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A Fume Concentration Model of Underground Mine Fire and Its Calculation

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Abstract

In order to obtain fume concentration distribution of underground mine fire spread process, a fume concentration calculation model, which takes into accounts into the effect of the fume's diffusion effect and the transport effect of the airflow, is established with the gradient transfer theory. The corresponding calculation steps are put forward. Then through calculating the fire fume concentration of a typical underground mine, the risk range of certain time after the fire accident can be given according to related standards. The results verify the validity and accuracy of the model and can provide references for the evacuation and rescue of underground mine fire accident.

Keywords: underground mine fire; fume concentration model; gradient transfer theory

1. Introduction

As one of major disasters seriously affecting the safety of underground mine, the high temperature fume and poisonous gases produced by fire pose a serious threat to underground miners. As a result, this paper will analyze the spread law of fire fume in underground mine. Then the fume concentration model is established, which can calculate the fume concentration in the fire spreading process in underground mine, and provide technical support for underground miners' evacuation.

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Underground mine roadways space is narrow and semi-closed. Currently, there are many study and research on the simulation of fire fume in narrow channel and tunnel [1-7]., which mainly adopt kinds of numerical simulation of computational fluid dynamics and use mature fluid dynamics software to simulate the fume's spatial distribution. But there are some differences between the roadways fire of underground mine and the tunnel fire. Firstly, the size of the tunnel is larger than the roadway so that the fire fume temperature and concentration is different between roadway and tunnel fire; secondly, the roadway's ventilation resistance factors of the roadway are not the same as the tunnel's.; lastly, the structures of tunnels are simple, but the structure of underground mine roadways are much more complex. In a words, the research can provide some reference for undermine roadway fire researches, which must take the features of the roadway in underground mine into account.

Research on roadway fire at home and abroad are widely developed, such as, Jiang Jun-cheng and Wang Sengshen established field model to simulate fume movement in the fire road [8-9]; ZHU Yan-yan and JIANG Zhong-an simulated the movement of undermine fire fume, conducted numerical calculation, and verified the results by comparing with experimental data [10]; WANG Wen-cai studied laws of fire fume flow in inclined and horizontal roadway [11], etc. But most of these researches merely consider the transport effect of the airflow on the fume; ignore the part fume diffusion effect plays in the process, which affects the accuracy of numerical simulation results. Therefore, taking the transport effect and fume's diffusion effect into full considerations, a fume concentration model based on gradient transfer theory is established, which will accurately simulate the distribution law of fire fume flow.

2. Gradient transport theory

The spread of the fire fume flow in underground mine is actually transfer process of fume in underground mine roadway, namely mass transfer process. The mass transfer process of fume flow, similar to momentum and heat transfer process, includes material mass transfer and convective mass transfer process. The material mass transfer of fume flow is actually the diffusion process of the fume; the convective mass transfer process of fume flow is mainly about the transport effect of air flow for fume flow in roadways. The Fick's law is a basic law linked the diffusion flux to concentration gradients to describe the steady diffusion mass transfer process [12]. The Fick's law holds that: in the stabilization of diffusion mass transfer process, the diffusion material flow of component i in unit time perpendicularly flows through to the direction of the diffusion in unit cross-sectional area (diffusion flux, J) , is proportional to the concentration gradient of the section area, namely greater concentration gradient, greater diffusion flux.

3. Fume concentration model

The spread of fume in roadways should consider the fume's diffusion effect and the transport effect of the airflow, and then the transfer-diffusion equation can be given. Fig. 1 shows the two effects on the spread of fume.

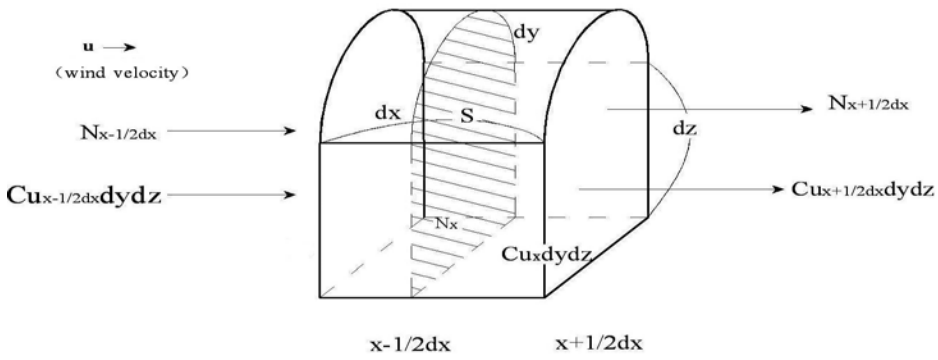

Fig. 1 Fume mass transport and diffusion of roadway

3.1 Diffusion effect of fume

The diffusion effect of fume is the primary factors. Let the mass diffusion rate of fume at x point is denoted by N_x, then the mass change fraction of control volume per unit of time is ($N_{x+1/2dx}$—$N_{x-1/2dx}$). According to the Fick's law, we can get

$$N_x = -D\frac{\partial C}{\partial x}dydz \tag{2}$$

Based on the Taylor series extension theory, we can obtain that

$$(N_{x+1/2dx} - N_{x-1/2dx}) = \left\{\left[\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)\right]dx\right\}dydz \tag{3}$$

