Abstract. The three-dimensional wind field and atmospheric dispersion models for a nuclear accident have been developed for estimating the overall wind patterns and the concentration distributions of pollutants over a complex terrain. The field tracer experiment near the Kori nuclear power plant was carried out for the purpose of analyzing the site-specific environmental characteristics and validating the atmospheric dispersion model in May 2001. SF₆ as tracer gas was released and the sampled gas was analyzed using a gas chromatography. The wind fields were one of the most important factors for calculating the concentration of the pollutants in the atmosphere. Several numerical experiments using the measured wind data were performed to get more accurate concentration distributions compared with the analyzed values of the tracer gas. As a comparative study, the calculated concentration distributions were compared with the measured values.

1. Introduction

The environmental effects by the transport and diffusion of pollutants released into the atmosphere due to a nuclear accident must be evaluated rapidly and accurately for the safety of the surrounding population and ecosystem. After the TMI-2 and the Chernobyl accidents, a research for developing the national emergency preparedness system has been widely performed to predict and minimize the radiological damage for the surrounding 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 to understand the dispersion processes of radioactive materials over a complex terrain. The diagnostic mass-consistent wind field model using terrain conformal coordinates is adopted for the generation of a wind filed over the whole domain using measured wind data at several points. In the case of the real-time fast calculations, diagnostic wind models have advantages over the prognostic ones.

A Lagrangian particle model for a local scale atmospheric dispersion was developed to estimate the air concentrations over a complex terrain. The random walk method is used for the calculation of the concentration distribution of the radionuclides in the atmosphere. The atmospheric dispersion is evaluated by the motion of fictitious particles consisting of a deterministic part due to the mean wind and a stochastic part related to the turbulent flow. And the movement of a particle is represented by the sum of the movements due to the advection and the turbulence.

The field tracer experiment near the Kori nuclear power plant was carried out for the purpose of analyzing the site-specific environmental characteristics and validating the atmospheric dispersion model on May 31, 2001. Automatic sequential gas samplers were devised. SF₆ as a tracer gas was released and the sampled gas was analyzed using a gas chromatography. The calculated results for several numerical simulations were compared with the measured ones using statistical methods.

2. Wind Field Model

The mass-consistent wind model using terrain conformal coordinates was developed for the generation of a wind field over a complex terrain. The model produces a three-dimensional mass-consistent wind field based on the sparse wind data observed at arbitrarily located points. The mathematical formulations of the diagnostic mass-consistent model are based on the variational calculus approach suggested by Sasaki [1]. 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 the Lagrange multiplier theory, the constraint equation (continuity equation) can be incorporated into
the minimization integral by the calculus of the variations. Mathematically, the minimization functional can be rewritten as follows.

\[
E(u, v, \tilde{w}, \lambda) = \int \left| \int \left[ \alpha_1^2 (\mu - \pi u \theta)^2 + \alpha_1^2 (\nu - \pi v \theta)^2 + \alpha_2^2 (\tilde{w} - \pi \tilde{w} \theta)^2 + \right] \right| dV 
\]

\[
= \int \left( \frac{\partial \mu}{\partial x} + \frac{\partial \nu}{\partial y} + \frac{\partial \tilde{w}}{\partial \sigma} \right) dV 
\]

\[
\sigma(x, y) = \frac{H_T - z}{H_T - h(x, y)} - \frac{H_T - z}{\pi} 
\]

Where \( \alpha_1 \) and \( \alpha_2 \) are Gauss precision moduli that are used to determine the relative adjustment to be made between the horizontal and vertical wind components. The level \( \sigma = 1 \) corresponds to the ground and \( \sigma = 0 \) 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, \( u^0, v^0, \tilde{w}^0 \) are the initial velocity, \( u, v, \tilde{w} \) are the final adjusted velocities, and \( \lambda \) is the Lagrange multiplier. The condition for a stationary value of \( E \) leads to the following Euler-Lagrange equations.

