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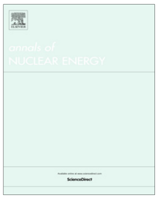

Terrain and building effects on the transport of radioactive material at a nuclear site

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ABSTRACT

This study identified the terrain and building effects on the atmospheric dispersion of radioactive materials at the Wolsong Nuclear Site. To analyze the atmospheric dispersion of radioactive materials, the AERMOD-PRIME model, CFD model and meteorological data from 2010 were used. The terrain and building effects on the atmospheric dispersion of radioactive materials within a 1 km radius of the site were statistically significant. The maximum concentration of the radioactive material increased by 7 times compared to the concentration when the terrain and building effects were not considered. It was found that the terrain and building influenced the decrease in the concentration of radioactive material in a concentric circle with a 914 m radius from the center of the site. The concentration of radioactive material in a concentric circle with a 350 m radius was two-times higher than the concentration estimated at the backside of the building, which is the downwind side, without any consideration of the terrain and building effects. In consideration of the Korean situation, in which multiple nuclear reactors are built on the same nuclear site, it is necessary to evaluate the risk that may affect workers and nearby residents by reflecting the terrain and building effects.

1. Introduction

A nuclear facility consists of a nuclear reactor and annex buildings. Atmospheric dispersion models are used for an environmental impact assessment on the construction and operation of a nuclear power plant. In Korea, the PAVAN program, developed by the US Department of Energy (DoE), is mainly used for a pre-environmental impact assessment, and the XOQDOQ program is used for offsite dose calculation (ODC), which is an environmental impact assessment of a nuclear power plant in operation (PNNL, 1982). All commercial nuclear power plants in Korea have been built on coastal areas. In particular, the nuclear sites located in East coast areas have mountains in the background. Therefore, there have always been disputes in reflecting the terrain and building effects when conducting an environmental impact assessment of a nuclear power plant.

Atmospheric dispersion programs for regulatory purpose employ a Gaussian Plume Model. As for PAVAN developed by the US DoE, to adjust the ground concentration of radioactive materials caused by the terrain elevation, this model used a method to correct the height of the receptor by adding the terrain elevation value at the calculation grids. Many studies have pointed out the possibilities of accumulation and recirculation of pollutants caused by the terrain effect (Canepa, 2004; Gupta et al., 2012). The accumulation of radioactive materials caused by the terrain effect may increase the risk of workers in a nuclear power plant or its neighbors. On the other hand, as the building effect is reflected in the PAVAN program by inputting the cross section area of the building on the leeward side of the wind as a way to increase atmospheric dispersion, the concentration of the radioactive material decreases. There is a limitation in reflecting the increase in concentration around the building caused by a downwash of the plume and the building wakes owing to the building layouts.

ISC (Industrial Source Complex) and AERMOD (AMS/EPA Regulatory Model), which are the representative regulatory models of the US Environmental Protection Agency (EPA), are combined with the PRIME (Plume Rise Model Enhancements) model to reflect the terrain and building effects on the concentration of pollutants. The PRIME model was developed under control of the Energy & Resources Research Institute (ERRI) so that it can reflect the plume rise, downwash, and building wakes caused by the building in calculating the concentration of the pollutants.

This study evaluated the terrain and building effects on the atmospheric transport of radioactive materials in the Wolsong Nuclear Site using the AERMOD-PRIME model and CFD (computational fluid dynamics) model. To understand the meteorological properties at the site, meteorological data in 2010 measured at the meteorological tower were analyzed. The changes in the concentration of radioactive material caused by the terrain and building effects were quantified through a statistical method.

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2. Material and methods

2.1. AERMOD-PRIME model

The AERMOD model is an atmospheric dispersion model co-developed by the American Meteorological Society (AMS) and Environmental Protection Agency (EPA). It is a atmospheric dispersion model for regulatory purposes recommended by the US EPA (US EPA, 1998). The AERMOD model uses a Gaussian Plume Model and assumes the weather conditions and released radioactive materials to be in a steady state. In the planetary boundary layer (PBL), it considers dispersion changes toward the vertical direction, while in stable boundary layer (SBL), it assumes a Gaussian distribution in the vertical and horizontal directions. On the other hand, in the convective boundary layer (CBL), it assumes a Gaussian distribution in the horizontal direction, while calculating the concentration distribution with a bi-Gaussian probability density function (PDF) in the vertical direction. By incorporating the concept of the dividing streamline height, in elevated terrain, AERMOD's total concentration is calculated as a weighted sum of the concentrations associated with these limiting cases or plumes. The concentration of pollutants is calculated as follows in the AERMOD model (Cimorelli et al., 2004).

$$C_T\{x_r,y_r,z_r\} = f\cdot C_{c,s}\{x_r,y_r,z_r\} + (1-f)\cdot C_{c,s}\{x_r,y_r,z_p\} \tag{1}$$

where $C_T\{x_r,y_r,z_r\}$ indicates the total concentration, subscript c represents the convection, and s is a stable state. $C_{c,s}\{x_r,y_r,z_r\}$ indicates the concentration in the horizontal direction, and $C_{c,s}\{x_r,y_r,z_p\}$ represents the concentration of the plume flowing along the terrain. Herein, $z_p(z_r - z_t)$ is the distance from the ground level to the receptor point. z_t represents the terrain height. f indicates a weighted value, and $\{x_r,y_r,z_r\}$ is a coordinate at the receptor point. When modeling the flow of a complex terrain, the concept of dividing the streamline is applied. That is, the plume concentration is modeled in consideration of the terrain-following state and terrain-impacting state. As shown in Eq. (2), the weight value is calculated with φ_p (receptor-specific terrain height scale) of the plume and the concept of a critical dividing streamline (Venkatram et al., 2001).

$$\varphi_p = \frac{\int_0^{H_c} C_s\{x_r,y_r,z_r\}dz}{\int_0^{\infty} C_s\{x_r,y_r,z_r\}dz} \tag{2}$$

$$f = 0.5(1+\varphi_p) \tag{3}$$

where H_c is the height of the critical dividing streamline.

