the stochastic value of concentration, although they still influence the time delay as well (the difference between S2 and S6).

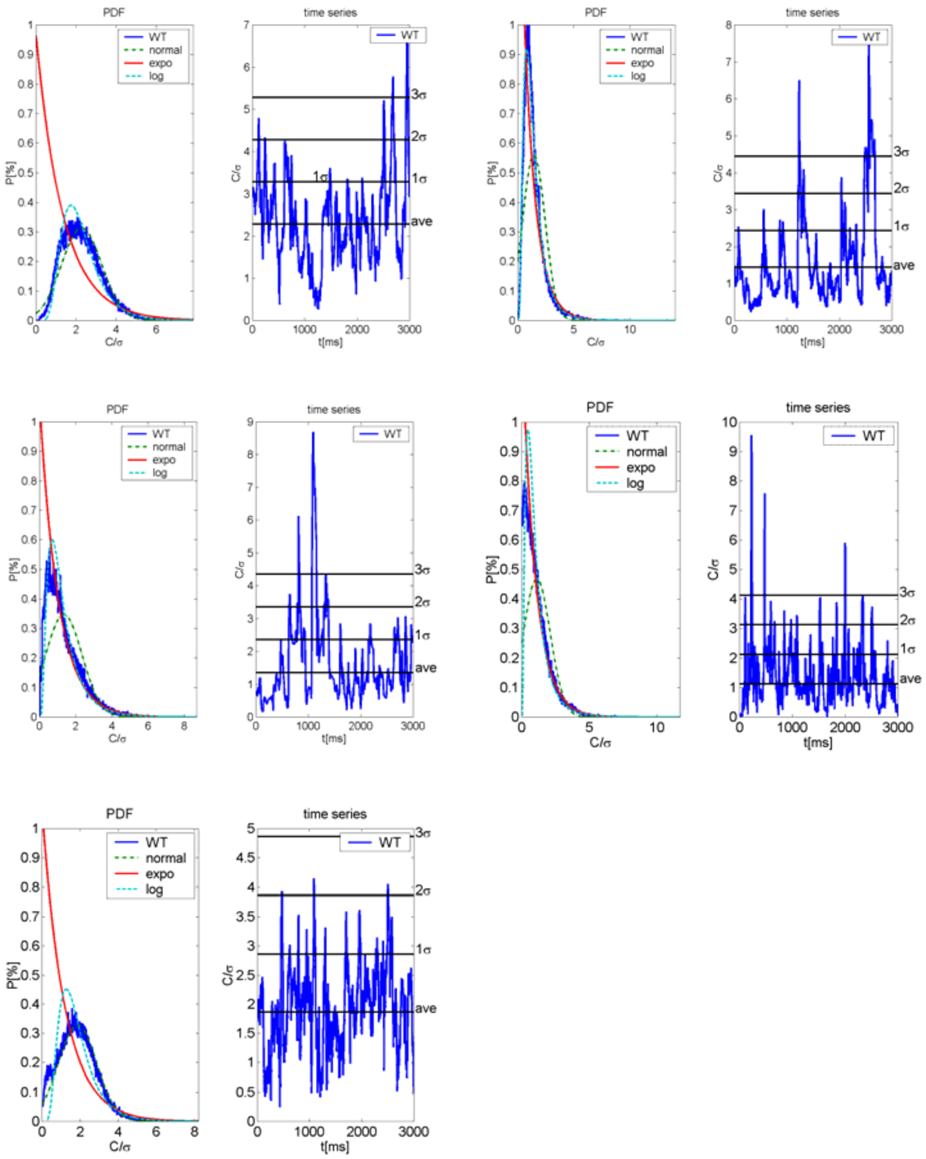

Fig. 9 Probability Density Distributions and Fluctuations

References

B. Leitl, F. Pascheke, M. Schatzmann, “Atmospheric Dispersion Study, Oklahoma City, July 2003” Final Report Phase I 08-2003 Generation of Wind Tunnel Data Sets in Support of the Joint Urban 200

Csanady, G.T., “Turbulent diffusion in the environment” Kluwer Academic Publishers

Steven R. Hanna, “The exponential probability density function and concentration fluctuation in smoke plumes” Boundary-Layer Meteorology 29 (1984) 361~375. By D. Reidel Publishing Company.