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MSc Thesis

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# Study on Coal Spontaneous Combustion in Goaf of Dashe Coal Mine

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Date(dd/05/2019)



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## **Declaration of Authorship**

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„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet.”



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## Abstract

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As the largest coal producing and consuming country in the world, the safe production of coal mine in China is related to the long-term development of coal industry of China, and mine fire is one of the most serious safety problems. Taking Dashe Coal Mine as an example, this paper studies the regularity of various gases released from coal sample in the programmed-temperature heating experiment, including CO, O<sub>2</sub>, C<sub>2</sub>H<sub>2</sub> and C<sub>2</sub>H<sub>4</sub>, etc. Based on the data of programmed-temperature heating experiment, the function curve of the gas concentration and temperature of coal sample is fitted. The change of CO concentration is most obvious with the increase of temperature, which can be selected as the index gas to monitor the coal spontaneous combustion in goaf of Dashe coal mine. The distribution of oxygen in goaf under different number of faults and different volume of air leakage is simulated by FLUENT software. The oxygen concentration of 8% and 18% is taken as the criteria for dividing the three zones(heat dissipation zone, oxidation zone and suffocative zone) of goaf. With the increase of the number of faults, the width of oxidation zone in goaf increases, which makes it more difficult to prevent coal spontaneous combustion in goaf. According to the mining data of Dashe coal mine, the quantity of nitrogen injection needed in goaf was calculated, and the effects of different nitrogen injection locations before and after passing through faults on oxygen concentration distribution in goaf were simulated respectively. In addition, the oxygen concentration in goaf in y=0m, y=60m and y=120m was monitored by the monitoring pipeline system. It was found that the fault in goaf reduced the effect of nitrogen injection.

**Keywords:** Coal mining face, Goaf, Coal spontaneous combustion, Three zones, Nitrogen injection



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# 1 Introduction

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## 1.1 Background and significance of this research

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Mine fire is one of the major disasters in coal mines production, especially coal spontaneous combustion is a serious problem. About 56% of the coal mines in China have a coal seam spontaneous combustion hazards, while the thick coal seams are more serious (He Min, 2017). The spontaneous combustion of coal has become one of the major disasters that restrict the high productivity and efficiency of China's coal industry. The mines with coal spontaneous combustion hazards account for about 47% in China, of which the spontaneous combustion in the goaf accounts for 60% of the internal fires (Yu Guisheng, et al 2012). According to statistics, between 2010 and 2014, there were 25 major coal seam fire accidents in coal mines in China, resulting in 249 deaths and huge economic losses. At present, there are nearly 800 residual fire areas in state-owned coal mines, and the amount of waste coal has reached more than 200 million tons (Lu Xinxiao, 2016). Coal mine spontaneous combustion often cause mine gas explosions, often accompanied by water and coal gas explosions, and the production of toxic and harmful gases pose a great threat to the safety of miners (Yu Minggao, 2013). In recent years, China has extensively carried out high-yield and high-efficiency coal mine project (Liu Na, 2016), and mine production has gradually developed into high-yield and high-efficiency intensive development, but at the same time the seriousness and danger of coal mine spontaneous combustion have increased. There are many residual coals left in the goaf and serious air leakage, which makes the spontaneous combustion become one of the main factors restricting the development of the coal mine in China.

The Dashe coal mine in Fengfeng mining area contains a large number of faults. At the fault location, the coal seam is subjected to tension, extrusion and other effects to produce a large number of cracks. The coal body is broken and it is easy to form a large amount of float coal. The air leakage channel near the fault is complex, providing ventilation and oxygen supply conditions for coal oxidation and spontaneous combustion. The separation of coal and rock at the fault is obvious, and the geological structure is complex. During the mining period, mining activities

such as shooting, coal cutting and rock cutting generate more heat and have a good heat accumulation environment. During the period of passing through fault of the working face, the fault has caused the original continuity and integrity of the coal seam, which brings great difficulties to the underground mining (Wang Jingyi, et al 2010)). Due to the moving speed of the working face is slow, which makes the goaf long-term in the state of air leakage oxidation. With the continuous oxygen supply environment, the oxidation and heat storage time increases, and spontaneous combustion easily occurs.

In 2005, there was an open flame in the 92709 coal mining face of Dashe coal mine. Before the construction of the fire monitoring and early warning system, about 50 goafs of had high temperature points and CO overruns, indicating that the mine has frequent problem of coal spontaneous combustion in the goaf.

Therefore, it is necessary to study the coal spontaneous combustion mechanism and treatment technology of goaf under multi-fault conditions. Developing targeted technical solutions and preventive measures to eliminate potential fire hazards and create conditions for safe production.

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## **1.2 Research status**

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### **1.2.1 Current status of coal spontaneous combustion theory**

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#### (1) The process of coal spontaneous combustion

Without external heat source heating, coal-oxygen reaction leads to oxidation heat accumulation, so the phenomenon that the temperature rises to the ignition point causing coal combustion is called spontaneous combustion of coal, also known as coal spontaneous combustion (Yu Minggao, 2013). The spontaneous combustion process of coal is a complex physical and chemical reaction process. The molecular structure of coal is very complex and contains a variety of functional groups and chemical bonds (Zhao Wenbin, et al 2018). Therefore, when the temperature of coal rises, it is accompanied by the phase transformation, mass transfer, heat transfer and oxidation reaction of coal. Under such complicated and varied chemical reaction conditions, the molecular structure of coal is constantly changing (Jiao Hanlin, 2015), and then the ignition point causes spontaneous combustion of coal. Studies have shown that the spontaneous combustion process of coal can be roughly divided into

three periods, namely the incubation period, the self-heating period and the combustion period (Deng Jun, et al 2018).

The accelerated oxidation process of coal and the accelerating heat storage process of coal are the essence of coal spontaneous combustion (Wang Yang, 2009). Because the oxidation rate of coal is fast and the heat generated by the oxidation process of coal is much larger than the heat dissipated to the outside, resulting in the continuous accumulation of heat inside the coal body. Once the ignition point is reached, coal spontaneous combustion will occur. The oxidation process of coal can be carried out at any temperature, except that the rate of oxidation increases with increasing temperature. The oxidation process of coal is actually the process of coal oxidation reaction, when the oxidation reaction of coal continues, it will inevitably lead to a decrease in the oxygen content in the surrounding air.

## (2) Coal spontaneous combustion theory

Researchers have been studying the theory of coal spontaneous combustion for more than 100 years, and there have been many related theories and hypotheses about this. Lots of scholars have carried out a lot of research on the mechanism of coal spontaneous combustion, and put forward various theories such as "pyromeroin theory", "bacterial action theory", "phenol-based action theory" and "coal oxidation theory" from various aspects, various ideas explain the reasons for the coal spontaneous combustion.

Nowadays, most scholars and scientific researchers agree with the theory of coal-oxygen interaction (Tian Baizheng, 2018). Coal and oxygen are the two important substances for coal spontaneous combustion. Coal can adsorb oxygen, and the adsorption process is divided into physical adsorption and chemical adsorption. The physical adsorption of coal to oxygen is a process of adsorption on the surface of the coal, and there is also a small part of the chemical reaction, so a small amount of heat is generated. The physical adsorption process promotes the temperature rise and provides a thermodynamic source for the chemical adsorption of coal to oxygen, thus allowing more oxygen to be adsorbed and promoting the occurrence of coal and oxidative reactions. The whole process releases a large amount of heat, and once the heat is accumulated to the ignition point, coal spontaneous combustion

can occur. The main factor leading to the spontaneous combustion of coal is the continuous generation and accumulation of heat (Chen Junzhao, 2014).

The spontaneous combustion of coal can be studied from the relationship between the molecular structure of coal and chemical reaction. For example, Li Zenghua (1996) discussed the factors causing the change of free radicals in coal molecule, the reaction process of free radicals in coal molecule with oxygen, and studied various gas components produced in the reaction process of coal and oxygen. Finally, the theory of free radical action in the molecule of coal spontaneous combustion was obtained. He Qilin (2005) discussed the initial stage of coal spontaneous combustion. Moisture has two functions: catalytic effect on spontaneous combustion of coal and inhibition effect on spontaneous combustion of coal. The physical and chemical effects of water molecules during spontaneous combustion of coal are studied. The effects of water molecules on spontaneous combustion of coal in some mining areas and the effects of spontaneous combustion of coal on water molecules are analyzed.

The spontaneous combustion of coal can be studied from kinetics of chemical reaction. Peng Benxin (1990) measured the propensity of coal spontaneous combustion by calorimetric method. Eight kinds of coal produced in China, namely long flame coal, fat coal, coking coal, anthracite, lean coal, lignite, gas coal and lean coal, were tested by TGA, DTA and thermal analysis infrared spectroscopy. It is concluded that CO is the marker gas of coal spontaneous combustion.

The spontaneous combustion of coal can also be studied from reactivity. Wang Baojun (2006) summarized the changes of chemical bonds and thermodynamic variables during coal pyrolysis, and studied the application of calculation methods in quantum chemistry in reaction kinetics. The change mechanism and kinetics of coal surface structure under the co-existence of carbon dioxide and methane are studied, and the characteristics and functions of quantum chemical calculation method in coal reaction are discussed. Zhang Jinglai calculated the electron cloud distribution of each atom in the molecular structure of coal by quantum chemical calculation method, analyzed the mechanism of adsorption of macromolecule gases or other substances on the surface of coal particles, and explained the reason of adsorption of anionic macromolecules on the surface of negatively charged coal particles.

Through the research of many scholars and coal experts, many results of coal spontaneous combustion have been obtained, which are scientific to a certain extent, but there are not very specific and convincing research results, and the essential law of coal spontaneous combustion has not been fully revealed. Most of them use thermodynamic methods for qualitative analysis and lack of quantitative analysis and research. Therefore, the process of spontaneous combustion of coal still needs more efforts of scholars to study and analyze, to obtain more scientific and convincing research results, and to reveal more accurately the nature of coal oxidation in the process of spontaneous combustion of coal.

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### **1.2.2 Research status of coal spontaneous combustion prevention and control technology**

Coal oxidation is the main factor leading to spontaneous combustion of coal (Zhang Yanni, 2012). Surface chemical structure of coal, concentration of oxygen and mine temperature are the three main factors affecting spontaneous combustion of coal. To prevent coal seam spontaneous combustion, measures should be taken from three aspects: one is to isolate coal from oxygen so that coal can not spontaneously ignite due to lack of oxygen; the other is to reduce coal temperature so as to slow down the oxidation reaction rate of coal, so that heat can not be accumulated, so as to inhibit coal spontaneous combustion; the third is to inert the surface active structure of coal, so as to reduce the compound speed of coal and oxygen, effectively prevent coal spontaneous combustion.

In recent years, researchers at home and abroad have developed and studied many new technologies to prevent coal spontaneous combustion by means of inerting, cooling and blocking air leakage. After summarizing, there are the following several kinds: air leakage stopping technology in goaf (WANG D, et al 2016), water injection fire prevention technology (Peng Xianqing, et al 2016), grouting fire prevention and extinguishing technology (Niu Dezheng, 2017), pressure equalizing fire prevention technology (Zheng Zhongya, et al 2018), fire retardant fire prevention technology (Wen Hu, 2016), inerting fire prevention and extinguishing technology, high water and temperature resistant colloid fire prevention technology (Dengjun, 2011), comprehensive fire prevention technology, etc.

(1) Air leakage stopping technology in goaf

One of the necessary conditions for spontaneous combustion of coal in goaf is continuous oxygen supply. Effective air leakage stopping technology can reduce or even completely prevent the supply of oxygen to coal in goaf, thus effectively preventing internal fire in coal seam.

#### (2) Grouting fire prevention and extinguishing technology

Grouting fire prevention and extinguishing technology is to inject slurry into the goaf, which will encapsulate the coal body, absorb heat and cool down the coal body, isolate coal from oxygen, cementing the roof, and reduce the void rate of the goaf, thereby increasing the air leakage resistance.

At present, this technology has been relatively mature, and has been widely used in spontaneous combustion mines in China. This method has good fire prevention and extinguishing effect and is one of the main effective measures to prevent and control underground internal fire. However, there are some drawbacks of this technology: large amount of engineering, difficult to solidify (slurry dehydration volume is large), which deteriorates the working environment. Because of the strong fluidity of slurry, the slurry will concentrate in the lower position of goaf.

#### (3) Inert fire prevention and extinguishing technology

Inert fire prevention and extinguishing technology refers to injecting inert gas or other inert substances into the treated fire area in the closed area caused by fire or spontaneous combustion of coal. In recent years, many inert substances, such as yellow mud, inhibitor, shale mud, inhibitor mud, fly ash and tailings sludge of coal preparation, have been used as inert substances for fire prevention and extinguishing. The inert substances mainly play two functions: inerting and cooling. Fly ash grouting and chemical inhibitor have been widely used in thick coal seam mining.

Injecting inert gas into the fire area is the main means of inert gas fire prevention and extinguishing technology. At present, the inert gas source mainly consists of nitrogen and carbon dioxide gas. Injecting inert gas into the fire area can increase the concentration of inert gas and reduce the oxygen concentration in the fire area, which is more conducive to fire prevention and extinguishing.

#### (4) Comprehensive fire prevention and extinguishment technology

Comprehensive fire prevention and extinguishing technology combines the above two or more fire prevention and extinguishing technologies. At present, because the causes of mine fire are various and complex, if only one kind of fire prevention and extinguishing technology is used, the effect of fire prevention and extinguishing will not be very good, so a comprehensive fire prevention and extinguishing technology combining multiple fire prevention and extinguishing technologies must be used.

