Journal of Environmental Sciences Vol. 11, No. 4, pp. 474—479, 1999 ISSN 1001—0742 CN11—2725/X

Article ID: 1001-0742(1999)04-0474-06

Random walk modeling of wake dispersion for the exhaust tower of an underground tunnel in urban area

JIANG Wei-mei[1], YU Hong-bin[1], LI Xin[2]

(1. Department of Atmospheric Sciences, Nanjing University, Nanjing 210093, China; 2. LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China)

Abstract: In this paper, some experimental studies on the impact of effluent from an exhaust tower of an underground tunnel with special construction are reported. By measuring the flow field downstream of the tower in NJU meteorological wind tunnel, some flow characteristics in the make area were established. Based on these, an advanced random-walk dispersion model was set up and applied successfully to the simulation of dispersion in the wake area. The modelling results were in accordance with wind tunnel measurements. The computed maximum of ground surface concentration in the building case was a factor of 3 – 4 higher than that in the flat case and appeared much closer to the source. The simulation indicated that random walk modelling is an effective and practical tool for the wake stream impact assessment.

Key words: exhaust tower; air pollution in urban area; atmospheric dispersion; random walk modelling

CLC number: X169 **Document code**: A

Introduction

Recently, some installations with special construction for extracting contaminant gas, such as an exhaust tower of the underground tunnel, etc. were set up in urban and industrial complex areas. The effects of these constructions on the flow and thereby on the local dispersion of the air pollutants were significant in the field of air pollution meteorology.

A wake is generally understood to be a region of disturbed flow downstream of the construction. It consists of a cavity region immediately in the lee of the construction and a transition region extending to some distances downstream. There are some characteristics in the wake, such as speed defect, high turbulent intensity and non-uniformity of the turbulence. Wind tunnel simulation experiment are often used to test theory and provide guidance for developing mathematical models. By now, it is common to use wind tunnel for simulation on study on the wake stream properties and providing a guidance for modification with regular Gaussian plume model. In term of turbulent mechanics and precision of analysis. Gaussian models are not the best one. "Until our understanding on building wake effects is more complete. It may not be appropriate to extend a generalized Gaussian plume model for all situations" (Huber, 1991). The U.S.EPA regulatory modelling program is still seeking improved techniques for the ISC2 model (Touma, 1995).

Random walk modelling is an advanced approach and has been used in many fields, especially in inhomogeneous, non-steady, non-Gaussian turbulence and in the region near the source. Though random walk modelling is the appropriate way for simulation of wake dispersion.

In this study, a contaminant emission source with special construction—exhaust tower for underground transportation tunnel was considered. Based on analysis of wake stream properties determined by wind-tunnel experiments, an advanced random walk model was set up and has been used to evaluate the distribution of air pollutant in the wake. The computations of air pollutant concentration were compared with the results of the tracer concentration in the wind tunnel. Finally, some numerical tests have been introduced in order to study the building effects on wake dispersion.

Foundation item: Key Project of Chinese Academy of Sciences (No. KZ952-S1-405)

1 Research and analysis on the wake stream characteristics

The outline of the exhaust tower of underground tunnel for ventilation is illustrated in Fig. 1. At the end of underground tunnel, the main construction of the exhaust tower for ventilation is a cylinder with height 67m and diameter 29.7m. There is also a 20m-high auxiliary building adjacent to the main building. The contaminant is emitted from the upper window with average height 50m.

The experimental study was conducted in an open-circuit meteorological wind tunnel with a test section 2m wide. 1.4m high and 16m long at Nanjing University. The wind tunnel was described in detail by Jiang (Jiang, 1994). A nominally 0.7m-thick simulated atmospheric boundary layer was obtained using the "roughness elements and vortex generator" method. The model of the construction with scale 1:324 was set on the center of test section floor. The flow was characterized by measuring mean flow speed and turbulent intensity with a hot-wire/film probe system. Smoke visualization tests were also performed to identify the properties of the isolated tower wake. Meanwhile, series of tracer experiments were conducted to study the dispersion behavior within the wake region from the tower emission.

