Research on the Diffusion of Harmful Gases from Ships Based on Gaussian Plume Model

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Abstract. After a harmful gas diffusion accident occurs on ships, grasping the harmful gas diffusion behavior and possible impact range is the key to emergency rescue. In this paper, a Gaussian plume model is used to construct a simulation system for the diffusion of harmful gases from ships, and four comparative experiments are designed. The simulation is realized based on MATLAB platform programming. Under the conditions of different geographical locations, time periods and meteorological conditions when the accident occurs, the distribution of harmful gas diffusion concentration and the range of influence are analyzed. This work may provide a scientific basis for evacuation and emergency response plan formulation in the water area surrounding the accident.

1. Introduction
Due to the high intensity of coastal shipping activities in China, the probability of ship accidents is relatively high. If the accident leads to the diffusion of harmful gases, the consequences are often more serious, causing great harm to the society and the ecological environment. On January 6, 2018, the Panamanian oil tanker "SANCHI" collided in the Yangtze River Estuary. During the accident, due to the burning of the ship, a variety of harmful gases were produced, which caused serious pollution to the marine and atmospheric environment in the accident area and the surrounding area. Dispersion accidents of harmful gases from ships are often sudden, difficult to control, and have a wide range of influence. It is particularly important to grasp the gas diffusion behavior and the range of areas that may be affected, so as to provide a scientific basis for timely formulation of emergency rescue plans and reduce accident losses. The gas diffusion model can describe the diffusion behavior of harmful gases in the atmosphere, so it can provide a basis for the emergency management of harmful gas diffusion accidents from ships.

At present, there are many air pollution diffusion models developed in China and abroad. Among the conventional diffusion models, the Gaussian model has been applied relatively earliest and is relatively more widely used. Scholars applied Gaussian model to simulate the leakage and diffusion of harmful gases during transportation [1], simulate the dangerous goods leakage accidents in chemical parks [2], study the harmful gas diffusion in subway stations [3], simulate and analyze the diffusion law of PM2.5 pollution source [4], simulate the city gas leakage accident [5], simulate the natural gas leakage accident [6, 7], study the diffusion of ship exhaust gas [8], research the leakage and diffusion of railway gas dangerous cargo [9], simulate the spatial distribution of particulate matter emitted by thermal power plants [10].

This paper constructs a model for the diffusion of harmful gases from ships based on Gaussian plume, and designs four comparative experiments to study the diffusion law, impact range, hazard degree and
the development trend of air pollutants caused by accidental combustion under different geographical locations, time periods and meteorological conditions. This work may provide a scientific basis for evacuation and emergency response plan formulation in the water area surrounding the accident.

2. Material and methods

2.1. Simulation system

This paper adopts the Gaussian plume model and makes the following four assumptions[11]: (1) The gas diffusion concentration conforms to the Gaussian (normal) distribution in the space; (2) In the entire diffusion space, the wind speed is uniform and stable, and the wind speed is greater than 1 m/s; (3) The emission source is continuous and uniform; and (4) The quality of pollutants is conserved during the diffusion process, and the influence of its chemical transformation and sedimentation can be ignored.

In the Gaussian model coordinate system, the wind direction is the x-axis, the downwind direction is the positive direction of the x-axis, the crosswind direction is the y-axis, and the wind direction is rotated 90° counterclockwise as the positive direction of the y-axis. Then the average concentration of pollutants at any point \((x, y, z)\) in the downwind direction is:

\[
C(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z} e^{-\left(\frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right)}
\]  

Where
- \(Q\) = the emission source (g/s)
- \(\sigma_y, \sigma_z\) = the standard deviation of the pollutants in the y and z directions (m)
- \(u\) = the average wind speed (m/s)

Taking into account the influence of the water surface on gas diffusion, the "image source method" is used to process it. The pollutant concentration at any point P is the sum of the two parts (Figure 1), the first one is the pollutant concentration when there is no water surface, and the second one is the increased pollutant concentration due to water surface reflection.

