Scientific and Social Research, 2025, Volume 7, Issue 4
https://ojs.bbwpublisher.com/index.php/SSR
Online ISSN: 2981-9946
Print ISSN: 2661-4332

Study on the Diffusion Law of Radionuclides Based on the Improved Gaussian Plume Model

Jianyong Dai[1,2]*, Yue Li[1,2], Meiyan Gan[2,3]

[1]School of Resources, Environment and Safety Engineering, University of South China, Hengyang 421000, Hunan, China

[2]Key Laboratory of Emergency Safety Technology and Equipment of Nuclear Facilities in Hunan Province, Hengyang 421000, Hunan, China

[3]School of Nuclear Science and Technology, University of South China, Hengyang 421000, China

**Author to whom correspondence should be addressed.*

Abstract: This study aims to improve the prediction accuracy of the diffusion trajectory of radioactive pollutants in the atmosphere. First, based on the traditional Gaussian plume model, the model is improved by introducing two key control factors: rainfall intensity and ground roughness. Secondly, the factors affecting gas diffusion under different rainfall intensities and ground roughness are analyzed, as well as the diffusion characteristics of radioactive pollutants in the atmosphere under the influence of these two factors. Finally, taking the radioactive nuclide leakage of Daya Bay Nuclear Power Station as an example, according to the analysis of the concentration distribution characteristics in the downwind and crosswind directions, the results show that rainfall intensity and ground roughness have a significant effect on the diffusion concentration and diffusion range of radioactive nuclides. With the increase of rainfall intensity and the improvement of ground roughness, the diffusion concentration is significantly reduced, and the area of the dangerous area is significantly reduced. Compared with the traditional simulation results, the improved model is reasonable and has certain guiding significance, which provides a scientific basis for nuclear accident emergency response and risk assessment.

Keywords: Radionuclide; Gaussian plume; Precipitation; Numerical simulation

Online publication: May 2, 2025

1. Introduction

The growth of global energy demand has pushed nuclear energy to become a key component of the future energy structure, but its development and utilization are accompanied by the risk of radioactive nuclides leakage [1]. Radioactive substances released by nuclear accidents or facility operations can threaten the environment and public safety through atmospheric diffusion. Current radionuclide diffusion models mainly include the Gaussian model, Lagrangian model, Euler equation, and CFD numerical simulation [2–7]. The Gaussian model is based on the assumption of stable meteorological conditions and describes the Gaussian distribution characteristics of pollutants in the y/z direction. It is suitable for early close-range rapid simulation of nuclear accidents, but it needs to be corrected in combination with actual meteorological parameters [8]. Wang Kongsen verified the applicability of the Gaussian model in gas leakage simulation [9]; Huafeng Jiao analyzed the influence of meteorology and terrain on diffusion and the removal effect of rainfall on soluble nuclides [10]; Sun Zhikuan team introduced wind field correction and optimized boundary conditions such as wall reflection [11].

This paper takes the radioactive nuclide Cs from the nuclear leakage of Daya Bay Nuclear Power Station as the research object, considers the effects of different rainfall intensities and different ground roughness on diffusion at a certain height, analyzes the numerical relationship between these two factors and the diffusion concentration and diffusion distance, and simulates the concentration range of radioactive nuclides diffusion.

2. Mathematical model

2.1. Gaussian plume model

The Gaussian plume model has the advantages of few input parameters, a simple and convenient calculation method, and low calculation cost. It has been widely used in the study of atmospheric diffusion of radioactive substances. In the study of the diffusion behavior of radionuclides, the effect of their radioactive decay on the concentration of nuclides is particularly significant, especially when dealing with nuclides with short half-lives. This shows that when applying the Gaussian plume model to analyze the diffusion of nuclides, the radioactive decay effect must be taken into account. During the diffusion process, radioactive decay has a significant effect on the spatial distribution of nuclide concentrations in the atmosphere. Since radionuclides follow classical decay laws, their three-dimensional movement in the atmosphere can be described by the following control equations.

$$\frac{\partial c}{\partial t} = E_x \frac{\partial^2 c}{\partial x^2} + E_y \frac{\partial^2 c}{\partial y^2} + E_z \frac{\partial^2 c}{\partial z^2} - u_x \frac{\partial c}{\partial x} - u_y \frac{\partial c}{\partial y} - u_z \frac{\partial c}{\partial z} - \lambda c \tag{1}$$

Where: c is the concentration of radionuclide, Bq/m^3; E_x, E_y, E_z are the turbulent diffusion coefficients in the x, y, and z coordinate directions; u_x, u_y, u_z, are the flow components in the x, y, and z coordinate directions; λ is the decay coefficient of the radionuclide, s^{-1}; y is the lateral distance, m; z is the vertical distance, m.