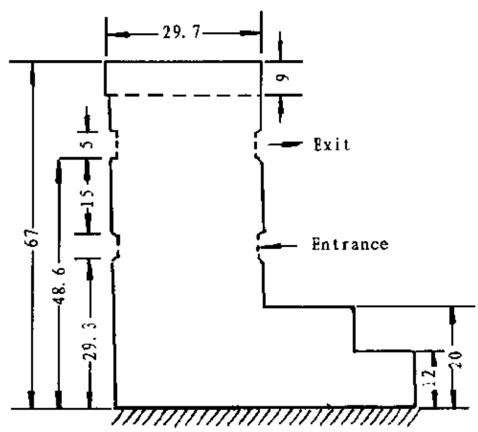

Fig. 1 Outline of the exhaust tower (unit: m)

The distributions of the mean flow speed (u) and longitudinal turbulent intensity (i_x) downstream of the construction are, presented in Fig. 2(a) and Fig. 2(b), respectively. In the figures, the flow speed defect and intensity were normalized with approaching flow speed (u_0), i. e. $(u_0 - u)/u_0$, and $i_x/i_{x,\max}$, was normalized. The distributions characterizing the aerodynamic effects of the exhaust tower. The speed defected and turbulence intensified region are extending to 7—8 times and 2—3 times of tower height in longitudinal and vertical directions, respectively.

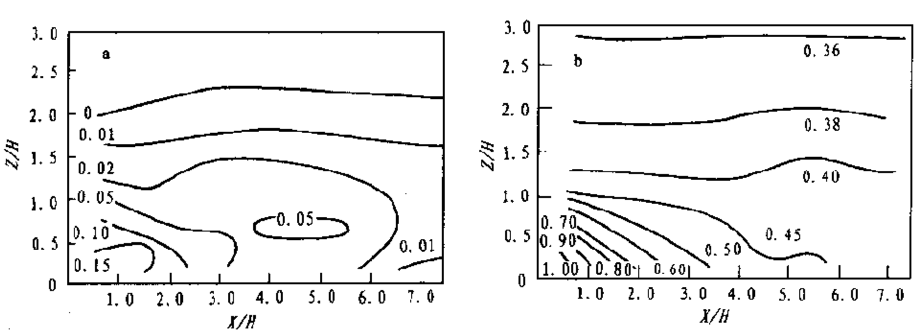

Fig. 2 The flow distribution downward the tower
a. mean speed defect ($(u_0 - u)/u_0$); b. normalized turbulent intensity ($i_x/i_{x,\max}$)

Flow visualization in wind tunnel showed that plume downwash occurred when the ratio of environmental man speed at source height to the horizontal exiting velocity of the effluent was greater than 1.8. The greater the ratio was, the closer the distance of touchdown point from the source was. With the mean speed varied from 2.6 m/s to 5.2 m/s, the distance of touchdown point from the source was decreased from a factor of 6 tower heights to 2 tower heights.

The features of the wake flow are important in developing the dispersion models in the wake. These include the longitudinal and transverse variations of mean speed and turbulence and the longitudinal variation of the wake boundary. In this study, the special emission source was considered as an equivalent flat plate implanted in the ground surface. The exposed half of the plate was H in height and W in width. It was supposed that $W = 30\text{m}$ and $2H = 134\text{m}$. So the plate aspect ratio $R(W/2H)$ was equal to 0.25 and the plate characteristic dimension $L(2RR^{1/2})$ was equal to 60m. Based on the measurements in wind tunnel, the following empiric formulas incorporating the theory of axi-symmetric wakes were obtained:

$$(u_0 - u_4)/u_0 = 0.54(X/L)^{-2/3}R^{1/3}$$

$$\text{or} \quad u_a = (1 - 6.2819X^{-2/3})u_0, \tag{1a}$$

$$Z_b/L = 0.98(X/L)^{1/3-1/10}$$

$$\text{or} \quad Z_b = 17.29X^{1/3}, \tag{1b}$$

where, u_0 is the longitudinal mean velocity of background flow (m/s) at the source height; u_4 is the longitudinal mean velocity in the wake axis (m/s); X is the downstream coordinate from the plate (m); Z_b is the wake boundary coordinate defined as the distance from the wake axis to the point where the mean velocity defect was 10% of the maximum speed defect at the downstream distance.

