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A CFD Modeling Method of Realistic Parameters for Predicting Easily Coal Spontaneous Combustion Zone Accurately in the Gob of Long wall Face

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Abstract: *The accurate prediction of coal spontaneous combustion zone is the precondition for the coal fire prevention. In this study, we prevent the coal spontaneous combustion on the basis of oxygen concentration and oxidation time. 10% of oxygen concentration (volume percent) is used to determine the easily coal spontaneous combustion zone and the quick advancement is used to avert the coal fire. A three-dimensional, steady flow, CFD modeling method based on realistic parameters of seepage, ventilation and working face is established and the preliminary modeling results of the spontaneous combustion zone are compared with the pipes observation for validating and amending the parameters of CFD model. The easily spontaneous combustion zones under the conditions of different air volume are quantitatively evaluated by the amended model. Simultaneously, the minimum advancing rate for averting the coal fire is determined, and the effect of accelerating advancement for the coal fire prevention is examined as well. The approach of accurate prediction is also applicable to other similar gob areas.*

Keywords: *coal spontaneous combustion, realistic parameters, numerical simulation, predicting model; model validation and amendment*

1. Introduction

The spontaneous combustion of coal seams continues to be a serious problem in both underground and surface coal mining [1-3]. In China, about 10~20 million tons of coal per year are affected with $125~250 million worth of economic damage [4]. Similar problems are faced in the United States, India, Australia, Indonesia and South Africa [5]. Coal spontaneous combustion refers to a range of complex physico-chemical processes involving consumption of oxygen, formation of solid oxygenated complexes, thermal decomposition of solid oxygenated complexes and generation of gaseous oxidation products [6]. If sufficient oxygen and conditions of heat accumulation are available, there will occur a fire. The fire induced by the coal spontaneous combustion, especially in the gob area of underground coal mining, presents accessibility problems regarding detection, fairly precise locating and fire extinguishment. If there is methane with favorable concentration, the fire can lead to a major disaster, explosion. Therefore, averting the coal fire is essential for coal mine work safety.

The accurate prediction of coal spontaneous combustion zone is the precondition for the coal fire prevention. At present, two kinds of methods are used to predict the spontaneous combustion zone. One is numerical simulation, and another is in situ observation [7]. Although in situ observation is realistic and direct, there are difficulties in comprehensively understanding the distribution for the spontaneous combustion zone in the gob area because of the accessibility problems and the severe environment. Numerical simulation provides a possibility to understand the spontaneous combustion zone due to its economic and convenient. A lot of modeling studies have been performed to investigate the spontaneous heating tendencies of coal in the gob, some models are very complicated [8,9]. Those help us understand the processes of coal spontaneous combustion comprehensively. However, less attention is paid to how to predict the spontaneous combustion zone accurately. Because the in situ measurements of real objects and environmental conditions are a skillful and empirical operation, and the parameters switch from real conditions to the ideal model needs a right method.

In this study, the commercial computational fluid dynamics (CFD) software, FLUENT, was used to predict the spontaneous combustion zone in the longwall gob area. A three-dimensional, steady flow model of the longwall district operating in the Xieqiao Coal Mine had been developed. 10% of oxygen concentration (volume percent) was the index to determine the easily coal spontaneous combustion zone. The quick advancement was the main preventive measure to avert the coal fire. The CFD modeling method based on realistic parameters of seepage, ventilation and working face was established and the preliminary modeling results of the spontaneous combustion zone were compared with the pipes observation for validating and amending the parameters of CFD model. On the base of the amended model, the easily spontaneous combustion zones under the conditions of different air volume were quantitatively evaluated. Simultaneously, the minimum advancing rate for averting the coal fire was determined, and the effect of accelerating advancement for the coal fire prevention was examined as well. The approach of accurate prediction is also applicable to other similar gob areas.

2. NUMERICAL MODEL AND EVALUATION INDEX

The essential conditions of coal spontaneous combustion in the gob are sufficient oxygen, favorable heat accumulation and oxidation time. Although the coal oxidation inducing self-heating is the final cause of coal spontaneous combustion, the parameters of coal oxidation reactions and heat release obtained by experimental methods exist complex scaling effects, and the heat measurement is hard to operate in the gob because of the accessibility problems and the severe environment. Therefore, in this research, we prevent the coal spontaneous combustion on the basis of oxygen concentration and oxidation time.

