Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 4, p. 451–454 (March 2004)

Estimation of the Concentration Distribution according to the Variations in a Wind Field over a Complex Terrain

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A three-dimensional wind field and an atmospheric dispersion model have been developed for real-time accident consequence assessment for a nuclear accident. A diagnostic mass-consistent wind field model was adopted for the generation of a wind field over the whole domain using several measured data. A Lagrangian particle model was used for the calculation of the concentration distribution of the radionuclides in the atmosphere. The field tracer experiment near the Younggwang nuclear power plant was carried out for the purpose of analyzing the site-specific environmental characteristics and validating the atmospheric dispersion model in May 1996. The calculated concentration distributions were compared with the measured values. The generation of the three-dimensional wind field was one of the most important factors for calculating the concentration of the released particles in the dispersion model. Several numerical experiments using the measured wind data were performed to get more accurate concentration distributions compared with the results of the field tracer experiment of SF_6. The developed numerical models are being used as a basic tool for emergency preparedness in Korea.

KEYWORDS : wind filed and atmospheric models, field tracer experiment, emergency preparedness

Ⅰ. Introduction

After the TMI-2 and the Chernobyl accidents, researches for developing the national emergency preparedness system have been widely performed to predict and minimize the radiological damage for the surrounding environment. A system for the radiological emergency preparedness for a nuclear accident must be established to evaluate and minimize the harmful effects on the surrounding population and environment. The transport of radioactive materials released into the atmosphere is mainly dependent on the environmental conditions such as wind field and topography. Therefore, it is important to estimate the reliable wind profiles for understanding the dispersion processes of radioactive materials over a complex terrain.

A diagnostic mass-consistent wind field model using terrain conformal coordinates was adopted for the generation of a wind field over the whole domain using measured wind data at several points. A three-dimensional Lagrangian particle model for a local scale atmospheric dispersion was developed to estimate the air concentrations over a complex terrain.

The field tracer experiment near the Younggwang nuclear power plant was carried out for the purpose of analyzing the site-specific environmental characteristics and validating the atmospheric dispersion model in May 1996. During the experiment, meteorological data was measured at several locations using equipment such as the SODAR, Air Sonde and portable wind systems. Meteorological data was also measured at 10 and 58 meter height of the meteorological tower.

A large-scale field tracer experiment has been conducted for the purpose of improving the accuracy of the wind field and atmospheric dispersion models. The calculated concentration distributions by several numerical experiments were compared with the measured ones.

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Ⅱ. Wind Field Model

The most mass-consistent wind models may be run in either Cartesian or terrain conformal coordinates. In Cartesian coordinates, the topography represented by obstacle cells is strongly dependent on the chosen cell resolution. It may be a drawback to the efficient computation of a wind field over complex terrain. In terrain conformal coordinates, it is possible to use of variable vertical zoning allowing a higher resolution near the terrain surface. In addition, the terrain surface can be represented more accurately due to the characteristics of the coordinate transformation itself. Therefore, the lower boundary becomes a coordinate surface and an "obstacle cell" approximation of the surface is no longer necessary[1]. The use of terrain conformal coordinates allows better representation of the surface topography and more accurate treatment of the bottom boundary.

The model developed in this study produces a three-dimensional mass-consistent wind field based on the sparse wind data observed on arbitrarily located points. The mathematical formulations of the diagnostic mass-consistent model are based on the variational calculus approach suggested by Sasaki[2]. The variational technique is to minimize the difference between the initial wind field and the adjusted wind field subject to the constraint that the divergence should vanish. Using Lagrange multiplier theory, the constraint equation (continuity equation) can be incorporated into the minimizaion integral by the calculus of variations. Mathematically, the minimization functional can be rewritten as follows.