Since the Gaussian point source model assumes that the radioactive nuclides move in a stable state, the following is obtained:

$$\frac{\partial c}{\partial t} = 0 \tag{2}$$

The analytical solution of the above control equation is obtained by calculating Equation (1) and Equation (2):

$$c(x, y, z, t) = \frac{Q \times e^{-\lambda t}}{\left(x_0 + \sqrt{4\pi E_x t}\right)\left(y_0 + \sqrt{4\pi E_y t}\right)\left(z_0 + \sqrt{4\pi E_z t}\right)} e^{-\frac{(x-u_x t)^2}{4E_x t}} e^{-\frac{\left(y-u_y t\right)^2}{4E_y t}} e^{-\frac{(z-u_z t)^2}{4E_z t}} \tag{3}$$

For Formula (3), Q is the source release rate, Bq/s;

Let $\sigma_x^2 = 2E_x t, \sigma_y^2 = 2E_y t, \sigma_z^2 = 2E_z t$, and Equation (3) is transformed into

$$c(x,y,z,t)=\frac{Q\times e^{-\lambda t}}{(x_0+\sqrt{8\pi\sigma_x})(y_0+\sqrt{8\pi\sigma_y})(z_0+\sqrt{8\pi\sigma_z})}e^{-\frac{(x-u_xt)^2}{2\sigma_x^2}}e^{-\frac{(y-u_yt)^2}{2\sigma_y^2}}e^{-\frac{(z-u_zt)^2}{2\sigma_z^2}} \tag{4}$$

Where, σ_x is the downwind diffusion coefficient, m; σ_y is the horizontal diffusion parameter, m; σ_z is the vertical diffusion coefficient.

The concentration distribution of the ground continuous point source Gaussian plume model can be obtained from Formula (4).

$$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\left\{exp\left[\frac{-(z-H)^2}{2{\sigma_z}^2}\right]+exp\left[\frac{-(z+H)^2}{2{\sigma_z}^2}\right]\right\} \tag{5}$$

Formula (1): C (x, y, z) is the air concentration at x meters downwind, y meters horizontally, and z meters above the ground, Bq/m^3; u is the average wind speed, m/s; σ_y is the horizontal diffusion parameter, m; σ_z is the vertical diffusion coefficient, m; y is the horizontal distance, m; and z is the vertical distance, m.

$$C(x,y,z,H)=\frac{Q}{2\pi u\sigma_y\sigma_z}exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\left\{exp\left[\frac{-(z-H)^2}{2{\sigma_z}^2}\right]+exp\left[\frac{-(z+H)^2}{2{\sigma_z}^2}\right]\right\}exp\left(-\frac{\lambda x}{u}\right) \tag{6}$$

Where: H is the effective release height, that is, the chimney height plus the plume lifting height, m.

If the half-life of a radionuclide is $T_{1/2}$, then the half-life $T_{1/2}$ can be expressed as:

$$T_{1/2}=\frac{ln\,2}{\lambda} \tag{7}$$

Therefore, the Gaussian plume model considering the attenuation of radionuclides is as follows:

$$C(x,y,z,H)=\frac{Q}{2\pi u\sigma_y\sigma_z}exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\left\{exp\left[\frac{-(z-H)^2}{2{\sigma_z}^2}\right]+exp\left[\frac{-(z+H)^2}{2{\sigma_z}^2}\right]\right\}exp\left(-\frac{0.693x}{3600T_{1/2}u}\right) \tag{8}$$

2.2. Wet deposition

Wet deposition refers to the removal of atmospheric pollutants by precipitation (such as rain and snow) through adsorption or settling of water droplets. The effect of precipitation on pollutants in the plume Λ is expressed by the washoff coefficient. The relationship between the washoff coefficient Λ and rainfall intensity is expressed as follows:

$$\Lambda=aI^b \tag{9}$$

Where I is the rainfall intensity (mm/h); a,b is the empirical coefficient, and its value can be found in **Table 1**.

