WANG YUE-HONG
WU YI
and
LI ZHI

Experimental partition and numerical simulated "three-zone" of spontaneous combustion in the gob

Based on the mechanism of spontaneous combustion of coal, the theory of gas drainage and the theory of three zones of spontaneous combustion, the application and research status are summarized at home and abroad.The preliminary understanding of gas drainage and spontaneous combustion in gob is expounded. And research status and the source of subject of spontaneous combustion and gas drainage in gob in domestic and foreign on influence of spontaneous combustion is introduced in detailed. The application study of spontaneous combustion of abandoned coal in gob of numerical simulation is mainly studied. The research background that is based on 5242Z working face in gob in lvjiatuo coal of Kailuan group, it introduces duct monitoring system that is established in 12# coal seam of 5242Z working face. Beam tube monitoring is the main method in the experiment.Through the beam tube are arranged reasonable in gob, the gas bladder with regular sampling was analyzed by gas chromatography. It has achieved continuous monitoring to spontaneous combustion in gob and has measured the distribution situation of oxygen concentration of different locations inside the gob. To measure the "three zones" division of spontaneous combustion more accurate, by setting the parameters under the same conditions, the COMSOL numerical simulation software is used to solve the mathematical model of oxygen concentration and the field distribution of oxygen concentration in mined out area can be obtained. According to the simulated results, the range of three spontaneous combustion zones in goaf is determined, and the accuracy of the division of "three zones" is ensured. According to the oxygen concentration index, the result is that the heat dissipation zone is mainly distributed in the coal wall 0~15m area from the working face, the spontaneous combustion zone is mainly distributed in the coal wall 15~45m area from the working face and the suffocation zone is mainly distributed in gob outside the coal wall 45m of the working face, which provides a reference for the formulation of the technical scheme for mine fire prevention and control in the later period. The comparison between the measured and simulated the actual results of the monitoring of the beam pipe in the mined out area shows that the actual measurement coordinate points essentially coincide with the contour lines that are processed by simulation results. There is little difference in the division of "three zones" of spontaneous combustion in gob to monitoring results and simulation calculation results of beam and tube in mined out area. Therefore, the validity of the numerical simulation is verified.

Keywords: *Duct monitoring system; three zones of spontaneous combustion; numerical simulation; oxygen concentration.*

1. Introduction

As is known, when it comes to the five natural disasters in coal mine, fire of mine bear the brunt. It has caused great threat to the safety production of the enterprises of coal mine and greatly restricted the steady development of the enterprises of coal mine[1]. The fire of spontaneous combustion in gob is an important disaster for coal mining enterprises, especially those with natural ignition tendency in coal seam [2]. It is important to study the law of spontaneous combustion in gob and make effective measures for preventing spontaneous combustion to coal mine safety and this is also the focus of research in the field of mine safety[3-4]. However, the spontaneous combustion process and the geological structure of the coal mine are also complicated. At present, it is still difficult to monitor and surveillance the temperature and oxygen concentration in the gob in real time, and the monitoring data is distorted. The similar simulation experiments of spontaneous combustion have many problems, such as lower stability and poor accuracy, which are difficult to solve. Therefore, in order to better measure the distribution of "three zones" of spontaneous combustion in gob, the industrial test of beam tube monitoring by means of bladder sampling are adopted to measure the distribution of concentration of each gas. The results of measured in experiment are compared to the numerical simulation results. Therefore, it verifies the

Messrs. Wang Yue-hong, Wu Yi and Li Zhi, Mining Engineering College, North China University of Science and Technology, and also with Key Laboratory of Mining Exploitation and Safety Technology in Hebei Province, Tangshan 063 009, Hebei, China

rationality of the model [5].

