The impact of atmospheric dispersion coefficients of off-site consequence analysis codes on atmospheric dispersion factors

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1. Introduction

In Level 3 Probabilistic Safety Assessment (PSA), several computational codes for off-site consequence analysis have been used in the nuclear power plant (NPP) accident analysis. Mathematical model in atmospheric dispersion modeling is the basis of off-site consequence analysis codes[1]. It calculates atmospheric dispersion phenomenon of radionuclide using numerical solution of governing equation. In general, atmospheric dispersion factor (X/Q) is calculated by several variables based on Gaussian plume equation.

There is a difference in the calculation of atmospheric dispersion coefficients (σ_y and σ_z) among the off-site consequence analysis codes. MACCS2[2] uses the power-law function that calculates the horizontal and vertical dispersion coefficient as a function of distance. WinMACCS[3] uses the time-dependent function with linear coefficient when model is switched to long-range dispersion model. RASCAL[4] uses time-dependent function which is an integral form of lateral turbulence factor.

As horizontal dispersion coefficient formulas of each code are detailed, wind speed is directly considered in WinMACCS and RASCAL. Horizontal dispersion coefficients in MACCS2 are defined by atmospheric stability class[5-6]. The horizontal dispersion coefficient in MACCS2 remains unchanged by wind speed under the same atmospheric stability condition while atmospheric dispersion factor is dominantly affected largely by wind speed.

In this study, horizontal dispersion coefficients and atmospheric dispersion factors are calculated by MACCS2, WinMACCS and RASCAL respectively in order to investigate the influence of horizontal dispersion coefficients on atmospheric dispersion factors for each code.

2. Atmospheric dispersion coefficients

In this section, the equations of atmospheric dispersion coefficients for MACCS2, WinMACCS and RASCAL are described. Three codes calculate atmospheric dispersion coefficients based on Gaussian Plume model. Radionuclide concentration on the ground level can be calculated by Gaussian Plume equation[2] in Eq. 1.

$$\chi(\mathrm{x},\mathrm{y},0) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\exp\left(-\frac{H^2}{2\sigma_z^2}\right) \qquad (1)$$

In Eq. 1, Q represents the amount of radionuclide released. σ_y and σ_z indicate horizontal and vertical dispersion coefficient respectively. $\bar{u}$ represents the average wind speed. H represents the effective release height.

2.1 MACCS2

The horizontal and vertical dispersion coefficient in MACCS2[2] are described as below.

$$\sigma_{yi} = a_i x^{bi} \qquad (2)$$
$$\sigma_{zi} = c_i x^{di}$$

In Eq. 2, i represents atmospheric stability and there are 6 atmospheric stability classes by Pasquill-Gifford classification[5-6]. x indicates the distance along the wind direction. The values of linear term(*a* and *c*) and exponential term(*b* and *d*) are defined for each stability class.

2.2 WinMACCS

The equation of horizontal dispersion coefficient of WinMACCS[3] changes to the time-dependent function from the distance-denpendent function when the distance(*x*) exceeds the designated distance, x_c. It is defined as below.

$$\sigma_y = \begin{cases} a\left(\frac{x}{x_0}\right)^b & x < x_c \\ a_c t & x \geq x_c \end{cases} \qquad (3)$$
$$\sigma_{zi} = c_i x^{di}$$

In Eq. 3, horizontal dispersion coefficient from the distance x_c varies with the coefficient a_c and the time t. a_c is a linear coefficient of time-based, crosswind dispersion and its value can be defined by users. The equation of vertical dispersion coefficient is as same as that of MACCS2.

2.3 RASCAL

The equation of horizontal dispersion coefficient in RASCAL[4] is described as below.

$$\sigma_y = \begin{cases} 0.5\int_0^t \sigma_v(t)dt\ (t \leq 3600s) \\ \sigma_y(3600) + 0.2(t-3600)(t > 3600s) \end{cases} \qquad (4)$$

In Eq. 4, σ_v represents a lateral turbulence component and it may vary along the puff paths. The turbulence parameter σ_v varies with few atmospheric conditions.

