A Tracer Experiment to Understand Dispersion Characteristics at a Nuclear Power Plant Site-Focusing on the Comparison with Predictive Results using Reg. Guide 1.145 model

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1. Introduction

To analyze the behaviors of radioactive materials released to the atmosphere from a nuclear power plant, the United States Nuclear Regulatory Commission (US NRC) suggests various methods applicable to analyzing normal operation and possible accidents [1-3]. Korea amended some of the regulatory guidelines and software developed by the US, and adopted them to regulate the design and operation of nuclear power plants in Korea. Under normal operation, the XOQDOQ program is used for analyzing the atmospheric dispersion of radioactive materials. In case of an accident, the PAVAN program, which is based on a Gaussian plume model, is used for the analysis of air dispersion.

There remains disagreement regarding the application of a Gaussian plume model in PAVAN, as it relates to the complicated geographical features of a coastal area. Therefore, this study was performed in order to figure out the characteristics of the PAVAN program that was developed based on the equations of Gaussian Plume Model, which reflected the actual measured concentration of radioactive materials released to the air. It also evaluated the appropriateness of using a Gaussian plume model for assessing the environmental impact of radiation from a nuclear power plant.

In order to analyze the dispersion characteristics of radioactive materials released into the air from the Wolsong nuclear power plant, SF_6 gas was released from the site at night for one hour under stable atmospheric conditions disadvantageous to dilute a tracer gas in this study. The measured concentrations were compared with theoretical estimates derived from meteorological data observed during the experiment period to evaluate the prediction capabilities of the Gaussian plume model.

2. Methods and Results

2.1. Tracer dispersion experiment

The tracer dispersion experiment was conducted at the Wolsong nuclear power plant site at 22:30 for one hour on December 3, 2013 using the tracer gas SF_6. The release rate of a tracer is determined by the background tracer concentration, the detection limit of the analysis device, and the prediction of the dispersion results. The desirable range of the concentration of the sampled tracer for an analysis was set to 5.069E+05 μg/sec in consideration of signal to noise ratio (S/N ratio). The release point of the tracer gas was determined in conjunction with the wind direction and accessibility at the time of the experiment. Wind direction and wind speed were measured with 7 simplified meteorological measuring instruments disposed on the site. Meteorological data measured on the ground and in the upper atmosphere were used in analyzing the experimental tracer data, and also for simulating atmospheric dispersion via the model.

2.2. Atmospheric dispersion

Reg. 1.145 is the guidelines of US NRC regarding the analysis of the atmospheric dispersion of radiation involving nuclear facilities. It suggests analyzing the atmospheric dispersion of radioactive materials using the straight line trajectory equations of the Gaussian Plume Model [4]. It suggests three equations based on atmospheric stability and wind speed that have an influence on the atmospheric dispersion of radioactive materials.

$$\chi / Q = \frac{1}{\overline{U}_{10}(\pi\sigma_y\sigma_z + A/2)} \tag{1}$$

$$\chi / Q = \frac{1}{\overline{U}_{10}(3\pi\sigma_y\sigma_z)} \tag{2}$$

$$\chi / Q = \frac{1}{\overline{U}_{10}\pi\sum y\sigma_z} \tag{3}$$

$$\sum y = M\sigma_y \qquad (x \le 800)$$

$$\sum y = (M-1)\sigma_{y\,at\,800m} + \sigma_y \qquad (x > 800)$$

In the event that atmospheric stability is A, B, or C, which is advantageous to the atmospheric dispersion of radioactive materials, or the wind speed is higher than 6 m/sec, the larger ChiQ value, which is calculated by Equation 1 and Equation 2, is used as an atmospheric dispersion factor. On the other hand, if the atmospheric stability is D, E, F, or G, which indicates a stable state of the atmosphere, or the wind speed is less than 6 m/sec, the larger ChiQ value that was calculated by Equation 1 and Equation 2 is compared with the ChiQ calculated by Equation 3 and the smaller one is selected as an atmospheric dispersion factor.