$$E(u,v,\tilde{w},\lambda)=\iiint[\alpha_1^2(\pi u-\pi u^0)^2+\alpha_1^2(\pi v-\pi v^0)^2+\alpha_2^2(\pi\tilde{w}-\pi\tilde{w}^0)^2+\lambda\left(\frac{\partial\pi u}{\partial x}+\frac{\partial\pi v}{\partial y}+\frac{\partial\pi\tilde{w}}{\partial\sigma}\right)]dV \quad \text{--------- (1)}$$

$$\sigma(x,y)=\frac{H_T-z}{H_T-h(x,y)}=\frac{H_T-z}{\pi} \quad \text{------------------------ (2)}$$

Where α_1 and α_2 are Gauss precision moduli that are used to determine the relative adjustment to be made between the horizontal and vertical wind components. The level σ =1 corresponds to the ground and σ =0 corresponds to the top of the model, $h(x,y)$ is the height of the terrain, H_T is the height of the top of the domain, $u^o,v^o,\tilde{w}^o$ are the initial velocities, $u,v,\tilde{w}$ are the final adjusted velocities, and λ is the Lagrange multiplier. The condition for a stationary value of E leads to the following Euler-Lagrange equations.

$$u=u^0+\frac{1}{2\alpha_1^2}\left[\frac{\partial\lambda}{\partial x}+\frac{\sigma}{\pi}h_x\frac{\partial\lambda}{\partial\sigma}\right],$$

$$v=v^0+\frac{1}{2\alpha_1^2}\left[\frac{\partial\lambda}{\partial y}+\frac{\sigma}{\pi}h_y\frac{\partial\lambda}{\partial\sigma}\right],$$

$$\tilde{w}=\tilde{w}^0-\frac{1}{2\alpha_2^2}\left[\frac{1}{\pi}\frac{\partial\lambda}{\partial\sigma}\right] \quad \text{---------------------------------- (3)}$$

$$\frac{\partial(\pi u)}{\partial x}+\frac{\partial(\pi v)}{\partial y}+\frac{\partial(\pi\tilde{w})}{\partial\sigma}=0 \quad \text{------------------------------ (4)}$$

Where $h_x=\partial h/\partial x$ and $h_y=\partial h/\partial y$ are the terrain slopes respectively in x, y directions, $\pi = H_T - h(x, y)$.
Rearranging the above equations (3) and (4), the Poisson equation for can be obtained as follows.

$$\frac{\partial}{\partial x}\left[\pi\frac{\partial\lambda}{\partial x}+\sigma h_x\frac{\partial\lambda}{\partial\sigma}\right]+\frac{\partial}{\partial y}\left[\pi\frac{\partial\lambda}{\partial y}+\sigma h_y\frac{\partial\lambda}{\partial\sigma}\right]+\frac{\partial}{\partial\sigma}\left\{\left[\left(\frac{\alpha_1}{\alpha_2}\right)^2+\sigma^2\left(h_x^2+h_y^2\right)\right]\frac{1}{\pi}\frac{\partial\lambda}{\partial\sigma}\right\}+\frac{\partial}{\partial\sigma}\left\{\sigma\left[h_x\frac{\partial\lambda}{\partial x}+h_y\frac{\partial\lambda}{\partial y}\right]\right\}=-2\alpha_1^2\left[\frac{\partial\pi u^0}{\partial x}+\frac{\partial\pi v^0}{\partial y}+\frac{\partial\pi\tilde{w}^0}{\partial\sigma}\right] \quad \text{---------------------- (5)}$$

The equation (5) is solved iteratively using a successive over relaxation method with the appropriate boundary conditions, after the expansion of finite difference approximations. The upper and the lateral boundaries represent the “flow-through” boundaries and the lower boundary represents a “no-flow-though” boundary. The final adjusted velocity field can be obtained by equation (3) .