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### **1.3 Main research content of this thesis**

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The main contents of this thesis are as follows:

- (1) The parameters of coal samples in Dashe coal mine were obtained by the programmed-temperature heating experiment, and the concentration of various gases released during the process of temperature rising was obtained. It can also be used as an index gas for monitoring coal spontaneous combustion in goaf.
- (2) The distribution of oxygen concentration in goaf was simulated by FLUENT software, which is used as the criterion for dividing three zones of coal spontaneous combustion in goaf, and the distribution of three zones in goaf under different fault conditions was compared. The monitoring data and simulation results are also compared.
- (3) The quantity of nitrogen injection needed to prevent coal spontaneous combustion in goaf was calculated. The distribution of oxygen concentration in goaf was simulated before and after nitrogen injection, and the actual monitoring data of oxygen concentration were compared with the simulation results.





## **2 General situation of Dashe coal mine and geological distribution of faults**

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### **2.1 General situation of Dashe coal mine**

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Dashe Mine is located in Dashe Town, Fengfeng Mining Area, about 30km southwest of Handan City, Hebei Province. The geographic coordinates of minefield Center are  $36^{\circ}33'$  north latitude and  $114^{\circ}11'$  east longitude. The administrative area where Dashe Mine is located belongs to Fengfeng Mining Area of Handan City. The property rights of the mine belong to Yuzhong Energy Fengfeng Group Co., Ltd. The elevation of the main shaft is +234.8m (the highest flood water level +230m), and the ventilation shaft is located at the top of Xigang slope of Nanwang Village, with an elevation of +204.3m (the highest flood water level +190m).

The shape of Dashe mine field is irregular, the west is wider, the East is narrower, the average strike length is about 6000 m, the average inclination width is 2838.1 m, the area is  $16.9926 \text{ km}^2$ , the mining elevation is from + 270 to -720 m. The main mining coal seams in Dashe Coal Mine are No.2 coal seam, No.4 coal seam and part of No.6 coal seam that elevation is above -300m. Because of the threat of Ordovician limestone aquifer, the No.7 coal seam, No.8 coal seam and No.9 coal seam have not been mined at present.

By the end of 2015, there were 54.517 million tons of industrial reserves, 107.183 million tons of prospective reserves and 27.616 million tons of recoverable reserves. According to the current coal production of Dashe coal mine about 1.5 million tons per year, the remaining service life of the mine is 13.2 years.

Dashe coal mine is located in a temperate continental semi-arid monsoon climate zone. The annual precipitation ranges from 1273.4 mm (1963) to 374.9 mm (1965), with an average of 616.1 mm. The maximum daily precipitation is 196.7 mm on August 4, 1963, and the annual evaporation is generally 2000 mm, which is larger than the precipitation.

The historical maximum temperature is  $41.9^{\circ}\text{C}$  (July 10, 1962), the minimum temperature is  $-15.7^{\circ}\text{C}$  (January 15, 1967), the annual average temperature is  $12.6^{\circ}\text{C}$ , and the maximum frozen soil depth is 0.22 m. The north wind is dominant

in winter and the south wind in summer. The average wind speed in Dashe coal mining area is 1.7m/s and the maximum wind speed is 20m/s.

This coal mining area is located in the seismic activity zone of the Pacific earthquake tectonic belt, with frequent earthquakes and high magnitude. Since the earthquake records began in 230BC, there have been many earthquakes in the periphery of the history. The largest earthquake in that area was in June 12 and 26, 1930. The magnitude level was 7.5, and the epicenter was in Xiguyi area. The death toll of 1930 earthquake was 5,485, and it affected 140 counties in six provinces. According to the Division Map of Seismic Intensity in China (1990), the seismic intensity in this area is VII. According to the Division Map of Seismic Parameters in China (GB18306-2001), the peak acceleration of ground motion in this area is 0.15g.

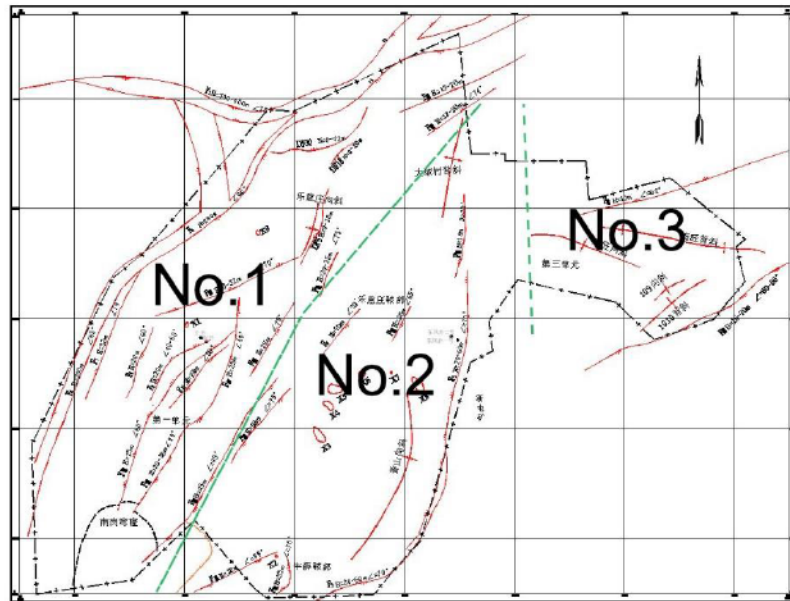
Dashe coal mine has a long mining history, the geological conditions in the underground are complicated with lots of faults and folds. Complex geological conditions lead to more residual coal in the goaf and more serious air leakage, which is likely to cause spontaneous combustion of coal.

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## **2.2 Geological characteristics of Dashe coal mine**

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Dashe coal mine is located in the northeast of Fengfeng Coalfield. The basic law of the development of Dashe minefield is that the central structure is relatively simple, the structure in the southwest and northeast is more complicated, and the structure in the northwest is the most complicated. According to the size, distribution characteristics, extension length and distribution density of the faults in the minefield, the Dashe minefield is divided into three sections, as shown in Figure 2.1.



**Figure 2.1 Fault distribution in Dashe coal mine**

No.1 section is located between the faults of F<sub>13</sub>, F<sub>36</sub>, F<sub>16</sub>, F<sub>18</sub> and east of F<sub>4</sub>. The strike of faults is N10°~ 40°E, and the dip angle is about 65°. Large and medium faults and small faults are relatively developed in No.1 section. The strikes of faults in No.1 section are mainly NNE or NE, and the dip angle range from 60° to 80°.

No.2 section is located between the faults of F<sub>13</sub>, F<sub>36</sub>, F<sub>16</sub>, F<sub>18</sub> and F<sub>3</sub>. The strike of faults in the north part is N10°E, and the strike of faults in the south part is N50°~70°E. The dip angle ranges from 60°~ 71°. The geological structure of No.2 section is relatively simple, most fault structure is small, and the larger fault distribution is less.

No.3 section is located between the faults of F<sub>14</sub> and F<sub>3</sub>. The strike of faults in the north part is N70°E, and the strike of faults in the south part is N30°E. This section is mainly composed of fold structure, mainly consisting of 109 syncline structure, Nanwang syncline structure and 1010 anticline structure, and Nanwang anticline structure. Due to the influence of the geological structure, the occurrence of strata in the area varies greatly.

The faults in the Dashe coal mine are very developed. It has been found that there are 42 faults with a drop of more than 5m, of which 25 faults with a drop of more than 20m account for 59.52% of the faults that have been revealed. There are 17 faults with a drop of 5m ~ 20 m, accounting for 40.48% of the faults that have been revealed. There are about thousands of small faults that are extremely developed.

All the exposed faults are all high-angle normal faults with an inclination angle of 55° ~ 75°.

The width of fault varies from 0.1m to 4m, and the substance in the fault zone is complex, consisting of fault gouge, fault breccia and mylonitic material. The information of faults in Dashe coal mine are shown in Table 1.

**Table 2.1 The information of faults in Dashe coal mine**

Number of faults	Occurrence			H	Location
	Strike	Inclination			
F <sub>4</sub>	N20°E	SE	65°	200m	Drillhole1032, Drillhole1007, Drillhole9008, Drillhole9030, Drillhole1001
F <sub>7</sub>	N20°E	NW	74°	32m	Drillhole9033
F <sub>6</sub>	N30°E	SE	60°	20m	Drillhole1005, Coal mining face9255, Coal mining face 9227
F <sub>5</sub>	N20°E N65°E	SE SSE	60°,40°	20m	Coal mining face 9221, Coal mining face 9210, Coal mining face 9424, Coal mining face 9460
F <sub>15</sub>	N70°E	NW	75°	32m	Drillhole1301
F <sub>12</sub>	N20~45°E	SW	60°	40m	Drillhole690
F <sub>10</sub>	N30°E	SE	55°	45m	Drillhole710, Coal mining face 9220, Coal mining face 9221, Coal mining face 9409
F <sub>10'</sub>	N30°E	SE	40°	25m	Drillhole1010
F <sub>11</sub>	N30°E	SE	50°	28m	Coal mining face 9201, Coal mining face 9202, Coal mining face 9203
F <sub>61</sub>	N30°E	SE	75°	25m	Drillhole1045
F <sub>13</sub>	N30°E	SE	45°	45m	Drillhole1022, Coal mining face9255, Coal mining face 9227
F <sub>13'</sub>	N40°E	SE	75°	58m	Drillhole1026
F <sub>23</sub>	N70°E	SE	37°	30m	Coal mining face 9409, Coal mining face 9202
F <sub>68</sub>	N50°E	SE	70°	35m	Coal mining face 9409
F <sub>14</sub>	N30°E~ N70°E	SE S	50°, 56°	15m	Drillhole69, Drillhole81
F <sub>9</sub>	N70°E	SE	65°	40m	Coal mining face 9221
F <sub>22</sub>	N70°E	NW	65°	55m	Drillhole12

Number of faults	Occurrence			H	Location
	Strike	Inclination			
F <sub>44</sub>	N42°E	SE	73°	10m	Drillhole81
F <sub>86</sub>	N45°E~ N15°E	SE	62°	30m	Coal mining face 9409
F <sub>8</sub>	N20°E	NW	55°	12m	Coal mining face 9229, Coal mining face 9228, Coal mining face 9429
F <sub>38</sub>	N30°E	SE	65°	10m	Drillhole 43
F <sub>21</sub>	N50°E	SE	55°	7m	Coal mining face 9248 Drillhole1677 Drillhole1621
F <sub>69</sub>	N10°E	SE	75°	7m	Coal mining face 9248 Coal mining face 9249
F <sub>65</sub>	N45°E	NW	55°	10m	Coal mining face 92505, Coal mining face 92507, Coal mining face 94505, Coal mining face 94507
F <sub>71</sub>	N30°E	NW	75°	15m	Drillhole1308
F <sub>43</sub>	N45°E	SE	70°	10m	Drillhole1444, Drillhole1211, Drillhole1074
F <sub>19</sub>	N25°E	SE	62°	30m	Drillhole204
F <sub>3</sub>	N10°E	NW	70°	71m	Roadway 94604
F <sub>6</sub>	N20°E	SE	75°	8m	Roadway 92507 Roadway 92706
F <sub>24</sub>	N15°~25°E	NW	65°	12m	Coal mining face 92603, Coal mining face 92605, Coal mining face 94603, Coal mining face 94605, Coal mining face 94607
F <sub>25</sub>	N25°E	NW	75°	14m	Coal mining face 92601, Coal mining face 92603, Coal mining face 94601, Coal mining face 94603
F <sub>26</sub>	N40°E	NW	70°	10m	Coal mining face 92605, Coal mining face 92607
F <sub>62</sub>	N40°E	SE	60°	7m	Drillhole 1029
F <sub>63</sub>	N45°E	SE	60°	8m	Drillhole 1039
F <sub>27</sub>	N45°E	NW	75°	14m	No.10 panel
F <sub>28</sub>	N45°E	NE	70°	8m	No.10 panel
F <sub>17</sub>	N17°E	NW	73°	20m~ 25m	Roadway 92624

Number of faults	Occurrence			H	Location
	Strike	Inclination			
F <sub>49</sub>	N80°E	SE	75°	5m~21m	No.11 panel Roadway 92116
F <sub>37</sub>	N50°E	NW	50°	10m~ 25m	Drillhole 1023
F <sub>30</sub>	N70°E	NW	75°	10m~ 25m	Drillhole 1017
F <sub>29</sub>	N45°E	SE	56°	30m	Drillhole 1047
F <sub>22</sub>	N70°E	NW	65°	55m	Drillhole 92104, Drillhole 92103, Drillhole 92102, Drillhole 92101

### 2.3 Mine development

The way of mine development is vertical shaft development, underground inclined shaft development and multi-level development. The main and auxiliary shafts are drilled to the first level (+30m), and extended to the second level (-120m) and the third level (-280m) through the underground inclined shafts. Eastern air shaft and return air shaft were drilled to - 280m level. Longwall mining method is mostly used in Dashe coal mine.

There are three mine safety outlets: auxiliary shaft, eastern air shaft that is equipped with ladders for personnel and safety inclined shaft. At present, the production of Dashe coal mine is mainly in No.6 panel area, No.7 panel area, northeast area of minefield and west area of No.5 panel area.

Coal mining face in Dashe mine is equipped with double drum shearer to drop coal and automatically load coal. Flexible scraper conveyor is used to transport coal in the working face, and the coal is transferred to the floor-mounted retractable belt conveyor by a transporter after it reaches the transport roadway. Hydraulic single prop is used for upper and lower ends support and advance support.

The technology of coal roadway excavation is mechanized excavation. The fully mechanized excavation team of Dashe mine is equipped with equipment such as fully mechanized coal roadway excavator, belt conveyor and scraper conveyor to form a comprehensive mechanized operation line of coal roadway excavation. Rock roadway excavation technology is blasting. The blasting team of Dashe mine is equipped with pneumatic rock drill, hydraulic drill truck, bucket loader, side

unloading rock loader and other components of rock roadway mechanized excavation.

## 2.4 Spontaneous combustion propensity of coal

The spontaneous combustion characteristics of No.2 coal seam in Dashe coal mine were identified by the Fire Prevention Laboratory of Resources and Safety Engineering College of China University of Mining and Technology (Beijing). The identification of coal spontaneous combustion is completed according to the requirement of "AQ/T 1068-2008(China) the text method of oxidation kinetics for the propensity of coal to spontaneous combustion".

