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STUDY ON FLOW AND TURBULENCE CHARACTERISTICS MEASURED BY AN ON-SITE METEOROLOGICAL STATION AT A NUCLEAR FACILITY FOR A REAL-TIME ATMOSPHERIC DISPERSION SIMULATION

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Abstract: We have been developing a real-time atmospheric dispersion model by coupling LES-database of wind flows within roughness sublayer and on-site meteorological observation (OBS) above it that takes into account both individual buildings and real meteorological conditions. However, the LES-database currently used in the framework were created under an assumption of a neutral atmospheric stability condition. Therefore, the effects of the atmospheric stability conditions should be introduced into the LES-database. In this study, we analyzed half-a-year meteorological data of wind speed, turbulence intensity, and atmospheric stability at the nuclear facility and investigated the flow and turbulence characteristics based on the atmospheric thermal stability conditions for improving prediction accuracy of a real-time atmospheric dispersion simulation.

Key words: *Turbulence characteristics, On-site meteorological observation, Large-eddy simulation, A real-time atmospheric dispersion simulation*

INTRODUCTION

In safety and consequence assessment of nuclear facilities and plume monitoring at short distances (i.e., up to several kilometers) from a stack under a normal operation condition, it is important to accurately predict air concentrations at the evaluation point for internal doses and the three-dimensional (3D) and surface distributions for external doses in consideration of individual buildings and local terrain variability. For investigating plume dispersion over complex surface geometry, large-eddy simulation (LES)-based computational fluid dynamics (CFD) models are useful. The advantage of the LES models is that they can well capture plume dispersion behaviors in complex turbulent flows such as impinging, separated, and recirculating flows around buildings. Here, a serious issue is encountered because they have a significant disadvantage of calculation time for real-time plume monitoring because of unsteady calculations at grid spacing of a few meters with a time step usually less than 0.1 seconds.

To solve the problem of calculation time, we proposed a framework for a real-time atmospheric dispersion simulation using a Lagrangian particle dispersion model based on a coupling of LES-database of wind flows within roughness sublayer and on-site meteorological OBS above it that takes into account both individual buildings and real meteorological conditions (Nakayama et al., 2021). To demonstrate the effectiveness of the framework, we conducted the meteorological OBS with a Doppler LiDAR and simple plume release experiments using a mist-spraying system at the site of Japan Atomic Energy Agency. Compared to the instantaneous shots of dispersion behaviors of the real mist plume, it was shown that the transport direction of the simulated plume was reproduced well.

However, the LES-database currently used in the framework were created under an assumption of a neutral atmospheric stability condition. In the atmosphere, heating and cooling within a boundary layer due to solar cycle during a day result in temperature differences, which introduce buoyancy forcing. The most common stability classification scheme is the Pasquill-Gifford (P-G) (Turner, 1970), which defines six stability classes namely A (highly unstable), B (moderately unstable), C (slightly unstable), D (neutral), E (moderately stable), and F (extremely stable). The plume spreads over a flat ground surface in the typical meteorological conditions are determined by the P-G chart. The stack height in nuclear facility is usually greater than 100 m and plume dispersion are sensitively influenced by thermal stability conditions rather than individual buildings. Therefore, the effects of the atmospheric stability conditions should be introduced into the LES-database.

In this study, we first analyze half-a-year meteorological data at a nuclear facility site and then investigate the flow and turbulence characteristics based on the atmospheric thermal stability conditions for improving the framework of a real-time atmospheric dispersion simulation.

FRAMEWORK FOR A REAL-TIME ATMOSPHERIC DISPERSION SIMULATION

Schematic

In our proposed framework, atmospheric conditions are created by coupling LES-database of wind flows within roughness sublayer and on-site meteorological OBS above it. Wind flows over a target site under an assumption of a neutral atmospheric stability condition are pre-calculated by LOHDIM-LES code (Nakayama et al., 2022). The dataset of 3D distributions of mean and turbulent components is created for 36 mean wind directions at 10°class interval. Wind flows above roughness sublayer are measured by meteorological instruments such as Doppler Sodar and LiDAR. The formulation is as follows:

$$U_{coup}(x,y,z) = U_{OBS}(x,y,h_{OBS}) \text{ for } z > h_{OBS} \quad (1)$$

$$U_{coup}(x,y,z) = U_{LES}(x,y,z)\,\frac{U_{OBS}(x,y,h_{OBS})}{U_{LES}(x,y,h_{OBS})} \text{ for } z \le h_{OBS} \quad (2)$$

where U_{coup}, U_{OBS}, U_{LES}, and h_{OBS} are the mean wind velocity estimated by a coupling of the LES-database and on-site OBS, the OBS wind velocity linearly interpolated on the LES calculation grids, the LES database of mean wind velocity, and the lowest measurement height of the meteorological device, respectively. U_{LES} is extracted from the LES-database pre-calculated for 36 different mean wind directions at class interval 10° in accordance with the target meteorological condition.

