An evaluation method of the topographical effects on exhaust gas dispersion using a personal computer version of a turbulent dispersion model

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1 Introduction

The law for environmental impact assessment was enforced in Japan in 1999. Consequently, the need for an effective and efficient method of predicting the atmospheric dispersion of air pollutants, particularly for evaluating topographical effects on exhaust gas dispersion, has increased because topographical features in Japan are complex. The effects of topography on exhaust gas dispersion have conventionally been evaluated by means of wind tunnel experiments. Recently, a numerical model of exhaust gas dispersion for environmental impact assessment of thermal power plants was developed, and a method for evaluating topographical effects using this numerical model was proposed (Ichikawa and Sada, 1999). The numerical model consists of a turbulence closure model and a Lagrangian particle dispersion model.

The proposed evaluation method improves the efficiency of environmental impact assessment, since supercomputers are more common than large wind tunnel facilities and the use of a numerical model is superior to wind tunnel experiments in terms of cost and evaluation time. However, it is necessary to evaluate the topographical effects on exhaust gas dispersion using a personal computer (PC) instead of a supercomputer, to further enhance the efficiency and practicability. The turbulent dispersion model for a supercomputer was therefore transferred to a PC. The performance and practicability of the PC version of the model were examined through comparison with the supercomputer version and the wind tunnel experiment. Furthermore, the turbulent dispersion model was simplified to nearly two dimensions to obtain calculation results more quickly.

2 Turbulent dispersion model

The Lagrangian particle dispersion model proposed by Thomson (1987) was applied for the prediction of exhaust gas dispersion over a complex terrain. The governing equations of the Lagrangian particle dispersion model are stochastic differential equations which represent the random motion of a particle:

$$du^i = a^i(\mathbf{x}, \mathbf{u}, t)dt + b^{ij}(\mathbf{x}, \mathbf{u}, t)d\xi^j \quad , \tag{1}$$

$$d\mathbf{x} = \mathbf{u}dt \quad , \tag{2}$$

where **u** and **x** are the velocity and the position of a fluid element or particle, respectively, t is the time, and $d\xi^j$ is the increment of a Wiener process. The coefficients a and b describe the effects of dynamic characteristics and noise, respectively. They are calculated from turbulent statistics such as the mean velocity, the normal stress and the energy dissipation rate. The turbulent statistics were predicted using a turbulence closure model. This model is based on the Reynolds stress model developed by Gibson and Launder (1978). The advection and diffusion terms of the Reynolds stress equations are simplified and the Reynolds stress is expressed using algebraic equations (Rodi, 1976).

A total of 380,000 particles were emitted from the effective stack height. Equations (1) and (2) were integrated by a finite difference scheme with a time step of 2 sec. In the turbulence closure model, a horizontal mesh size of 500 m was used and vertical mesh sizes ranged with height from approximately 30 m near the ground surface to approximately 400 m near the upper boundary at a height of 3000 m. The numbers of grids in the crosswind direction were 61 and 3 in three-dimensional and nearly two-dimensional calculations, respectively.

3 Evaluation of topographical effects on exhaust gas dispersion

In Japan, topographical effects on exhaust gas dispersion have conventionally been evaluated in terms of the following indices.

α=(maximum concentration for topography)/(maximum concentration for flat terrain)
β=(distance of the point of maximum concentration from the source for topography)/
(distance of the point of maximum concentration from the source for flat terrain)
$\gamma(x)$=(concentration distribution along the ground surface plume axis for topography)/
(maximum concentration for flat terrain)

When we use these indices, it is first necessary to calculate air flow and dispersion for a flat terrain. The calculation was carried out so that plume widths would fall between the one-hour Pasquill-Gifford's values for atmospheric stabilities C and D.

The turbulent dispersion model was applied to predict dispersion in an actual region in southern Japan. Three wind directions (Topography 1-3) and two source conditions were studied. The vertical sectional planes of topography along the wind direction axis are shown in Fig. 1. The positions of the effective stack height, 434m and 481m, are plotted as solid and open triangles.