The equations of the Gaussian Plume Model suggested in Reg. 1.145 are straight line trajectory equations that take into considerations only 16 wind directions. They are very useful in the control of nuclear power station facilities, but it is difficult to use the equations as a model to analyze the results of the dispersion experiment, because they compare the concentrations obtained from only 16 directions which is at a certain distance from the releasing point. Therefore, in order to compare the measured value of the dispersion experiment with the calculated value of the model, this study applied the following Gaussian Plume Model equations by adding y and z coordinates to Equations 1, 2, and 3 in the Gaussian Plume Model, as suggested in Reg. 1.145.

$$\chi(x,y,z)=\frac{1}{n}\sum_{i=1}^{n}\frac{Q}{2\pi U_i\sigma_{yi}\sigma_{zi}}\exp\left(-\frac{y^2}{2\sigma_{yi}^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_{zi}^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_{zi}^2}\right)\right] \tag{4}$$

$$\chi(x,y,z)=\frac{1}{n}\sum_{i=1}^{n}\frac{1}{3\cdot 2\pi U_i\sigma_{yi}\sigma_{zi}}\exp\left(-\frac{y^2}{2\sigma_{yi}^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_{zi}^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_{zi}^2}\right)\right] \tag{5}$$

$$\chi(x,y,z)=\frac{1}{n}\sum_{i=1}^{n}\frac{1}{2\pi M_i U_i\sigma_{yi}\sigma_{zi}}\exp\left(-\frac{y^2}{2\sigma_{yi}^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_{zi}^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_{zi}^2}\right)\right] \tag{6}$$

$\chi(x, y, z)$: Air concentration of tracer gas ($\mu g/m^3$).
Q: Release rate ($\mu g/s$).
σ_{yi}, σ_{zi}: Horizontal and vertical dispersion parameters (m).
H: Effective release height (m).
U_i: Wind speed (m/s).
n: Number of data set for wind direction, wind speed, and atmospheric stability, which is put in the data files.
$M_{ij}(x)$: Meandering factor for lateral plume spread for wind-speed, wind-direction and stability class, i [2].

2.3 Tracer concentration modeling using dispersion experiment data

A northwesterly wind (between 278 and 289 degrees) was dominant. Wind speed was relatively low (between 1.4 m/sec and 2.7 m/sec). Atmospheric conditions were found to be stable, as estimated from the vertical temperature distribution recorded in the upper air. Since the atmospheric conditions were stable (category E) and wind speed was less than 6.0 m/sec, the larger of the values calculated using Equation 4 and Equation 5 is compared with that from Equation 6, of which the smaller value is selected as air concentrations of tracer. Fig. 1 shows the concentration distribution of SF_6 estimated via the modified Gaussian plume model, using the 10-minute averaged meteorological data recorded during the 1-hour experimental. As a result of the dominant northwesterly wind, the tracer seemed to be distributed in a southeasterly direction overall. Among the sample bags located along the road within the nuclear site, it was assumed that a relatively high concentration of SF_6 was observed in those located in the north. In the model suggested in Reg. 1.145, the air concentrations of tracer were inversely proportional to wind speed. As shown in Fig. 3(a), during the period 21:30–21:40 hr. the wind speed was lowest (1.4 m/sec) and atmospheric concentration was highest. It was expected that the maximal concentration would be lowest during the period 22:10–22:20 hr., when wind speed was highest (2.7 m/sec). However, the lowest maximal value (9.92E+01 $\mu g/m^3$) was estimated from 22:00 to 22:10, during which the wind speed was 2.5 m/sec. This result was attributed to the meandering effect of the atmospheric dispersion model between wind speeds of 2.0 m/sec and 6.0 m/sec, as shown in Equation 3.

Fig. 2 compares the measured data with the values estimated by the Gaussian plume model. In all of the six data sets estimated at 10-minute intervals, the estimated concentration of SF_6 was higher than the calculated value of the model in the areas where concentration was less than 10 $\mu g/m^3$. Because the SF_6 tracer is regularly distributed along the wind direction, it was assumed that the concentrations calculated at locations far from the central line of the plume would be close to zero. Furthermore, the estimated value might be significant even at locations far from the central line of the plume. On the other hand, the measurements are not zero as a result of instantaneous changes in wind direction or the influence of the buildings located on the site. For this reason, in the place that has a low calculated value, the actual measured value tends to be shown high.

