Research on fire prevention and extinguishing technology in underhand working face of easy spontaneous combustion coal seam

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Abstract: The management of fire prevention and extinguishing in goaf becomes a major problem due to short spontaneous combustion period, poor roof caving conditions, large air leakage in goaf and difficulties for grouting. Oxygen consumption rate and the productivity of carbon monoxide are measured through the XK-VI spontaneous combustion test-bed, while prediction index gas for spontaneous combustion of the coal is obtained. Through the engineering practice test, the range of the gob “triple-zone” under the condition of nitrogen injection is acquired. Take 113101 working face of Bojianghaizi coal mine as an example. The method for detecting the fire prevention effect is to inject nitrogen into the goaf, supplemented by measures such as forced anchoring in the intake and return wind lane, constructed of the sandbag separation wall, and embedded the beam tube through the goaf. The volume fraction of carbon monoxide in the return corner and the $R_2$ value are used as predictors of fire prevention. Engineering practice test shows that there is no danger of spontaneous combustion in the working face when the volume fraction of carbon monoxide in the return corner is less than $200*10^{-6}$ and the value of $R_2$ is less than 0.2. The process has reference significance for the fire prevention management of the Bojianghaizi Mine and other similar conditions.

1. Introduction
The spontaneous combustion of the coal is one of the main natural disasters in China's mines, while residual coal in gobs is one of the prime reasons of the mine fire[1]. With the development of mine fire prevention technology, nitrogen injection has become one of the main technologies to prevent spontaneous combustion of residual coal in gobs[2,3]. At present, the research on fire extinguishing technology of nitrogen injection is mainly based on engineering practice field test and numerical simulation. Then it can confirm the technological parameters and nitrogen injecting volume, which is beneficial to study the oxygen concentration and the change of oxidation heating zone in the goaf after nitrogen injection[4-8]. Li Zongxiang et al[9]carried out simulation research based on heterogeneous air leakage seepage equation, gas seepage-diffusion equation and porous media seepage comprehensive equation. Yang Shengqiang et al[10,11]used fluent software to simulate the air leakage field in the goaf, which proved that spontaneous combustion in the goaf is a process of oxygen-heat microcirculation. Shi Guoqing et al[12,13]obtained the distribution of seepage velocity and oxygen concentration by numerical simulation in the goaf. These research results have effectively promoted the development of fire-fighting techniques of nitrogen. Due to the short spontaneous combustion
period of 113101 working face in Bojiang Haizi coal mine and the influence of unfavorable factors such as residual coal, roof caving and underhand stopes of working face, the hidden danger of spontaneous combustion in the goaf is more serious. By means of laboratory experiments and engineering practice, the author has confirmed the oxygen consumption rate, carbon monoxide production rate, spontaneous ignition period, fire prevention prediction index, the range of spontaneous combustion "triple-zone" and the technological parameters of nitrogen injection in the goaf. The spontaneous combustion in the goaf is eliminated through the injection of nitrogen, supplemented by forced anchoring in the intake and return wind lanes, constructed sandbag separation wall in the goaf.

2. General situation of mine
Bojianghaizi coal mine is located in the northwestern part of Ordos. The overall topographical trend is high in the south and low in the north. The main coal-bearing strata are the Jurassic Middle and Lower Yan'an Formation. The main coal seam in the mine is non-coking and long flame coal with low metamorphism. The 113101 working face is the first mining face in mine, which the length is 2600 meters, the width is 200 meters, and the thickness of coal seam is from 3.8 to 6.9 meters, with an average of 4.8 meters. It belongs to spontaneous combustion coal seam. The elevation of working face is from 850m to 799.2m, which is a sublevel mining face. There are three reasons of fire hazard in the goaf during coal extraction. First, there is amount of residual coal in the intake and return wind lanes, which provides the necessary conditions for spontaneous combustion; Second, the roof caving conditions of the intake and return wind lanes are poor, which leads to increasing air leakage in the goaf, and provides oxygen for spontaneous combustion. At last, the effect of grouting for fire prevention is poor in the underhand stopes, and the coal falling from the upper roof of the goaf can not be covered by slurry[14,15]. Therefore, it is urgent to confirm the characteristic parameters and the "triple-zone"of spontaneous combustion in the 3-1 working face. It can also provide reference for fire prevention management in the following working face.