The classification index of coal spontaneous combustion propensity is obtained by measuring oxygen concentration at the outlet of the coal sample reactor and the crossing point temperature after the coal sample temperature reaches 70°C. The calculation method of the classification index is as follows:

$$I_{C_{O_2}} = \frac{C_{O_2} - 15.5}{15.5} \times 100 \quad (2.1)$$

$$I_{T_{cpt}} = \frac{T_{cpt} - 140}{140} \times 100 \quad (2.2)$$

$$I = \Phi(\Phi_{C_{O_2}} I_{O_2} + \Phi_{T_{cpt}} I_{cpt}) - 300 \quad (2.3)$$

$I_{C_{O_2}}$ ——Oxygen concentration index in outlet of coal sample reactor when coal sample temperature reaches 70°C.

$C_{O_2}$ ——The oxygen concentration in the outlet of the coal sample reactor when coal sample temperature reaches 70°C.

15.5——Calculating factors of oxygen concentration at outlet of coal sample reactor.

$I_{T_{cpt}}$ ——The crossing point temperature index of coal under the programmed-temperature heating.

$T_{cpt}$ ——The crossing point temperature of coal under the programmed-temperature heating.

140——The calculation factor of crossing point temperature.

$I$ —The classification index of coal spontaneous combustion propensity.

$\phi$ —Amplification factor, 40.

$\phi_{C_{O_2}}$ —The weight of low temperature oxidation stage, 0.6.

$\phi_{T_{cpt}}$ —The weight of accelerated oxidation stage, 0.4.

300—Correction factor.

In the programmed-temperature heating experiment, the oxygen concentration at the outlet of the coal sample reactor was 18.92% when the temperature of the coal sample reaches 70°C, and the crossing point temperature of the coal under the programmed-temperature heating condition is 177.5°C. The classification index of coal spontaneous combustion propensity can be calculated with the above formula:  $I = 658.08$ .

According to the AQ/T 1068-2008(China), coal spontaneous combustion propensity can be divided into three grades.

**Table 2.2 The classification of coal spontaneous combustion**

The grade of spontaneous combustion	Classification index— $I$
I : Easy to spontaneous combustion	$I < 600$
II : Spontaneous combustion	$600 \leq I \leq 1200$
III: Hard to spontaneous combustion	$I > 1200$

Therefore, the spontaneous combustion propensity of No.2 coal seam of Dashe coal mine is II.

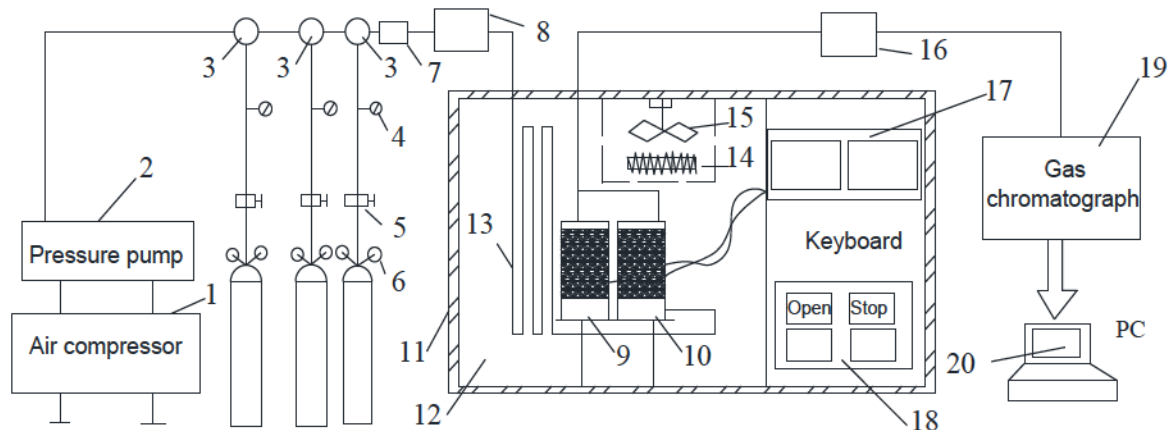


### 3 Experimental study on index gases of coal spontaneous combustion

During the process of coal oxidation and heating, CO, CO<sub>2</sub>, alkanes, olefins and alkynes are released. The generation of these gases changes regularly with the increase of temperature of coal, which can predict and reflect the propensity of coal spontaneous combustion.

#### 3.1 Programmed-temperature heating experiment system for coal spontaneous combustion

The variation of gas components released at different temperatures during coal spontaneous heating in Dashe coal mine is studied by programmed-temperature heating experiment system, which provides a theoretical basis for determining the index gases of coal spontaneous combustion. Based on the "AQ/T 1068-2008(China) the text method of oxidation kinetics for the propensity of coal to spontaneous combustion", the programmed-temperature heating experiment system was designed by the fire prevention research group of China University of Mining and Technology (Beijing). The system is shown in the figure 3.1.



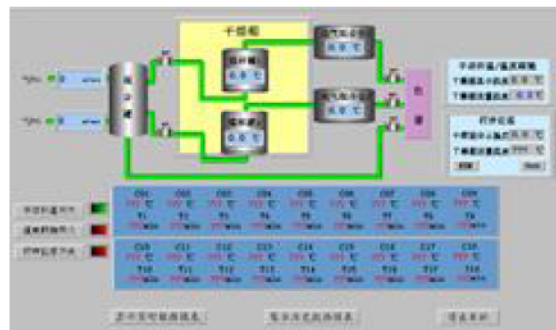
**Figure 3.1 Programmed-temperature heating experiment system**

1-Air compressor 2- Pressure pump 3-Joint 4- Barometer 5- Valve 6- Gas source  
 7- Dust collector 8- Gas mixing bin 9-Sample reactor 1 10- Sample reactor 2  
 11- Thermal insulation layer 12- Temperature control box 13- Preheat pipe  
 14- Heating wire 15- Fan 16- Exhaust bin 17- Monitor 18- Control button  
 19- Gas chromatograph 20-PC

(1) The programmed-temperature heating control and display part is shown in Figure 3.2. The temperature control box is used to heat coal samples at constant temperature. Thermal insulation material is filled between the inner wall and the outer shell of the temperature control box. The heat source power is 2.3 kW. The temperature field in the box is evenly distributed by using with a temperature control fan. Temperature in the control box and sample temperature can be adjusted by industrial control software, which can make temperature control from room temperature to 250°C. Temperature of experiments can be fed back to the digital instrument of programmed temperature control box through thermocouple temperature sensor.



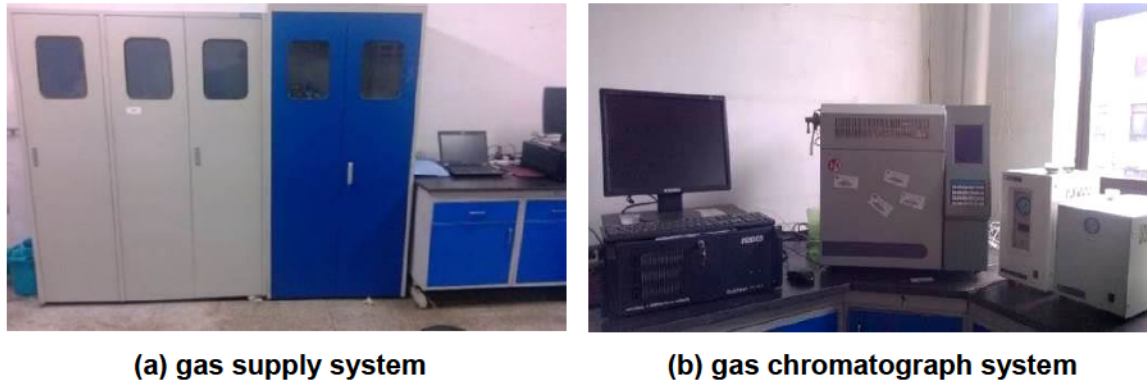
(a) temperature control box



(b) industrial control software

Figure 3.2 Temperature control box and industrial control software

(2)The gas supply part is shown in Figure 3.3(a). The experimental gas is supplied by gas cylinder and air compressor. The gas chromatograph and other specific required gas are supplied by gas cylinder, and the gas of programmed temperature oxidation is supplied by air compressor. Because the gas temperature supplied by air compressor is indoor temperature, in order to avoid the influence of temperature difference caused by gas directly entering the coal sample reactor, a 20 m preheated copper tube is usually installed in the temperature control box to ensure that the gas temperature is consistent with the ambient temperature in the temperature control box, and to effectively prevent the accidental heat outflow of coal sample. In addition, a drying and impurity removal device is installed at the end of the gas supply path of the temperature control box to avoid the adverse effect of moisture of the collected gas on the accuracy of gas chromatograph.



(a) gas supply system

(b) gas chromatograph system

**Figure 3.3 Gas supply and gas chromatograph system**

(3) The cylinder tank with diameter of 5.5 cm and height of 16.5 cm is used for coal sample reactor. The steel structure with good thermal conductivity is used for the material of coal sample reactor. Stainless steel mesh with 0.15 mm aperture at both ends of the tank top and bottom, and free space of about 0.5 cm are left, so that gas can pass through the coal sample evenly in the coal sample reactor. There is a thermocouple temperature sensor inside the coal sample reactor. The temperature of the coal sample inside the reactor can be accurately collected by industrial control software.

(4) The data collection and gas chromatography part is shown in the Figure 3.3(b). Gas chromatograph system is a fixed table type of China DongXi electronic GC4000A, which can realize three-channel one-time sampling test for gas. The gas chromatograph is equipped with a hydrogen flame ionization detector (FID) and a thermal conductivity detector (TCD). The flame ionization detector carrier gas  $N_2$  purity 99.99%,  $H_2$  purity 99.99%; thermal conductivity detector carrier gas  $H_2$  purity 99.99%. The temperature of box, thermal conductivity, bridge wire, vaporization and transformation are  $60^\circ C$  ,  $100^\circ C$  ,  $130^\circ C$  ,  $150^\circ C$  ,  $360^\circ C$  , respectively.

## **3.2 The procedures of programmed-temperature heating experiment for coal spontaneous combustion**

### (1) Coal sample collection and processing

After collecting coal samples in the coal mining face according to "Sampling of coal seam(China) GB/T482-2008", the coal samples were sealed and wrapped with fresh-keeping film and sent to the laboratory in time for crushing. The remaining coal samples were put into the refrigerator for refrigeration and reserve. The coal samples were then crushed in a sealed prototyping machine. After screening by

vibration screening machine, 40g coal samples with particle size of 1.25mm-1.6mm, 1.6mm-2mm, 2mm-3.5mm, 3.5mm-5mm and 5mm-7mm were collected and evenly mixed into a coal sample reactor.

#### (2) Drying of coal sample

The coal sample in the coal sample reactor was dried by using the nitrogen high temperature drying function of the programmed-temperature heating system. The drying temperature was set to 105°C and dried at a constant temperature for 10 hours to ensure the drying effect.

#### (3) Setting up heating program

The coal sample cooled to room temperature was connected to the gas supplied by air compressor. The gas flow rate was set to 60 ml/min. The temperature of the coal sample is raised from room temperature to 30°C within 30 minutes, and then it is heated from 30°C to 200°C at the rate of 0.5°C/min.

#### (4) Data recording and graphing

During the programmed-temperature heating period, the gas is collected every 10°C and sent to the gas chromatograph for chromatographic analysis. After data recording was completed, Origin Pro software was used for graphing.

### 3.3 The results and analysis of programmed-temperature heating experiment

After the programmed-temperature heating experiment of the coal sample of No.2 coal seam sample in Dashe Coal Mine, the experimental results are shown in Table 3.1.

**Table 3.1 Gas concentration in coal sample during programmed-temperature heating**

T(°C)	Gas concentration (ppm)						
	O <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>2</sub>
30	210500	58.76	0.60	488.01	0.00	24.21	0.00
40	208900	70.59	3.15	590.84	0.00	28.92	0.00
50	204500	79.49	7.85	677.01	0.00	32.07	0.00
60	198000	83.34	9.86	687.14	0.00	33.71	0.00
70	189200	97.63	13.77	846.26	0.00	40.67	0.00
80	176700	121.73	26.60	1022.87	0.00	49.17	0.00
90	160900	165.54	53.77	1327.87	0.00	65.87	0.00
100	141500	213.77	103.80	1683.67	0.00	91.16	0.00
110	116000	296.74	185.86	2086.75	0.00	125.84	0.00
120	86300	421.06	386.80	2665.73	0.00	179.35	0.00
130	54700	514.25	513.85	2984.85	0.00	209.87	0.00
140	29600	683.85	826.29	3612.68	0.00	272.52	0.00
150	19600	911.46	1245.41	4125.34	0.55	334.20	0.00
160	18300	1121.13	1740.42	4913.73	1.99	383.61	0.00
170	18700	1352.71	2408.95	5834.37	2.11	464.82	0.00
180	18500	1654.68	3606.23	7414.52	2.61	505.43	0.00
190	18700	1915.43	5005.67	9284.31	2.95	579.78	0.00

In the process of low temperature oxidation of coal, coal reacts with oxygen to produce CO, CO<sub>2</sub> and H<sub>2</sub>O. The chemical adsorption and reaction of coal and oxygen are strengthened with the increase of temperature, releasing CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub> and other gases. The programmed-temperature heating experiment of coal spontaneous combustion mainly obtains the change trend of gases in each temperature stage by programmed temperature control, and then finds out the index gases which changes significantly with temperature.

The index gases can be divided into two categories: single index gases(CO, O<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>2</sub>H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>) and composite index gases(CO/ $\Delta$ O<sub>2</sub>, CO/CO<sub>2</sub>). According to the current research, the change of CO is obvious, and generally can be used as a index gas. The appearance of ethylene can be used as an auxiliary index at about 100°C. The gas detection in underground coal mining area is through bundle tube system or other gas measuring system to obtain the changing trend of various gases in different time periods, and then analyze the spontaneous combustion of coal. Therefore, the current temperature reached in the spontaneous combustion zone can be found by determining the gas concentration or index gas.

