An Optimized Gaussian Plume Model for Radiological Consequence Analysis Program (RCAP)

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1. Introduction

As a steady-state atmospheric dispersion model, Gaussian plume model has been widely adopted in nuclear regulation and application for radiological consequence analysis due to accidental release of radiation materials from nuclear facility including Level 3 Probabilistic Safety Assessment (PSA) [1,2,3]. Typical Gaussian plume model has been adopted in Radiological Consequence Analysis Program (RCAP) developed by KAERI for applying Level 3 PSA. Since there are many application regimes in the Gaussian plume model [4], it is necessary to select an appropriate regime and optimal parameters values for practical application. This paper presents the application of the Gaussian plume model focused on the application regime and the selection of optimal parameters values for the RCAP code [5].

2. Methods and Results

2.1 Gaussian Plum Model

Typical Gaussian plume equation is known as an analytic solution of the advection-diffusion equation under the specific assumptions. For a practical application of this equation to air pollution, the application model proposed by Pasquill and established by Gifford and Turner has been widely used in the application and regulation of nuclear power plants [6,7,8]. Although, from Pasquill's proposal, a number of application models, i.e., application regimes, have been proposed as summarized in IAEA report [4], Pasquill-Gifford (PG) model has been adopted for RCAP code.

For application of PG model, three key contents has been prepared as follows:

- Gaussian plume formula,

$$\chi(x,\ y,\ z) = \frac{Q}{\bar{u}} \cdot \frac{exp(-\frac{y^2}{2\sigma_y^2})}{\sqrt{2\pi}\sigma_y} \cdot \frac{exp\left(-\frac{(\mathrm{z}+\mathrm{h})^2}{2\sigma_z^2}\right) + exp\left(-\frac{(\mathrm{z}-\mathrm{h})^2}{2\sigma_z^2}\right) + f(\mathrm{h},\ L)}{\sqrt{2\pi}\sigma_z}$$

(Skip nomenclatures)

- Atmospheric stability classification (Table 1), and

Table 1. PG stability classification

Wind speed	Day Incoming Solar Radiation (Insolation)			Night time cloud cover	
(m/s)	Strong	Moderate	Slight	High	Low
< 2	A	A-B	B	-	-
2 ~ 3	A-B	B	C	E	F
3 ~ 5	B	B-C	C	D	E
5 ~ 6	C	C-D	D	D	D
> 6	C	D	D	D	D

- PG dispersion coefficients scheme (Figure 1).

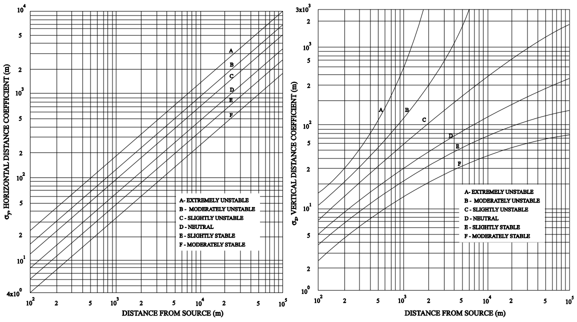

Figure 1. PG dispersion coefficients scheme

2.2 Application Parameters and Related Models

To calculate a dispersion $\chi(x, y, z)$, main parameters which consist of release amount Q, average wind speed $\bar{u}$, literal and vertical dispersion coefficients (σ_y and σ_z) release height h, and mixing height L in the Gaussian equation should be assigned and supporting implicit parameters which consist of surface roughness r_0, sensible heat H, sampling time t_s, deposition velocity v_d and precipitation rate p, to determine the main parameters.

