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LES STUDIES FOR PREDICTING PLUME CONCENTRATIONS AROUND NUCLEAR FACILITIES USING AN OVERLAPPING TECHNIQUE

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Abstract: We have attempted to develop a practical and quick local-scale atmospheric dispersion calculation method using an overlapping technique for plume concentration distributions in an emergency response to nuclear accidents. In order to evaluate the overlapping approach, we compared the spatial distributions of plume concentrations estimated by the overlapping technique with those under the realistic meteorological condition. It is shown that the concentration distribution patterns are reasonably simulated by the overlapping method. It can be concluded that the atmospheric dispersion calculation method using the overlapping technique has high potential performance for emergency responses to nuclear accidents.

Key words: *Large-eddy simulation, Plume dispersion, Overlapping technique, Emergency response*

INTRODUCTION

In an emergency response to nuclear accidents, it is important to accurately and quickly estimate spatial extent of contaminated areas. There are typically two approaches of predicting plume dispersion in a local-scale: one is the Gaussian plume model, and the other is a computational simulation technique by computational fluid dynamics (CFD). The former is an analytical solution based on the steady state Gaussian dispersion equation including the pollutant reflection from the ground surface and is commonly used because of its high practical use and easy familiarity for industrial exhausts or accidental releases. However, it has a serious problem that building effects cannot be explicitly represented. The latter has been recognized as a helpful tool with the rapid development of computational technology. In principle, there are two different approaches, Reynolds-averaged Navier-Stokes (RANS) and large-eddy simulation (LES) models. In RANS, a mean wind flow is computed, delivering a time-averaged solution, and all turbulent motions are modeled. The main advantage of RANS model is its efficiency in computing a mean flow field with relatively low computational cost. However, it was pointed out that complex separated flows around obstacles are not reproduced well (Murakami et al., 1990). LES resolves large-scale turbulent motions and models only small-scale ones. The effectiveness for an accurate prediction of complex turbulent flows and plume dispersion under building effects has been shown by many researchers (e.g. Tominaga and Stathopoulos, 2012). However, we encounter a problem that LES has the significant disadvantage of computational time. Since computing time is an essential problem, emergency response system designed based on LESs of unsteady turbulent flows is impractical.

In order to avoid the trade-off problem between computational accuracy and time, Boris (2002) and Patnaik et al. (2010) developed an assessment system called “CT-Analyst” in an emergency response to terrorist attacks in urban environments. This system composes of pre-calculated data structures based on high-resolution LESs of turbulent flows in specific urban areas for 18 different mean wind directions and plume shapes can be displayed with very rapid response (a few seconds) through the procedure “Dispersion Nomographs”. Although this system does not quantitatively predict the distribution of a plume, such estimated danger zones could be helpful information in a situation in which source locations are unknown in terrorist incidents. On the other hand, source locations can be identified in case of nuclear accidents in advance. Therefore, it would be desirable to develop an emergency response system which can quantitatively estimate spatial distributions of plume concentrations under real atmospheric conditions in detail. In this study, we propose a practical and fast atmospheric dispersion calculation method using an overlapping technique. First, we pre-calculate LESs of plume dispersion around nuclear facilities for 36 mean wind directions, and make a dataset of the 10-minute averaged concentrations for each wind direction. Then, we estimate the 1-hour averaged concentration distributions by overlapping the pre-calculated concentration data depending on the frequency of mean wind directions. Our objective is to compare with the LES results under realistic atmospheric conditions using the meteorological data as the model input and evaluate the performance of the overlapping technique.

OVERLAPPING TECHNIQUE

The formulation of the overlapping technique is expressed by the following equation:

$$C = \int F(\varphi) c(\varphi) d\varphi \tag{1}$$

where C is the estimated concentration, F is the frequency probability of mean wind directions φ, and $c(\varphi)$ is the concentration for the mean wind direction. Usually, C is 1-hour averaged concentration and c is 2-10 minute averaged concentration. The prediction method using the overlapping technique was examined by Kothari et al. (1981). They conducted wind tunnel experiments of plume dispersion around nuclear facilities and made a dataset of mean concentrations for eight different mean wind directions. It was shown that the estimated concentration data are similar to the field observed data.