The suppression of turbulence in vertical by the ground surface indicated that the real wake stream was not axi-symmetric as in the case of the suspended flat plate. It may be inferred, therefore, that the wake boundary in vertical will be narrow, comparing with that in horizontal, $Z_b = 0.52Y_b$ proposed by Halitsky (Halitsky, 1977), the horizontal wake boundary Y_b in this study was:

$$Y_b/L = 1.89(X/L)^{1/3}R^{\ 1/10}$$

$$\text{or} \quad Y_b = 33.25X^{1/3}, \tag{2}$$

where, Y_b is horizontal wake boundary coordinate, it is the lateral boundary distance where mean speed defect is 10% of maximum defect.

Referring to fitted curves (Halitsky, 1977), the transverse variation equations were:

$$\Delta = (u_0 - u)/(u_0 - u_4)$$

$$= 1.167 + 0.167\sin[7.121(Y/Y_b - 0.221)] \quad (0 < Y/Y_b < 0.441), \tag{3a}$$

$$\text{or} \quad = 0.733 + 0.600\sin[3.141 - 5.622(Y/Y_b - 0.162)]$$

$$(0.441 < Y/Y_b < 1), \tag{3b}$$

where Δ is mean speed defect ratio or rms turbulence excess ratio, Y is transverse coordinate (m); subscript "0" and "a" denoted background and wake axis. The above analyses and empiric equations will be used as meteorological and turbulent fields inputed to the random walk dispersion model.

2 Stochastic modelling of pollutant dispersion in wake

The features of the wake are important in the wake dispersion simulation obviously. It is demonstrated by the experiments that within the wake, the turbulence construction and the dispersion characteristics are more active and inhomogeneous and it is specially discovered in a small extent, for example 100—200m, far from the source. Regular Gaussian plume models, are not appropriate for the inner wake dispersion. Though some modified Gaussian plume models (Jiang, 1991) would be successful to some extent, the performances of the models were greatly dependent on empiric assumptions. Recently, the random walk, modelling has been applied successfully in some special dispersion cases. Its physical concept is clear and the numerical treatment is simple. It is more suitable to the dispersion simulation under the conditions of inhomogeneous, non-steady, non-Gaussian turbulence and in the area near the source. In this paper, this method was employed to simulate the wake dispersion.

The random walk method of modelling the dispersion of a passive tracer consists of numerically simulating the motion of many random tracer particles in order to build up a picture of the concentration distribution. The trajectory of each particle is simulated by modelling the evolution of the particle velocity over a succession of time steps. An important assumption in the random walk dispersion model is that the turbulent velocity of dispersion particle can be described by the Markov process. It is usually assumed that the velocity at one time step depends linearly on that at the previous time step, i.e.:

$$v_i'(t+dt) = v_i'(t)R_1 + (1-R_i^2)^{1/2} i\sigma_i\nu + (1-R_i)T_{Li}(\partial\sigma_i^2/\partial z)\delta_{3i} \qquad (i = u, v, w), \tag{4}$$

where v_1' denotes the turbulence fluctuation velocity (m/s); dt is the time interval (s); σ_1 is the standard deviation of fluctuation velocity (m/s); T_{Li} is the Lagrangian time scale (s); v is a Gaussian random number with zero mean and unit variance; R_i ($i = u, v, w$) is auto-correlation coefficient, and is taken simply as exponential form. The last term in Equation (4) is an additional drift term (Legg, 1982) to account for particle accumulation in zones of low turbulent kinetic energy; δ_{3i} is the Kroneker delta and implies that the drift correction term is added only to the w equation.