The 5424Z working face of lvjiatuo coal mine in Kailuan Group belongs to spontaneous combustion coal seam[6]. There is a large amount of coal left in the return airway, more ways of air leakage and a large amount of air leakage quantity, so there is possibility of spontaneous combustion in gob[7]. In order to prevent the spontaneous combustion of the remaining coal in gob of 5424Z, a series of prevention and extinguishments for fire technology solutions are formulated according to the division of the three zones of spontaneous combustion in gob. To ensure the effectiveness of the scheme, the division of the “three zones” of gob spontaneous combustion must be accurate. Therefore, two sets of scheme of field duct monitoring technology and numerical simulation were adopted to determine the “three zones” of spontaneous combustion in gob[8].

2. Engineering situation

The 5424Z working face of lvjiatuo coal mine in Kailuan Group strike length is 550m, inclination length is 100m, thickness of coal seam is 1.8~3.5m, the average thickness is 2.5m, structure of coal seam is complex, coal seam dip is 5 deg~18 deg, recoverable index is 1, coefficient variation is 20%, the design average height is 2.5m, which belongs to the stability of coal seam. The working face of 12# coal seam is □ class spontaneous combustion coal seam, the period of spontaneous combustion is 6 to 12 months, relative gas emission is 0.95 m^3/t (daily 1500t calculation), which have explosion hazards and its explosion index is 34.97%. The working face is advancing along the inclined arrangement of the coal seam, adopt the longwall coal mining of the top coal and take the method of fully caving coal mining to deal gob. It adopts ventilation of full wind pressure. According to the meteorological conditions of working face, the gas emission, carbon dioxide emission, the harmful gases of professional and after blasting production requirements, the needing of air quantity of coal working face were respectively calculated, and then take the maximum value of 585.56 m^3/min as the air quantity of working face.

There are some reasons to analyse the spontaneous combustion of coal seam in 5424Z working face. For example, the mine pressure is large, and the fracture density and connectivity of the coal seam are reduced. The seepage and diffusion of gas are blocked, which results in larger gas emission at the working face. In order to control the gas accumulation at the upper corner, it is necessary to maintain a larger air volume and wind exhaust gas, while the increase of air flow will lead to the increase of air leakage in the gob, so the scope of the spontaneous combustion zone will also become larger. The 5424Z working face has more remaining coal in the gob, which provides sufficient material foundation for spontaneous combustion. Considering the above factors, 5424Z working face gob must make the fire prevention scheme reasonably and effectivly to ensure safe and efficient mining working face. Before the making plan, we must firstly get the distribution of "three zones" division of spontaneous combustion accurately.

3. In situ measurement

Field test of gob is carried out by using embedded pipe monitoring technology, and bundle tube monitoring system is used to monitor and analyze the gas composition in the process of oxidation of coal[9]. The system can realize continuous monitoring of coal spontaneous combustion and analysis reliable data, so as to realize early detection and prediction of spontaneous combustion of coal.

According to the actual situation of the 5424Z working face, the beam pipe is arranged to monitoring site (the back of tail beam bracket) as required. A total of 4 beam tubes are planned to lay, and a measuring point sampler with a protective sleeve is connected at each port of each beam pipe port. The beam pipe must be hung for laying, and the tube must also be equipped with a seamless steel tube with a length of 100m and a diameter of 20mm, so as to prevent the tube from being smashed and broken. The 2 beam pipe are laid from the return airway to upper corner direction, monitoring points are arranged in the upper corner and head position near the road; another 2 beam tube are laid from intake entry to up corner direction, monitoring points are arranged on intake entry and head position near the road. The layout of the specific measuring points is shown in Fig.1. According to the beam pipe monitoring point at that time, the spot will be adjusted. With the advance of working face, the four beam tube sampler gradually go into the gob to be monitoring gas.

