Research on Gas Diffusion Law of Coal Mine Roadway Based on Gauss Plume Model

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Abstract: The gas environment of coal mine is complex, so it is urgent to monitor gas automatically and accurately through fixed instruments and mobile equipment. Combine with gas diffusion theory, a gas concentration prediction method based on the Gauss plume model was proposed, and the gas diffusion model in coal mine roadway was constructed. According to the virtual image source method, the influence of boundary reflection on gas diffusion was introduced, and the gas diffusion coefficient was modified by genetic algorithm. The results of simulation analysis and actual data analysis indicate that this method can reveal the gas distribution law of coal mine roadway, besides it can improve the real-time, convenience and reliability of gas concentration detection in the roadway.

1. Introduction
The detection of gas environment information in coal mine has always been a research hotspot of daily inspection and rescue [1]. The gas environment information in coal mine mainly includes gas, carbon monoxide, carbon dioxide, oxygen, temperature, humidity, wind speed and direction, pressure [2]. At present, the combination of online monitoring and manual inspection is mainly used by the environmental detection in coal mine. Research on the gas distribution law of coal mine contributes to the rapid development of coal mine safety production and accident rescue.

Gauss gas model is used to research the distribution law of light gas or gas with the same density as air. It is a kind of probability model. The simulation is carried out from the macro level. Through the probability statistics at a time point, the gas diffusion and concentration distribution in this time period can be obtained. The calculation is small and it is suitable for real-time application in engineering with high requirements. There are two types of Gauss model: Gauss puff model and Gauss plume model. Gauss puff model is suitable for instantaneous leakage mode and Gauss plume model is suitable for continuous leakage mode [3].

Sánchez Sosa Jorge Edwin proposed a verification method of Gauss plume model in an empty room, he believed that the simplicity of the Gauss plume model and its variables closer to reality can better explain the behavior of pollutants through the wind [4]. Liu X used genetic algorithm to determine the best diffusion parameters, and obtained the best diffusion parameter value that can be used to predict CO₂ diffusion by Gauss plume model, and the Gauss model can quickly estimate the level of CO₂ concentration was established [5]. Based on the traditional Gauss plume model, Xie Xueling introduced the reflection coefficient and the collision times of the horizontal boundary of the finite space,
established the improved Gauss plume model suitable for the gas diffusion in the finite space\(^6\). Wang Dan used Gauss plume model to research the influence factors of leakage and diffusion of liquid ammonia storage tank, and determined the dangerous area of liquid ammonia diffusion poisoning\(^7\). In view of the shortcomings of Gauss prediction model, Li Shiwei introduced the dynamic change of leakage intensity, and synthesized the wind speed and the diffusion speed of radioactive gas itself by the way of included angle coefficient, which can better simulate the gas concentration in different periods, regions and airflow states during the diffusion process of radioactive gas\(^8\). Liu Yongli used gauss puff model to simulate the toxic gas propagation of gas explosion in coal mine. It can be seen from the comparison between the experimental and theoretical data that the calculation results of the mathematical model were close to the experimental data and had certain reliability \(^9\). Jia Zhiwei improved the Gauss puff model according to the actual situation of gas diffusion in gas explosion accident, and obtained the formula suitable for the gas diffusion rule of gas explosion accident underground, at the same time, modified the diffusion parameters in the formula\(^{10}\).

In conclusion, the Gauss gas diffusion model can better reflect the continuous gas diffusion distribution. In view of this, this paper fully considers the diffusion law of gas in the finite space, and establishes a Gauss plume model suitable for coal mine roadway. Based on the influence of roadway boundary on gas diffusion, the influence degree of different gas emission speed, diffusion coefficient and wind speed on gas diffusion of roadway is simulated, in order to express the distribution law of gas in coal mine roadway with a mathematical model and provide theoretical basis for intelligent detection.

2. Gas diffusion law of coal mine roadway

In the normal mining of coal mine, the air exchange between underground and ground is carried out by setting ventilation equipment, so as to ensure the pressure balance inside and outside the air flow in the tunnel is relatively stable, the gas diffusion is affected by the undifferentiated atmospheric environment, and the final control is within the safe value range. The special environment in the limited space of coal mine ensures the invariance of wind direction and the stability of wind speed, which makes the direction of gas diffusion and wind direction highly unified\(^{11}\).

2.1. Gauss plume model

In the normal mining of the working face, the gas is gushed out from the working face, the goaf and the falling coal, and then enters the return airways under the action of the air flow\(^{12}\). Assuming that the gas reaches the return airway continuously and at a constant speed, the concentration and temperature inside the gas cluster are evenly distributed at the initial moment; the change of temperature inside the cloud cluster is not considered in the diffusion process, and the heat transfer, convection and radiation are ignored; the leaked gas is an ideal gas, which complies with the state equation of the ideal gas; in the horizontal direction, the atmospheric diffusion coefficient is isotropic; during the whole diffusion process, the size and direction of the wind speed remain unchanged; the bottom plate does not absorb the leaked gas; and there is no chemical reaction in the whole process.