Wind tunnel experimental data were used to examine topographical effects evaluated by the turbulent dispersion model. The wind tunnel experiment using the overlapping technique (Okabayashi et al., 1991) was conducted by the Nagasaki Research and Development Center for Mitsubishi Heavy Industries. The overlapping technique uses a turntable which rotates from side to side to simulate a one-hour average concentration of exhaust gases. The turntable with a diameter of 12 m was placed in a working section 3 m wide, 2 m high and 25 m long. The tracer gas was ammonia and the scale of the topographical model was 1/5000.

Figure 2 shows the relative concentration distribution ($\gamma(x)$) for Topography 1 and the effective stack height of 481m. Results calculated using the supercomputer (SC model) and PC (PCn61 model, where "n61" means 61 grids) versions of the three-dimensional turbulent dispersion model are shown by thick solid line; two sets of results coincide. The solid circles represent the results of the wind tunnel experiment. Very good agreement between the turbulent dispersion model and wind tunnel experiment is also obtained. The thin solid line represents the results obtained using the nearly two-dimensional turbulent dispersion model (PCn3 model, where "n3" means 3 grids). The concentration of exhaust gas calculated using the PCn3 model is lower than that obtained using the PCn61 model beyond the downwind distance of 18 km. The reason is that the outflow boundary condition is set at side faces of the domain regardless of the narrow width of the study region.

The comparisons of the ratios α and β between the turbulent dispersion models and the wind tunnel experiment are shown in Fig. 3. This figure includes all six cases (combinations of the three topographical conditions and the two effective stack heights). The open circle represents the results for flat terrain and in this case, the values of both α and β are equal to 1. The results calculated using by the SC model and the PCn61 model coincide with each other. The values of α and β evaluated by the turbulent dispersion model varied between 1 and 3 and between 1 and 0.4, respectively, depending on topographical features. These results agreed reasonably well with the results of wind tunnel experiment irrespective of using the supercomputer or PC version or the three-dimensional or nearly two-dimensional model.