The flushing coefficient (s^{-1}) is usually used to describe the effect of rainfall on the cleansing of pollutants in the smoke plume, and the rainfall intensity value can be used instead of the rainfall amount.

Table 1. a and b reference values

Airborne emissions	Aerosol	Iodine elements	Organic iodine compounds
a	1.2×10^{-5}	8×10^{-5}	8×10^{-7}
b	0.8	0.6	0.6

For plume loss caused by wet deposition, the source strength can be corrected by using the wet deposition attenuation factor, which can be expressed as:

$$\frac{\partial c}{\partial t} = E_x \frac{\partial^2 c}{\partial x^2} + E_y \frac{\partial^2 c}{\partial y^2} + E_z \frac{\partial^2 c}{\partial z^2} - u_x \frac{\partial c}{\partial x} - u_y \frac{\partial c}{\partial y} - u_z \frac{\partial c}{\partial z} - \lambda c - \Lambda c \tag{10}$$

The Gaussian plume model with control is as follows:

$$f_w = e^{-\Lambda t} = exp(-\Lambda \frac{x}{u}) \tag{11}$$

In a steady state $\frac{\partial c}{\partial t} = 0$, the Gaussian plume model of radionuclides can be expressed as:

$$C(x, y, z, H) = \frac{Q}{2\pi u \sigma_y \sigma_z} exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\left\{exp\left[\frac{-(z-H)^2}{2{\sigma_z}^2}\right] + exp\left[\frac{-(z+H)^2}{2{\sigma_z}^2}\right]\right\} exp\left(-\frac{0.693x}{3600T_{1/2}u}\right) \tag{12}$$

2.3. Surface roughness

There are two meanings of ground roughness. One is to indicate the degree of unevenness of the ground, and the other is a comprehensive mechanical parameter that indicates the effect of the surface of an object on the fluid, which is the interaction between the surface and the atmosphere. The ground roughness uses the following formula:

$$\sigma_{y1} = \sigma_y(1 + 0.38Z_0) \tag{13}$$

Where, Z_0 is the roughness coefficient, and σ_{y1} is the lateral diffusion coefficient perpendicular to the dominant wind direction after adding the roughness element.

$$\sigma_{z1} = \sigma_z(2.53 - 0.13 \times log\,x) \times \frac{Z_0^{(0.35 - 0.03 \times log\,x)}}{0.55 + 0.042 \times log\,x} \tag{14}$$

Where is σ_{y1} the lateral diffusion coefficient perpendicular to the dominant wind direction after adding rough elements.

The diffusion parameters are determined by the horizontal and vertical coefficients based on the atmospheric stability level and the basic terrain conditions around the leak source. Atmospheric stability is usually determined using the Pasquill classification method. The Paasquill-Gifford model diffusion coefficients are shown in **Table 2**.

Table 2. Classification of atmospheric stability levels

Atmospheric stability						
Surface or 10 m high wind speed, u (m/s)	**Solar radiation level**					
	-3	**-2**	**-1**	**0**	**1**	**2**
<2	A	A-B	B	D	E	F
2≤u<3	A-B	B	C	D	E	F
3≤u<5	B	B-C	C	D	D	E
5≤u<6	C	C-D	D	D	D	D
U≥6	D	D	D	D	D	D