For stable atmospheric conditions, when the plume height z_p divided by the mixing height H is less than 0.9, the model uses Eq. 5 where u_* is a scaling velocity in the atmosphere. f is the Coriolis parameter, which is a function of latitude and earth's rotation rate. L is the Monin-Obukhov length.

$$\sigma_v = \begin{cases} 1.3u_*\left(1-\frac{z_p}{H}\right), stable, z_p < 0.9H \\ 1.3u_*\exp\left(-\frac{2fz_p}{u_*}\right),\ neutral \\ u_*\left(12-\frac{0.5H}{L}\right)^{1/3}, unstable \end{cases} \qquad (5)$$

The vertical dispersion coefficient of RASCAL[4] is calculated with Eq. 6.

$$\sigma_z = \int_0^t \sigma_w(t) f_z(t) dt \qquad (6)$$

$$f_z(t) = \left\{1.0 + 0.9\sqrt{t/T}\right\}^{-1}, T = 50s$$

In Eq. 6, σ_w represents the vertical turbulence factor. f_z is the Coriolis parameter for vertical direction.

Table 1. Classification of atmospheric dispersion coefficient equations by wind effect

Wind speed (U)	*Equation*	
Direct consideration		(3), (4), (6)
Indirect consideration	(2)	

In Table 1, atmospheric dispersion coefficient equations are classified with whether wind speed is directly taken into account in the equation or indirectly. WinMACCS and RASCAL which are based on the time-dependent function, directly consider the wind speed into the calculation of atmospheric dispersion coefficient. MACCS2, however, horizontal dispersion coefficient is defined with the coefficients determined by atmospheric stability class.

3. Method

The influence of atmospheric dispersion coefficient(σ_z and σ_y) on the atmospheric dispersion factor (X/Q) for each code is investigated. In this section, influence of horizontal dispersion coefficient (σ_y) is investigated since vertical dispersion coefficient(σ_z) cannot be identified in the output of RASCAL. The calculation of horizontal dispersion coefficient and atmospheric dispersion factor was carried out based on the following information.

Table 2. Source term information

Nuclear Unit	*Power (MWt)*	*Release height(m)*	*Event*	*Core recovery (hr)*	*Leak rate (%/d)*
Vogtle Unit 1 (PWR)	3626	10	LOCA	2	0.1

In Table 2, source term information is described. Loss Of Coolant Accident (LOCA) was occurred at Vogtle unit 1 at 0:00am on 30th January, 2019 and core was uncovered simultaneously with the shutdown of the reactor. Release pathway was set up as containment leakage and core was recovered at 2:00am after two hours of core uncovery. Containment sprays were off in this scenario. Leak rate was set as designed value. Release height was set as 10 meters.

Table 3. Meteorology

Wind speed (m/s)	*Atmospheric stability*	*Precipitation*	*Wind direction (from deg)*
3 / 5/ 10	D	None	90

In Table 3, meteorological information is described. The weather condition is the same as a constant weather for each code. It is assumed that wind blows to the west at a speed of 3, 5 and 10m/s respectively when atmospheric stability is fixed as D class which is based on the Pasquill-Gifford stability class.

Horizontal dispersion coefficient of WinMACCS is adjusted to that of RASCAL by modifying linear coefficient in Eq.3 to compare atmospheric dispersion factors of two codes under the same horizontal dispersion coefficient condition.