In PG model, there are a lot of models to determine the main parameters and supporting parameters, but the applied relevant models could be roughly classified as follows (Table 2):

- Stability classification scheme
- Dispersion coefficients formulas
- Lateral correction with meandering effect
- Vertical correction for surface roughness effect
- Vertical wind profile with wind direction
- Plume rise by internal heat of plume
- Building wake effect
- Mixing height correction
- Depletion by radionuclide decay
- Depletion by dry and wet deposition
- Weathering effects of ground contamination for long-term behavior

Table 2. Parameters determination model for PG model

Model		Application model in RCAP
Stability classification scheme		- EPA cited: PGT, SRDT, delta θ, delta ω - NRC: DT
PG dispersion coefficient charts		- Tadmor-Gur /Briggs/ISC3 - Eimutis-Konicek [1972]
Lateral correction (meandering)		- Mueller [1985]/Gifford [1960] - NRC method (Reg. Guide 1.145)
Vertical correction (surface roughness)		- Smith [1974]
wind profile		- Irwin [1979]
Plume rise		- Briggs formula (buoyancy) [1969] - Lift-off criteria [on/off] [Hanna, 1998]
Building wake		- Virtual source [Turner, 1969]
Mixing height		- Stability class - Average mixing height chart [Holzworth, 1972] - Single value [Ehrhardt, 1988]
Depletion	Decay	- Bateman Eq. [1910]
	Dry	- Source depletion method [Chamberlain, 1953]
	Wet	- Jylhä [1991]
Weathering effects		- Gale [1964]

2.3 Optimized Parameters

It is not an easy process to obtain optimized parameters for the PG model including the involved models. In some cases, the optimal values can be easily obtained from existing application cases, but in many cases it is not [9]. Generally, in most cases, the optimal values should be determined by reflecting the intention of the analyzer.

In the development of RCAP code, we tried to obtain the optimized parameters values based on the adopted models of RCAP code as follows:

- Determination of wind speed and direction,
- Determination of atmospheric stability,
- Effect of building wake as initial condition,
- Lift-off criterion for the plume rise,
- Correction of lateral dispersion coefficients including meandering effect,
- Correction of vertical diffusion coefficients for surface roughness effects,
- Determination of mixing height, and
- Application of the source dilution models.

Considering the issues derived from the optimization process, the optimal parameters values have been derived based on the models for RCAP code.

2.4 Applicability of PG Model

For the applicability of PG Gaussian model of RCAP code, the results were compared with the data of the Prairie Grass experiments [10,11]. Fig. 2 and 3 show a comparison of the calculation results of the RCAP code and those of the Prairie Grass experiments. It can be identified that approximately 90% of the experimental data are distributed within the range of 2 times. From the comparison result, the optimized model has been identified as a considerable accuracy of their application.

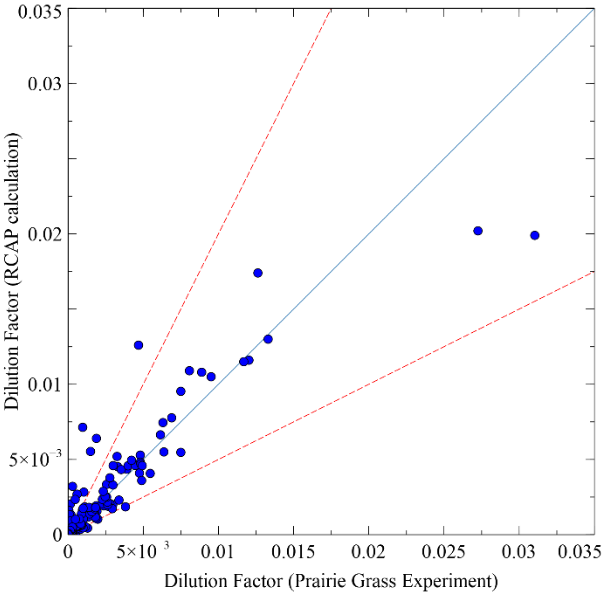

Figure 2. Comparison of dilution factor between results of RCAP from optimized parameters and Prairie Grass experiments (linear scale)