2.1. Air Seepage and Oxygen Diffusion

As the coal is extracted from the panel, the overlying coal and rock mass are caved, which forms the fractured and porous zone called gob. There may be some ventilation air leaking from the face into the gob. The mathematical model of the air leakage can be simplified as a steady flow when the ventilation is stable. The model uses equations of mass, momentum, energy and species transport [10]. In these equations, the descriptions of air seepage and oxygen diffusion is very important to simulate the distribution for oxygen concentration in the gob.

The air leaking channel of the gob is anomalistic and interlaced, which results in the very small airflow. Thus the air seepage can be treated as laminar using Darcy law:

$$\bar{Q}_x = k_x \frac{\partial H}{\partial x},\quad \bar{Q}_y = k_y \frac{\partial H}{\partial y},\quad \bar{Q}_z = k_z \frac{\partial H}{\partial z} \tag{1}$$

Where H is the pressure in the gob, Pa; $\bar{Q}_x, \bar{Q}_y, \bar{Q}_z$ is the air velocity in x, y, z direction, m·s^{-1}; k_x, k_y, k_z is the permeability in x, y, z direction of the gob, m^2.

The coal spontaneous combustion in the gob is a range of coal oxidation processes by the way of oxygen diffusion. The diffusion of oxygen concentration follows Fick law:

$$\bar{Q}_x \frac{\partial C}{\partial x} + \bar{Q}_y \frac{\partial C}{\partial y} + \bar{Q}_z \frac{\partial C}{\partial z} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} \tag{2}$$

Where D_x, D_y, D_z is the diffusion coefficient of oxygen in x, y, z direction of the coal bodies, m^2·s^{-1}, C is the oxygen concentration, mol·m^{-3}.

2.2. Definition of Easily Spontaneous Combustion Zone

The air seepage and oxygen diffusion lead to the distribution of oxygen concentration in the gob, which influences coal oxidation processes. The distribution for oxygen concentration determines the coal spontaneous combustion zone. Some researches show that the coal oxidation is restricted when the oxygen concentration less than 10% and even suppressed when less than 5% [11]. Thus 10% of oxygen concentration can be the index to determine the coal spontaneous combustion zone. The zone that oxygen concentration is greater than 10% in the gob is easily spontaneous combustion zone.

2.3. Oxidation Time and Advancement

It is quite obvious that coal spontaneous combustion would happen where meets enough oxidation time. That is to say:

$$t > t_{\min} \tag{3}$$

Where t is the oxidation time, d, and t_{min} is the minimum period of coal spontaneous combustion, d, which is obtained by the larger scale experiment or field statistics.

However with the face advancing, the contour line of oxygen concentration 10% follows, which leads to dynamically changes of the easily spontaneous combustion zone in the gob. If the face advancing velocity (V) follows the Eq. (4), the coal spontaneous combustion would not happen.

$$V > [V_{min} = D_{max} / t_{min}] \tag{4}$$

Where D_{max} is the largest distance from the face to the contour line of oxygen concentration 10%, m, V_{min} is the minimum advancing velocity to advert coal spontaneous combustion, m·d^{-1}.

3. Modeling Method of Realistic Parameters

3.1. Parameters of Seepage

The porosity of the gob varied with the location of the site. It is largest around the perimeter of the gob and immediately behind the face shields. The value in the vertical direction decreases with power function. The porosity followed the equation ascertained by field simulation experiment[12]:

$$\varphi(x, y, z) = \left(0.2e^{-0.022x} + 0.1\right) \times \left[e^{-0.12\left(\frac{L}{2} \pm y\right)} + 1\right] \times 0.98^{z} \tag{5}$$

Where φ is the porosity of the gob; x is the depth of the gob, m, y is the distance from the site to the middle line of the gob, m, z is the height of the gob, m, L is the length of the longwall face, m.