3. Combustion simulation experiment and prediction index determination

3.1. Analysis of characteristic parameters of coal combustion
In order to accurately grasp the rule of spontaneous combustion, it is necessary to confirm the change of index gas in different stages of spontaneous combustion, especially in the exothermic oxidation stage. Using the XK-VI experimental equipment developed by Xi'an University of Science and Technology, the spontaneous combustion simulation experiment was carried out by collecting the 3-1 coal samples. The experimental conditions are shown in Table1. The corresponding relationship between the rate of oxygen consumption, the rate of carbon monoxide production and temperature in the 3-1 coal seam at different stages was confirmed.

| Coal sample | Average particle size | Height | Quality | Volume | Density | Bulk density | Void fraction | Volume of blast | Initial temperature |
|-------------|----------------------|--------|---------|--------|---------|--------------|---------------|------------------|---------------------|
|             | d50/(mm) | (cm)   | (kg)    | (cm³)  | (g/cm³) | (g/cm³)      | (/m³/h)       |                  | (T)                 |
| 3-1         | 2.71     | 180    | 1828.8  | 203472 | 1.40    | 0.8988       | 0.358         | 0.1~1.6          | 32.9               |

According to the experimental data, the oxygen consumption rate is calculated, and the relationship between the rate of oxygen consumption and temperature is obtained, as shown in Figure 1. It can be seen that the rate of oxygen consumption in the oxidation process is basically exponential with temperature. The increase of this coefficient indicates that the possibility of spontaneous combustion of coal is increasing. The curve of oxygen consumption can provide key technical parameters for the fire.
area treatment, which is of great significance to the safe of the fire zone.

Figure 1. the curve of oxygen consumption rate with temperature.

Carbon monoxide and carbon dioxide are the products from exothermic oxidation of coal. According to the programmed heat experiment, the amount of them produced at different temperature are measured. On the basis of the calculation, the curves of carbon monoxide and carbon dioxide production rate are obtained, as shown in figure 2. The relationship between the volume fraction of ethylene and ethane and temperature is shown in Figure 3. With the increase of molecular velocity, more carbon monoxide and carbon dioxide will be produced. Since the coal sample is in an oxygen-enriched state, the growth rate of the carbon dioxide is much larger than that of the carbon monoxide. Furthermore, the rates of carbon monoxide and carbon dioxide production are exponentially related to the temperature.

Figure 2. The curves of generation rate of carbon monoxide and carbon dioxide with temperature

Figure 3. The volume fraction of ethylene and ethane with temperature
Under the experimental conditions, the spontaneous combustion period of the 3-1 is 29 days. According to the actual temperature of the mine is 25°C, the spontaneous combustion period is 31 days[16].

3.2. Analysis of fire prediction index

The release of gases in the process of exothermic oxidation are different due to different conditions. So the indicator gas must have sensitivity, regularity and measurability. In the process of spontaneous combustion, the index gases can be divided into oxidation gases and pyrolysis gases. Oxidation gases are mainly carbon monoxide and carbon dioxide; and pyrolysis gases are mainly methane, ethane, propane, ethylene and acetylene. Although the measurable temperature range of the oxidation gases is relatively wide and the productions is large, it is greatly affected by the wind and the environment. However, the measurable temperature range of the pyrolysis gases is relatively narrow, the amount of production is relatively small, and it is easily diluted by the wind, which is greatly affected by factors such as detection means. The oxidation gases is compared with the oxidation gases, and the ratio can be used as a characterization parameter for confirming the degree of spontaneous combustion. The advantage is that the influence of air volume and environmental factors can be excluded. \( R_2 \) (the ratio of the increase of the volume fraction of carbon monoxide to the decrease of the volume fraction oxygen) can be used as an indicator of the speed of oxidation. Through the experiment of temperature increasing, it was found that the carbon monoxide appeared in the first and in the whole process. When the coal temperature reached 78.4°C, ethylene began to appear. Therefore, the appearance of ethylene can be used as the temperature of the residual coal in the goaf reaches about 78.4°C.