3.2 Transport effect of fume

Then we take transport effect of fume into account. Let u be the wind velocity, then $(Cu_{x-1/2dx}dydz - Cu_{x+1/2dx}dydz)$ is equal to the mass change fraction of control volume per unit of time owing to the transport effect. Similarly, we can get

$$Cu_{x-1/2dx}dydz - Cu_{x+1/2dx}dydz = \left[-\frac{\partial}{\partial x}(Cudydz)\right]dx \tag{4}$$

3.3Comprehensive effect of fume

Through the above analysis, we can know that the mass change fraction of control volume is

$$\frac{\partial C}{\partial t}\bullet dxdydz = \left\{\left[-\frac{\partial}{\partial x}(Cudydz)\right]dx\right\} + \left\{\left[\frac{\partial}{\partial x}(D\frac{\partial C}{\partial x})\right]dxdydz\right\} \tag{5}$$

Simplifying formula 5, the comprehensive effect of fume concentration model is

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} + D\frac{\partial}{\partial x}\left(\frac{\partial C}{\partial x}\right) \tag{6}$$

Further, an extended model in three-dimensional condition can be gained

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = D_x\frac{\partial^2 C}{\partial x^2} + D_y\frac{\partial^2 C}{\partial y^2} + D_z\frac{\partial^2 C}{\partial z^2} \tag{7}$$

where: u, v, w —wind velocity in x, y, z direction , m/s ; D_x, D_y, D_z —diffusion coefficient of x, y, z direction, $kg\ /\ m^2 \cdot s$.

Particularly, using the above model to calculate the fume concentration, according to actual situation of undermine fire, formula 7 can be changed into

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = D_x\frac{\partial^2 C}{\partial x^2} + D_y\frac{\partial^2 C}{\partial y^2} + D_z\frac{\partial^2 C}{\partial z^2} \tag{8}$$

Solving formula 8, the fume concentration model can be gained, that is

$$C(x,y,z,t) = \frac{Q}{(64\pi^3 t^3 D_x D_y D_z)^{1/2}}\exp\left\{-\left[\frac{(x-ut)^2}{D_x} + \frac{y^2}{D_y} + \frac{z^2}{D_z}\right]\frac{1}{4t}\right\} \tag{9}$$

where: Q —fume flow rate of fire source in t period of time.

Let $\sigma_x = 2\sqrt{D_x t}, \sigma_y = 2\sqrt{D_y t}, \sigma_z = 2\sqrt{D_z t}$, then formula 9 can be changed into

$$C(x,y,z,t) = \frac{Q}{(\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\left(\frac{(x-ut)^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right] \tag{10}$$

In the course of study on spread of fire fume simulation of underground mine, due to the special situation of underground mine fire, this article considers only the spread of fire smoke flow in longitudinal direction, ignoring the situation of fume attenuation in the spread process, then the concentration formula is

$$C(x,t) = \frac{Q}{(\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\left(\frac{(x-ut)^2}{\sigma_x^2}\right)\right] \tag{11}$$

According to the Martin empirical formula, the three-dimensional diffusion factors $\sigma_x, \sigma_y, \sigma_z$ can be obtained: $\sigma_x = \sigma_y = ax^b, \sigma_z = cx^d + f$ and the coefficients a, c, d, e and f can be obtained in Table 1. Atmospheric stability can be divided into strong instability, instability, weak instability, neutrality, relative stability and stability according to the Amendment P.S classification recommended by the national standards HJ/T2.2-93. These five different degrees of atmospheric stability are denoted as A、B、C、D、E and F, of which specific value can be obtained by corresponding standards.

Table 1 Parameters of Martin empirical formula

Atmospheric Stability	$x<1$ km				$x\geq 1$ km			
	a	c	d	f	a	c	d	f
A	213	440.8	1.941	9.27	213	459.7	2.094	-9.6
B	156	106.6	1.149	3.3	136	108.2	1.098	2.0
C	104	61.0	0.911	0	104	61.0	0.911	0
D	68	33.2	0.725	-1.7	68	44.5	0.516	-13.0
E	50.5	22.8	0.678	-1.3	50.5	55.4	0.305	-34.0
F	34	14.35	0.740	-0.35	34	62.6	0.180	-48.6

There are many import and export points in the underground mine roadway network, which make the network more complex, therefore, the calculation of concentration at these particular points need be adjusted on the basis of calculation model. Let these import and export points be a new fume source. For the export point, the fume flow rate is calculated according to the distribution of air volume, the formula is

$$C_j(x,t)=\frac{C_{ij}Q_{ij}}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{(x-u_jt)^2}{\sigma_x^2}\right)\right] \tag{12}$$