For the underground tunnel, the gas diffusion occurs in the Z, Y direction (between the roof, floor and the both side walls), and then along the main direction of the air flow in the X direction. Compared with the atmospheric diffusion, the gas diffusion cross section in the tunnel is small, which is equivalent to the point source diffusion. It satisfies the characteristics of Gaussian plume model. The Gaussian plume model is as follows formula (1).

\[
X(x, y, z) = \frac{Q}{2\pi\sigma_x\sigma_y\sigma_z} \exp \left[ - \left( \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} \right) \right] \tag{1}
\]

The above is the Gauss model formula of continuous point source diffusion in unbounded space. In coal mine roadway, because of the existence of floor, roof and side walls, the diffusion of plume is bounded. In this paper, only an ideal case is discussed. It is assumed that the roadway boundary has no adsorption on the gas, and the gas collides with the floor, roof and side walls in the vertical and horizontal directions respectively. The floor, roof and side walls are regarded as mirrors, and the gas...
reaching the roadway boundary is completely reflected back to the roadway, and the principle of virtual image source method is used for processing [13], and its principle is shown in Figure 1.

![Schematic diagram of correction principle of image source method for Gaussian plume model](image)

**Fig 1. Schematic diagram of correction principle of image source method for Gaussian plume model**

Based on the literature, it can be concluded that the height of leakage source \( H \) is the height of roadway [9][10]. The location of leakage source is set in the middle of the roof of the intersection of the working face and the return airway, and the projection of leakage source to the base plate is taken as the coordinate origin, then a Gaussian rectangular coordinate system is established, where: the downwind direction is the x-axis direction, which is, the extension direction of the return airway; the y-axis is the width direction of the lane; and the z-axis is the height direction of the lane. The concentration at any point \( P \) can be regarded as the sum of the contributions of five parts: the first part is the concentration of the leakage when there is no boundary; the second and the third part are the concentration of the leakage increased by the reflection of the bottom and top plate, because the leakage source is on the top plate, the real source coincides with the virtual source, the concentration of the added leakage source is twice of that without top plate; the fourth and fifth part are the concentration of the leakage increased due to the reflection of the side walls. Then the leakage concentration is equal to the sum of the leakage concentration at point \( P \) caused by the real source at \((0, 0, H)\) and the image source at \((0, 0, -H)\) when there is no boundary. The contribution of the real source is:

\[
C_l(x, y, z, H) = \frac{Q}{2\pi \sigma_y \sigma_z} e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{(z-H)^2}{2\sigma_z^2}}
\]  

(2)

As shown in Figure 1, the contribution of image source of roof and floor is as follows:

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

(3)

\[
C_3 = \frac{Q}{2\pi \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} e^{-\frac{(z-H)^2}{2\sigma_z^2}}
\]  

(4)

In the same way, the contribution of the image sources on both side walls is as follows:

\[
C_4 = \frac{Q}{2\pi \sigma_y \sigma_z} e^{-\frac{(y+L/2)^2}{2\sigma_y^2}} e^{-\frac{z^2}{2\sigma_z^2}}
\]  

(5)

\[
C_5 = \frac{Q}{2\pi \sigma_y \sigma_z} e^{-\frac{(y-L/2)^2}{2\sigma_y^2}} e^{-\frac{z^2}{2\sigma_z^2}}
\]  

(6)

The actual concentration is:

\[
C = C_1 + C_2 + C_3 + C_4 + C_5
\]  

(7)
Where, \( x, y, z \) is the coordinate of the point, \( m \); \( C \) is the gas diffusion concentration, \( \text{kg/m}^3 \); \( \sigma_x, \sigma_y, \sigma_z \) are the diffusion coefficients of gas in \( x, y, z \) direction respectively; \( Q \) is the gas or pollutant leakage speed, \( \text{kg/s} \); \( u \) is the air flow speed in \( x \) direction, \( \text{m/s} \); \( t \) is the diffusion time, \( s \); \( H \) is the leakage source height, \( m \); \( L \) is the roadway width, \( m \).

2.2. Wind speed analysis
When the coal mine is working normally, the ventilator is used to convey fresh air to the working face. The power and air volume of the ventilator are fixed. In the actual coal mine, the height of the roadway is generally within 3 meters, and the wind speed will not change in the longitudinal direction, but the cross section of the roadway will change with the progress of the mining work, which will cause the change of the wind speed in the extension direction. According to the formula, the wind speed in the coal mine roadway is inversely proportional to its cross section.

\[
\begin{align*}
    u &= \frac{Q_{\text{air volume}}}{S_{\text{cross section}}} \\
    \text{(8)}
\end{align*}
\]

Where, \( Q_{\text{air volume}} \) is the air volume of the ventilator, in \( \text{m}^3/\text{min} \); \( S_{\text{cross section}} \) is the cross-sectional area, in \( m^2 \).