PRIME is a Gaussian dispersion model that was developed to more accurately simulate a plume rise, downwash, and wake of a plume caused by the building. For such flow characteristics, new models have been developed by applying a PRIME algorithm to the existing SCREEN3, ISC, and/or AERMOD model. The PRIME algorithm applied to AERMOD uses the following formulae (Schulman et al., 2000).

$$C = \gamma C_{PRIME} + (1-\gamma)C_{AERMOD} \tag{4}$$

$$\gamma = \exp\left[\frac{-(x-\sigma_{xg})^2}{2\sigma_{xg}^2}\right]\exp\left[\frac{-(y-\sigma_{yg})^2}{2\sigma_{yg}^2}\right]\exp\left[\frac{-(z-\sigma_{zg})^2}{2\sigma_{zg}^2}\right] \tag{5}$$

where x is the distance between the receptor and upstream edge of the building, y is the lateral distance between the receptor and center of the building, and z is the height of the receptor from the ground level. σ_{xg} is a vertical size of the wake, σ_{yg} is the distance from the lateral edge of the wake to the center of the building, and σ_{zg} is the height of the wake from the receptor.

2.2. Statistical test

To evaluate the transport of the radioactive materials at the Wolsong Nuclear Site, a paired *t*-test is used to analyze the difference in concentrations according to the presence/absence of the terrain and building effects. SPSS17.0 is used for a statistical analysis (SPSS, 2009).

2.3. Computational fluid dynamics

The effects of building geometries and terrains on atmospheric dispersion characteristics were evaluated using computational fluid dynamics model. The computational fluid dynamics solves differential equations on the governing equations such as mass balance, advection and diffusion, whereas the Gaussian Plume Model use approximate analytical solutions. κ–ε equations and advection/diffusion equations were used to assess the flow and dispersion around buildings and other large roughness obstacles. The governing equation for an environmental system can be given as a form of a partial differential equation involving a combination of the first derivative in time and the first and second derivatives in space as follows;

$$\frac{\partial c}{\partial t} + \nabla\cdot(-D\nabla c + cu) - kc = 0 \tag{6}$$

where c denotes the radionuclide concentration (Bq/m), D denotes its diffusion coefficient ($\mathrm{m^2\,s^{-1}}$) and $\mathbf{u}$ the velocity vector ($\mathrm{m\,s^{-1}}$). The velocity vector can be given by the solution of the κ–ε equations as follows;

$$\rho\frac{\partial u}{\partial t} - \nabla\cdot\left[\left(\eta + \rho\frac{C_\mu}{\sigma_k}\frac{k^2}{\varepsilon}\right)\nabla k\right] + \rho u\cdot\nabla u + \nabla p = 0 \tag{7}$$

$$\nabla\cdot u = 0 \tag{8}$$

where ρ denotes the density ($\mathrm{kg\,m^{-3}}$), $\mathbf{u}$ the velocity vector ($\mathrm{m\,s^{-1}}$), η the viscosity ($\mathrm{N\,s\,m^{-2}}$), and p the pressure (Pa), k the turbulent energy ($\mathrm{m^2\,s^{-2}}$), ε the dissipation rate of the turbulence energy ($\mathrm{m^2\,s^{-3}}$) and C_μ is a model constant. The turbulence energy is given through solving Eq. (9) and the dissipation through solving Eq. (10) as in the following equations:

$$\rho\frac{\partial k}{\partial t} - \nabla\cdot\left[\left(\eta + \rho\frac{C_\mu}{\sigma_\varepsilon}\frac{k^2}{\varepsilon}\right)\nabla k\right] + \rho u\cdot\nabla k = \rho C_\mu\frac{k^2}{\varepsilon}\left(\nabla u + (\nabla u)^T\right)^2 - \rho\varepsilon \tag{9}$$

$$\rho\frac{\partial \varepsilon}{\partial t} - \nabla\cdot\left[\left(\eta + \rho\frac{C_\mu}{\sigma_\varepsilon}\frac{k^2}{\varepsilon}\right)\nabla \varepsilon\right] + \rho u\cdot\nabla \varepsilon = \rho C_{\varepsilon 1}C_\mu k\left(\nabla u + (\nabla u)^T\right)^2 - \rho C_{\varepsilon 2}\frac{\varepsilon}{k^2} \tag{10}$$

At the inlet boundaries of an nuclear site geometry, the system has a constant flow velocity. At the outlets, neutral boundary conditions where the normal component of the stress tensor is set to zero are used as follows;

$$n\cdot[-pI + \eta(\nabla u + (\nabla u)^T)] = 0 \tag{11}$$

The fluid in the modeling domain is air with a viscosity of $1.73\times10^{-5}\ \mathrm{N\,s\,m^{-2}}$ and a density of $1.23\ \mathrm{kg\,m^{-3}}$ at 15 °C. Model constants are as follows in the above equations; C_μ as 0.10, $C_{\varepsilon 1}$ as 0.13, $C_{\varepsilon 2}$ as 1.90, σ_k as 1.0 and $\sigma_{k\varepsilon}$ as 1.5, respectively. Wind speed for boundary condition in the x-direction, u, was set to 1.5 m/s, while the velocity in the y-direction, v, was set to zero.