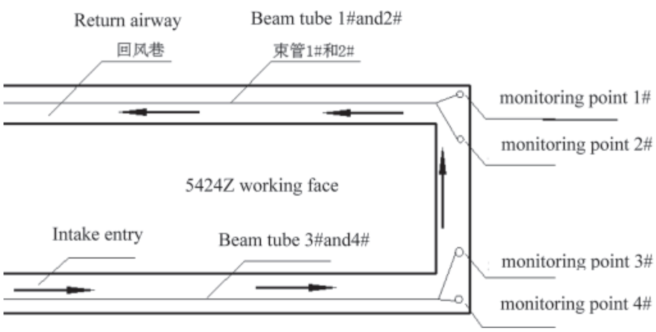

Fig.1 Schematic diagram of laying of beam tube monitoring points

Take return airway 1# monitoring site as an example, when working face advance 5m, 10m, 15m, 20m, 25m, 30m, respectively, the gas was collected to the ground by ball sampling. O_2, N_2, CO, CO_2, CH_4, C_2H_2, C_2H_4, C_2H_6 and other gas parameters are analyzed by means of gas chromatography, continuous observation and analyzed by gas chromatograph and the data is shown in Table 1.

As the work surface is advancing, gas samples are collected continuously and analyzed by gas chromatography.

Table 1: Analysis results of the gas sample laboratory at the 1# monitoring point

Propelling distance /m	O_2	N_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
5	19.782	79.3048	0	0.0989	1.1125	0.0012	0	0
10	19.7323	79.5186	0	0.0726	0.7464	0.0007	0	0
15	19.4812	79.4831	0	0.0649	1.0136	0.0015	0	0
20	18.5851	79.147	0	0.0754	0.9604	0.0008	0	0
25	19.4002	78.1297	0	0.1699	1.3217	0.0001	0	0
30	18.7285	78.1929	0	0.2732	2.1063	0.0003	0	0

Gas samples are taken every day until the working surface is pushed into the position of 100m[10]. The extraction parameters of oxygen concentration of 4 monitoring points taken from the gas chromatographic analysis results. According to the volume concentration of 4 monitoring points, draws a line chart of the oxygen concentration distribution in gob as shown in Fig.2. According to the data obtained from the monitoring of the pipe before the gas is released by the buried pipe, the image is drawn. The variation trend of oxygen concentration is analyzed, and three zones of spontaneous combustion are divided according to oxygen concentration index. The oxygen concentration of the cooling band is greater than 18%, and the range of oxygen concentration in the spontaneous combustion zone is 10% - 18%, and the oxygen concentration in the suffocation zone is less than 10%. From the analysis of Fig.2, it can be seen that the heat dissipation zone is within the 15m range of the coal wall of the working face, and the spontaneous combustion zone is from the coal wall 15m to 45m in the face area, and the suffocation belt is outside the coal wall 45m outside the working face. And the maximum width of the spontaneous combustion zone is located in the middle of the goaf, and the maximum width is 30m.

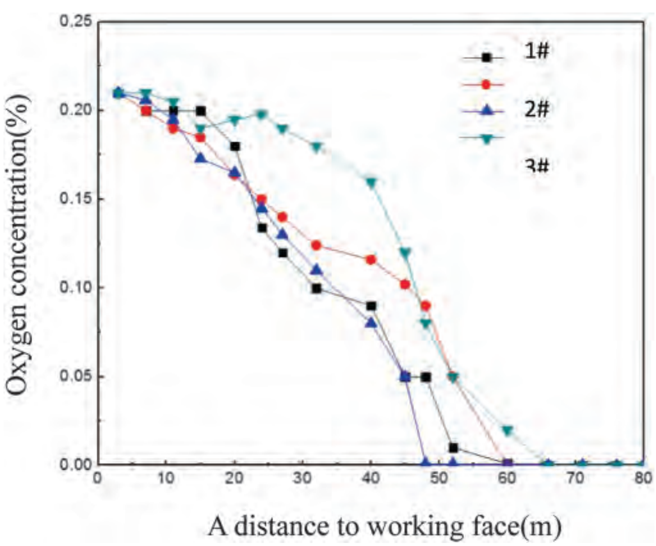

Fig.2 Line chart of measuring oxygen concentration distribution in gob

4. Numerical simulation

The spontaneous combustion of remaining coal in gob is mainly caused by the accumulation of heat generated by the oxidation and heat release of coal[11]. In general, the process of spontaneous combustion of coal involves heat, flow and chemical reaction. To study the process of the spontaneous combustion of coal in gob, coal rock of the gob is usually studied as porous medium[12]. However, the gas seepage in the gob has strong non-darcy characteristics, the percolation state of transition region is described by using non-darcy equation. Based on the continuity equation, momentum equation and energy equation, the mathematical model of multi-physics field for spontaneous combustion in gob is established as follows:

(1) Seepage equation:

$$\frac{\partial(\varepsilon\rho)}{\partial t}+\nabla\cdot(\rho\mu)=0 \quad \text{...} \quad (1)$$

$$\frac{\rho}{\varepsilon}\cdot\frac{\partial \mathrm{u}}{\partial \mathrm{t}}=\Delta\cdot\left[-\mathrm{p}I+\frac{\mu}{\varepsilon}\left(\nabla\cdot\mathrm{u}+(\nabla\cdot\mathrm{u})^{\mathrm{T}}\right)-\frac{2\mu}{3\varepsilon}(\nabla\cdot\mathrm{u})I\right]-\left(\frac{\mu}{\kappa}+\beta|\mathrm{u}|+\frac{Q}{\varepsilon^2}\right)\mathrm{u}+\rho\mathrm{g}\left(1-\frac{T_0}{T}\right) \quad \text{...} \quad (2)$$

(2) Oxygen concentration equation:

$$\frac{\varepsilon\partial \mathrm{c}}{\partial \mathrm{t}}+\Delta\cdot(-\varepsilon D\nabla\cdot\mathrm{c})+\mathrm{u}\nabla\cdot\mathrm{c}=\gamma(1-\varepsilon) \quad \text{...} \quad (3)$$

(3) Temperature equation:

$$(\rho C_{\mathrm{p}})_{\mathrm{eq}}\frac{\partial T}{\partial \mathrm{t}}+\rho C_P\,\mathrm{u}\nabla T=\nabla(K_{\mathrm{eq}}\nabla T)+\gamma(1-\varepsilon)\Delta H \quad \text{...} \quad (4)$$

$$(\rho C_{\mathrm{p}})_{\mathrm{eq}}=\theta_{\mathrm{p}}\rho_{\varsigma}C_{\varsigma}+(1-\theta_{\mathrm{p}})\rho C_P \quad \text{...} \quad (5)$$

$$K_{\mathrm{eq}}=\theta_{\mathrm{p}}K_{\varsigma}+(1-\theta_{\mathrm{p}})K_{\mathrm{p}} \quad \text{...} \quad (6)$$

Where ε porosity of coal in mined out area; ρ is air density and its unit is kg/m^3; t is time and its unit is s; u is seepage velocity its unit is m/s; p is the sum of static pressure of air pressure, and dynamic pressure and its unit is Pa;□ is unit vector; μ is dynamic viscosity of air and its unit is Pa.s; κ is permeability and its unit is m^2; β is Forchheimer coefficient; Q is gas source phase and its unit is kg/(m^3.s); g is acceleration of gravity and its value is 9. 8 m/s^2; T is physical field temperature and its unit is K; T_0 is initial temperature and its unit is K; c is concentration of oxygen substance and its unit is mol/m^3; D_0 is diffusion coefficient of oxygen in loose coal and its value is m^2/s; r is oxygen consumption rate of residual coal and its unit is mol (m^3·s); C_p is specific heat of fluid and its unit is J/(kg·K); K_{ep} is the equivalent thermal conductivity, subscript eq, represents the corresponding equivalent variable; ΔH is the heat produced by the reaction of unit coal and its unit is J/mol; θ_p is volume fraction of solid material; C_s is the specific heat capacity of solids and its unit is J/(kg·K); ρ_s is density of solid material and its unit is kg/m^3; K_p is thermal conductivity of fluid and its unit is W/(m·K); K_s is thermal conductivity of solids and its unit isW/(m·K).