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### **3.3.1 The concentration change law of CO in programmed-temperature heating**

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During the programmed-temperature heating experiment, the concentration change of CO can be divided into five stages, as shown in Figure 3.4.

(1)Stage: Temperature <60°C

At about 30°C , CO produced by low-temperature oxidation can be detected, but the low concentration of CO does not exceed 10 ppm. In the underground mining area, the surface of coal produces unstable oxides, which emit little heat and do not accumulate on the surface of coal.

(2)Stage II : 60°C<Temperature <90°C

In stage II , the CO can be detected obviously, and the concentration of CO increased almost five times from 9.86ppm to 53.77ppm. During that stage, the oxidation exothermic was increasing, the coal temperature and its environmental temperature increase, producing CO, CO<sub>2</sub> and hydrocarbon (C<sub>m</sub>H<sub>n</sub>) gas products, and emitting kerosene and other aromatic odors.

(3)Stage III:  $90^{\circ}\text{C} < \text{Temperature} < 120^{\circ}\text{C}$

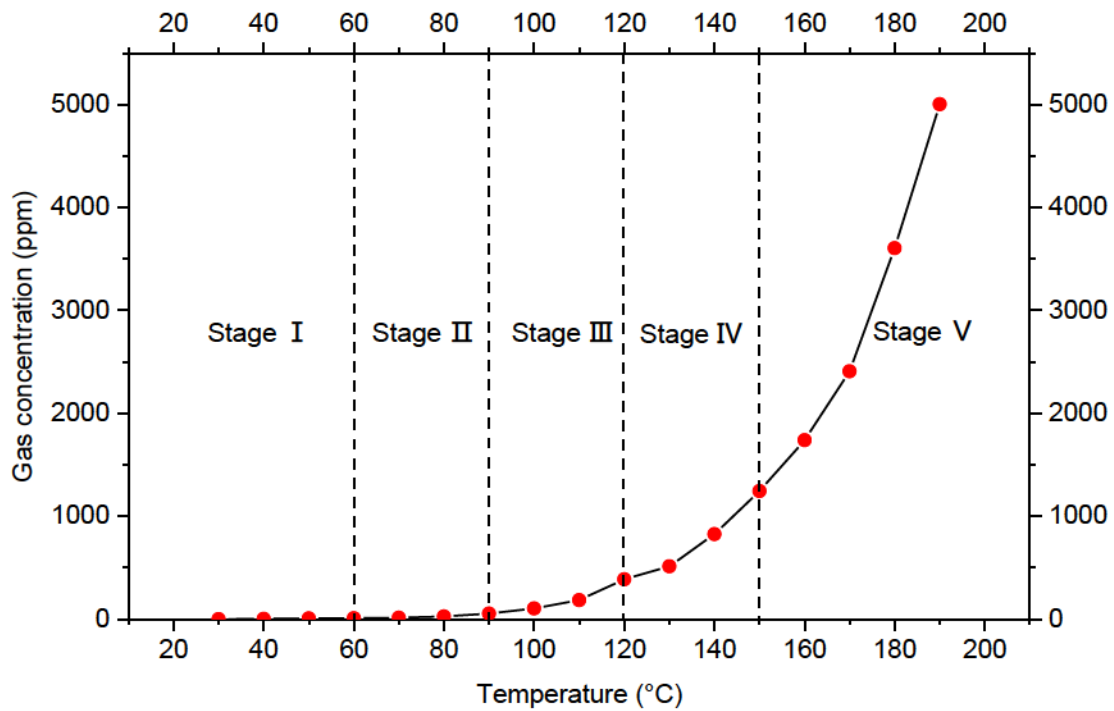
In stage III, more CO was produced due to the intense physical and chemical reactions. Oxygen content in air decreases significantly and CO<sub>2</sub> content increased rapidly. At the same time, more CO was produced due to incomplete combustion and thermal decomposition of CO<sub>2</sub>.

(4)Stage IV:  $120^{\circ}\text{C} < \text{Temperature} < 150^{\circ}\text{C}$

In stage IV, the concentration of CO increased three times from 386.80ppm to 1245.41ppm.

(5)Stage V:  $\text{Temperature} > 150^{\circ}\text{C}$

When the temperature exceeded 150°C, the concentration of CO was around thousands of ppm and increased significantly



**Figure 3.4 CO concentration curve**

According to the trend of CO growth, the curve is approximately an exponential function. After curve fitting by Origin Pro software, the function relation of curve was obtained as follows:

$$C_{CO} = -62.06 + 6.47e^{\frac{T}{28.48}} \quad (3.1)$$

$C_{CO}$  — The concentration of CO (ppm)

$T$  — The temperature in programmed-temperature heating experiment ( $^{\circ}\text{C}$ )

$R^2_{CO}$  — The goodness of fit = 0.99904.

### 3.3.2 The concentration change law of other gases in programmed-temperature heating

Besides the CO produced by the reaction of coal with oxygen in the programmed-temperature heating, other types of gases can also be detected and can be used as index gases.

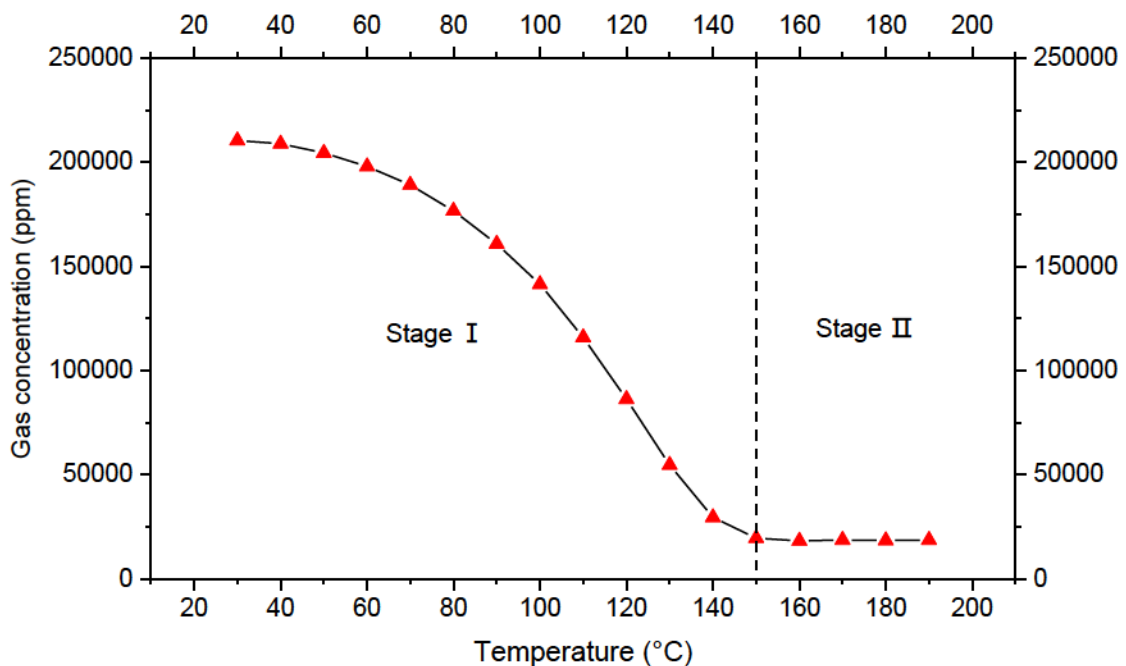


Figure 3.5 The  $\text{O}_2$  consumption curve

In the process of programmed-temperature heating experiment, the chemical reaction between coal and oxygen produced various gases, and the consumption of oxygen increases rapidly. After reaching a certain temperature, the consumption of oxygen did not increase any more and remained at about 2%. The whole process can be divided into two stages:

(1) Stage I : Temperature  $< 150^{\circ}\text{C}$

Fitting by Origin Pro software, the function relation of curve was obtained as follows:

$$C_{O_2} = -16600e^{\frac{T}{72.98}} - 17666e^{\frac{T}{72.98}} + 271875 \quad (3.2)$$



$C_{O_2}$  — The consumption of  $O_2$  (ppm)

$T$  — The temperature in programmed-temperature heating experiment ( $^{\circ}C$ )

$R_{O_2}^2$  — The goodness of fit = 0.9853.

(2) Stage II : Temperature  $> 150^{\circ}C$

In stage II, there was no more oxygen to be consumed and the concentration of oxygen remained unchanged.