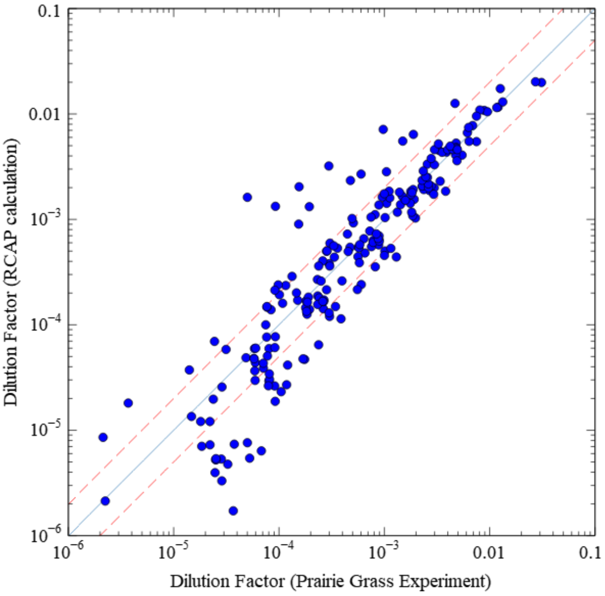

Figure 3. Comparison of dilution factor between results of RCAP from optimized parameters and Prairie Grass experiments (logarithmic scale)

According to the recommendations of ASTM [12], if the diffusion model is bound approximately 2 times, it is recognized as a model with considerable accuracy. Therefore, it could be confirmed that the PG model of RCAP code is an adequate model to be used in the radiological offsite consequence analysis including Level 3 PSA. This fact could be naturally inferred from existing studies and application cases.

3. Conclusions

The PG Gaussian plume model was adopted for the atmospheric dispersion model which is the main frame of the developed RCAP code. For the application of the adopted models, an optimization of model parameters values is also required. In this study, overall features of optimization of the model parameters was briefly described. Although additional work for verification is required for the application of RCAP code, it is identified that the adopted PG model has considerable accuracy from the comparison with the Prairie Grass experiment.

Although the optimization of parameters has many issues, it could be primarily conformed that the applicability of the adopted PG model has a reasonability to apply the radiological offsite consequence analysis including Level 3 PSA.

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Table 3. Local Scale Empirical Gaussian Models. [IAEA, 1986]

Model Name	Functions	Stability Indicators	Limitations and Remarks
Pasquill-Gifford*	Given graphically for 0.1 - 100 km for each stability category	Original: U_{10m}+Insolation (day-time) and cloud cover (night time) Correlated; $\Delta T/\Delta z$ (between 10 m and 60 m), σ_θ, net radiation	Smooth terrain, surface release, based on data up to 0.8 km Sampling time - 3 min for σ_y 10 min for σ_z Extensively used because of simplicity.
ASME/BNL**	$y = a\,x^p$ $z = b\,x^q$ a, b, p and q are constants varying with stability	Original: Gustiness characteristics Correlated: $\Delta T/\Delta z$, σ_θ	Rural terrain, elevated release, data up to 50 km, hourly averages. Not reliable for low winds (< 2 m/s)
McElroy (1969)	Same as above with different sets of constants	Original: Ri Correlated: σ_θ	High roughness, near surface release, data up to 25 km, hourly averages. Generally used for urban locations.
Vogt (1977)	Same as above with different set of constants	Original: wind speed + $\Delta T/\Delta z$ (between 20 m and 100 m)	Major surface roughness Elevated releases, up to 10 km.
Doury (1976)	$\sigma_x - \sigma_y = (A_\mathrm{h} t)^{K_\mathrm{h}}$ $\sigma_z = (A_z t)^{K_z}$ for two stabilities	$\Delta T/\Delta z$	A puff model, σ_s functions of travel time. Parameters given only for two stability classes defined by $\Delta T/\Delta z$ A & K vary with travel time.

* Pasquill (1961), Gifford (1959), Luna and Church (1972)
** ASME (1968), Singer and Smith (1966)