Using the values of porosity, an exponential relationship was used to compute the permeability of the gob as follows[12]:

$$k = k_0 e^{\beta\varphi} \tag{6}$$

Where k_o is the base permeability of the gob at the maximum porosity, m^2, and β is the empirical coefficient. The value of k_o was taken as 2x10^{-5} m^2 which occurred behind the face shields[13], and the value of β is determined by the in situ observation amending simulated results. The triaxial permeability experiment show that the value of β is about 10~30 under the conditions of confining pressure 6MPa, pore pressure 0.6MPa and temperature 293K[14].

Taking the example of 13413 panel of Xieqiao coal mine, the length of the longwall face is 206m. The values of the porosity in the gob can be calculated by the Eq. (5), and the 3D distribution for the porosity is displayed in Fig. 1

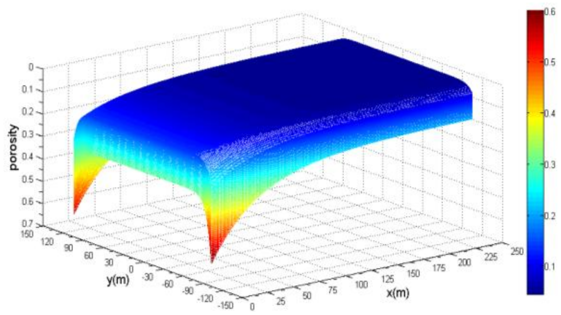

Fig1. *The 3D distribution for the porosity in the gob*

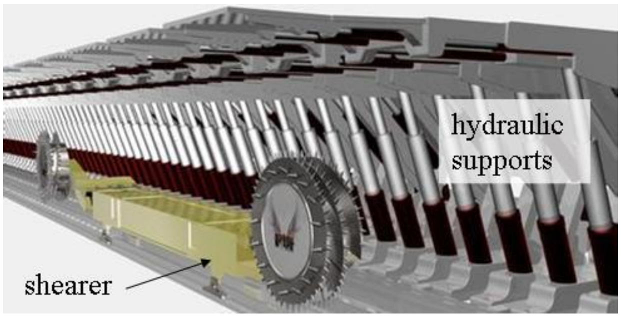

Fig2. *The structure of long wall face*

3.2. Parameters of Ventilation

When air is moving in the roadways, the airflow is influenced by the friction resistance, especially in the longwall face, which include a mechanical shearer and hydraulic supports as shown in Fig. 2. The influence of the friction resistance can be reflected by pressure distribution. According to the Bernoulli's equation, the pressure difference between two points, $P_{R1,2}$, equal the ventilating resistance, which can be calculated as follows:

$$P_{R1,2} = P_{b1} - P_{b2} + (P_{a2} - P_{a1}) + \frac{1}{2}\rho_1 v_1^2 - \frac{1}{2}\rho_2 v_2^2 + g\rho_{m1,2} z_{1,2} \tag{7}$$

Where P_{ai} is relative static pressure on the base point when the test point i is measuring, Pa

P_{bi} is relative static pressure of the test point i, Pa

ρ_i is air density of the test point i, kg·m^{-3}

v_i is air speed of the test point i, m·s^{-1}

g is acceleration of gravity, m·s^{-2}

ρ_m is average density of the air between two test points, kg·m^{-3}

$Z_{i,i+1}$ is elevation difference between test point i and i+1, m

The air density can be calculated as the following equation[15]:

$$\rho_i = 3.484\frac{P}{T}\left(1 - \frac{0.378\lambda P_{sat}}{P}\right) \tag{8}$$

Where P is absolute atmospheric pressure, KPa, T is absolute air temperature, K, λ is relative air humidity, %, and P_{sat} is saturation vapor pressure, KPa.

The airflow resistance coefficient, R_{12}, Ns^2·m^{-8}, can be written as[15]:

$$R_{12} = \frac{P_{R12}}{Q^2} \tag{9}$$

Where Q is air volume of roadway, m^3·s^{-1}. The airflow resistance coefficient is the intrinsic attribute of the roadways, which does not vary with the air volume variation. Thus the pressure difference of roadways with different air volume can be calculated by the Eq. (9).

The test instruments are the precision digital barometer, wet and dry bulb thermometer and mechanical anemometer of high, medium and low speed as shown in Fig. 3. The precision of the precision digital barometer is 0.1 and the precision of the wet and dry bulb thermometer is 0.5.