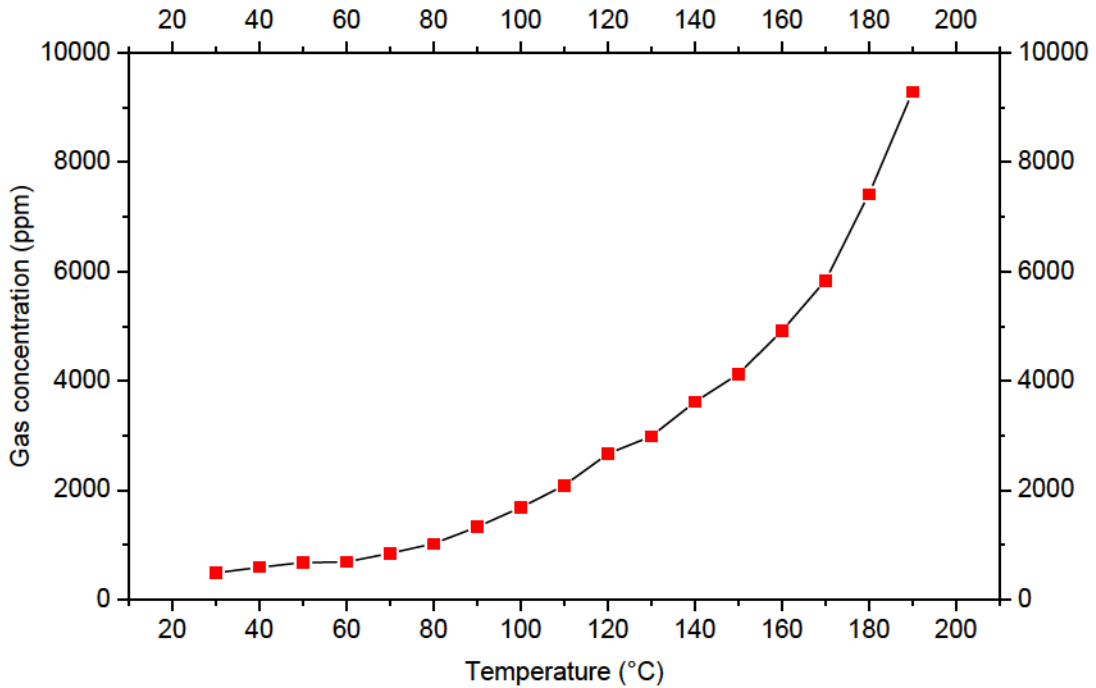


Figure 3.6 The  $CO_2$  concentration curve

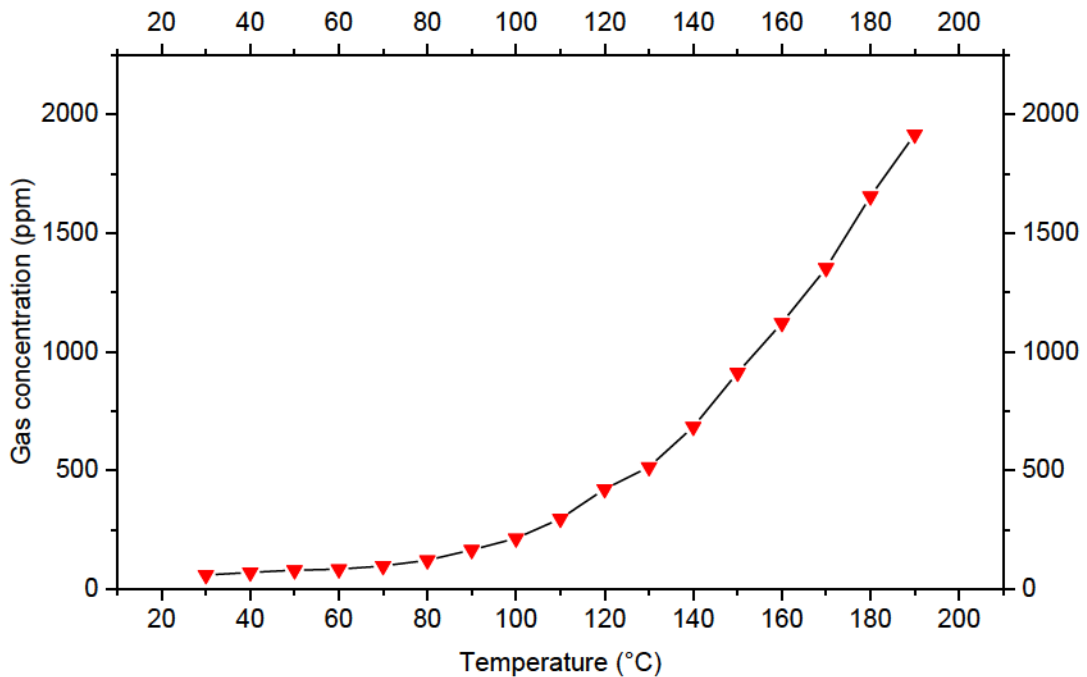


Figure 3.7 The  $CH_4$  concentration curve

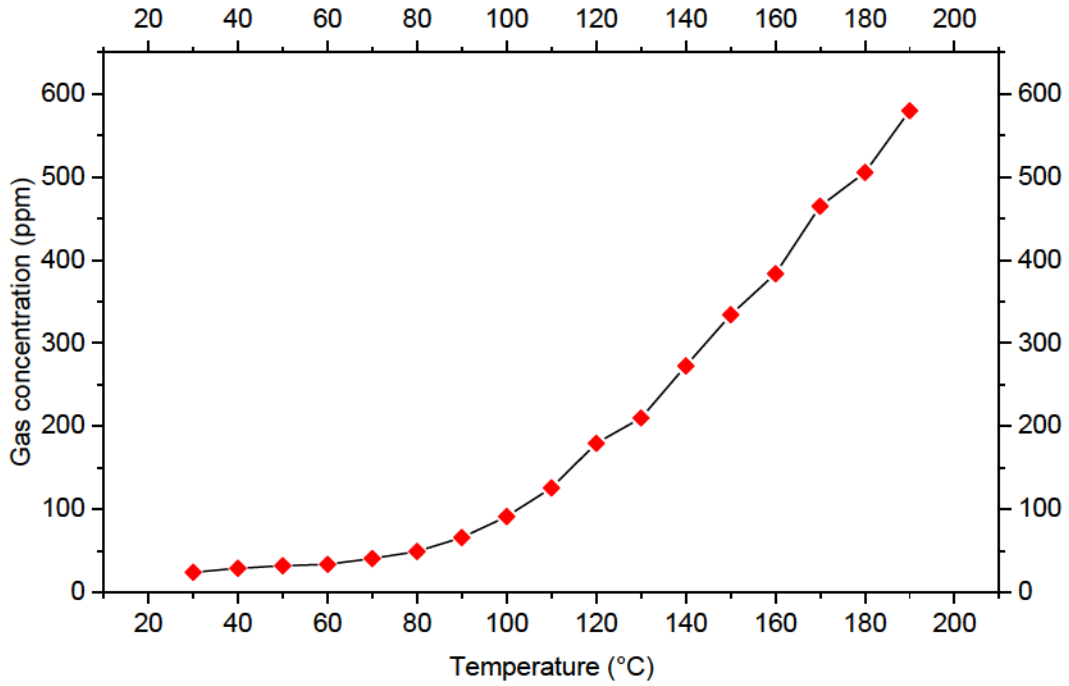


Figure 3.8 The C<sub>2</sub>H<sub>6</sub> concentration curve

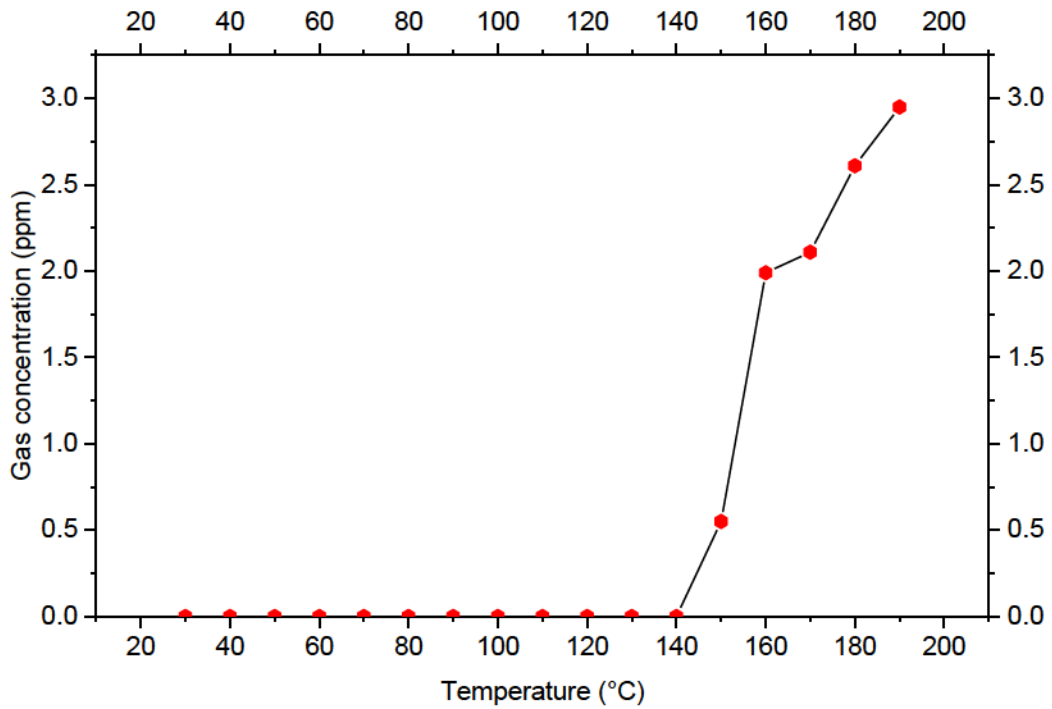


Figure 3.9 The C<sub>2</sub>H<sub>4</sub> concentration curve

By using Origin Pro software to analysis the programmed-temperature heating experiment data, Tthe functional relations of different gases concentration can be expressed as follow:

$$C_{CO_2} = 218.1e^{\frac{T}{51.12}} + 92.99 \tag{3.3}$$

$$C_{CH_4} = 48.3e^{\frac{T}{50.56}} - 80.75 \quad (3.4)$$

$$C_{C_2H_6} = 43.34e^{\frac{T}{69.32}} - 67.64 \quad (3.5)$$

$$C_{C_2H_4} = 2.67 - \frac{2.69}{1 + e^{(T-156.18)/dT}} \quad (3.6)$$

$R_{CO_2}^2$  —The goodness of fit =0.9966       $R_{CH_4}^2$  —The goodness of fit =0.9948

$R_{C_2H_6}^2$  —The goodness of fit =0.9897       $R_{C_2H_4}^2$  —The goodness of fit =0.9844

According to the changing trend of coal temperature and different gas concentration in the programmed-temperature heating experiment, the gas whose composition concentration corresponds well with coal temperature is used as the index gas.

From Figure 3.5 and Figure 3.7, it can be seen that there is a good correspondence between the gas concentration changes of O<sub>2</sub> and CH<sub>4</sub> and temperature, but the gas concentration of oxygen and methane is affected by the mine ventilation system, and there are many factors affecting mine ventilation, so O<sub>2</sub> and CH<sub>4</sub> cannot be used as index gases.

From Figure 3.8, it can be seen that C<sub>2</sub>H<sub>6</sub> can be detected in the whole programmed-temperature heating experiment process, and the concentration of C<sub>2</sub>H<sub>6</sub> increased exponentially with the increase of temperature. When temperature reached 70°C, the gas growth rate of C<sub>2</sub>H<sub>6</sub> accelerated obviously.

According to the programmed-temperature heating experimental data and Figure 3.9, the critical temperature of C<sub>2</sub>H<sub>4</sub> is 150°C. The occurrence of ethylene indicates that coal has entered the stage of accelerated oxidation. The production of ethylene increases monotonously with the increase of coal temperature. The rate of ethylene production accelerated obviously after 180°C, indicating that coal and oxygen reacted strongly at this time. According to the coal sample of No.2 coal seam in Dashe coal mine, as long as C<sub>2</sub>H<sub>4</sub> is detected, the temperature of coal has reached 150°C. In practice, when C<sub>2</sub>H<sub>4</sub> is detected in underground air, the coal has entered the stage of accelerated oxidation, so C<sub>2</sub>H<sub>4</sub> can not be used as an index gas for detecting spontaneous combustion in No.2 coal seam of Dashe coal mine.

In addition,  $C_2H_2$  did not appear in the whole process of programmed-temperature heating. A large number of experimental analysis and on-site detection showed that if  $C_2H_2$  was detected in underground coal mine, it indicated that coal entered the stage of intense oxidation and the temperature should be more than  $200^\circ C$ .

By comparing different index gases, CO can be used as the main index gas of coal spontaneous combustion in Dashe coal mine. The CO can be produced in low temperature at  $30^\circ C$  or even lower temperature. The growth rate of CO concentration is much faster than that of other gases in the programmed-temperature heating experiment.

In addition to the single index gas, the composite index gas can also be used. The index of carbon monoxide (ICO) is also known as Graham's index. The carbon monoxide index refers to the ratio of carbon monoxide to oxygen consumption ( $CO/\Delta O_2$ ) produced by oxidation of coal during spontaneous combustion, which is proportional to the temperature of oxidation source and oxidation time. This index can be used to predict the propensity of coal spontaneous combustion. The increase of ICO value indicates that the spontaneous combustion of coal continues to develop. The calculation of ICO value is as follows:

$$ICO = \frac{CO}{0.265(N_2 + Ar) - O_2} = \frac{CO}{\Delta O_2} \quad (3.7)$$

Based on the variation of different kinds of gas concentration, it can be divided into five stages: stage I ( $< 60^\circ C$ ), stage II ( $60^\circ C - 90^\circ C$ ), stage III ( $90^\circ C - 120^\circ C$ ), stage IV ( $120^\circ C - 150^\circ C$ ), stage V ( $> 150^\circ C$ ). The single index gases and composite index gases are shown in Table 3.2.

The selection of index gases is often influenced by actual production. In order to accurately predict and detect spontaneous combustion of coal, both single index gases and composite index gases need to be considered.

Table 3.2 Single index gases and composite index gases

Stage		I	II	III	IV	V
Temperature(°C)		30 - 60	60 - 90	90 - 120	120 - 150	>150
Single index gases and composite index gases	$CO$ (ppm)	0.60-9.86	9.86-59.77	59.77-386.80	386.80-1245.41	>1245.41
	$CO_2$ (ppm)	488.01-687.14	687.14-1327.87	1327.87-2665.73	2665.73-4125.34	>4125.34
	$CH_4$ (ppm)	58.76-83.34	83.34-165.54	165.54-421.06	421.06-911.46	>911.46
	$C_2H_4$ (ppm)	0	0	0	0	>0.55
	$C_2H_6$ (ppm)	24.21-33.71	33.71-65.87	65.87-179.35	179.35-334.20	>334.20
	$\frac{CO}{\Delta O_2}$ ( $10^{-2}$ )	0.006-0.079	0.079-0.16	0.16-0.52	0.52-1.87	>1.87
	$\frac{CO}{CO_2}$ ( $10^{-2}$ )	0.123-1.43	1.43-4.50	4.50-14.51	14.51-30.19	>30.19
	$\frac{C_2H_6}{CH_4}$ ( $10^{-3}$ )	412.01-404.48	404.48-397.91	397.91-425.95	425.95-366.67	>366.67
	$\frac{C_2H_4}{C_2H_6}$ ( $10^{-3}$ )	0	0	0	0	>1.65



## **4 Coal spontaneous combustion in goaf under multi-fault condition**

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### **4.1 The influence factor of coal spontaneous combustion in goaf under multi-fault condition in Dashe coal mine**

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The dangerous area of spontaneous combustion of coal in goaf under the condition of multiple faults is quite different from general conditions, because it exposes more faults in the goaf. At the multi-fault area, the coal seam is tensioned and extruded to produce a large number of cracks. When the coal body is fractured, it is easy to form a large amount of float coal accumulation. The serious air leakage near the fault provides enough oxygen for coal oxidation and spontaneous combustion. Therefore, further study is needed to analyze the dangerous area under the condition of multi-faults in Dashe coal mine.

Coal spontaneous combustion must have three conditions at the same time: 1) coal has spontaneous combustion propensity (high oxidation activity); 2) continuous oxygen supply conditions; 3) heat accumulation. The first is the internal factor, which depends on the physical and chemical properties of coal, indicating the ability of interaction between coal and oxygen. The second and third are external factors, which are determined by the geological conditions and mining technology of the mine. Therefore, the process of spontaneous combustion of coal is a complex dynamic process, which is determined by the internal factor and external factors.

In 2005, open fire occurred in the goaf of 92709 coal mining face in Dashe coal mine. Before the construction of fire monitoring and early warning system, about 90% of the goaf of 50 coal mining faces had high temperature point and CO over-limit phenomenon, which indicated that there had been frequent coal spontaneous combustion of goaf in Dashe coal mine. There are a lot of faults in underground mining area of Dashe coal mine, and there are many exposed faults in the roadway of coal mining face. At the multi-fault area, the coal seam is tensioned and extruded to produce a large number of cracks. The coal body is fractured, and it is easy to accumulate large amount of float coal.

The separation of coal and rock was obvious at the multi-fault area, and the geological structure was more complex than usual. During the advancing period of coal mining face, blasting and shearer cutting rock through the fault may be used to generate more heat and make a good heat accumulation environment.

Considering the geological structure, mining plan, fire prevention and extinguishing technical measures of the mine comprehensively, the influence of multi-fault conditions on the internal and external causes of coal spontaneous combustion is summarized.

#### 4.1.1 The internal factors of coal spontaneous combustion under multi-fault conditions.

##### (1) The propensity of coal spontaneous combustion

The internal causes of coal spontaneous combustion include the degree of coal metamorphism, coal petrographic composition, sulfur content of coal, coal particle size, pore characteristics and fragmentation degree, gas content of coal, the influence of moisture on coal spontaneous combustion, etc. Because the integrity of coal is destroyed and the coal is crushed under compression in multi-fault area, the propensity of coal spontaneous combustion is significantly improved. Crushed coal not only increases the contact area between coal and oxygen, but also reduces the temperature required for spontaneous combustion. Some studies have shown that the spontaneous combustion tendency of coal increases with the increase of porosity and fragmentation.