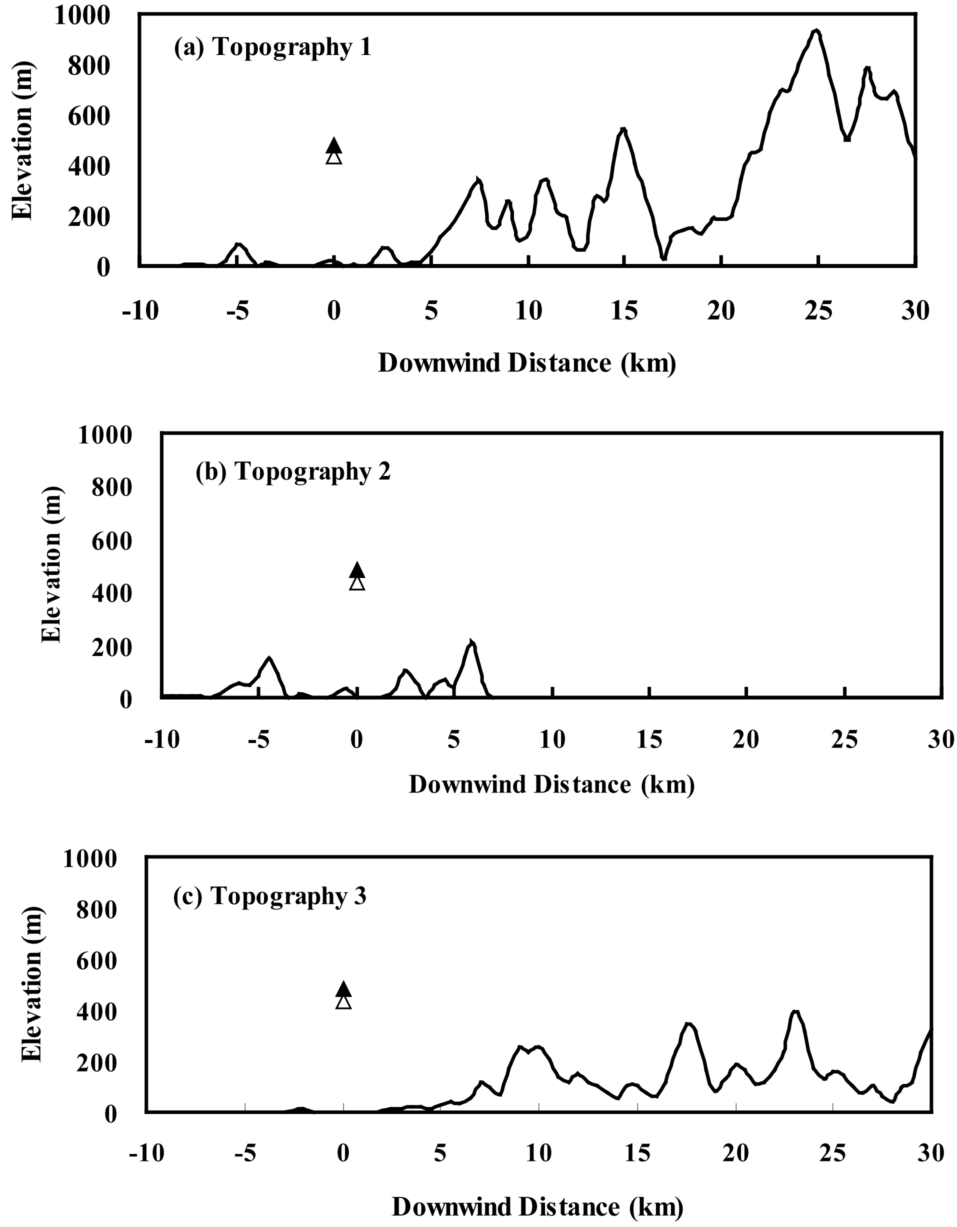

Figure 1 Topographical features (vertical sectional plane along the wind direction axis).
▲and Δ indicate the positions of effective stack heights

Table 1 summarizes the memory size and CPU time per calculation case. The CPU of the personal computer used in this study is Pentium II 450 MHz. The OS and language are Turbo Linux release 4.0 and FORTRAN PGF77, respectively. Considering that the CPU of the latest PC is more than 1 GHz, the turbulent dispersion model should be able to provide the evaluation of topographical effects on exhaust gas dispersion in a few days. If the nearly two-dimensional model is used for the evaluation of maximum concentration and its position, only several hours are needed. The use of the turbulent dispersion model instead of the wind tunnel experiment enables us to reduce the cost and period required for environmental impact assessment by 70-80 percent.

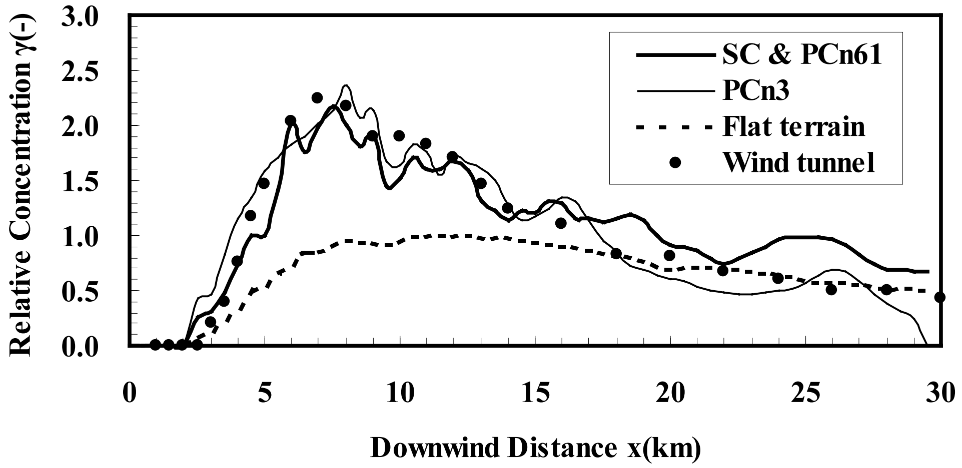

Figure 2 An example of comparison of relative ground surface concentration distributions along the plume axis between the turbulent dispersion model and the wind tunnel experiment (SC: supercomputer version, PCn61and PCn3: personal computer versions of three-dimensional and nearly two-dimensional models, respectively).