(a) the precision digital barometer (b) the wet and dry bulb thermometer (c) the mechanical anemometer

Fig3. *The instruments for air resistance test*

3.3. Modeling Parameters of the Working Face

During mining of a panel, roof rocks are temporarily supported with hydraulic supports to protect the workers and the equipment. The supports automatically advance and the gob are formed behind. The backplate of each hydraulic support is used to prevent caved rocks from rolling in the workplace. As shown in Fig. 4, the edge interval of each backplate is about 80mm and the middle interval of each hydraulic support is about 1.5m, which are set as rectangular walls. These realistic parameters are used for modeling.

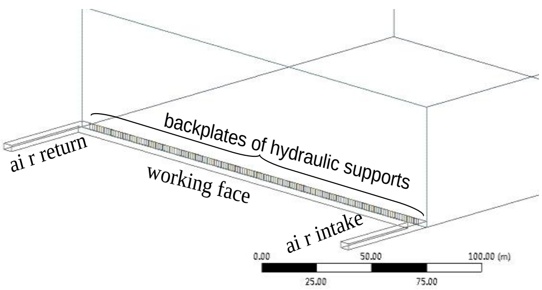

Fig4. *The model parameters for backplates of hydraulic supports*

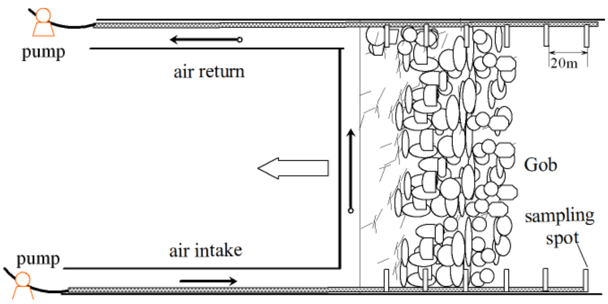

Fig5. *The arrangement for sampling observation in the gob*

3.4. Method of Validation and Amendment

Due to the complex mining environment, the simulated results are prone to error. Therefore, the validation and amendment of modeling parameters are quite essential. The in situ measuring method of pipes observation is available for validation and amendment. Basically, the pipes are buried in the roadways beforehand and the air samples are taken from pumping the pipes. Multiple sampling spots are arranged for accurate testing, which interval is 20m. The oxygen concentration is tested by the chromatography as the working face advancement leading to the pre-buried pipes going into the gob, as shown in Fig. 5. The different oxygen concentration of different sites are obtained for validation and amendment by comparing with simulated results consequently. The empirical coefficient β of Eq.(6) is amended as well.

4. PREDICTING EASILY COAL SPONTANEOUS COMBUSTION ZONE

4.1. Parameters of the Model

The 13413 panel of longwall face situated at the Xieqiao mine of Huainan city operated with the caving method of retreat mining. The length of the face is 206 m, the mining height of the face was 4 m, and the gob height was assumed to be ten times larger than the mining height, i.e. 40 m starting from the bottom of the coal seam. The calculated length of air intake and return is 50m. A back return U-ventilation system was used with an airflow rate of 2500 $m^3 \cdot min^{-1}$ in the intake. The ventilation roadways are 3 m high and 5 m wide. The calculated depth of the gob is 250m. The model is sketched in Fig. 6.

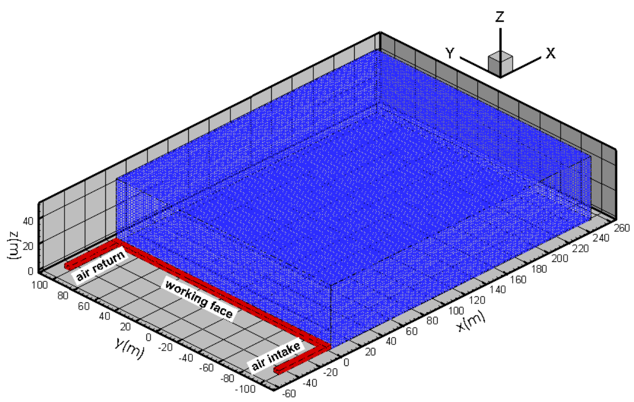

Fig6. *The 3D model and grid cells of the longwall district*

4.2. Basic Approach to Numerical Modeling

A three-dimensional, steady flow numerical model of the longwall district has been developed with the commercial CFD software program FLUENT (Ansys, Inc.), version 14.0. The cells grid for the simulation is created using mesh generator of Workbench (Ansys, Inc.). The cells of the gob are the shape of regular hexahedrons with a side length of 2 m. The grid cells are sketched in Fig. 6.