The concentration of pollutants caused by the actual source at point P is:

\[
C_1 = \frac{Q}{2\pi\sigma_y\sigma_z} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{(z-H)^2}{2\sigma_z^2}\right)\right]
\]  

\[
C_2 = \frac{Q}{2\pi\sigma_y\sigma_z} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{(z+H)^2}{2\sigma_z^2}\right)\right]
\]  

**Figure 1.** Schematic diagram of the contribution of actual and image sources to the concentration of point P.
The pollutant concentration at point P is the sum of the effects of the actual source and the image source, i.e. \( C = C_1 + C_2 \)

\[
C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \times \left[ \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right]
\] (4)

When a ship burning accident occurs, the gas lift is often high. Therefore, in this paper, when simulating it using the Gaussian plume model, the influence of the image source is ignored, the following equation is used to calculate the pollutant concentration at any point:

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

Where \( Q \) = the emission source (g/s)  
\( \sigma_y, \sigma_z \) = the standard deviation of the pollutants in the y and z directions (m)  
\( u \) = the average wind speed (m/s)  
\( H \) = the effective height of the emission source (m)

2.2. Parameters

(1) Wind

Generally, the measured wind speed is the wind speed at a height of 10 meters above the ground, which can be converted into the wind speed at the corresponding height by Equation 2.6 [14].

\[
\frac{u}{u_1} = \left(\frac{h}{h_1}\right)^n
\] (6)

Where \( u \) = the wind speed at height h (m/s)  
\( u_1 \) = the monitored wind speed (m/s)  
\( h_1 \) = the height of monitoring wind speed (m), namely 10 meters  
\( n \) = a constant, the values of different ground types are shown in Table 1 [15], and the value in the marine environment is 0.1.

**Table 1.** The values of \( n \) in different ground types.

| Ground types                          | \( n \)  |
|---------------------------------------|--------|
| Sea surface, flat and open land       | ≤0.1   |
| Crop area                             | 0.1-0.3|
| Villages, scattered woods              | 0.3-1  |
| Scattered city                        | 1-4    |
| Dense buildings                       | 4      |

(2) Atmospheric stability

The atmospheric stability is determined according to Table 2 [11]. According to conventional meteorological data such as cloud cover, cloud shape, solar radiation status and ground wind speed (average wind speed at a height of 10m above the ground) when the accident occurs, the atmospheric stability level is determined according to Table 2.

**Table 2.** Pasquill Atmospheric Stability classes.

| Ground wind speed (10m above the ground) (m/s) | Day Solar radiation status | Cloudy (day or night) | Thin clouds covering the sky or low clouds | Cloud cover ≤4/10 |
|----------------------------------------------|---------------------------|------------------------|------------------------------------------|------------------|
| <2                                          | A°                        | D°                     | E°                                      | F°               |
| 2-3                                         | A-B                       | D                      | E°                                      | F°               |
| 3-5                                         | B                         | D                      | D                                       | E°               |
| 5-6                                         | C                         | D                      | D                                       | D°               |
| >6                                          | C                         | D                      | D                                       | D°               |

\( ° \) Extremely unstable; \( ° \) Unstable; \( ° \) weakly unstable; \( ° \) Neutral; \( ° \) weakly stable; \( ° \) Stable.
(3) Diffusion coefficient
After the atmospheric stability is determined, the corresponding diffusion coefficient can be determined according to Table 3 [15].

Table 3. Diffusion coefficient equation.

| Atmospheric Stability classes | $\sigma_y$                | $\sigma_z$                |
|------------------------------|---------------------------|---------------------------|
| A                            | $0.22x(1+0.0001x)^{0.5}$  | 0.20x                     |
| B                            | $0.16x(1+0.0001x)^{0.5}$  | 0.12x                     |
| C                            | $0.11x(1+0.0001x)^{0.5}$  | $0.08x(1+0.0002x)^{0.5}$  |
| D                            | $0.08x(1+0.0001x)^{0.5}$  | $0.06x(1+0.0015x)^{0.5}$  |
| E                            | $0.06x(1+0.0001x)^{0.5}$  | $0.03x(1+0.0003x)^{0.5}$  |
| F                            | $0.04x(1+0.0001x)^{0.5}$  | $0.016x(1+0.0003x)^{0.5}$ |

(4) Emission source
The emission source and the effective height are determined according to the actual situation of the accident.

2.3. Comparative experiments
Assuming that an oil spill and combustion accident occurred and caused the diffusion of harmful gases, the emission source Q was 1000g/s and the source height H was 100 meters. The different accident geographical locations (Inland River or Coast), time periods (day or night) and meteorological conditions would lead to different consequences. In order to clearly understand the influence of different parameters on the diffusion of harmful gases, the following comparative experiments are designed.