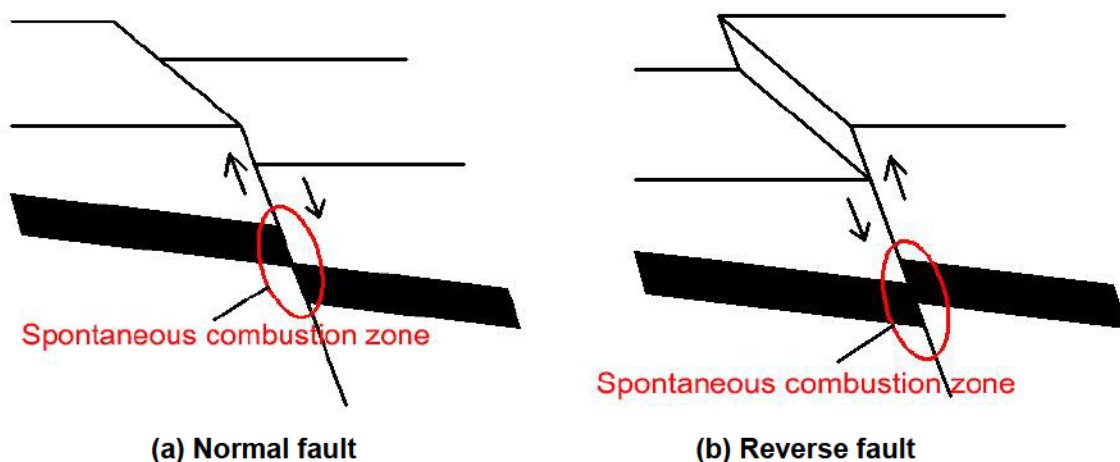


Figure 4.1 The relationship between fault and coal spontaneous combustion



## (2) Coal spontaneous combustion period

Coal spontaneous combustion period is a time measure of coal spontaneous combustion danger and the time needed for coal body from exposure to air environment to ignition. The influence of a large number of faults on coal spontaneous combustion is reflected in the propensity of coal spontaneous combustion. The high degree of coal fragmentation at the multi-fault area leads to strong propensity of spontaneous combustion and short period of spontaneous combustion. On the other hand, the influence of multi-faults on coal spontaneous combustion period is reflected in the external conditions. There are more float coal at the multi-fault area, so there is a good oxygen supply and heat storage environment, and it may ignite in a short time.

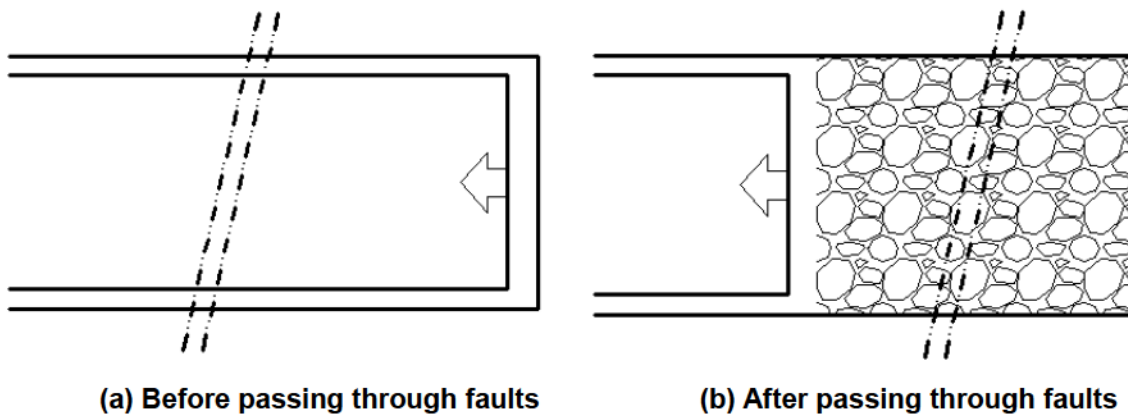


Figure 4.2 Before and after passing through faults in coal mining face

### 4.1.2 The external factors of coal spontaneous combustion under multi-fault conditions.

#### (1) Air leakage condition

At the multi-fault area, a large number of cracks are produced by the action of tension and extrusion. The coal body is broken and the air leakage near the fault is complex. Underground air flow is easy to pass through cracks and faults on both sides of the working face, resulting in serious air leakage, which provides oxygen supply conditions for coal spontaneous combustion.

#### (2) The advancing speed of coal mining face

During the coal mining face passing through the faults, because the fault destroys the original continuity and integrity of the coal seam, it brings great difficulties to the

mining of the working face. Because of the continuous oxygen supply environment, the oxidation storage time of the goaf increases and spontaneous combustion is prone to occur. The normal advancing speed of coal mining face in Dashe mine is 2-3 m/d, and the advancing speed can only reach about 0.8m/d under the multi-faults conditions.

### (3) Nitrogen injection for fire prevention and extinguishing

The essence of nitrogen fire prevention and extinguishing technology is to send nitrogen into the spontaneous combustion area, so that the air in the spontaneous combustion area is inert, and the oxygen concentration is reduced to below the critical concentration of coal spontaneous combustion, so as to inhibit coal oxidation and spontaneous combustion until the fire area is extinguished.

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## **4.2 The simulation of coal spontaneous combustion in goaf under multi-fault condition in Dashe coal mine**

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### **4.2.1 Theoretical basis**

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For a specific goaf of coal mining face, the spontaneous combustion of float coal in goaf mainly depends on five parameters: the concentration of oxygen, the thickness and fragmentation of float coal, the intensity of air leakage, the advancing speed of coal mining face and the initial temperature of coal (rock) body. When the advancing speed of coal mining face is zero and the initial temperature of coal (rock) body is constant, the spontaneous combustion of float coal in goaf depends on the other three parameters. Therefore, the area where float coal in goaf can cause spontaneous combustion must have a larger thickness of float coal, appropriate air leakage intensity and sufficient oxygen concentration.

The goaf can be divided into heat dissipation zone, oxidation zone and suffocative zone. At present, there are three criteria for the division of three zones of the goaf.

(1) Based on the speed of air leakage in the goaf, it is divided into heat dissipation zone( the area with air leakage velocity greater than 0.24m/min in the goaf), oxidation zone(the area with air leakage velocity between 0.24 m/min and 0.1m/min; suffocative zone(the area with air leakage velocity less than 0.1m/min).

(2) Based on the concentration of O<sub>2</sub>: heat dissipation zone(the concentration of O<sub>2</sub> is more than 18%), oxidation zone(the concentration of O<sub>2</sub> is between 18% and 8%), suffocative zone(the concentration of O<sub>2</sub> is less than 8%).

(3) Based on the heating rate, the oxidation zone(possible spontaneous combustion zone) is defined as heating rate  $K > 1^{\circ}\text{C/d}$  in the goaf.

It is considered that the oxygen concentration (commonly used 18%) is not perfect as the the boundary between the heat dissipation zone and the oxidation zone. Because the formation of the heat dissipation zone is due to the excessive air leakage which takes away the heat generated by oxidation, but not because the oxygen concentration is greater than a certain value and can not spontaneously ignite. For the spontaneous combustion of coal, oxygen has only a lower critical limit and no upper critical line. The transformation of coal oxidation from “heat dissipation” to “heat storage” is not simply affected by the concentration of oxygen, but by air leakage, heat dissipation, oxygen supply and other factors. However, using oxygen as the standard to simulate three zones of goaf, the transition of simulated image is smoother.

In addition, it is hard to classify the “three zones” accurately with the air leakage velocity as the main index in the field measurement, because the underground observation in goaf is inconvenient, the accuracy of measuring instruments is not very high, and the direction of air flow in goaf is unpredictable, so it is more convenient and feasible to use it in numerical simulation.

Temperature should not be used as the main index for the division of “three zones” of spontaneous combustion in goaf, because not all the temperature in goaf will rise to a certain value. The change of temperature is not only affected by the oxidation of coal in goaf. Even if the condition of coal oxidation accumulated heat is formed in the goaf, if a certain factor can restrict the accumulated heat in the goaf. For example, the existence of collapse area in the upper part of goaf, there is a large amount of water in the collapse area, because the evaporation of water will consume a lot of heat, it is difficult for the coal temperature to rise significantly outside the goaf before the water evaporates completely. In addition, the suffocative zone can be formed either by oxygen consumption or by mass generation of inert gas. The temperature of the latter does not necessarily rise significantly. Therefore, it is inappropriate to regard temperature as the main index for the division of “three

zones". It can only be used as an auxiliary index or in combination with other indicators.

At low temperature, the coal in goaf oxidizes slowly and produces little CO gas. Only when the temperature reaches a certain level, the coal body will oxidize violently and decompose to produce a large amount of CO. The change of CO concentration can directly reflect the degree of coal oxidation in goaf. With the advancing of coal mining face, the air leakage intensity in goaf is relatively small. The contact oxidation between float coal in goaf and oxygen produces CO. At the same time, because of the roof caving, CO is gathered. After a period of time, because of the complete roof caving, low porosity, very small air leakage and low oxygen concentration, float coal in goaf no longer oxidizes to produce CO. However, using CO concentration as the simulation standard of three zones in goaf can not distinguish heat dissipation zone from oxidation zone.

According to the geological conditions of Dashe coal mine, it is most reliable and accurate to use oxygen concentration as an index to simulate the three zones of goaf.

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#### **4.2.2 The basic parameters of simulation in goaf of Dashe coal mine**

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The geological conditions of Dashe Mine are complex and there are a lot of faults. The air leakage from the faults will affect the distribution of the three zones in the goaf. In order to study the influence of faults on the distribution of three zones of spontaneous combustion in goaf, the models of goaf before and after passing through faults are built. The distribution of oxygen concentration in goaf can be obtained by numerical simulation with FLUENT software, and then the three zones of goaf can be divided.

The conditions of coal mining face are complex and changeable, and there are some errors in the parameters of numerical simulation, including roadway and working face. Because of the reasons of coal miners and materials of mining equipment, the area of coal mining face and roadway in the actual production process is different from that in the simulation process. Therefore, according to the actual conditions of coal mining face and the needs of numerical simulation, numerical simulation is carried out. The process assumes that:

(1) The coal mining face, intake and air return roadway and goaf are regarded as regular hexahedron, ignoring the influence of personnel and mining equipment on ventilation.

(2) The goaf area is divided according to the calculated porosity.

(3) Oxygen consumption rate of coal oxidation reaction in goaf is proportional to oxygen concentration, and the diffusion and heat conduction of oxygen in goaf is a steady-state process, eventually reaching the uniform distribution of oxygen.

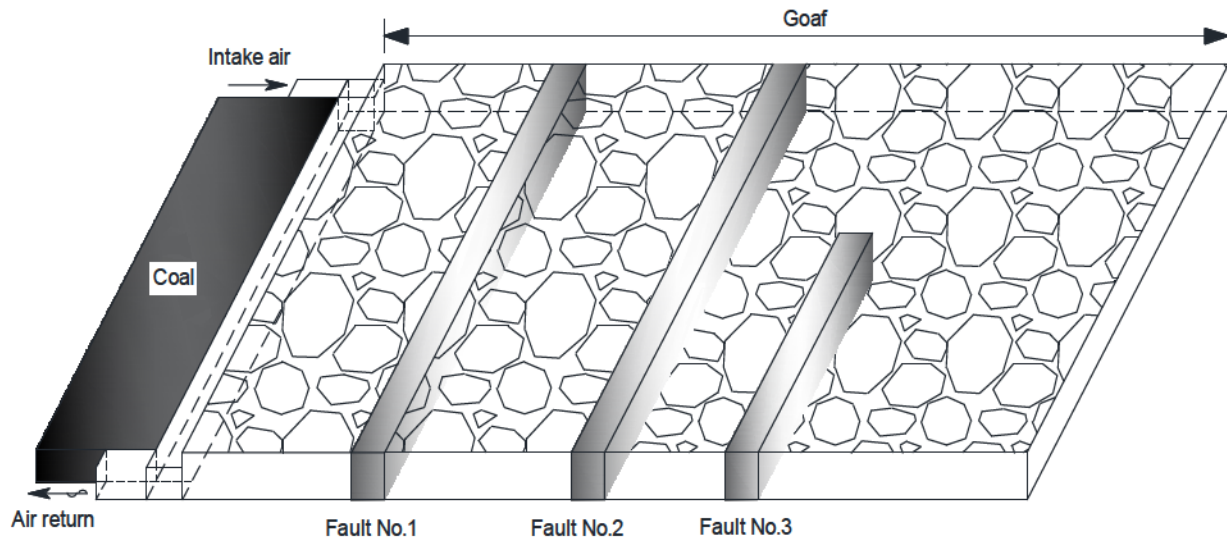
In order to facilitate the build of the model and the division of the grid, the parameters of each roadway are determined as follows: the height of the intake and air return roadway is 3m, the width is 4m, the length is 10m, the length of coal mining face is 120m, the width is 8m, and the height is 3m. The normal air volume of the working face is 900m<sup>3</sup>/min, the air flow velocity of the intake airflow side of the coal mining face is 1.25m/s, the oxygen concentration is 21%, the mass percentage is 23%, and the internal porosity is 0.167~0.333 according to the data of Dashe coal mine. Based on the above parameters, the three-dimensional physical model of goaf is built by software, and then it is divided into grids with the step size of 1m×1m. In order to study the influence of faults in goaf on coal spontaneous combustion, based on the above models, three situations were simulated:

(1) Only existence of fault No.1

(2) Existence of fault No.1 and fault No.2

(3) Existence of fault No.1, fault No.2 and fault No.3.

Among them, fault No.1 is 30m~40 m away from coal mining face, fault No.2 is 50m~60 m away from coal mining face, fault No.3 is 80m~85 m away from coal mining face, fault width is 3m, air leakage area is above the roof, air leakage volume is discussed in two cases: 0.774 kg/s and 6.45 kg/s.