As for the export point, the fume flow rate is sum of each branch, the formula is

$$C_j(x,t)=\frac{\sum_i C_{ij}Q_{ij}}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{(x-u_jt)^2}{\sigma_x^2}\right)\right] \tag{13}$$

where: c_j —the fume concentration of roadway j , kg/m^3 ; c_{ij} —the fume concentration at meeting point of roadway i and j , kg/m^3 ; Q_{ij} —the air volume flowing in roadway j from roadway i , m^3/s ; u_j — wind velocity of roadway j , m/s ;

4. Calculation of fume concentration in roadways

Based on the above built fume concentration model, the fume concentration calculation process for roadways in underground mine fire is shown in Fig 2, the algorithm is as follows.

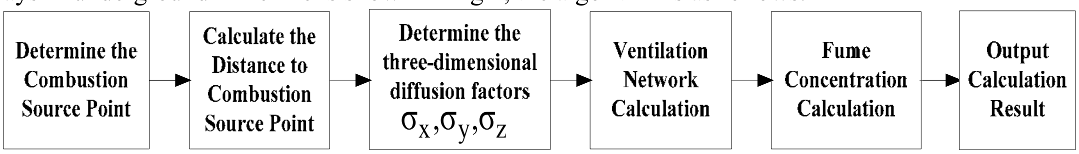

Fig. 2 Fume concentration calculation process of underground mine fire

(1) The first step is to initialize parameters of fire source, including the location of fire source, burning area, burning rate, etc.

(2) Secondly, calculate the longitudinal distance to the fire source point, then the diffusion factors can be obtained;

(3) Following that, the wind velocity of each roadway can be obtained through ventilation network calculation;

(4) Finally, through traversing the roadway, the fume concentration results can be obtained.

5. Analysis of the fume concentration in roadway

This paper takes a typical domestic underground mine as application example. It is assumed that when a cable fire occurred in a roadway, the burning rate of cable is11.290 $g / s \cdot m^2$, the burning area is 5 square meter, and the wind velocity is 3m/s through ventilation network calculation. Based on the fume concentration model and the above algorithm, the concentration of CO and CO_2 are calculated and shown in Fig. 3.

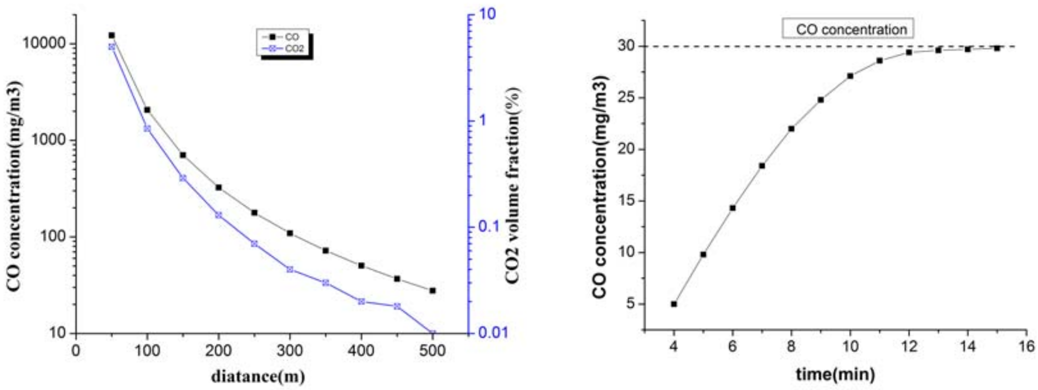

Fig. 3. (a) Calculation result of fume concentration after 10min; (b) CO concentration variation with time at 500 m position

Since CO is much more poisonous than CO_2, the dangerous scopes of underground mine fire should mainly consider the impact of CO concentration. According to “Fire Risk Analysis and Assessment of Polymer” and “Guidelines on Emergency Response System for Chemical Industry Parks”, the dangerous scopes can be divided into severe dangerous, moderate dangerous and light dangerous scopes. Therefore, a conclusion can be gained that: after 10 min combustion, the distance to fire source less than160m is severe dangerous scope, and the distance from 160m to 240m is moderate dangerous scope, while the distance farther than 240m is less dangerous. “Metal and Nonmetal Safety Rugulations”has stipulated that the CO concentration should not be higher than 30mg; the CO_2 volume fraction must be lower than 0.5%. Then the distance to fire source safety zone farther than 485m can be defined as safety zone. The calculation results can be well approached by the actual data, which verifies the reliability and validity of the model.

6. Conclusion

The fume concentration model can show the spread process of fire fume concentration distribution more accurately since it considers both the fume's diffusion and the transport effect of the airflow on the fume. Through the fire fume concentration's calculation and analysis of a typical underground mine, the dangerous scopes for underground staffs are given according to the fire accident, which can provide guides and references for underground staffs' evacuation and rescue under the circumstance of mine fire accident.

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