SIMULATION SETTINGS

Dataset of the meteorological observation

Figure 1 on the left shows the meteorological station located at Nuclear Fuel Cycle Engineering Laboratories, Japan Atomic Energy Agency (JAEA). Nakano et al. (2013) measured meteorological data by the Doppler Lidar (Windcube WLS7 made by Leosphere Co. Ltd.) for 1-year starting from 1st February 2012 and examined the applicability to the long-term meteorological observation in the nuclear facilities to assess the public dose around nuclear facilities. They compared with wind velocities obtained by the propeller type anemometer installed at the top of the meteorological observation tower located 70 m south from there. It was shown that the annual and the sequential 30-days missing rate are less than 10% and 30%, respectively. The missing rate of the Doppler Lidar at heights less than 180 m was satisfied with the recommended values shown in the meteorological guideline for safety analysis of nuclear power plant reactor in Japan (Nuclear Safety Commission of Japan, 1982). Especially, the data at 68 m above the ground level (100 m above sea level) had a good relationship with the propeller data. Therefore, the meteorological data obtained at 68 m height were used as reference data for the simulation model input conditions.

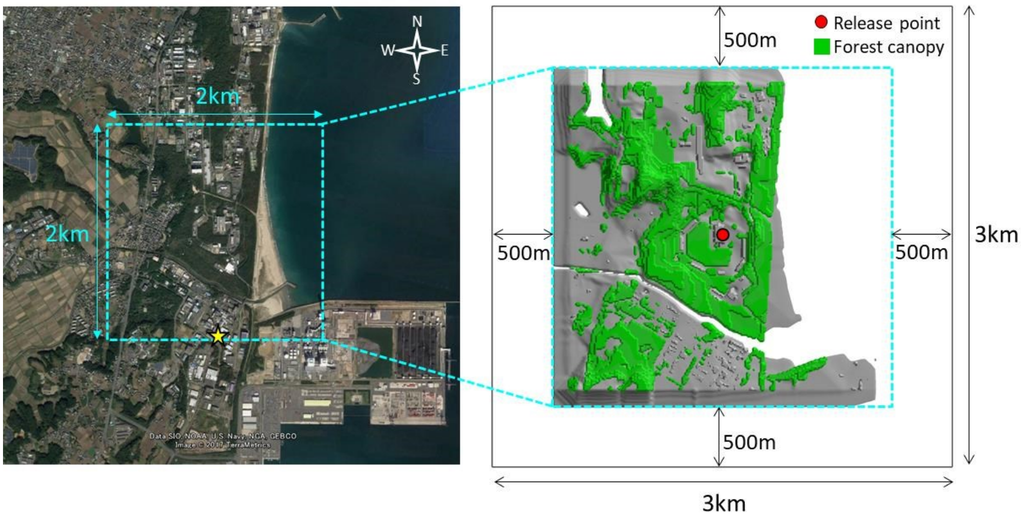

Figure 1. Meteorological station and computational area. The photograph on the left is reproduced by Google™ earth graphic. The star mark depicts the meteorological station. The figure on the right shows the computational area of the study site (the broken line). Buffer zones with a length of 500 m are set around the site.

Computational model

The model used here is the LOHDIM-LES developed by JAEA and the details are described in the Nakayama et al. (2016). The computational area of the study site is shown in Figure 1 on the right. The size of the computational domain is 3.0 km by 3.0 km in the horizontal directions with the depth of 500 m. The total mesh number is 300 by 300 by 72 nodes. The grid spacing is 10 m in the horizontal directions and 2.5-20 m stretched in the vertical direction based on an orthogonal grid system. Surface geometries, buildings, and forest canopy are explicitly represented by the use of a digital surface model dataset.

Boundary conditions

Mean wind directions often vary due to a change of weather conditions in a meteorological field. Therefore, vertical planes at the inflow and outflow boundaries should be automatically changed depending on mean wind directions. Figure 2 shows a schematic diagram of the treatment of inflow boundary conditions depending on different mean wind directions. For example, when the mean wind direction φ ranges from 0° to 90°, vertical boundary planes in the north and east sides are automatically set to inflow boundaries and those in the south and west sides are automatically set to outflow boundaries. In a similar manner, boundary conditions at other mean wind direction ranges are prescribed.

In order to drive an LES model, time-dependent turbulent inflow data should be imposed at the inflow boundaries. In this study, the mean wind velocity profiles represented by a power law of 1/7 and the fluctuating components generated by a combination of the recycling method (Kataoka and Mizuno, 2002) and the Langevin-type equation (Koutsourakis et al., 2016) are prescribed at them. At the outlet boundary, a free-slip condition is applied for each component of wind velocity. At the upper boundary, a free-slip condition for the horizontal velocity components and zero-speed condition for the vertical velocity component is imposed. At the bottom surface, the Monin-Obukhov similarity theory (Monin and Obukhov, 1954) is applied.