\[
u = \frac{u^0 \left[ \frac{\partial \lambda}{\partial x} + \frac{\sigma \lambda}{\pi h_x} \right]}{2 \alpha_1^2} + \frac{v^0 \left[ \frac{\partial \lambda}{\partial y} + \frac{\sigma \lambda}{\pi h_y} \right]}{2 \alpha_2^2} + \frac{\tilde{w}^0 \left[ \frac{\partial \lambda}{\partial \sigma} \right]}{2 \alpha_2^2} 
\]

\[
\frac{\partial (\mu)}{\partial x} + \frac{\partial (\nu)}{\partial y} + \frac{\partial (\tilde{w} \theta)}{\partial \sigma} = 0 
\]

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 \( \lambda \) can be obtained as follows.

\[
\frac{\partial}{\partial x} \left[ \frac{\partial \lambda}{\partial x} + \frac{\sigma h_x \partial \lambda}{\partial \sigma} \right] + \frac{\partial}{\partial y} \left[ \frac{\partial \lambda}{\partial y} + \frac{\sigma h_y \partial \lambda}{\partial \sigma} \right] + \frac{\partial}{\partial \sigma} \left[ \left( \frac{\alpha_1^2}{\alpha_2^2} \right) + \sigma^2 (h_x^2 + h_y^2) \right] \frac{1 \partial \lambda}{\partial \sigma} 
\]

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

The mass-consistent wind field model calculates the first guess wind field using the measured wind data. The observed wind data needed for the wind field model adjustment is provided by an interpolation-extrapolation scheme using information available at a given site to determine the velocity components at each grid point. Vertical profiles are constructed at each grid point using similarity theory expressions [2].

3. 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 the concentration at every time step because each particle diffuses independently regardless of the concentration gradient. Therefore the memory capacity and computing time can be reduced [3]. In three-dimensional space, a particle is transported due to advection by an averaged wind and turbulent diffusion. The movement of the particle is represented by the sum of the movements due to the advection and diffusion. The new position of a particle after time
step $\Delta t$ is represented by the following.

$$\begin{align*}
(x_{t+\Delta t}, y_{t+\Delta t}, z_{t+\Delta t}) = & \left[ x_t + (v + 2vV)\Delta t, y_t + (v + 2vV)\Delta t, z_t + (w + 2\xi W)\Delta t \right] \\
(6)
\end{align*}$$

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

$$\begin{align*}
U = \sqrt{\frac{6K_x}{\Delta t}}, \quad V = \sqrt{\frac{6K_y}{\Delta t}}, \quad W = \sqrt{\frac{6K_z}{\Delta t}}
(7)
\end{align*}$$

Where $\Delta t$ 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].

$$\begin{align*}
K_j = \frac{1}{2} \frac{d}{dt} \frac{d\sigma_j^2}{dr} = u \sigma_j \frac{d\sigma_j}{dr}
(8)
\end{align*}$$

Where $\sigma_j$ is the standard deviation of the plume distribution and it can be obtained from the Pasquill-Gifford chart as a function of the downwind distance and the atmospheric stability.

4. Field Tracer Experiment

The field tracer experiment near the Kori nuclear power plant was carried out for the purpose of analyzing the site-specific environmental characteristics and validating the atmospheric dispersion model on May 31, 2001. Kori nuclear power plant is located in close by the coast of the east and south direction. During the daytime, the wind blows from east and south by the effects of land-see breeze. Therefore, the wind patterns are very complicated in coupling with a complex topography. Automatic 12 interval sequential gas samplers were devised. SF$_6$ tracer gas was released and the sampled gas was analyzed using a gas chromatography. 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 meters from the meteorological tower at the released point.

For the experiment, 140 tracer gas samplers were disposed on two arc lines along the roads on the east side with the radius of about 3 km(A-line) and 12 km(B-line) respectively from the released point. The topography and sampling points around the site are shown in Fig. 1. Sulfur hexafluoride(SF$_6$) was used as a tracer gas. The tracer gas was released for 3.5 hours at the top of the meteorological tower at the nuclear site. The meteorological data was measured using equipment such as SODAR and portable wind systems. The measured meteorological data including the data (10 and 58 meters height) at the meteorological tower was used as the input data of the wind field model to generate the overall wind fields for simulation of the dispersion of the released tracer gas during the experiment.