The airflow at the longwall face and roadways is simulated as fully developed turbulent flow using an RNG k–ε model. The inlet of the air intake is set as velocity inlet and the outlet of the air return is set as pressure outlet. The pressure difference between the inlet and outlet was 162.1Pa by the in situ measurement with air volume 2500m^3/min. Thus the airflow resistance coefficient is 0.093 $Ns^2 \cdot m^{-8}$ according to the Eq. (9). The pressure difference between the inlet and outlet with air volume 2000m^3/min and 3000m^3/min are calculated as well, which are 103.7Pa and 233.3Pa respectively.

Using the model, the air velocity and oxygen concentration in the gob area can be simulated from the starting line of the longwall face up to the 250m depth of the gob.

4.3. Model Validation and Amendment

As shown in Fig. 7, The drop curves of the oxygen concentration at both sides of the gob are obtained by the pipes observation. At 124m and 88m from the working face, the oxygen concentration reaches 10%, and at 60m and 25m from the working face, the oxygen concentration reaches 18%. The value of the empirical coefficient β of Eq.(6) is 19.5 by repeated simulation so that simulated results meet the in situ observation.

As shown in Fig. 7, the distribution for the oxygen concentration field at gob bottom was obtained through simulations with air volume of 2500m^3/min. At the gob bottom, the contour line of 10% reaches the distance of 130m and 90m from the working face at both sides respectively. The contour line of 18% reaches the distance of 59m and 15m from the working face at both sides respectively.

The numerical simulation results are in good agreement with the in situ observation, validating the accuracy of numerical model. Therefore, the settings of the real parameters can be a basis of subsequent modeling.