3. Conclusions

This study conducted a tracer dispersion experiment at the site of Wolsong Nuclear Power Plant site in Korea to analyze the atmospheric dispersion characteristics of radioactive materials. It compared the experimental value with the calculated value using the Gaussian Plume Model as suggested in Reg. 1.145, based on the meteorological data observed in the experiment time period, and evaluated the conservative estimate of the calculated value. In the area where the calculated value is relatively high, the calculated value tends to show higher than the experimental value, which confirmed the conservative manner of the estimating of the calculated value using the Gaussian Plume Model. The short-term exposure of radiation to a human body caused by a nuclear accident would be higher in the area where the atmospheric concentration of radiation is high. Therefore, it is a sufficiently conservative manner to use the Gaussian Plume Model for an assessment of the environmental impact of radiation, as the model is used in getting government permits or gaining approval for building a nuclear power facility. However, in areas where the observed concentration is relatively low, there is greater divergence from the estimated value. In order to model the dispersion characteristics of pollutants accurately, more study is necessary to utilize a dispersion modeling technique that considers buildings being built and the location and geography of the buildings.

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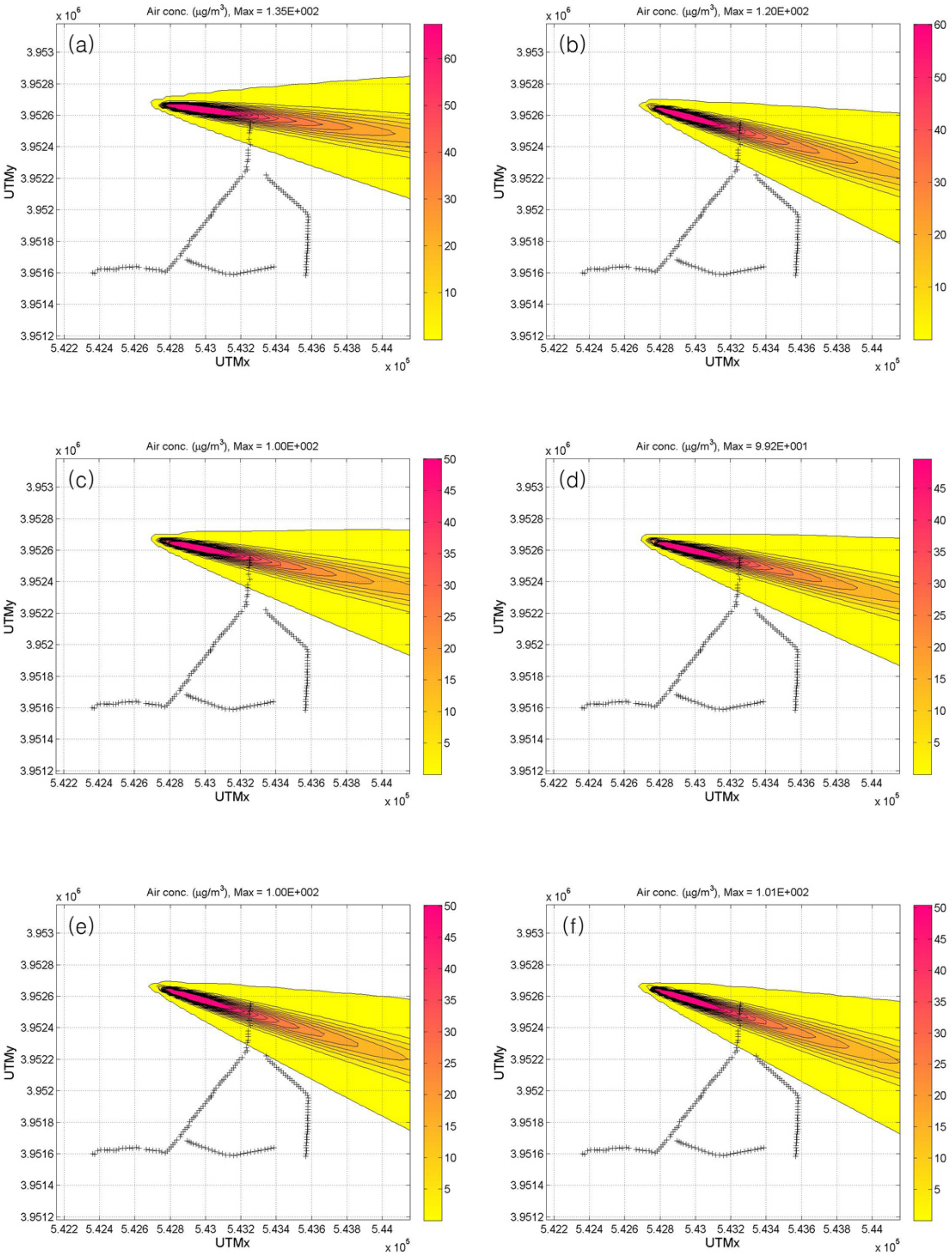

Fig. 1. Estimated atmospheric concentration of tracer gas, based on meteorological data collected at 10-minute intervals.