The accuracy of the numerical simulation results is fundamentally determined by the rationality of the established physical and mathematical model.Establishing a reasonable physical and mathematical model of the gob directly affects the accuracy of the simulation results of oxygen concentration in the gob.In this paper, according to the relevant data of 5424Z working face of Kailuan Group, the physical model of numerical simulation is established by the general situation of work surface, and the above mathematical model is combined. The COMSOL software is used to solve the numerical model. Through setting up physical model, dividing the grid, setting parameters and solving the related physical variables by solver can obtain the distribution of “three zones” in gob.

In order to better study the distribution range of “three zones” of gob spontaneous combustion, after the COMSOL numerical simulation, the distribution of oxygen concentration field in the gob can be obtained, as shown in Fig.3. The spontaneous combustion zone exhibits irregular zonal distribution, and the width of the spontaneous combustion band in the intake entry is larger than that on the return air side. The oxygen concentration used in the calculation process is molar concentration and the air inlet is about 9.5mol/m^3. To observe convenient that the oxygen concentration is converted to volume fraction (%) when graphical output is displayed. As we can see from Fig.3, the ratio of oxygen is 21.3% in air inlet. With the diffusion of oxygen and the oxygen consumption of the residual coal oxidation reaction, the oxygen concentration gradually decreases along the depth of the gob. Although there is oxygen consumption to remaining coal, the air leakage, the porosity, and the air flow rate is large in the area from 15m to 45m of the coal wall of working face. So to provide sufficient oxygen it can make oxygen concentration maintain at a high level. The high concentration of oxygen flowing from the air inlet have reached wind return side of gob after the process of flow, diffusion and consumption and the oxygen concentration has been greatly reduced. After the oxidation of the residual coal of the return air side, the oxygen concentration drops to a lower level and then flows out of the gob with the airflow.

Fig.3 shows that “three zones” division of spontaneous combustion in gob is unevenly distributed from the air inlet side to the return air side. According to the oxygen concentration, oxidized spontaneous combustion zone at intake side is 15m distance from the coal wall of the working face, and the width is 30m. But the upper corner of the return air side has higher concentration of gas and lower oxygen concentration. The width of spontaneous combustion zone shows a decreasing trend from the air inlet side to the return air side.

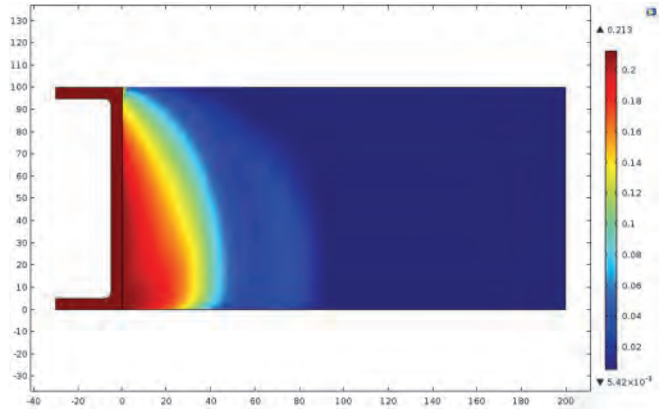

Fig.3 Simulation oxygen concentration in gob distribution curve

5. Conclusions

By establishing drainage system of the gob in 5424Z working face, it measures the distribution of oxygen concentration field in gob. It can use COMSOL numerical simulation software to simulate the distribution of oxygen concentration field in gob. The “three zones” of spontaneous combustion in gob are accurately divided by comparing the measured data and the numerical simulation results. The division results is that the heat dissipation zone is located in the 15m range of the coal wall of the working face, and the spontaneous combustion zone is within the 15m~45m range of the coal wall of the working face, and the suffocation belt is outside the 45m area of the coal wall of the working face.

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