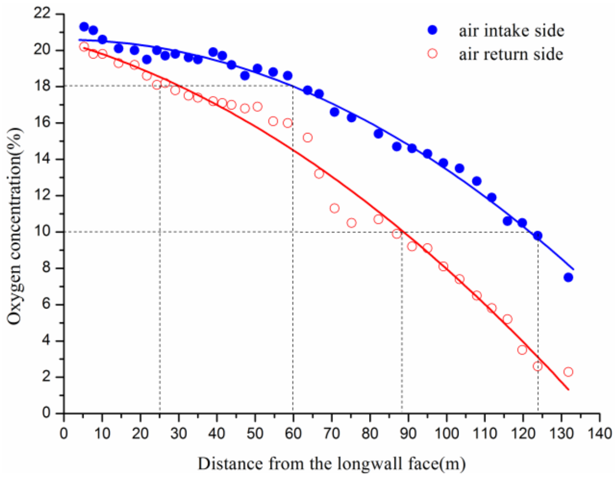

Fig7. *The pipes observation results in both sides of the gob*

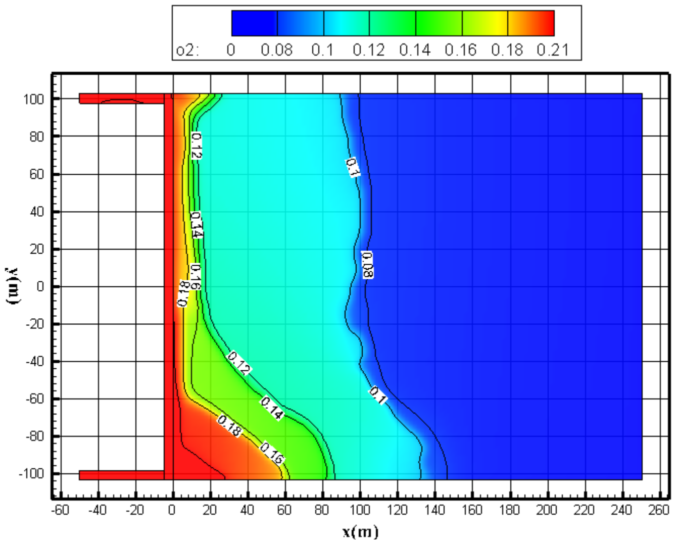

Fig8. *The oxygen concentration field at the gob bottom(2500m^3/min)*

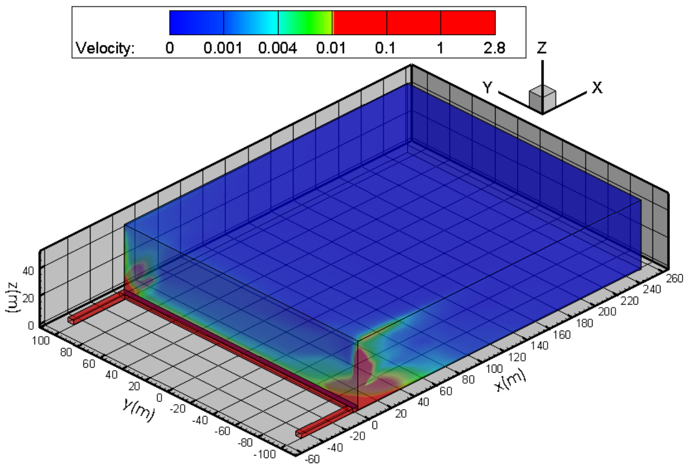

Fig9. *The 3D air velocity field in the gob(2500m^3/min)*

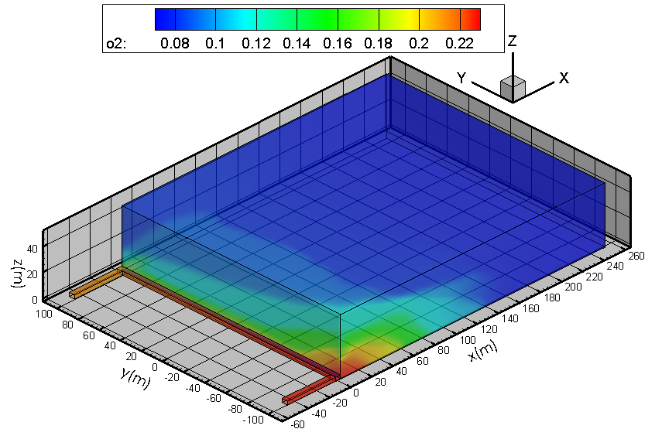

Fig10. *The 3D oxygen concentration field in the gob(2500m^3/min)*

4.4. Spatial Distribution of the Spontaneous Combustion Zone

Fig. 9. and Fig. 10. illustrate the distribution for the air velocity field and oxygen concentration field in the three-dimensional space. The air leakage is mainly concentrated at intake and return sides of the gob, and the air leakage of the intake side is larger than the middle and return side of the gob, resulting in the wider spontaneous combustion zone at the air intake of the gob. The distribution for easily spontaneous combustion zone is gradually decreased from the bottom to the top of the gob because of the decreases of permeability in the vertical direction. Thus the spontaneous combustion zone of the gob bottom is the widest zone, which is very significant for coal fire prevention.

4.5. Influence of Air Volume

In order to understand the influence of different air volume for easily spontaneous combustion zone, the oxygen concentration fields at gob bottom were obtained by simulations with air volume of 2000m^3/min and 3000m^3/min, see Fig. 11. and Fig. 12. The modeling parameters were based on the validated model. Table 1 shows the range of the easily spontaneous combustion zone at the air intake, return side and middle of the gob bottom. The easily spontaneous combustion zone of the air intake, return side and middle decrease by 20m, 33m and 5m respectively when the air volume decreases by 500m^3/min. The easily spontaneous combustion zone of the air intake, return side and middle increase by 20m, 0m and 15m respectively when the air volume increases by 500m^3/min. The results indicate that the easily spontaneous combustion zone of the air intake side increases significantly and the air return side increases slowly with the air volume increase, namely, the spontaneous combustion risk of the air intake side is greatest in the gob. Thus the distance of the easily spontaneous combustion zone at air intake of the gob bottom can be the basis for calculating the minimum advancing velocity to advert coal spontaneous combustion.