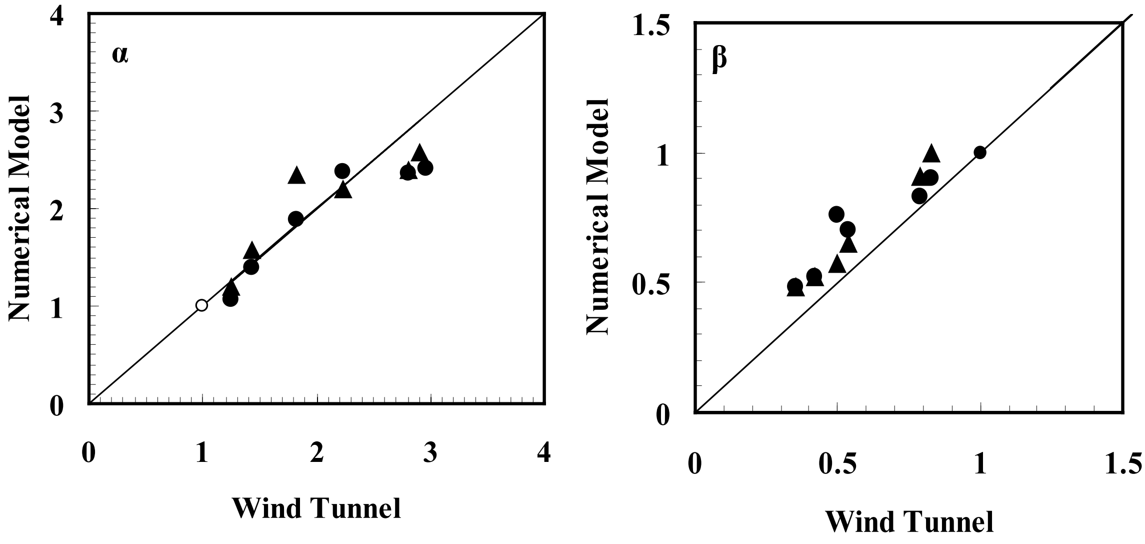

Fig. 3 Comparison of α (left) and β (right) between the turbulent dispersion models and the wind tunnel experiment, where α is the ratio of the maximum concentration for topography to that for flat terrain and β is the ratio of the distance to the maximum concentration for topography to that for flat terrain (.: PCn3 model, ▲: PCn61 model, .: flat terrain).

Table 1 Practicability of the personal computer version of the turbulent dispersion model.

Model	No. of grids (x, y, z)	Memory size (MB)		CPU time (hour)		
		Air flow	Dispersion	Air flow	Dispersion	Total
PCn61	(81, 61, 31)	54	40	75	36	111
PCn3	(81, 3, 31)	6	9	3	9	12

4 Conclusions

The turbulent dispersion model for a supercomputer was transferred to a PC. Calculated results of concentration distributions of exhaust gas obtained using both computers coincided, irrespective of the operating system and programming language. The model was simplified to nearly two dimensions to obtain calculation results more quickly. Topographical effects on exhaust gas dispersion were evaluated using both the three-dimensional and nearly two-dimensional PC versions of the turbulent dispersion model under three topographical conditions and two source conditions. The evaluation results were very similar to the results of wind tunnel experiments. The use of a PC enabled us to reduce the cost and shorten the period required for the evaluation of topographical effects. It is concluded that we can evaluate the topographical effects practicably and easily using a PC and that the evaluation results have the same accuracy as those of wind tunnel experiments.

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