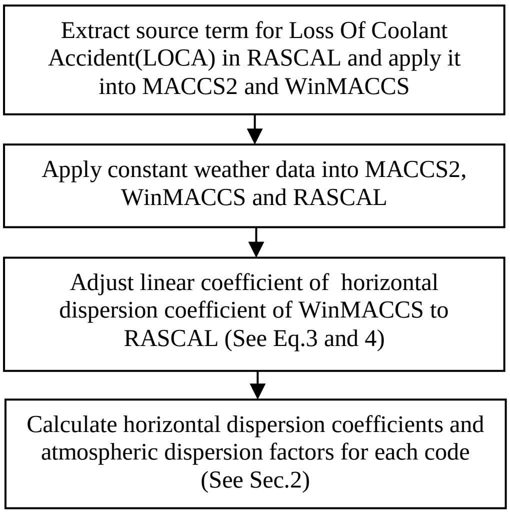

Fig. 1. Adjustment of source term and horizontal dispersion coefficient of MACCS2 and WinMACCS to RASCAL

Figure 1 describes the source term application and horizontal dispersion coefficient adjustment. Source term applied in MACCS2 and WinMACCS is extracted from RASCAL. Horizontal dispersion coefficients and atmospheric dispersion factors are calculated for each code under the identical constant weather condition. Horizontal dispersion coefficient of WinMACCS is adjusted to RASCAL by modifying linear coefficient in Eq. 3.

Table 4. Linear coefficient of WinMACCS

Wind speed (m/s)	3	5	10
Default Linear Coefficient (a_c) (m/s)	0.5		
Adjusted Linear Coefficient (a_c) (m/s)	0.33	0.4	0.58
Distance for the time-based dispersion model (x_c) (m)	0	0	0

(See Eq. 3)

In Table 4, adjusted values of linear coefficient (a_c) and distance for the time-based dispersion model(x_c) by wind speed are described. Default value of 0.5 is recommended by Hanna[7].

Horizontal dispersion coefficient of RASCAL was calculated by Eq. 4 and the linear coefficient of WinMACCS in Eq. 3 was adjusted to Eq. 4. For the horizontal dispersion coefficients of RASCAL and WinMACCS by each wind speed to be similar, the linear coefficient in Eq. 3 must be the value in Table 4. Distance for the time-based dispersion model in WinMACCS is set to 0 so that the horizontal dispersion coefficient is calculated based on time-dependent formula in Eq.3.

4. Application

4.1. Horizontal dispersion coefficient at wind speed of 3m/s

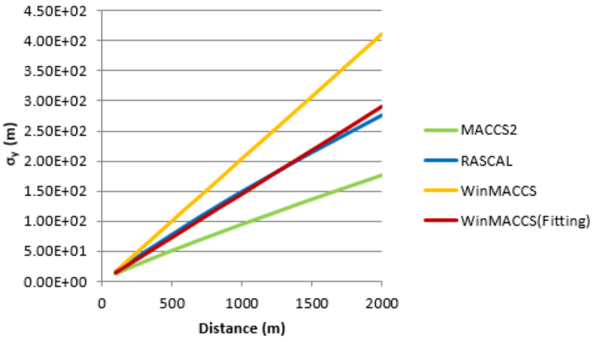

Fig. 2. Horizontal dispersion coefficients at wind speed of 3m/s

In Fig. 2, horizontal dispersion coefficient of MACCS2, WinMACCS and RASCAL at wind speed 3m/s are described. As the distance increases, the difference between horizontal dispersion coefficients of MACCS2, WinMACCS and RASCAL gradually increases.

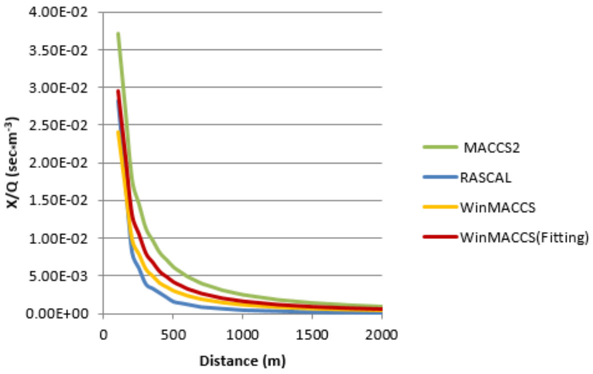

Fig. 3. Atmospheric dispersion factors at wind speed of 3m/s

Figure 3 shows the atmospheric dispersion factors of MACCS2, WinMACCS and RASCAL at wind speed of 3m/s. Atmospheric dispersion factors of RASCAL and WinMACCS(Fitting) are quite similar at first, however, the difference becomes greater into the distance since atmospheric dispersion factor of RASCAL decreases the most rapidly with distance. The difference of atmospheric dispersion factors of each code diminishes at a very long distance. The initial values atmospheric dispersion factors of MACCS2 and WinMACCS are different since initial values calculated from each code weren't considered as adjusted distance starts with 100m.