4. Classification of gobs spontaneous combustion "triple-zone"

Due to the short spontaneous combustion period of the 3-1 coal seam, there is hidden danger of spontaneous combustion in goaf. Therefore, it is of great significance to accurately confirm the range of gobs spontaneous combustion “triple-zone”. Combined with the relationship between the rate of oxygen consumption, the rate of carbon monoxide and the temperature in the spontaneous combustion test. The volume fraction of oxygen and carbon monoxide in goaf are measured by bundles buried in the intake and return wind lanes. Then, under the condition of nitrogen injection, the variation law of the oxygen volume fraction on the intake and return sides with the distance of the measuring point buried can be obtained respectively, as shown in Figures 4 and 5.

![Figure 4](image1.png) ![Figure 5](image2.png)

From Figure 4, it can be seen that the air leakage on the intake side is more serious, and the volume fraction of oxygen is smaller in the range of 0 to 55m. It is almost linearly decreased between 55m and 130m, and the volume fraction of oxygen is between 5% and 15%. It tends to be flat after 130m, which drops below 5%. From Figure 5, it can be seen that the volume fraction of oxygen are less than 15% at 20m and 5% at 70m on the return side respectively. With the depth of the measuring point buried in the goaf continues to increase, the measuring point enters the asphyxiation zone, and the
volume fraction of oxygen gradually decreases and tends to be stable. Therefore, assuming that the thickness of floating coal is enough to accumulate heat, the potential spontaneous combustion hazard is most likely in the range of 55m-130m on the intake side and 20m-70m on the return side of the working face, which is the key area of fire prevention management. The range of the “triple-zone” under the conditions of nitrogen injection is shown in Table 2 [17].

|                             | Scattered tropical | Oxidation temperate zone | Asphyxiation zone |
|-----------------------------|--------------------|--------------------------|-------------------|
| Intake air side goaf (m)   | 0~55               | 55~130                   | >130              |
| Return air side goaf (m)   | 0~20               | 20~70                    | >70               |
| Oxygen concentrations (%)   | >15                | 5~15                     | <5                |

5. Analysis of fire prevention and extinguishing measures and effect

5.1. Fire prevention measures of the nitrogen injection
According to the range of "triple-zone", the nitrogen release port of nitrogen injection pipe is set in the exothermic oxidation zone on the intake side, which is 0.3m higher than the coal seam floor and protected. The burial of the nitrogen injection pipe adopts a cyclic step method. The first nitrogen injection pipe is buried in the gobs from 55m to 130m, then the second nitrogen injection pipe is buried. When the first nitrogen release port enters the suffocation zone, the nitrogen injection is stopped, then the second nitrogen injection pipe is activated to inject nitrogen. The nitrogen release port is always kept in the oxidation heating zone until the end of the mining face.

5.2. The measures of mandatory retreating anchors (cables) and sandbags
Reducing the air leakage can minimize the spontaneous combustion of the residual coal in the goaf. The air leakage mainly comes from the intake and return wind lanes. Especially when the roof conditions of the two lanes are poor, the air leakage increases rapidly. Therefore, the mandatory retreating anchors (cables) are taken to create conditions for the roof collapse. If it is adopted, the two lanes still cannot be slammed in time, then the sandbag partition wall should be constructed at the end of the two sides of the working face.

5.3. Analysis of fire prevention effect
Based on the analysis of the pre-buried bundle tube sampling, the relationship between the volume fraction of carbon monoxide and oxygen and the distance of buried is obtained, as shown in Figure 6. The relationship between the volume fraction of carbon monoxide and the volume fraction of oxygen in the corner of the stope during the whole mining is shown in Figure 7. The variation of R² value in the corner of return side is shown in Figure 8.