Table 4. Comparative experiments

| Experiments | Geographical locations | wind speed (m/s) | Time periods | Meteorological conditions                  |
|-------------|------------------------|------------------|--------------|--------------------------------------------|
| E1          | Inland River           | 5                | Day          | Sunny day with strong solar radiation      |
| E2          | Inland River           | 5                | Day          | Cloudy                                     |
| E3          | Inland River           | 5                | Night        | Cloud cover $\leq 4/10$                    |
| E4          | Coast                  | 10               | Day          | Sunny day with strong solar radiation      |

3. Results and discussion
The four experimental parameters are input into the simulation system for the diffusion of harmful gases from ships based on the Gaussian plume model, and the simulation is realized based on the MATLAB platform programming. The results are shown in Figure 2 ~ Figure 4.

(1)The influence of meteorological conditions on gas diffusion
Except for the different meteorological conditions (Solar radiation), the other data of experiment E1 and experiment E2 are consistent. The results of gas diffusion simulation based on Gaussian plume model are shown in Figure 2.

As can be seen from the results, when other conditions are the same, the impact of solar radiation status on gas diffusion is quite obvious. The stronger the solar radiation, the more obvious the disturbance to the air. When the atmospheric environment is relatively unstable, the harmful gas diffuses faster, and the range of influence will be wider. The atmospheric environment in cloudy days is relatively stable, gas accumulation is not easy to diffuse, and the range of the influence is relatively small, but correspondingly, its concentration is high and the degree of pollution is high.
Figure 2. Meteorological conditions comparative experiments.

(2) The influence of accident time periods on gas diffusion
E1 and E3 are to investigate the impact of different time periods (day or night) on the diffusion of harmful gases. The simulation results are shown in Figure 3.
Similar to the solar radiation comparative experiments, the atmosphere environment is more unstable during the day due to factors such as strong solar radiation and high temperature. After a ship harmful gas diffusion accident occurs, the diffusion speed is faster than at night, and the gas concentration is lower due to the rapid mixing with the surrounding air. The temperature at night is low, the atmospheric environment is relatively stable, and the gas diffusion rate is slow, which is likely to cause high concentrations of harmful gases in the surrounding area of the accident.

(3) The influence of accident location on gas diffusion

There will be many factors that are different when harmful gas diffusion accidents occur in inland rivers and coastal areas. This article only simplified this to the difference in wind speed. E1 and E4 are comparative experiments to investigate the difference. The simulation results are shown in Figure 4.

From the results of the comparative experiment simulation of the impact of the accident location (wind speed) on gas diffusion, it can be seen that strong winds intensify the mass and heat transfer between the mixed gases, intensify the turbulent diffusion and heat exchange of the gas, and make the harmful gas diffusion distance significantly increase in the downwind direction after the accident.
4. Conclusions

In this study, Gaussian plume model was selected to build a simulation system for the diffusion of harmful gases from ships, and four comparative experiments are designed. The simulation was realized based on MATLAB platform programming. Under the conditions of different geographical locations, time periods and meteorological conditions when the accident occurs, the distribution of harmful gas diffusion concentration and the range of influence are analysed. The simulation results show that the influence of solar radiation on gas diffusion is quite obvious. Compared with cloudy days, harmful gases diffuse faster under strong solar radiation, and the range of the accident impact will be wider. The experimental results of the control group at different time periods show that the gas diffusion rate is slower at night than during the day, which is likely to cause higher concentration of harmful gases in the area surrounding the accident. Strong winds intensify the mass and heat transfer between the mixed gases, intensify the turbulent diffusion and heat exchange of the gas, and make the harmful gas diffusion distance significantly increase in the downwind direction after the accident.

Using the Gaussian plume-based simulation system for the diffusion of harmful gases from ships built by this research, combined with the meteorological conditions at the time of the accident, analyse the concentration distribution of harmful gases in space, and predict the impact range of the accident, which can provide scientific guidance for the construction of emergency rescue system and emergency management of the harmful gas diffusion accidents from ships, and provide decision-making basis for relevant management departments. It is worth noting that since the application of the Gaussian plume model is based on several assumptions and is in a relatively ideal state, the actual scene of a ship accident on water is much more complicated. When formulating emergency plans based on the results of gas diffusion simulations, the actual situation should also be combined to make the result more reasonable.

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