4.2. Horizontal dispersion coefficient at wind speed of 5m/s

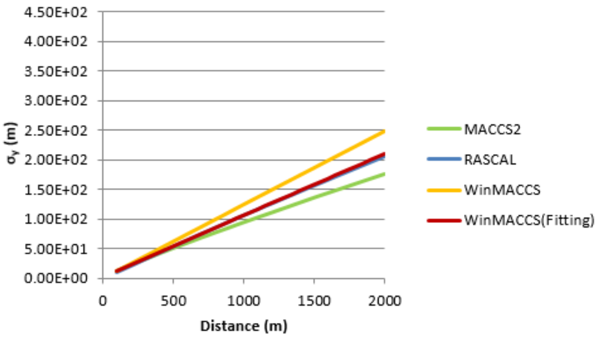

Fig. 4. Horizontal dispersion coefficients at wind speed of 5m/s

In Fig. 4, horizontal dispersion coefficient of MACCS2, WinMACCS and RASCAL at wind speed 5m/s are described. As the wind blows faster, horizontal dispersion coefficients of WinMACCS and RASCAL are decreased. The values of horizontal dispersion coefficient of MACCS2 is fixed, since horizontal dispersion coefficient in MACCS2 remains unchanged by wind speed under the same atmospheric stability condition.

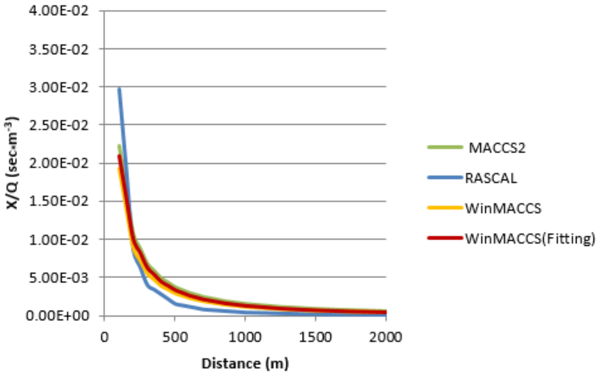

Fig. 5. Atmospheric dispersion factors at wind speed of 5m/s

In Fig. 5, atmospheric dispersion factors of MACCS2, WinMACCS and RASCAL at wind speed 5m/s are described. Atmospheric dispersion factor of MACCS2 influenced only by wind speed and decreased significantly at close range. As wind blows faster, the difference of atmospheric dispersion factors between RASCAL and WinMACCS(Fitting) becomes larger at a close range.

4.3. Horizontal dispersion coefficient at wind speed of 10m/s

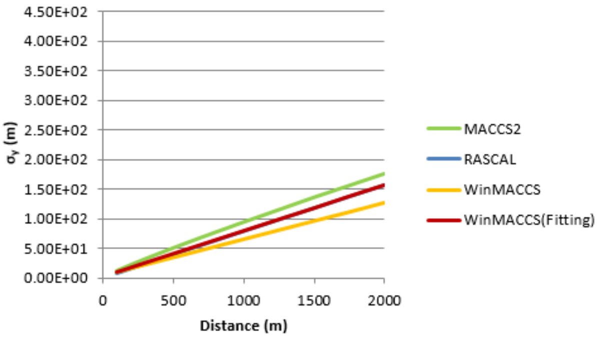

Fig. 6. Horizontal dispersion coefficients at wind speed of 10m/s

In Fig. 6, horizontal dispersion coefficient of MACCS2, WinMACCS and RASCAL at wind speed 10m/s are described. As the wind blows much faster, horizontal dispersion coefficients of WinMACCS and RASCAL are decreased. Horizontal dispersion coefficient of WinMACCS decreases the most significantly with the high wind speed compared to that of RASCAL and WinMACCS(Fitting).