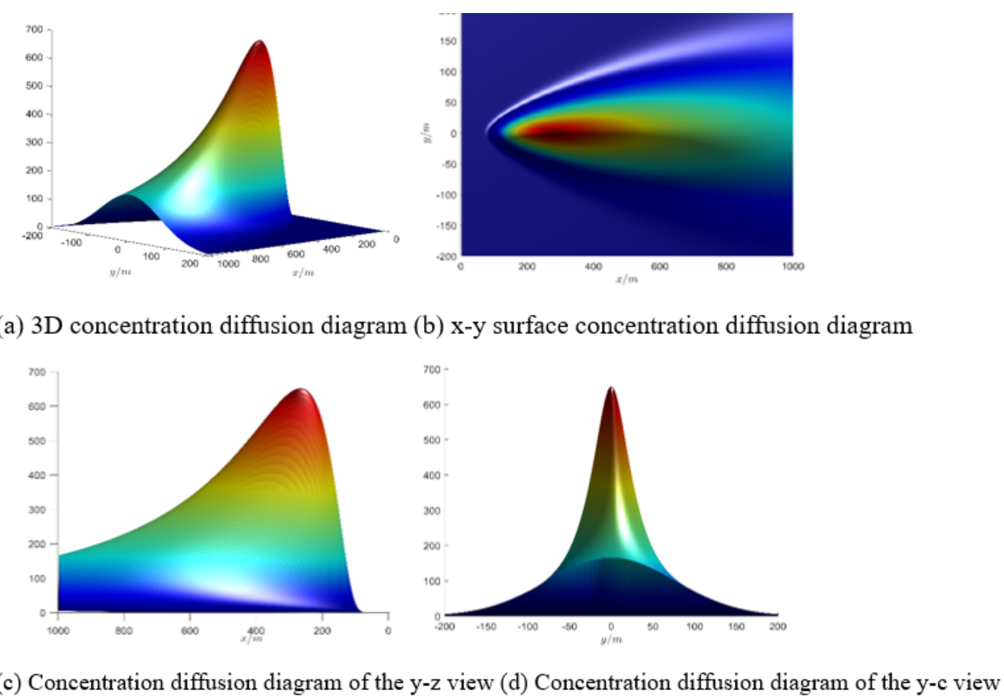
Introducing Equations (8), (9), and (10) into the Gaussian plume model equation (6), the Gaussian plume model equation after control correction can be obtained:

$$C(x,y,z)=\frac{Q\cdot f_W}{2\pi u\sigma_{y1}\sigma_{z1}}exp\left(-\frac{y^2}{2\sigma_{y1}{}^2}\right)\left\{exp\left[\frac{-(z-H)^2}{2\sigma_{z1}{}^2}\right]+exp\left[\frac{-(z+H)^2}{2\sigma_{z1}{}^2}\right]\right\}exp\left(-\frac{0.693x}{3600T_{1/2}u}\right) \tag{15}$$

3. Simulation and analysis

3.1. Traditional Gaussian plume model simulation

Based on the meteorological data of Daya Bay Nuclear Power Station (wind speed 2 m/s, stability level D), taking Cs-137 (source strength 8.7Bq/s, half-life 30.17a, effective height 20 m) as the object, MATLAB was used to construct a Gaussian plume model considering rainfall and ground roughness to simulate the nuclide diffusion concentration distribution, as shown in **Figure 1**.



(a) 3D concentration diffusion diagram (b) x-y surface concentration diffusion diagram

(c) Concentration diffusion diagram of the y-z view (d) Concentration diffusion diagram of the y-c view

Figure 1. Radionuclide ^{137}Cs diffusion diagram

Figure 1 shows the isoconcentration curves of nuclide diffusion in the z=20 m plane. The diffusion range in the x-axis direction stabilizes after 500 m downwind, which is mainly dominated by wind speed and wind direction. The diffusion in the y-axis direction tends to be stable after 50 m, which is controlled by molecular diffusion and turbulent diffusion. The wind field intensity determines the x-axis transmission distance, while the y-axis diffusion reaches equilibrium faster due to turbulent mixing.

3.2. Impact of rain washing

According to the precipitation classification published by the National Meteorological Administration, this paper selects I = 1.5 mm / h, 3 mm / h, and 15 mm / h as representatives, representing light rain, heavy rain, and extremely heavy rain, respectively. Substituting into Formula (11) to calculate and draw the radionuclide ^{137}Cs diffusion distribution map under different rainfall intensities, as shown in **Figure 2**.