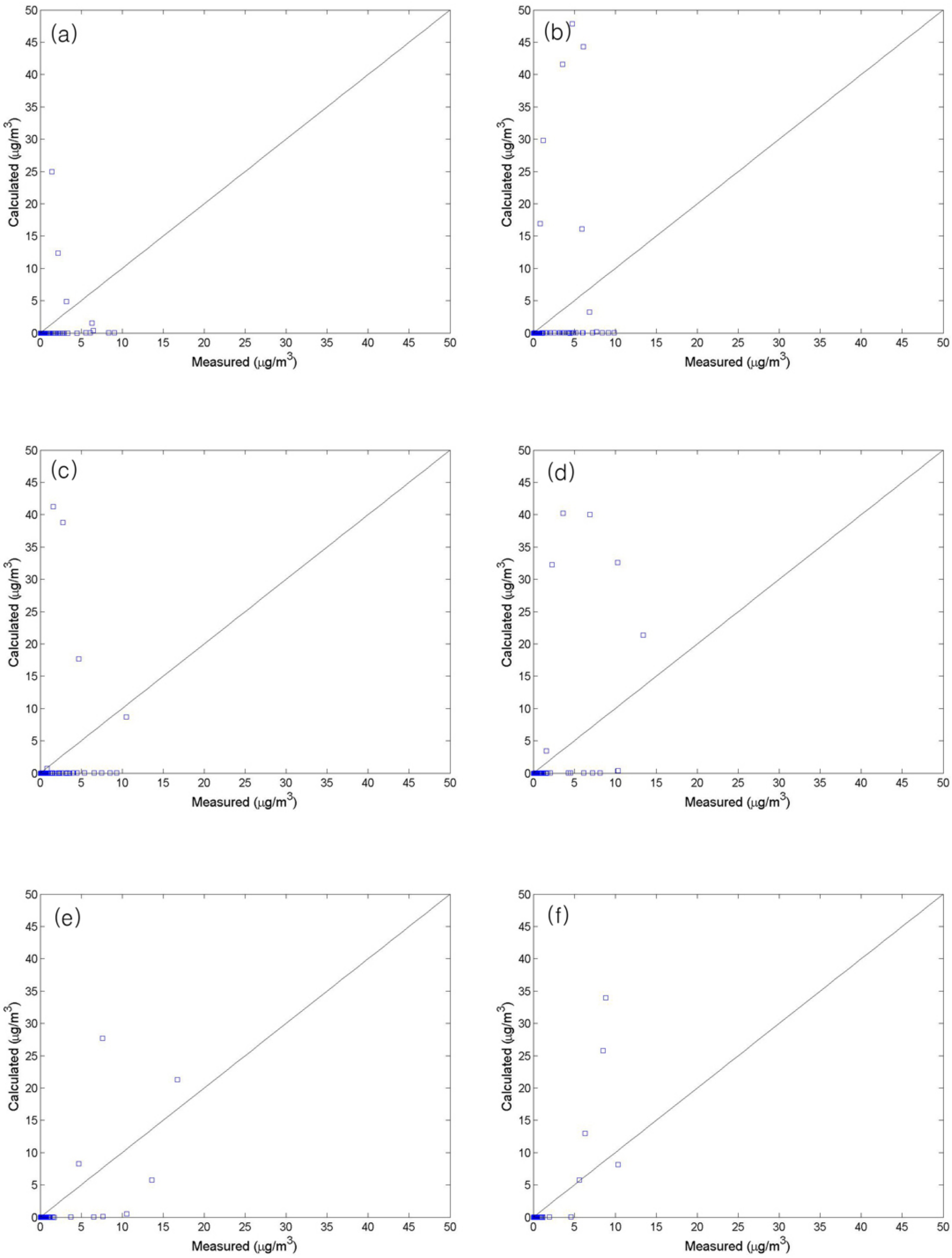

Fig. 2. Comparison between estimated values and actual measurements at the sampling points