Estimation of the turbulence standard deviation

In estimating a turbulent flow field, we adopt Normal Turbulence Model (NTM) proposed by the International Electrotechnical Commission (IEC) in the international standard (IEC61400-1, 2005) used for determining appropriate locations of wind turbines as shown in the following formulation.

$$\sigma_l(z) = I_{ref}(aU(z) + b) \quad (3)$$

where σ_l is the longitudinal turbulence standard deviation and U is the mean wind speed at a hub height over a 10-min period. I_{ref} is the expected value of the turbulence intensity at 15 m/s and has three values of 0.12, 0.14, and 0.16 depending on wind turbine classes, respectively. The constants of a and b are 0.75 and 3.8, respectively, for the mean turbulence standard deviation. The measurements are taken at a height of the hub height typically ranging from 60 m to 80 m. The applicability of NTM IEC was investigated by Ishihara et al. (2012).

Formulation of a quick atmospheric dispersion calculation

In our framework, the Lagrangian particle dispersion model proposed by Yamada and Bunker (1988) is used to quickly provide outputs of 3D air concentrations.

$$x_i(t+\Delta t) = x_i(t) + u_{pi}\Delta t \quad (4)$$

$$u_{pi} = U_i + u_i' \quad (5)$$

$$u_i'(t+\Delta t) = a u_i'(t) + b\sigma_{ui}\xi + \delta_{i3}(1-a)t_{Lxi}\frac{\partial \sigma_{ui}^2}{\partial x_i} \quad (6)$$

$$a = exp\left(-\frac{\Delta t}{t_{Lxi}}\right) \quad (7)$$

$$b = (1-a^2)^{1/2} \quad (8)$$

where x_i, u_{pi}, U_i, u_i', σ_{ui}, ξ, t_{Lxi}, δ_i, t, and Δt are the particle position in the *i*-direction (east-west direction, *i* = 1; north-south direction, *i* = 2; vertical direction, *i* = 3), velocity of the particle, mean wind velocity, turbulence velocity, standard deviation of the velocity fluctuation, a random number from a Gaussian distribution with zero mean and unit variance, the Lagrangian integral time, the Dirac delta function, time, and calculation time step interval, respectively.

OUTLINE OF THE METEOROLOGICAL OBSERVATION AT A STUDY SITE

Figure 1 shows the study site of Rokkasho Reprocessing Plant (RRP), the nuclear fuel reprocessing plant in Japan Nuclear Fuel Limited (JNFL), Japan. There are many structures and nine monitoring posts (MP) inside the RRP site. Forest canopy surrounds the area, and a marsh is located at the east side. The stack height is 150 m above ground level. The 10-minute averaged wind velocities were obtained at heights of 50 m, 75 m, 150 m, 250 m, and 300 m in the one-dimensional vertical direction with a 10-minute time interval by a Doppler sodar (Kaijo, monostatic type, AR-410) located about 700 m west side of the stack. The atmospheric stability is estimated from the wind velocities and solar radiation at 10 m above the ground-level, and the air temperature and net radiation at 2 m above the ground-level are obtained. The target period is from 1720 JST on 12 July 2007 to 0000 JST on 2 January 2008.

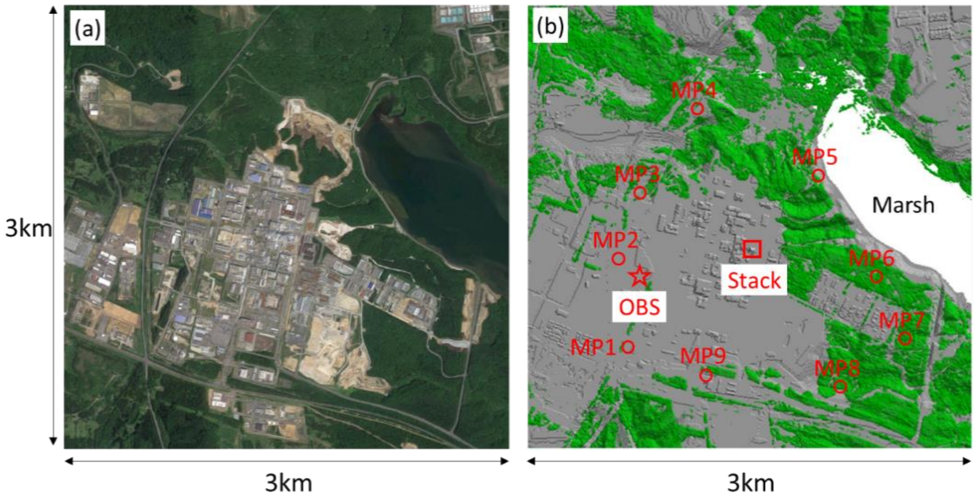

Figure 1. Study site in the nuclear fuel reprocessing plant in Rokkasho. The photograph on the left is reproduced by Google Earth graphics. The figure on the right shows the study site represented by the digital surface data. The square, star, and circle depict the plume stack, meteorological observation station, and MPs, respectively.