III. Dispersion Model

The random walk method is adopted in the dispersion model for the estimation of the atmospheric concentration distribution of the released radioactive materials. In the random walk method, it is not necessary to obtain the distribution of concentration at every time step because each particle diffuses independently regardless of the concentration gradient. Therefore memory capacity and computing time can be reduced[3]. In three-dimensional space, a particle is transported due to advection by averaged wind and turbulent diffusion. The movement of the particle is represented by the sum of the movements due to advection and diffusion. The new position of a particle after time step Δt is represented by the following.

$$\left(x_{t+\Delta t},y_{t+\Delta t},z_{t+\Delta t}\right)=[x_t+(u+2\mu U)\Delta t,\ y_t+(v+2\nu V)\Delta t, z_t+(w+2\xi W)\Delta t] \quad \text{-------------- (6)}$$

Where u,v,w are average wind components, U,V,W are turbulent wind components and μ,ν,ξ are uniform random numbers in x,y,z direction, respectively. The U, V and W components in the equation (6) are calculated as follows.

$$U=\sqrt{\frac{6K_x}{\Delta t}},\quad V=\sqrt{\frac{6K_y}{\Delta t}},\quad W=\sqrt{\frac{6K_z}{\Delta t}} \quad \text{--------------------- (7)}$$

Where Δt is the time increment and K_x, K_y and K_z are the diffusion coefficients in the x,y,z direction, respectively.

The diffusion coefficients are generally obtained from the empirical formula based on the measured data. The diffusion coefficient K_j is defined as follows[4].

$$K_j=\frac{1}{2}\frac{dr}{dt}\frac{d\sigma_j^2}{dr}=u\sigma_j\frac{d\sigma_j}{dr} \quad \text{--------------------------------- (8)}$$

Where σ_j is the standard deviation of the plume distribution and it can be obtained from the Pasquill-Gifford chart[5] as a function of the downwind distance and atmospheric stability.

IV. Filed Tracer Experiment

The field tracer experiment near the Younggwang nuclear power plant was carried out on May 29, 1996. The Younggwang nuclear site is located in the west of Korea and there are small mountains around the site. For the experiment, 91 tracer gas samplers were disposed along two arc lines with the radius of about 3 km(A-line) and 8 km(B-line) from the released point, respectively. The topography and sampling points around the site are shown in **Figure 1.** Sulfur hexafluoride(SF_6) which is an extremely stable gas was used as the tracer gas. The tracer gas was released about 90 minutes at the top of a meteorological tower at the nuclear site. The released tracer gas was sampled using automatic sequential gas samplers and analyzed with a gas chromatograph. For the realistic simulation of the atmospheric dispersion of the released materials, it is necessary to measure the meteorological data during the experiment. The meteorological data was measured using equipment such as SODAR and portable wind systems. The measured meteorological data including the data at the meteorological tower was used as the input data of dispersion model for the simulation of the dispersion of the released tracer gas during the experiment. **Fig. 2** shows the measured wind data at meteorological tower and some points along two arc lines(A-line and B-line).

The released tracer gas was sampled using automatic sequential gas samplers. The devised sampler is consisted of gas distributor, electronic control board, intake part and carrying box. The function of gas distributor is to transport the intake air into sample bag consecutively by individual port and it is operated by the signal from electronic control board. The individual valve at 12 radial ports is set up. When the cam on the rotating at center press the valve, the air enters into the sample bag connected with each port. The control board is the electronic circuit that the functions such as sampling starting time, sampling interval and the flow rate of pump are programmed. Control board controls pump and distributor to rotate, to inhale the air and to transport the air into sample bag. The power for the pump and electronic board is supplied by battery of 9 voltages. Carrying box is used to contain gas distributor, electronic control board, battery and sample bags. The volume of carrying box is about 75 liters. The sampled gas was analyzed using a gas chromatogarph.