Fig. 2 shows the measured wind data at the meteorological tower and some points along the two arc lines (A-line and B-line). The released tracer gas was sampled using automatic sequential gas samplers. The averaged release rate of 75.97 kg/hr was determined considering the weather conditions. Release of the tracer gas was started 2.5 hours earlier than the start of the sampling of the tracer gas and it lasted for 3.5 hours. The duration of sampling per sample bag was adjusted every 10 minutes.
5. **Numerical Simulation**

For the comparative study between the measured and the simulated concentration distribution, a three-dimensional wind field was generated over the domain of \(15 \times 15 \text{ km}^2\) in the X-Y plane, and 1000 m in the vertical direction. The domain was considered to consist of the cell with the size of \(\Delta x = \Delta y = 500\) m, and \(\Delta z = 100\) m. Fig. 4 shows the simulated wind field near the terrain surface using the measured wind data. The computational domain in the dispersion model was the same as the wind model. The domain in the 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 for the dispersion model. The time step used in the dispersion calculation was automatically controlled according to the wind speed and the grid size. The values of the standard deviation of the plume distribution were used from the Briggs formulas [4].

As a comparative study, the simulated 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 analyzed values of SF

<table>
<thead>
<tr>
<th>Run</th>
<th>Results for Overall Concentration Data Set</th>
<th>Comparison with Measured Concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calculated results were compared with the measured ones using the statistical methods. The results obtained by the four model runs for the overall concentration data set are summarized in Table 2. The NMSE (Normalized Mean Square Error), bias, RMSE (Root Mean Square Error), FB (Fractional Bias), FA2 and FA5 in Table 2 are used with the statistical parameters. The results in the case of run 3 have better than the other runs. But the calculated results do not generally agree with the measured concentrations. The reason was inferred due to the complicated wind patterns at Kori site that is located in close by the coast of the east and south direction.</td>
<td></td>
</tr>
</tbody>
</table>
FIG. 3. Calculated wind fields at terrain surface.

Table 1. Several numerical simulation conditions.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>conditions of wind data used in wind field model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>only used wind data at 10 m of meteorological tower</td>
</tr>
<tr>
<td>2</td>
<td>only used wind data at 58 m of meteorological tower</td>
</tr>
<tr>
<td>3</td>
<td>used data at 10 m of meteorological tower and data at nova points</td>
</tr>
<tr>
<td>4</td>
<td>used data at 58 m of meteorological tower and data at nova points</td>
</tr>
</tbody>
</table>

Table 2. Statistical results between calculated and observed concentrations.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>NMSE</th>
<th>Bias</th>
<th>RMSE</th>
<th>FB</th>
<th>FA2</th>
<th>FA5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.7</td>
<td>7.7</td>
<td>40.3</td>
<td>0.8</td>
<td>7.5</td>
<td>18.2</td>
</tr>
<tr>
<td>2</td>
<td>58.4</td>
<td>-0.7</td>
<td>35.0</td>
<td>-0.1</td>
<td>9.3</td>
<td>23.7</td>
</tr>
<tr>
<td>3</td>
<td>67.7</td>
<td>-1.4</td>
<td>34.5</td>
<td>-0.3</td>
<td>13.1</td>
<td>27.8</td>
</tr>
<tr>
<td>4</td>
<td>71.3</td>
<td>-1.6</td>
<td>34.6</td>
<td>-0.3</td>
<td>10.5</td>
<td>28.1</td>
</tr>
</tbody>
</table>

6. Conclusions

The three-dimensional wind field and atmospheric dispersion models were developed. These models were used to estimate the radiological consequences for a nuclear accident. A Large-scale field tracer experiment was conducted for the purpose of improving the accuracy of the 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 statistical methods. The result in the case of run 3 (the usage of the wind data at 10 meter height of the meteorological tower and the wind data by portable wind measurement at several points) has better than the other runs. But the overall calculated results show a discrepancy due to the complicated wind patterns during the experiment. Some modifications in dispersion model will be performed d to get more accuracy compared with measured concentration. The developed models are being used as a sub-module of the real-time radiological dose assessment system named FADAS [5]. Also, a more reliable dose assessment system may be constructed for estimating the radiological consequences against a nuclear emergency.
Acknowledgements
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References