A number of marked particles are released from the source continuously. The particle trajectory equation is as follows:

$$X_i(t+dt) - X_i(t) + (v_1 + v_1')dt \qquad (i = u, v, w), \tag{5}$$

where v_1 denotes mean wind speed; $X_i(t)$ is the antecedent X, Y, Z position of the particle and $X_i(t+dt)$ is its position aftertime interval dt. Then the concentration is calculated by counting particles in a sampling box. Let DX_i, DY_i and DZ_i represent the grid spacing in three directions of the ith grid; Q, the strength of the releasing source; N, the total number of the releasing particles. The concentration of pollutants in the definite grid can be expressed as

$$C_i(X, Y, Z) = Q\sum_{j=1}^{N} t_{ij}/NDX_iDY_iDZ_i), \tag{6}$$

where t_{ij} is the time of the jth particle staying in the ith grid. This modelling technique has been used successfully to simulate the dispersion in CBL, fumigation over shoreline area, dispersion in complex terrain, and so on (Yu, 1993; 1994a; 1994b).

Vertical distributions of the mean flow speed and the longitudinal turbulence intensity downstream the tower were obtained from the observations. Meanwhile, it was supposed that $\sigma_0 = \sigma_V$, and $\sigma_W = 0.52$, σ_u according to (1) and (3), the three-dimensional distributions of mean flow speed and turbulence are introduced to the random walk model; Hanna's formula (Hanna, 1982) for Lagrangian time scale was used in this paper.

The emission rate of CO emitted from the exhaust tower of the transportation tunnel was 43715 mg/s. In the simulation and 32000 marked particles were released and followed. The time step following the particles was taken as 0.1 T_{lw}. Perfect reflection was imposed on the ground surface. The statistical numbers of the air pollutant particles in each grid cell were calculated to obtain the concentration distribution. The ground surface concentration was computed according to the statistical particle numbers below 10m.

The distributions of ground surface concentration on the centerline downstream of the tower are illustrated in Fig. 3 and Fig. 4 with mean speed of 3.6 m/s and 6.2 m/s at source height, respectively. In addition, the observations in the wind tunnel and the results of modified Gaussian plume model (Jiang, 1991) were presented also in the figures. In Fig. 3, it was showed that the predicted concentrations using the present random walk model were about ten percents lower than the observation, but the location of maximum concentration was in good agreement with the

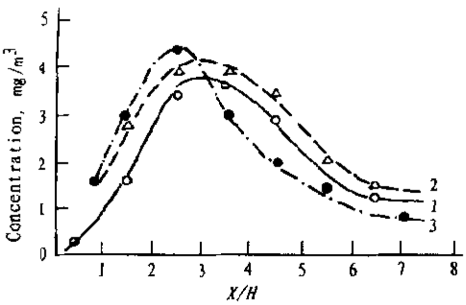

Fig. 3 Distribution of the ground surface concentration (mean speed 3.6 m/s)
1. random walk model; 2. wind tunnel experiment; 3. modified Gaussian model

observation. The computed maximum value by the modified Gaussian plume model was about five percents higher than the observation, but its location was so closer to the source. Downstream of the location of the maximum, however, the predicted values of the modified Gaussian model were smaller than the observations with the maximum underestimation about forty percents. In Fig. 4, it is seen that the location of the maximum concentration predicted by the random walk model were in good agreement with the observation, however, the predicted concentration values were lower. The results of modified Gaussian model showed the same behavior. In conclusion, the random walk model developed in this study could simulate wake dispersion functionally.

In order to analyze the effects of the constructions on ground-level concentration of air pollutant, some comparisons for concentration distribution under the conditions with and without the construction were made. Fig. 5 shows the concentration distributions at two different wind speeds. In the figure, solid line and dashed line represent the concentration distribution with and without construction, respectively. It is seen that the maximum concentration in the case of construction was a factor of 3—4 higher than that without the construction. The position of the maximum drifted toward the source in the case of construction. At a downstream distance of $X >$ 500m ($-8H$), both concentrations tended to be the same. These reflected clearly the effects of the construction. Tinarelli *et al*. (Tinarelli, 1994) studied the diffusion in the wake on the lee of a 2D hill and the observation indicated that the maximum concentration at ground surface with the hills higher by about 3 times than that in the flat terrain. Our result was in good agreement with theirs.