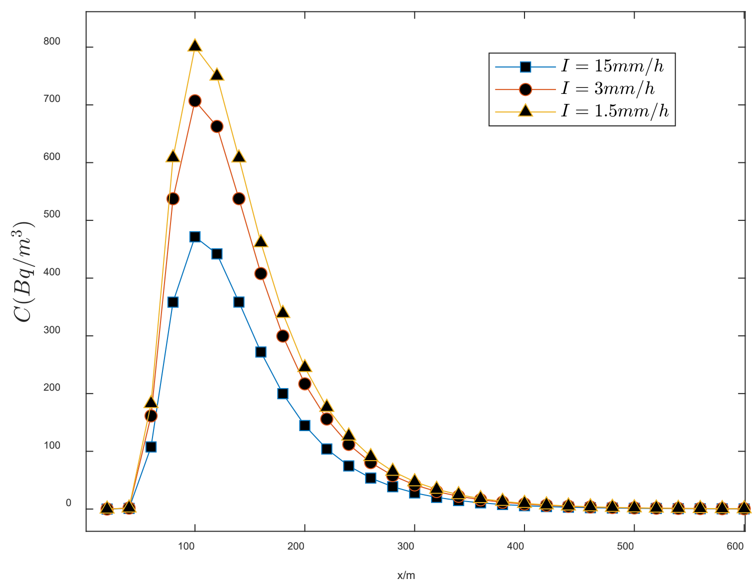
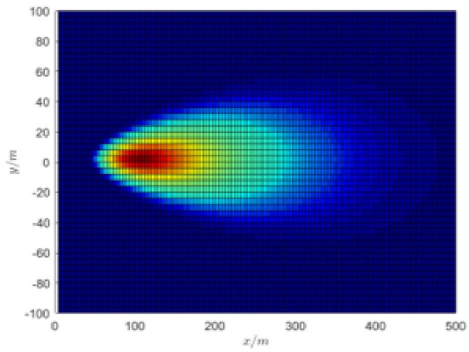


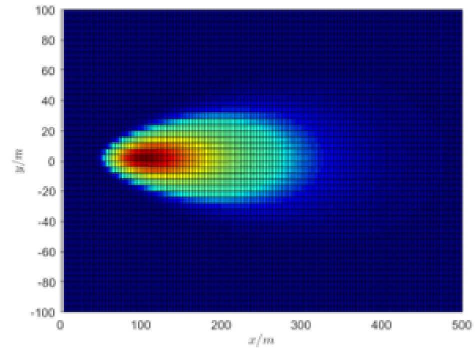
Figure 2. Variation curve of diffusion distance with rainfall intensity

Figure 2 shows the curve of the diffusion concentration and diffusion distance of the radioactive nuclides of the leakage source ^{137}Cs in the x-axis direction under different rainfall intensity levels. As shown in **Figure 2**, when I=15 mm/h, 3 mm/h, and 1.5 mm/h, the concentration reaches the maximum value at a distance of 100 m up and down the x-axis, and the maximum values are 472 Bq/m^3, 707 Bq/m^3, and 800 Bq/m^3, respectively. When I=15 mm/h, the curve is close to smooth at a distance of about 280 m up and down the x-axis, and the diffusion concentration tends to be stable. When I=3 mm/h and 1.5 mm/h, the concentration value tends to be stable only when the distance up and down the x-axis is about 400 m.

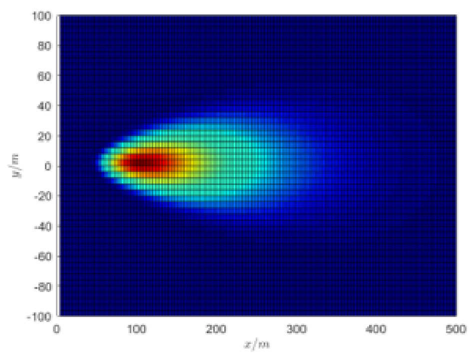
At a distance of 50 m downwind, the relationship between the diffusion concentration and distance under three different rainfall intensity levels was studied and the relevant diffusion concentration distribution diagram was drawn, as shown in **Figure 3**.