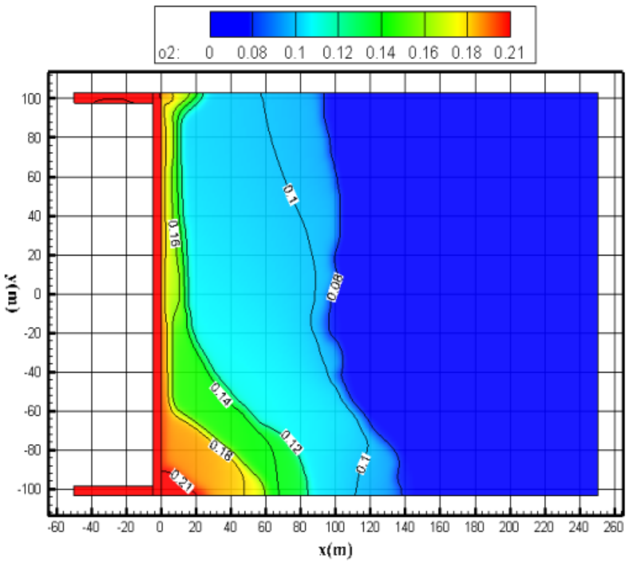

Fig11. *The oxygen concentration field at the gob bottom(2000m^3/min)*

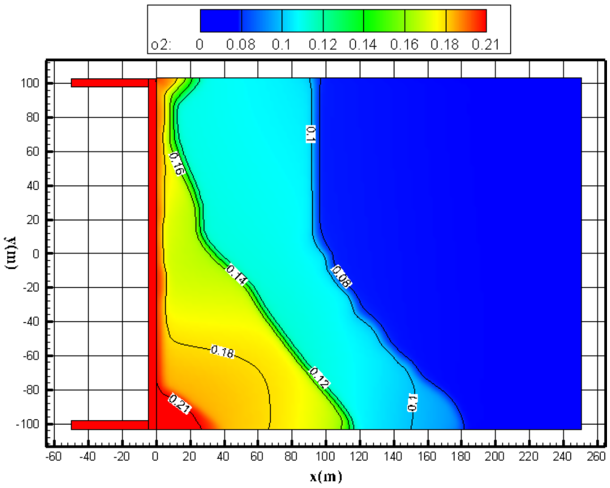

Fig12. *The oxygen concentration field at the gob bottom(3000m^3/min)*

Table1. *The distribution for easily spontaneous combustion zone*

Air volume (m^3/min)	The length of easily spontaneous combustion zone(m)		
	Air intake side	Air return side	Middle
2000	110	57	90
2500	130	90	95
3000	150	90	110

4.6. Effect of Preventing Spontaneous Combustion

The minimum spontaneous combustion period of the 13-1 coal seam of 13413 panel is 39d. According the present simulations and Eq.(4), the minimum advancing velocity of the working face must be faster than 85m, 100m and 116m per month with air volume of 2000m^3/min, 2500m^3/min and 3000m^3/min. During the 13413 panel mining, the average air volume was 2500m^3/min and the maximum air volume reached 3000m^3/min for controlling methane emission. The average advancing velocity was 120.9m per month and carbon monoxide was not detected in the air return. Thus the coal spontaneous combustion in the gob is successfully suppressed by accelerating advancement.

5. Conclusions

In this study, the CFD modeling based on the realistic parameters of seepage, ventilation and working face is used to predict spontaneous combustion zone. The results demonstrate that the numerical simulation is in good agreement with the in situ observation, validating the accuracy of numerical model. Then, the easily spontaneous combustion zones under the conditions of different air volume are quantitatively evaluated by the accuracy model. The results show that the spontaneous combustion zone at the air intake side of the gob bottom is the widest zone. The easily spontaneous combustion zone of the air intake side increases significantly and the air return side increases slowly with the air volume increase, namely, the spontaneous combustion risk of the air intake side is greatest in the gob. Finally, based the results, the minimum advancing velocity is calculated to advert coal spontaneous combustion, which proves that the coal spontaneous combustion in the gob is successfully suppressed by accelerating advancement.

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