**Figure 4.3 Multi-faults simulation in goaf**

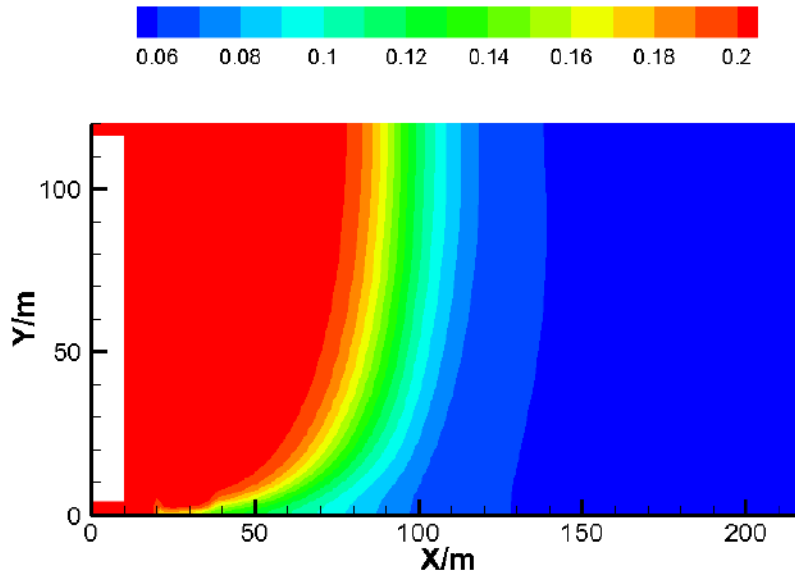
### 4.2.3 The results and analysis of simulation in goaf of Dashe coal mine

#### (1) The simulation of three zones in goaf before passing through fault

The distribution of oxygen concentration in goaf before passing through fault is shown in Figure 4.4. As can be seen from the figure, with the increase of the depth to the inner part of the goaf, the oxygen concentration in the goaf decreases gradually. The oxygen concentration in the intake roadway, air return roadway and coal mining face decreases about 20%, dropping to about 18% at 68m from the coal mining face, and to below 8% after 94m from the coal mining face.

From the distribution shape of the three zones, the width of the heat dissipation zone is different in the intake side, the middle of the goaf and the air return side, which are mainly determined by the different air leakage volume in the goaf.

By using 8%(0.08) and 18%(0.18) of oxygen concentration as the boundary of three zones, the three zones of spontaneous combustion in goaf are as follows: the heat dissipation zone in the intake side is 0m~82m, the oxidation zone is 82m~107m, more than 107m is suffocative zone; the heat dissipation zone in the middle of the goaf is 0m~80m, the oxidation zone is 80m~105m, the suffocative zone is more than 105m; the heat dissipation zone in the air return side is 0m~20m, the oxidation zone is 20m~88m, and the suffocative zone is more than 88m.



**Figure 4.4 Oxygen concentration distribution in goaf before passing through fault**

According to the oxygen concentration distribution shown in Figure 4.4, the three zones of goaf are divided by oxygen concentration index as shown in Table 4.1.

**Table 4.1 Three zones of goaf before passing through the fault**

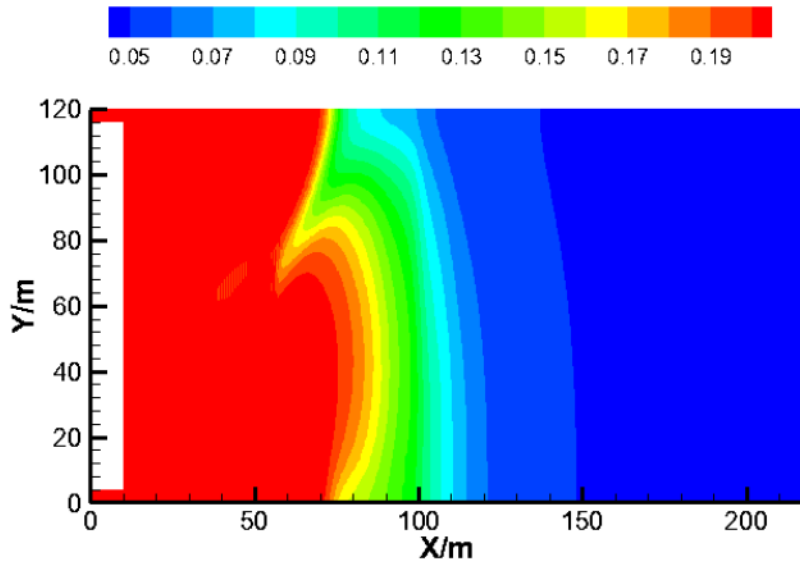
Location	Heat dissipation zone	Oxidation zone	Suffocative zone
Intake side (y=120m)	0m~82m	82m~107m	107m~∞
Middle of goaf (y=60m)	0m~80m	80m~105m	105m~∞
Air return side (y=0m)	0m~20m	20m~88m	88m~∞

(2) The simulation of three zones in goaf after passing through fault

The distribution of oxygen concentration with fault No.1 in goaf is shown in Figure 4.5 when the air leakage volume is 0.774kg/s. The width of heat dissipation zone is wider than that before passing through the fault, reaching 74m on the air return side of goaf, which is 54m longer than before passing through the fault. The oxidation zone also moves deep into the goaf, and the area of the oxidation zone increases compared with that before passing through the fault No.1.

By using 8%(0.08) and 18%(0.18) of oxygen concentration as the boundary of three zones, the three zones of spontaneous combustion in goaf are as follows: the heat dissipation zone in the intake side is 0m~70m, the oxidation zone is 70m~96m, more than 96m is suffocative zone; the heat dissipation zone in the middle of the goaf is

0m~80m, the oxidation zone is 80m~106m, the suffocative zone is more than 106m; the heat dissipation zone in the air return side is 0m~74m, the oxidation zone is 74m~112m, and the suffocative zone is more than 112m.



**Figure 4.5 Oxygen concentration distribution in goaf after passing through fault No.1**

According to the oxygen concentration distribution shown in Figure 4.5, the three zones of goaf after passing through the fault No.1 are divided by oxygen concentration index as shown in Table 4.2.

**Table 4.2 Three zones of goaf after passing through the fault No.1**

Location	Heat dissipation zone	Oxidation zone	Suffocative zone
Intake side (y=120m)	0m~70m	70m~96m	96m~∞
Middle of goaf (y=60m)	0m~80m	80m~106m	106m~∞
Air return side (y=0m)	0m~74m	74m~112m	112m~∞

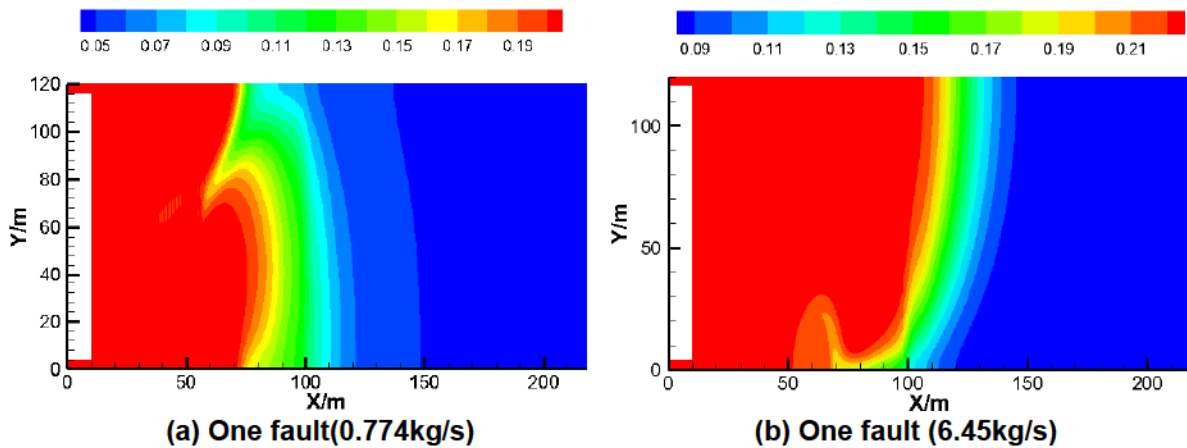
From the comparison of Figure 4.4 and Figure 4.5, it can be seen that the existence of faults have an influence on the distribution of oxygen concentration in goaf, which makes the area of oxidation zone larger and moves away from the working face. In the simulation of oxygen concentration distribution in the goaf of Dashe coal mine, three kinds of faults and two different kinds of air leakage are discussed. There are six kinds of simulation situations, which are shown in the table 4.3.



**Table 4.3 Six different simulations**

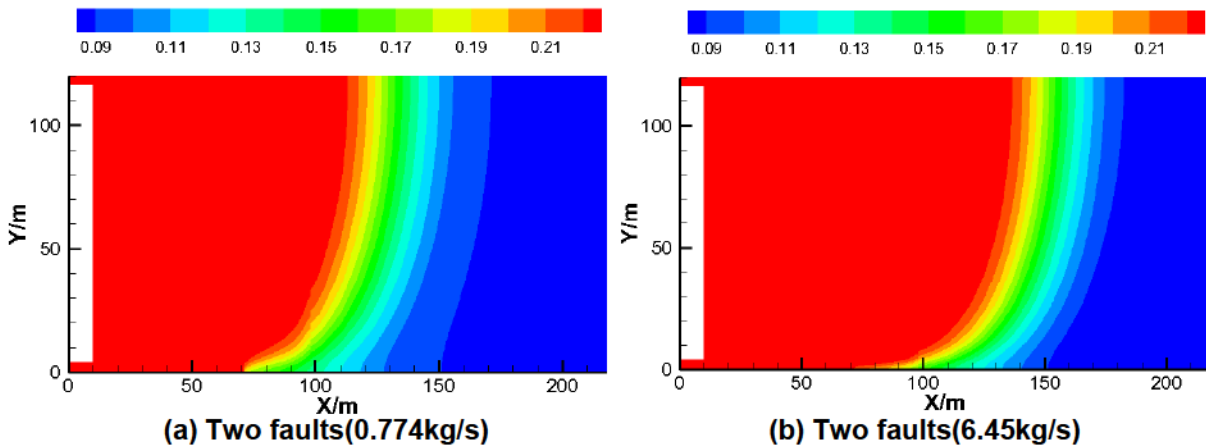
Faults	No.1	No.1 & No.2	No.1 & No.2 & No.3
Air leakage			
0.774kg/s	One fault(0.774kg/s)	Two faults(0.774kg/s)	Three faults(0.774kg/s)
6.45 kg/s	One fault(6.45 kg/s)	Two faults(6.45 kg/s)	Three faults(6.45 kg/s)

In the case of only one fault, the simulation of two different air leakage volume is shown in the Figure 4.6.



**Figure 4.6 Simulation of one fault in goaf with different air leakage volume**

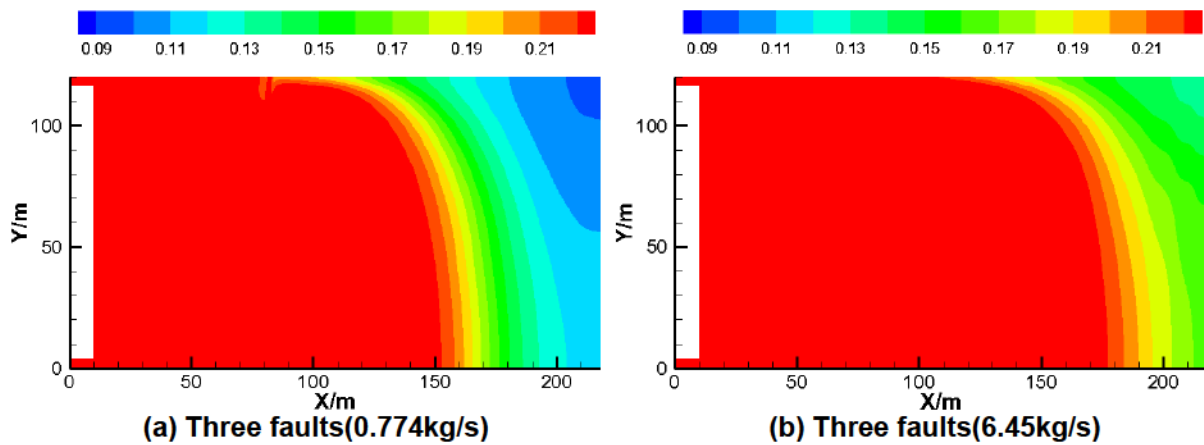
When there is only one fault in the goaf, the oxidation zone(0.08~0.18) is widened obviously, and the heat dissipation zone in the middle of the goaf(y=60m) is widened, which makes the oxidation zone in goaf and the air return side(y=0m) move to the deep part of the goaf.



**Figure 4.7 Simulation of two faults in goaf with different air leakage volume**

The existence of two faults makes the air leakage in the goaf easier than that in the only one fault. The heat dissipation zone and oxidation zone are widened, and the

oxidation zone moves deeper into the goaf, which will bring some difficulties to the fire prevention and extinguishing work in the goaf.



**Figure 4.8 Simulation of three faults in goaf with different air leakage volume**

When the small fault No.3 occurs, because the small fault is located on the side of air return ( $y=0\text{m}$ ), the heat dissipation zone on the side of air return is obviously enlarged and wider than that on the side of intake side, and the oxidation zone is also widened. The shape of the three zones is obviously changed. The oxidation zone moves deeper into the goaf, which makes the implementation of fire prevention and extinguishing work such as grouting and nitrogen injection more difficult.

Comparing the two kinds of air leakage volume, when the air leakage volume is large, the width of heat dissipation zone is larger, and the oxidation zone moves into the deeper area of goaf. The width of oxidation zone also increases, even more than  $X=200\text{m}$ , so the risk of spontaneous combustion of coal in the goaf increases accordingly.

Based on the simulation results and Figure 4.6, the oxygen concentration at  $y=60\text{m}$  in the middle of the goaf with the distance from the coal mining face is plotted as shown in Figure 4.9. At 80m away from the coal mining face, the oxygen concentration has dropped to 12% when the air leakage volume is 0.774kg/s, while the oxygen concentration remains about 20% when the air leakage volume is 6.45kg/s. It can be seen that with the increase of air leakage volume, oxidation zone is far away from the coal mining face, and fire prevention and extinguishing work in goaf will be more difficult.