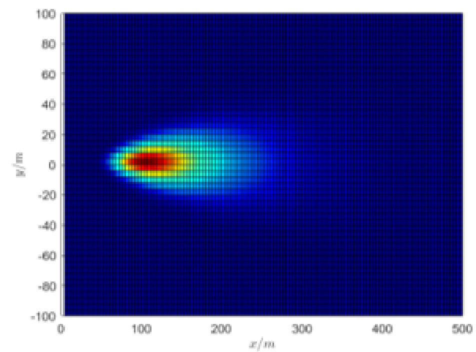
(a) I=0 mm/h



(b) I=1.5 mm/h



(c) I=3 mm/h



(d) I=15 mm/h

Figure 3. Diffusion isoconcentration curves under different rainfall intensities

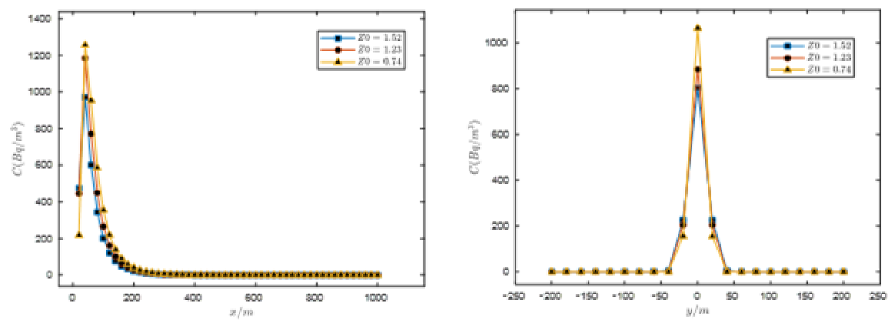
Figure 3 shows that as the rainfall intensity increases, the diffusion range of the nuclides in the z=20 m plane is significantly reduced. Taking the light blue concentration area as an example, the maximum diffusion distance decreases from 336 m when there is no rain to 20 m when there is heavy rainfall. Rainfall triggers the wet deposition of nuclides, accelerating the deposition of radioactive substances from the atmosphere to the ground, indicating that the rainfall intensity is strongly negatively correlated with the diffusion distance.

From Formula (9) and Formula (10), it can be seen that the surface roughness affects the gas diffusion by affecting the diffusion coefficient. The values of surface roughness are shown in **Table 3**.

Table 3. Ground roughness values

Height from ground/m	Roughness category		
	A	B	C
5	1.09	1.00	0.65
10	1.28	1.00	0.65
15	1.42	1.13	0.65
20	1.52	1.23	0.74

In this paper, the ground roughness at 20 m is selected for calculation. According to Formula (11), ^{137}Cs the relationship curve between the diffusion concentration of radionuclides and the roughness in different diffusion directions under different ground roughness is plotted, as shown in **Figure 4**.



(a) Downwind (b) Acrosswind

Figure 4. Relationship between diffusion concentration and roughness in different diffusion directions

Figure 4 shows that under different ground roughness conditions, the nuclide concentration in the x-axis direction increases to a peak value first and then stabilizes with the diffusion distance. When the ground roughness is 1.52, 1.23, and 0.74, the concentration reaches the maximum value at 40 m. Comparing the influence of rainfall intensity, it is found that the trends of the concentration distance curves of the two are similar, but the driving effect of rainfall intensity on concentration attenuation is more significant. Increasing the ground roughness (such as vegetation coverage) can effectively inhibit the diffusion range of nuclides.

The above experiments mainly studied the changes in the diffusion range of radionuclides. Therefore, the main measurement criteria are the diffusion area and concentration. The rainfall intensity can be taken as 15 mm/h, and the ground roughness can be 1.52. Substituting into Equation (11) for calculation, it can be simulated that when the rain washing effect and the ground roughness act together on the traditional Gaussian plume model, the concentration diffusion distribution of radionuclides ^{137}Cs is shown in **Figure 5**.

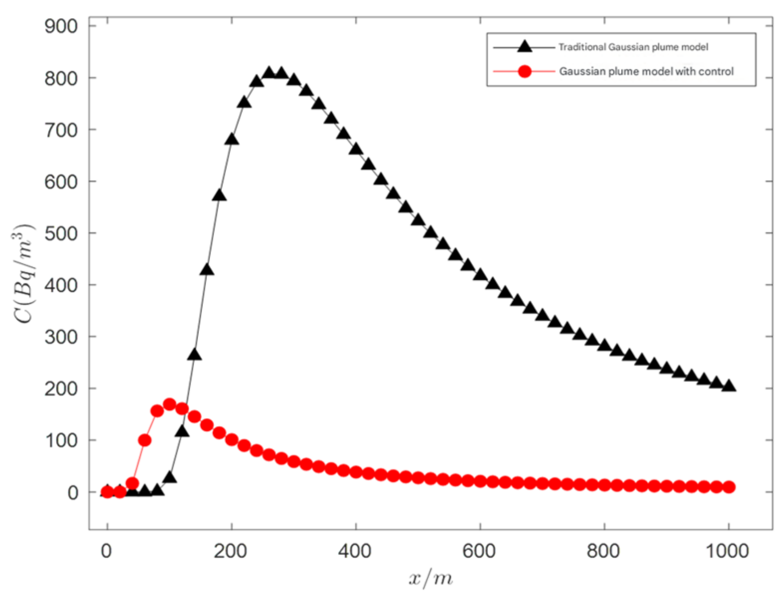


Figure 5. Relationship between downwind distance and diffusion concentration

Figure 5 shows that at the same downwind distance, the nuclide diffusion concentration of the improved model is lower than that of the traditional model. The improved model has a concentration peak of 166 Bq/m^3 at 80 m, while the traditional model has a peak of 812 Bq/m^3 at 260 m, and the diffusion range of the improved model is greatly reduced. This shows that the rain washing effect and the roughness of the ground cause the concentration peak to move forward and the diffusion range to be significantly reduced.