RESULTS

According to the evaluation study, Ito et al. (1996) cautioned that the longitudinal turbulence intensity obtained by Doppler Sodar are highly overestimated although the vertical one is reliable in comparison to the data of ultra-sonic anemometers. Therefore, we first obtained the vertical turbulence intensity σ_w and then estimated the longitudinal one σ_l by the following expression (IEC, 2005).

$$\sigma_w \geq 0.5\sigma_l \quad (9)$$

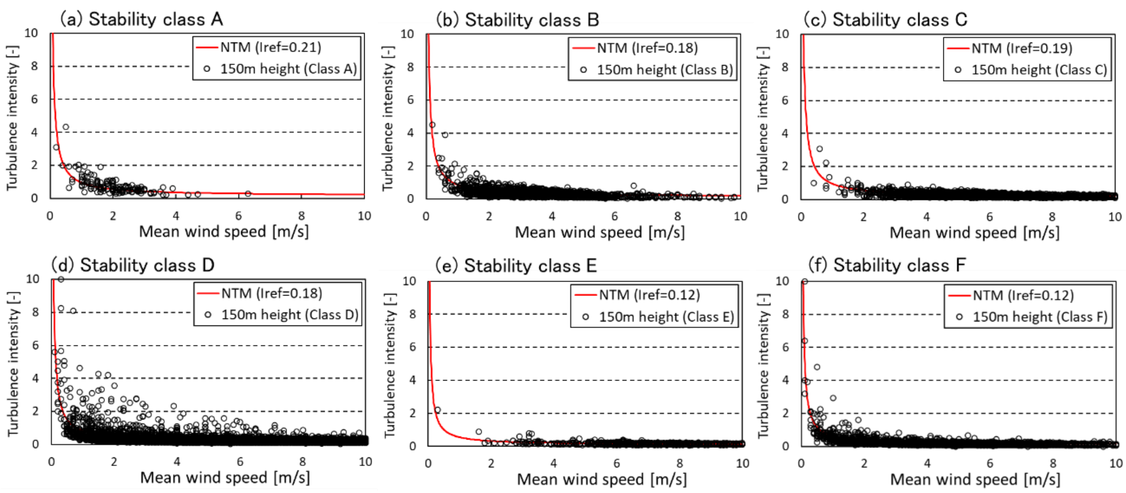

Figure 2. Variation of I_{ref} values with mean wind speeds at the stack height for each atmospheric stability class.

Figure 2 shows variation of I_{ref} values estimated by regression analysis with mean wind speeds at the stack height for each atmospheric stability class. It is found that the turbulence standard deviations are generally distributed well along the NTM curve for each atmospheric stability class.

Table 1 shows I_{ref} values as parameters of height and atmospheric stability thermal class. For each height, I_{ref} values become larger from the neutral class D to the highly unstable class A. Those values are almost similar between the moderately stable class E and the extremely stable class F. For each atmospheric stability thermal class, I_{ref} values generally decrease with height except those at 300 m height. Especially, for the class A, I_{ref} values are highly large at heights of 50 m and 75 m because of the effects of both mechanical and active thermal turbulences.

Table 1. I_{ref} values as parameters of height and atmospheric thermal stability class.

Class / Height	A	B	C	D	E	F
50 m	0.36	0.22	0.21	0.22	0.14	0.13
75 m	0.30	0.19	0.21	0.23	0.13	0.13
150 m	0.21	0.18	0.19	0.18	0.12	0.12
250 m	0.22	0.18	0.17	0.18	0.11	0.12
300 m	0.28	0.23	0.17	0.19	0.12	0.11

It is found from I_{ref} values results that those reasonably change in accordance with the stability classes. This indicates that each component of the turbulence standard deviations of the Doppler Sodar can be accurately estimated for giving to the Lagrangian particle dispersion model.

CONCLUSION

We first analyzed half-a-year meteorological data at a nuclear facility site and then investigated the flow and turbulence characteristics based on the atmospheric thermal stability classes for improving prediction accuracy of a real-time atmospheric dispersion simulation. The expected values of the turbulence intensity I_{ref} were estimated by regression analysis for each height and atmospheric thermal stability class. It is found that the turbulence standard deviations measured by the Doppler Sodar are generally distributed well along the NTM curve and those reasonably change in accordance with the stability classes.

In future work, we have a plan to conduct demonstrate experiments of the framework in consideration of the atmospheric thermal stability conditions in comparison to MP data in the vicinity of the nuclear facility.

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