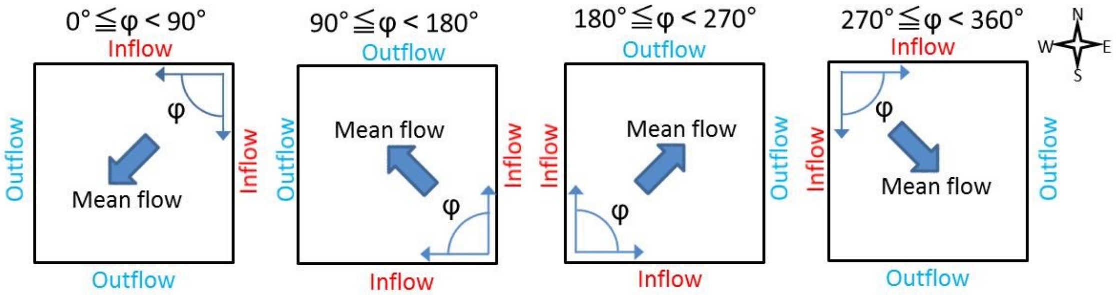

Figure 2. Schematic of the treatment of inflow and outflow boundaries depending on different mean wind directions.

Computational conditions and simulation periods

In this study, we focus on three 1-hour periods when mean wind directions were rapidly, intermediately changed, and nearly constant as shown in Table. 1. First, we conducted LESs of plume dispersion for 36 different constant mean wind directions and made a dataset of the 10-minute averaged concentrations for each case. Then, we estimated the spatial distributions of the plume concentrations by the overlapping technique depending on the frequency of mean wind directions for the target simulation period and compared them under three realistic atmospheric conditions.

Table 1. Simulation periods and atmospheric conditions.

Case	Simulation period	Atmospheric condition
Case A	10:00-11:00 JST 23th Sept 2012	Rapidly changing mean wind directions
Case B	11:00-12:00 JST 23th Sept 2012	Intermediately changing mean wind directions
Case C	12:00-13:00 JST 23th Sept 2012	Nearly constant mean wind directions

The forest canopy effects are expressed as follows;

$$f_{canopy} = -C_d \, a(z) U \overline{u_i} \tag{2}$$

where C_d is a drag coefficient with a constant value of 0.2, $a(z)$ is a plant area density determined by the forest leaf area index (*LAI*), U is a wind speed, and u_i is a wind velocity for the i-component. The canopy height is 15.0 m and the *LAI* is 4.0.The time step interval is 0.15 s. The length of the simulation run to make a dataset of plume concentrations is 1.3 hour. Those for realistic atmospheric condition cases are 2.0 hour. Plume is released at unit rate. A neutral atmospheric stability condition is assumed.

RESULTS

Figure 3 compares the spatial distributions of the plume concentrations near a ground surface estimated by overlapping the 10-minute averaged concentrations at mean wind direction intervals at 10°, 20°, and 30° with those under realistic atmospheric conditions. In the case (A) of rapidly changing mean wind directions, the regions where the concentration distributions are not overlapped are found for the mean wind direction intervals greater than 20°. However, the smaller the mean wind direction intervals become, the more similar the distribution patterns of plume concentrations estimated by the overlapping technique become to those under realistic atmospheric conditions. These tendencies are the same as in the case (B) of intermediately changing mean wind directions. In the case (C) of nearly constant mean wind direction conditions, those are similar to that under a realistic atmospheric condition independent of the mean wind direction intervals. However, the length of the high concentration regions is shorter than that under a realistic atmospheric condition.