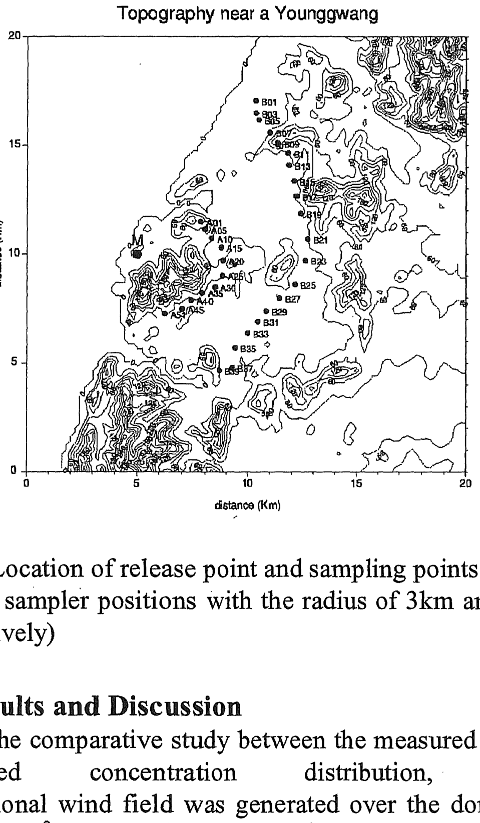

Fig 1. Location of release point and sampling points.
(A, B : sampler positions with the radius of 3km and 8km, respectively)

V. Results and Discussion

For the comparative study between the measured and the simulated concentration distribution, three-dimensional wind field was generated over the domain of 20 x 20 km^2 in X-Y plane, and 900 m in vertical direction. The domain was considered to be consisted of the cell with the size of $\Delta x = \Delta y = 500$ m, and $\Delta z =$

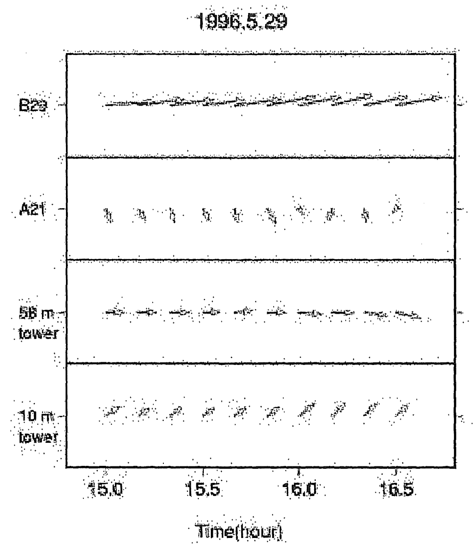

Fig 2. Measured wind data near a surface.

100 m. **Figure 3** shows the simulated wind field near terrain surface using the wind data measured (the usage of the wind data at 58 meter height of the meteorological tower and wind data by portable wind measurement at B line) during the experiment. The computational domain in dispersion model was the same with the wind model. The domain in dispersion model was considered to consist of a cell with the size of $\Delta x = \Delta y = 50$ m, and $\Delta z = 100$ m. The computed wind data was provided as input data into dispersion model. The time step used in dispersion calculation was automatically controlled according to the wind speed and the grid size. The values of standard deviation of the plume distribution were used from the Briggs chart[5].

Several numerical experiments using the measured wind data were performed to get more accurate concentration distributions compared with the analyzed values of SF_6. Numerical simulations according to usage of measured wind data are performed in four runs. There are only used 58 m wind data at met. tower in run 1, used 58 m data at met. tower and portable wind data at A-line in run2, used 58 m data at met. tower and portable wind data at B-line in run3 and used 58 m data , portable wind data at A- and B-line in run 4. For evaluating the model results, a certain number of graphical representations and statistical methods have been used. The scatter plots show the scatter diagram between calculated and observed concentration. The NMSE(Normalized Mean Square Error) is defined as $1/N\Sigma_i(C_i-O_i)^2/(\bar{C}\cdot\bar{O})$, where N is the number of data pairs, C is calculated values and O is observed ones. The Bias is defined as $1/N\Sigma_i(C_i-O_i)$. The RMSE(Root Mean Square Error) is defined as $\sqrt{1/N\Sigma_i(C_i-O_i)^2}$. The FB(Fractional Bias) is $1/2(\bar{C}-\bar{O})/(\bar{C}+\bar{O})$.