4. Conclusion

In this study, rain wash effect and ground roughness parameters were introduced into the traditional Gaussian plume model, and an improved model was constructed to quantify the independent and coupled effects of the two on the diffusion of radionuclides. Based on the cesium leakage scenario of Daya Bay Nuclear Power Station, the analysis shows that the rain wash effect is significantly enhanced with the increase of rainfall intensity, resulting in the acceleration of nuclide wet deposition and the shortening of the downwind diffusion distance by about 15%–30%; the increase of ground roughness improves the vertical diffusion efficiency by enhancing turbulent disturbance, reducing the crosswind diffusion distance by 20%–40%, and the inhibitory effect on lateral diffusion is stronger than that on longitudinal diffusion. The improved model is more in line with the actual data in the early prediction of the leakage, revealing that when the roughness and rainfall intensity act together, the peak concentration of nuclides near the ground is 10%–25% higher than that of the traditional model. The results show that the two factors directly affect the diffusion range and concentration gradient distribution characteristics by changing the deposition rate and turbulent structure.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Qi LL, 2023, Study on the Adsorption and Migration of Se (IV) and Sr (II) in Granite and the Influence of Crack Filling on it, thesis, Jilin University.

[2] Korsakissok I, Mathieu A, Didier D, 2013, Atmospheric Dispersion and Ground Deposition Induced by the Fukushima Nuclear Power Plant Accident: A Local-scale Simulation and Sensitivity Study. Atmospheric Environment, 2013(70): 267–279.

[3] Leelossy A, Meszaros R, Lagzi I, 2011 Short and Long-term Dispersion Patterns of Radionuclides in the Atmosphere around the Fukushima Nuclear Power Plant. Journal of Environmental Radioactivity, 102(12): 1117–1121.

[4] Mikkelsen T, Thykier-Nielsen S, Astrup P, et al., 1997, MET-RODOS: A Comprehensive Atmospheric Dispersion Module. Radiation Protection Dosimetry, 73(1–4): 45–55.

[5] Chino M, Hiromasa N, Haruyasu N, et al., 2011, Preliminary Estimation of Release Amounts of 131I and 137Cs Accidentally Discharged from the Fukushima Daiichi Nuclear Power Plant into the Atmosphere. Journal of Nuclear Science and Technology, 48(7): 1129–1134.

[6] Li H, Zhang HS, Cai H, et al., 2013, Numerical Simulation of Pollutant Diffusion and Accident Release Source Term Assessment of the Fukushima Nuclear Power Plant Leak Accident in Japan. Journal of Safety and Environment, 13(5): 265–270.

[7] Hu XF, Li D, Huang H, et al., 2014, Modeling and Sensitivity Analysis of Transport and Deposition of Radionuclides from the Fukushima Dai-ichi Accident. Atmospheric Chemistry and Physics, 14(20): 11065–11092.

[8] Leelossy A, Meszaros R, Kovacs A, et al., 2017, Numerical Simulations of Atmospheric Dispersion of Iodine-131 by Different Models. PloS one, 12(2): e0172312.

[9] Wang KS, 2012, Research on Rapid Estimation Method of Chlorine Leakage Concentration Distribution Based on Gaussian Model. China Occupational Safety Science and Technology, 8(9): 33–37.

[10] Hua FJ, 2017, Study on the Removal Characteristics of Urban Aerosols by Rainfall and Deposition Effects, thesis, Donghua University.

[11] Pirouzmand A, Zahra K, Peyman D, 2018, Atmospheric Dispersion Assessment of Radioactive Materials during Severe Accident Conditions for Bushehr Nuclear Power Plant using HYSPLIT Code. Progress in Nuclear Energy, 2018(108): 169–178.

[12] Sun ZK, 2013, Further Study on Gaussian Plume Diffusion Model. Environment and Sustainable Development, 38(5): 107–109.