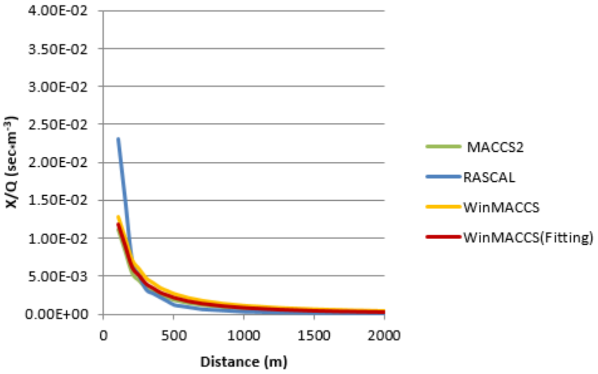

Fig. 7. Atmospheric dispersion factors at wind speed of 10m/s

In Fig. 7, atmospheric dispersion factors of MACCS2, WinMACCS and RASCAL at wind speed 10m/s are described. Atmospheric dispersion coefficients of MACCS2, WinMACCS and WinMACCS(Fitting) were quite similar as compare to that of RASCAL. As wind blows much faster, the difference of atmospheric dispersion factors between RASCAL and other codes including WinMACCS(Fitting) becomes much larger at a close range. Initial value of atmospheric dispersion coefficient of RASCAL decreased, however, the graph still shows a sharp decline.

5. Conclusion

In this study, the impact of horizontal dispersion coefficient (σ_y) on atmospheric dispersion factor $(\mathrm{X/Q})$ under three wind speed conditions for MACCS2, WinMACCS and RASCAL is investigated.

Even though, the horizontal dispersion coefficient of WinMACCS is adjusted with the RASCAL by modifying linear coefficient in Eq. 3, graphs show clear distinct between atmospheric dispersion factors and it becomes greater as wind blows faster.

Table 5. Variables affecting atmospheric dispersion factor

	Considered	*Necessary to be considered*
Variables	σ_y	σ_z, H, Plume rise, Wake effect etc

In Table 5, variables that affect atmospheric dispersion factor in Eq. 1 are described. Horizontal dispersion coefficient is investigated in this study. Vertical dispersion coefficient and effective height (H) for each code can be compared to verify the cause for the difference of atmospheric dispersion factors. Plume rise and wake effect might have an effect on the difference of atmospheric dispersion factors at close range. However, it is difficult to make two inputs same since those parameters cannot be customized by users in RASCAL. The comparison of variables affecting atmospheric dispersion factor among the codes would be much more accurate when the influence of other factors including plume rise and wake effect is blocked.

This study is summarized as

1. Horizontal dispersion coefficients(σ_y) for each code are calculated with different formulas and each formula is influenced by its own variables. It is necessary to investigate the influence of other variables such as vertical dispersion coefficients(σ_z) of each code and the influence of other variables such as plume rise and wake effect must be blocked.
2. Linear coefficient for time-based, crosswind dispersion(a_c) of WinMACCS, in Eq. 3, can be adjusted to be aligned with the horizontal dispersion coefficient of RASCAL. Even though horizontal dispersion coefficients of two codes are aligned with each other, atmospheric dispersion factors show substantial difference.
3. The difference of atmospheric dispersion factors among codes from site boundary to 1-mile which is the distance to evaluate the risk of early fatality becomes more distinctive in case of low wind speed.
4. In off-site consequence analysis, formulaic difference of variables that affect atmospheric dispersion factors and the value difference of atmospheric dispersion factors between codes must be considered.

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