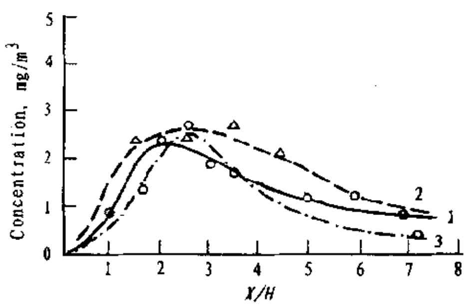

Fig. 4 Same as in Fig. 3, except wind speed 6.2 m/s
1. random walk model; 2. wind tunnel experiment; 3. modified Gaussian model

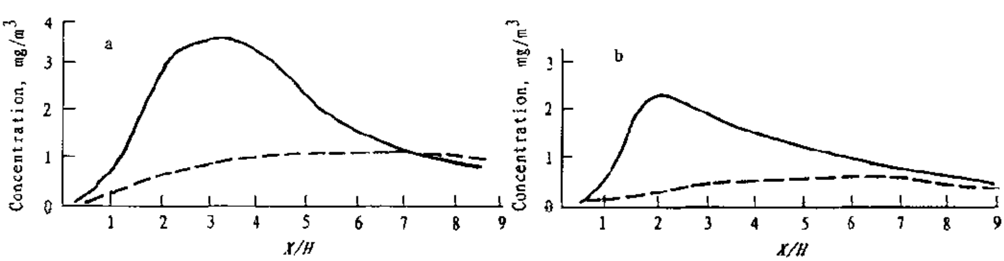

Fig. 5 Comparisons of the centerline concentration with and without the construction
a. wind speed 3.6 m/s; b. wind speed 6.2 m/s

3 Conclusions and discussion

In this study, an advanced random walk dispersion model that can be used in wakes has been developed and the fundamental features of air pollutant dispersion in the wake area of the exhaust tower were revealed. The simulation results were in accordance with the measurements obtained by tracer dispersion experiments in the wind tunnel. The model performance was superior to that of a modified Gaussian plume model. There were no more empirical assumptions and modifications in the model so that it is more reasonable and convenient to generalize and apply to real situations. It was concluded that, based on the research work in this paper, a new approach to study the air pollutant dispersion in the wakes has been introduced in the field of air pollution meteorology. Further research should be performed to raise and improve the modelling resolution on the turbulence properties and structures in the wake area in order to provide more sophisticated turbulence field for the dispersion modelling.

References:

Halitsky J, 1977. Atmospheric Environment [J], 11:577—596.

Hanna S R, 1982. Atmospheric turbulence and air pollution modelling [M] (Eds. by F. T. M. Nieuwstadt and H. Van Dop). Reidel, Dordrecht. 275—310.

Huber A H, 1991. Atmospheric Environment [J], 25a(7):1237—1249.

Jiang W M, Ma F J, Xie G L *et al.*, 1991. Quarterly Journal of Applied Meteorology [J], 2(3):234—241.

Jiang W M, 1994. Journal of Nanjing University (special issue) [J], January: 221—226.

Legg B J, Raupch M R, 1982. Engineering meteorology [M](Eds by Plate E J). New York. 481—526.

Tinarelli G, 1994. Journal of Applied Meteorology [J], 35:744—756.

Touma J S, Irwin J S, Tikvart J A *et al.*, 1995. Journal of Applied Meteorology [J], 34:731—737.

Yu H B, Jiang W M, 1993. Scientia Atmospherica Simica [J], 17(5):629—635.

Yu H B, Jiang W M, 1994a. Acta Scientiae Circumstantiae [J], 14(2):191 197.

(Received for review March 23, 1998. Accepted May 25, 1998)