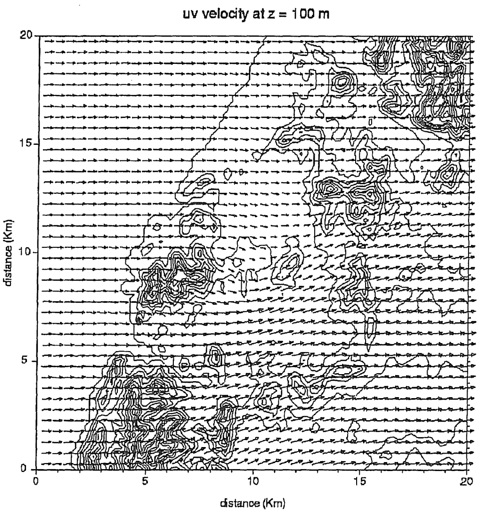

Fig 3. Calculated wind fields at terrain surface.

The calculated results for several cases were compared with the measured ones using a statistical method. The result in the case of the usage of the wind data at 58 meter height of the meteorological tower and wind data by portable wind measurement at B-line agreed well with the measured concentration. The results obtained by the four model runs for the overall concentration data set are summarized in Table 1.
As shown in Table 1, the result in the case of run 3 agreed well with the measured concentrations. It seems because of the effects of wind fields due to the released height (58 m at meteorological tower) of tracer gas. In the case of run 4, wind blows from NW direction at 3 km
(A-line) from the releasing point. Therefore, the results in run4 have a little discrepancy compared with the results in run 3.

VI. Conclusions

The three-dimensional wind field and atmospheric dispersion models have been developed. These models are used to estimate the radiological consequences against a nuclear accident. A large-scale field tracer experiment has been conducted for the purpose of improving the accuracy of wind field generation and atmospheric dispersion models, and analyzing the site-specific meteorological characteristics. The calculated concentration distributions by several numerical experiments were compared with the measured ones using a statistical method. The result in the case of run 3 (the usage of the wind data at 58 meter height of the meteorological tower and wind data by portable wind measurement at B-line) agreed well with the measured concentration. The developed numerical models are being used as a basic tool of emergency preparedness in Korea. The obtained knowledge through the site-specific dispersion analysis is useful in assessing the environmental effects of the effluents from both nuclear and non-nuclear industrial facilities.

Table 1 Statistical results between calculated and observed concentrations.

Run no.	NMSE	Bias	RMSE	FB
1	3.5	3.1	20.3	0.3
2	8.0	1.1	27.6	0.1
3	1.1	-0.2	10.8	-0.02
4	4.5	-1.9	17.5	-0.2

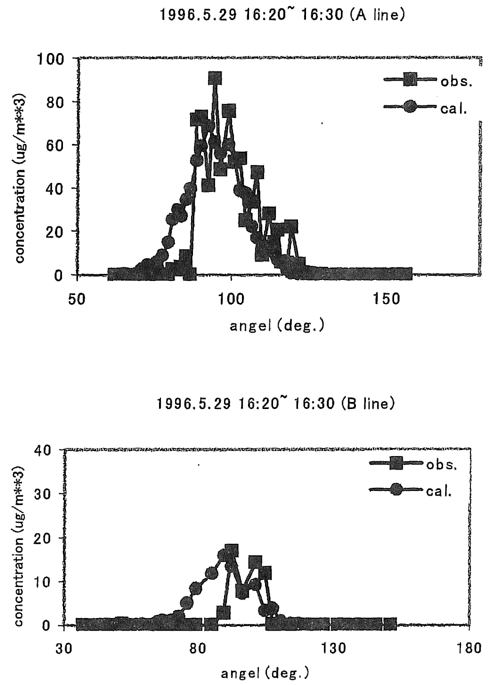

Fig 4. Comparison of calculated and measured concentrations along A-line and B-line in run 3.

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