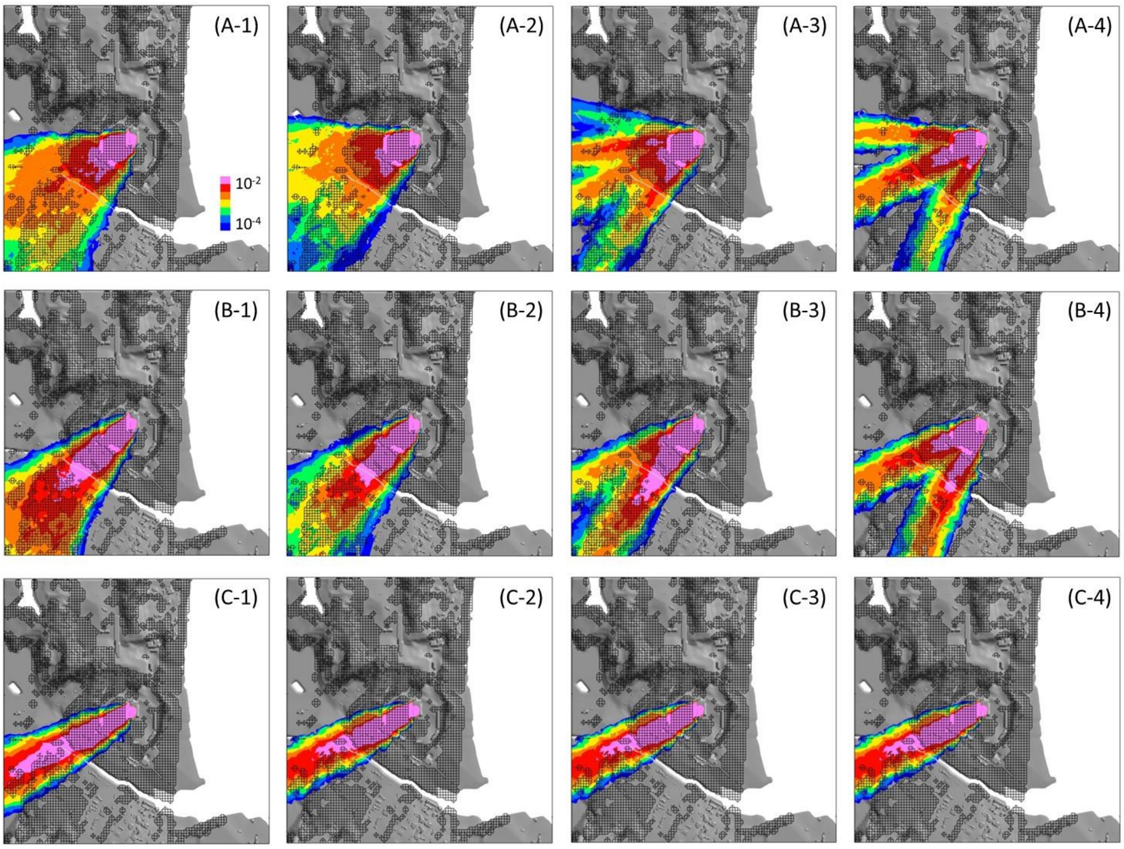

Figure 3. Spatial distributions of plume concentrations near a ground surface. (A-1) indicates the result under rapidly changing mean wind directions. (A-2), (A-3), and (A-4) indicate the results estimated by overlapping the mean concentration data at the mean wind direction intervals at 10°, 20°, and 30°, respectively. (B) and (C) indicate the results estimated under intermediately changing and nearly constant mean wind directions, respectively.

Table. 2 shows the performance of the overlapping technique depending on different mean wind direction intervals. Here, FAC2 is defined as a fraction which has the ratio of the results under realistic atmospheric conditions to those estimated by the overlapping technique within 0.5 - 2.0. From this definition, the best results are expected to have a value of 1.0. In the cases (A) and (B), the smaller the mean wind direction intervals become, the larger the FAC2 become. However, the increase is slight from 20° to 10° intervals for the case (A). In the case (C), the FAC2 shows 0.61 for each case. There are no significant differences of the FAC2 among various atmospheric conditions for 10° intervals, which imply that prediction accuracy by an overlapping technique levels off around mean wind direction intervals of 10°.

Table 2. Performance of the overlapping technique at different mean wind direction intervals.

Case	FAC2		
	10° interval	20° interval	30° interval
Case A	0.54	0.51	0.38
Case B	0.60	0.48	0.20
Case C	0.61	0.61	0.61

CONCLUSION

We estimated the spatial distributions of the plume concentrations by the overlapping technique depending on the frequency of probability of mean wind directions and compared with those under realistic atmospheric conditions. From the statistical analysis for the mean concentrations, the FAC2 values level off around mean wind direction intervals of 10°. It is concluded that the intervals of mean wind direction should be less than 10° to accurately estimate spatial distributions of plume concentrations using an overlapping technique. In future work, we plan to conduct LESs of plume dispersion under representative thermal stability conditions and examine the overlapping technique under more realistic atmospheric conditions.

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