From Figure 6, it can be seen that with the depth of the measuring point buried in the goaf increasing, the volume fraction of carbon monoxide increases at first and then decreases gradually,
while the volume fraction of oxygen decreases all the time. It is because of the measuring buried point enters the oxidation zone from the heat-dissipating zone, the thermal storage is conducive to the rapid oxidation of the residual coal. It produces a large amount of carbon monoxide. As the working face continues to mining, the measuring point slowly enters into the asphyxiation zone from the oxidation zone. After the fraction of oxygen volume is reduced to 5%, the oxidation rate of the residual coal gradually decreases and eventually stabilizes. From the volume fraction curve of carbon monoxide and oxygen, the volume fraction of carbon monoxide starts to rise rapidly at 25m, and reaches its peak at about 65m. At this time, the volume fraction of oxygen is between 5% and 15%, and then begins to gradually decrease. The results show that the range of oxidation heating zone is located in the 25-65m, which is the key area for fire prevention and monitoring. It basically coincides with the range of the gobs spontaneous combustion “triple-zone”, which is 20-70m. It also verified the accuracy of the “triple-zone”.

Figure 7. Volume fraction curve of Carbon monoxide and oxygen in the corner of return side.

Figure 8. Curve of R₂ value in the corner of return side.

From Figure 7, it can be seen that the volume fraction of carbon monoxide in the corner of return side decreases gradually during the whole mining. It is low at the beginning and after stopping of mining. Because when the working face is just beginning to mining, the residual coal is in the range of the heat dissipation zone, the heat of oxidation of the coal is difficult to accumulate. Then the oxidation rate is slow, and the amount of carbon monoxide generated is small. When mining is stopped, the sandbags partition wall at the corner of the intake and return sides is blocked in time. The pressure difference between the intake and return wind lanes is reduced, so the air leakage is reduced, and the oxidation speed of the residual coal is delayed to a certain extent. The volume fraction of carbon
monoxide in the working face is between 69*10^{-6} and 200*10^{-6} under normal circumstances.

From Figure 8, it can be seen that the change trend of R\textsuperscript{2} value in return corner is consistent with the volume fraction of carbon monoxide, both of which show a gradual downward trend. R\textsuperscript{2} value ranges from 0.06 to 0.2. There have been several cases where the R\textsuperscript{2} value is greater than 0.2 during the initial mining of the working face.

At present, the working face has been safely harvested, and there is no abnormality of the volume fraction of carbon monoxide during the whole process. There is no sign of spontaneous combustion in the goaf. Based on the statistical analysis of gas test data during mining and plotting of curves, it is found that when the volume fraction of carbon monoxide in the corner of return side is less than 200*10^{-6} and the R\textsuperscript{2} value is less than 0.2, there will be no hidden danger of spontaneous combustion occurs in the goaf.

6. Conclusion
(1) The most effective fire prevention measures for the working face with easy spontaneous combustion are the nitrogen injection, forced bolt withdrawal (cable) in the return wind lane and constructed sandbag partition wall.

(2) Through engineering practice test, the range of the 3-1 coal spontaneous combustion "triple-zone" under the condition of nitrogen injection is obtained.

(3) The variation curves of the volume fraction of carbon monoxide and R\textsuperscript{2} value in the corner of return side can be used as the prediction index of the fire prevention. Ethane and ethylene can be regarded as the temperature index gases with the temperature of residual coal reaching 43.5\degree C and 78.4\degree C respectively.

(4) There will be no potential spontaneous combustion in the goaf when the volume fraction of carbon monoxide in the return corner of the working face is less than 200*10^{-6} and R\textsuperscript{2} value is less than 0.2.

Fund projects:
Study on transition metal oxide synergistic flame retardant polyurethane in different fire scenes(2018M642541); Preparation of layered compound catalytic synergistic flame retardant polyurethane thermal insulation material and its flame retardant and toxic reduction mechanism studying(KJ2018A0593); Industrial ventilation and dust control(2016jkcx17); Preparation and properties of new intumescent flame retardant low density polyethylene(2017zr007).

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