2.3. Diffusion coefficient analysis
The diffusion coefficients \( \sigma_x, \sigma_y, \sigma_z \) are related to the structure of atmospheric turbulence, height from the ground, surface roughness, leakage duration, sampling interval, wind speed and distance from the leakage source and so on. The atmospheric turbulence structure and wind speed are considered in the atmospheric stability. It is quite complicated to determine the diffusion coefficient. In practical, the diffusion coefficients are determined by approximate estimation. According to Pasquell's classification method, with the increase of stable line of meteorological conditions, the atmospheric stability can be divided into six categories: A, B, C, D, E and F. Among them, A represents the most unstable meteorological condition, and F represents the moderately stable meteorological condition.

The environment underground coal mine is special, there is no solar radiation in the roadway, and the underground atmospheric stability is treated approximately. The air stability of the coal mine roadway is selected as Grade E, and the diffusion coefficient \( \sigma_y, \sigma_z \) and their mathematical expression are preliminarily determined: \( \sigma_y = 0.06x/(1+0.0001x)^{0.5}, \sigma_z = 0.03x/(1+0.0003x) \). Actually, the diffusion coefficient is different from the empirical expression of Pasquill due to the influence of the surface roughness and temperature of the coal mine roadway. Assuming that the influence function of the actual environment of the coal mine on the diffusion coefficient is a power function of the downwind distance \( x \), its expression is:

\[
\begin{align*}
    f_{\sigma_y}(x) &= p_{\sigma_y} x^{q_{\sigma_y}} \\
    f_{\sigma_z}(x) &= p_{\sigma_z} x^{q_{\sigma_z}} \\
    \text{(9)} \quad \text{(10)}
\end{align*}
\]

In the formula, \( p_{\sigma_y}, q_{\sigma_y}, p_{\sigma_z}, q_{\sigma_z} \) are constants. By analyzing the relationship between Gauss plume model and diffusion coefficient, the optimization of Gauss plume model can be realized by solving four constants using genetic algorithm on the basis of a large number of measured data.

3. Experiment and simulation

3.1. Measured data of a mine in Pingmei, Henan Province
The field measured data comes from a coal mine in Pingmei, Henan Province. The working face has been mined for a long time. The thickness of the coal seam is 2.8m, the air volume is 1900m$^3$/min, the average gas emission is 6.7m$^3$/min, and the temperature range is 30-32°C. At the beginning of the test,
the tail of the mining face is about 300m away from the special return airway, and about 4m of coal surface is be advanced every day. The roadway section is approximately rectangular, with the maximum section is 6m*3.5m (here is the chamber of endless rope winch), the minimum section is 3m*3m, and the monitoring value of gas concentration in the upper corner during the production period is 0.6-1%.

3.2. Simulation experiment and result analysis

MATLAB software is used to simulate two Gaussian plume models. The parameters of simulation experiment are set according to the actual data of a mine. The simulation results before and after model modification are shown in Figure 2.

From the Figure 2, it can be seen that after introducing the reflection effect of coal mine roadway wall on gas diffusion, the gas concentration value from the corrected model increases significantly when close to the roadway wall. Along the direction of main air flow, with the increase of distance x, the gas concentration value is gradually reduced and the gas distribution tends to be balanced. The high concentration gas is mainly concentrated in the height from 1.5m to the roof.

In order to verify the reliability of the simulation data, the test adopts the manual detection method to measure the gas concentration value at the position 1.2m away from the roadway side and 1.5m away from the bottom plate. Every 10m is a sampling point, 20 points are sampled continuously, once every 24 hours, a total of 30 times. The working conditions of this coal mine are relatively good, and the gas concentration is basically below 0.5%.

As shown in Figure 3, the simulation value of the modified model is closer to the actual value of the roadway than that of the original model, and its absolute error is basically within 0.1%, meeting the requirements of coal safety detection[21]. It can also be indicated that the calculation of the gas
concentration value of the coal mine roadway with MATLAB software is small in calculation amount and computer memory, which can meet the needs of engineering detection in a certain range.

![Fig 3. Comparison of measured data, simulation data after correction and before correction](image)

4. Conclusion

Through the theoretical analysis of gas diffusion in coal mine, the virtual image source method is used to modify the Gauss plume gas model, and the reflection of gas diffusion from the roof, floor and both sides walls of coal mine roadway is introduced into the Gauss plume model diffusion model. At the same time, the gas diffusion coefficient is modified by the genetic algorithm, thus the Gauss gas diffusion in coal mine roadway is proposed. The simulation results and measured data before and after the modification of the Gaussian plume model show that the concentration change of the modified Gaussian plume model is closer to the measured data. This method reveals the gas distribution law of coal mine roadway, and improves the real-time, convenience and reliability of the detection of roadway gas concentration.

Gauss plume model is based on some assumptions, and the values of various parameters in the calculation have certain errors. It is a very ideal diffusion state value. At the same time, there are many uncertain factors in the underground roadway in the coal mine, such as gas accumulation, gas leakage point, etc., which will cause the simulation concentration lower than the measured value, so it is necessary to repair the simulation analysis results and so as to provide more reliable reference for intelligent detection of coal mine.

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