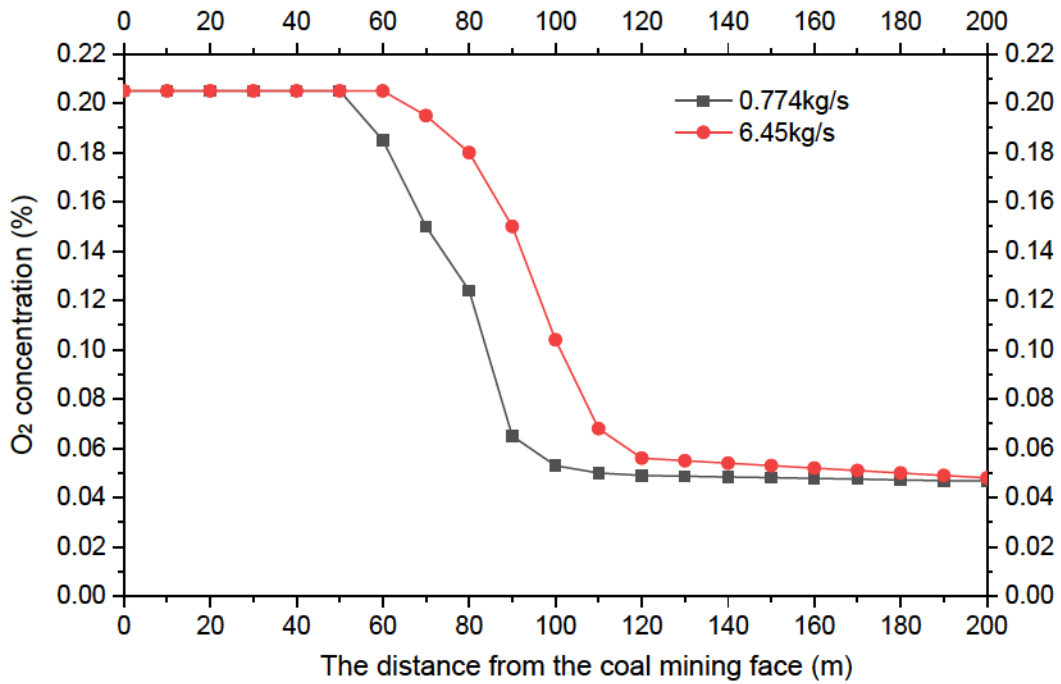


Figure 4.9 The O<sub>2</sub> concentration in the middle of the goaf (y=60m; one fault)

When there are two or three faults, the oxygen concentration at y=60m in the middle of the goaf with the distance from the coal mining face is plotted as shown in Figure 4.10 and Figure 4.11. Comparing the three cases, the same air leakage volume is 0.774 kg/s at 100m away from the coal mining face, the oxygen concentration in one fault is reduced to about 6%, in two faults is about 14%, while the oxygen concentration in three faults is still about 20%.

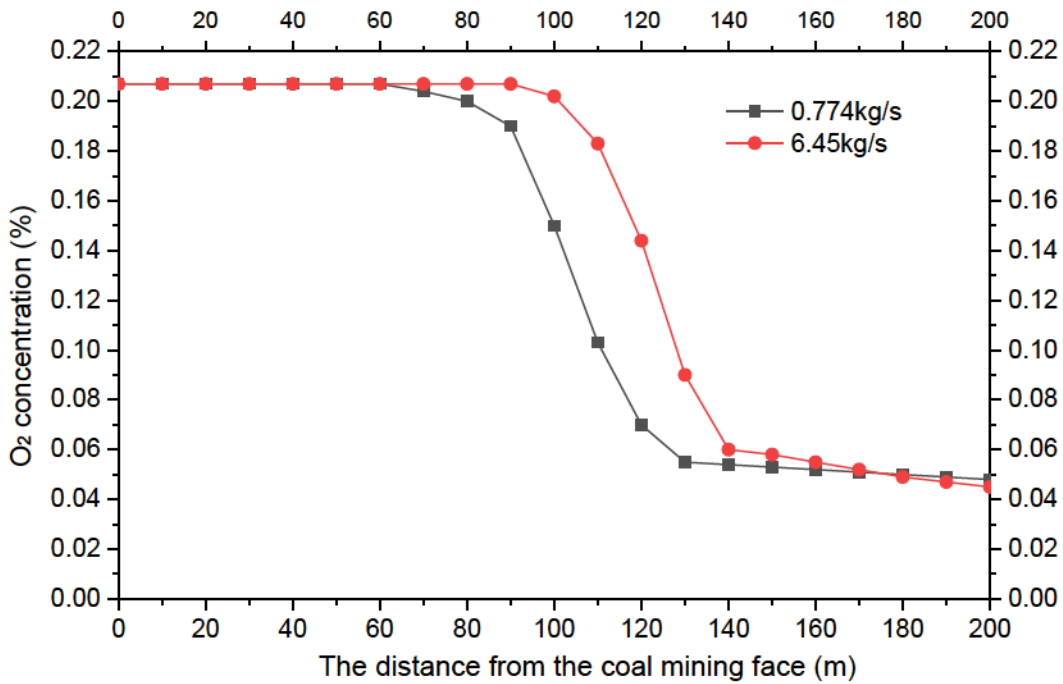
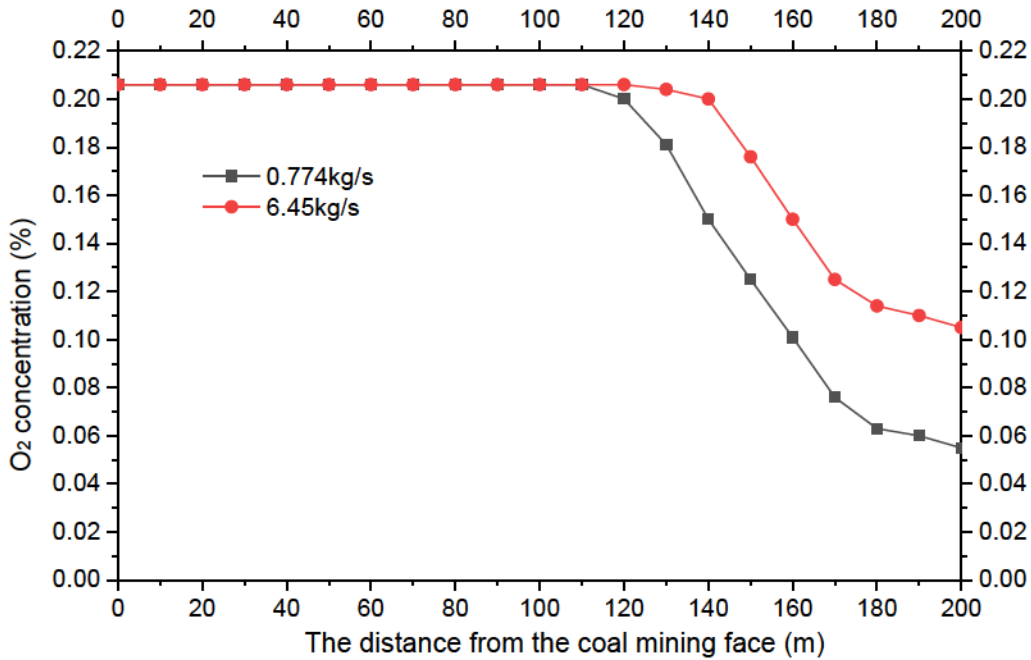


Figure 4.10 The O<sub>2</sub> concentration in the middle of the goaf (y=60m; two faults)

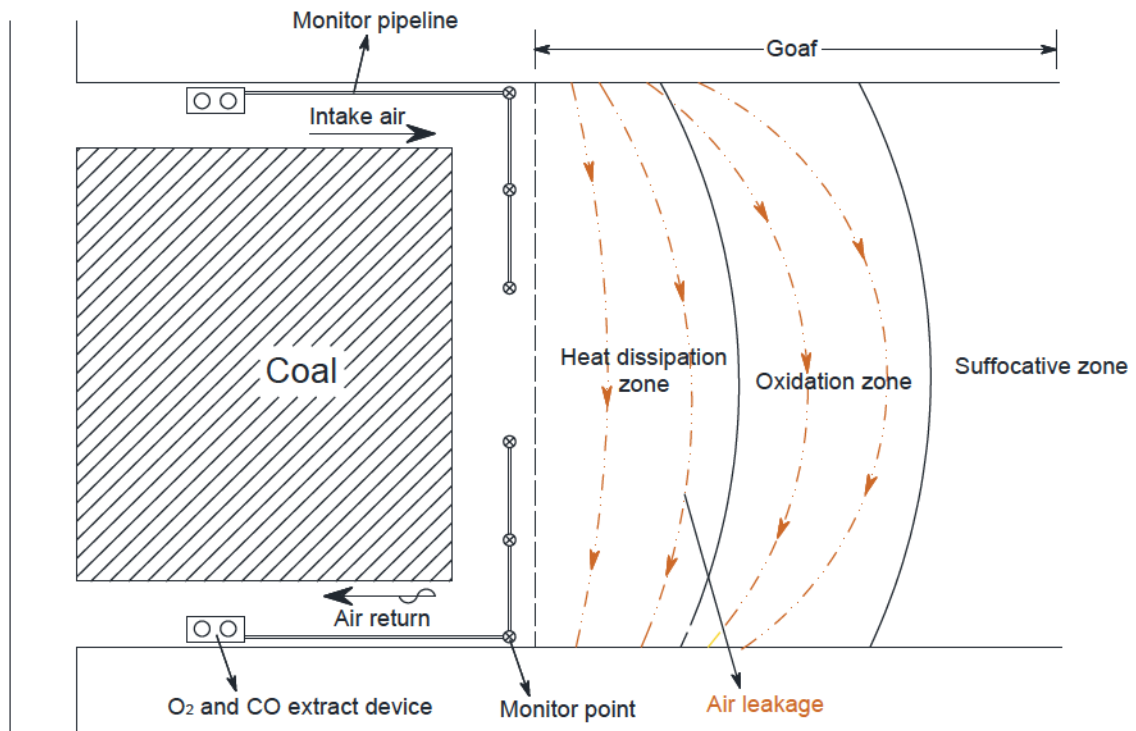


**Figure 4.11 The O<sub>2</sub> concentration in the middle of the goaf (y=60m; three faults)**

With the increase of the number of faults, the oxygen concentration curve moves to the right, which indicates that multi-faults in goaf make the oxidation zone move to the depth of goaf and widen the heat dissipation zone. Therefore, it is more difficult to prevent coal spontaneous combustion in goaf under multi-faults condition.

#### 4.2.4 On-site monitoring results of oxygen concentration in goaf

The change of O<sub>2</sub> concentration in the goaf with the advancing of coal mining face is monitored by the monitoring pipeline system. During the monitoring process, there is only one fault. The monitoring pipeline system installs monitoring device through the scraper conveyor behind the coal mining face. In order to reduce the pumping resistance of the pipeline and the power of the pumping pump, pipeline and conductors are laid in the intake side (y=120m) middle of goaf (y=60m) and air return side (y=0m) respectively, and the gas and temperature extract device that is 200m away from the coal mining face is used for controlling the pipeline. The monitoring pipeline system and the layout of the monitoring points are shown in Figure 4.12. In order to prevent the thermocouple from being damaged by the coal and rock falling from the goaf and to prevent the pipeline from being damaged or blocked by the falling coal to be unable to extract the gas sample, the sensor and the sampling pipe head are protected by other equipment.

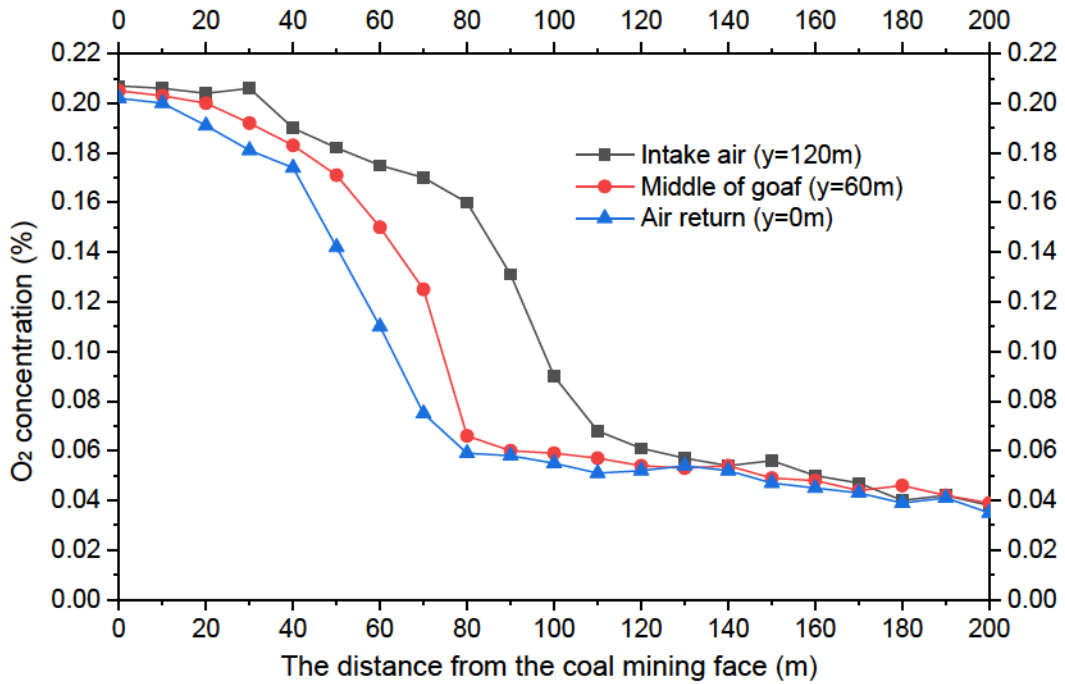


**Figure 4.12 Monitoring pipeline system**

With the advancing of coal mining face, caving rock blocks are gradually compacted, pore density decreases, wind resistance increases and air leakage volume decreases. On the one hand, it provides sufficient conditions for coal spontaneous combustion of float coal in goaf, on the other hand, the heat accumulated by coal spontaneous combustion will not be quickly dissipated, which provides extremely favorable conditions for spontaneous combustion of coal. However, with the continuous advance of the coal mining face, the caving rock blocks are basically compacted, the air leakage basically disappears, and the oxygen concentration at each measuring point decreases rapidly, which makes the spontaneous combustion process of coal unsustainable development, entering the "Suffocative zone" of the goaf.

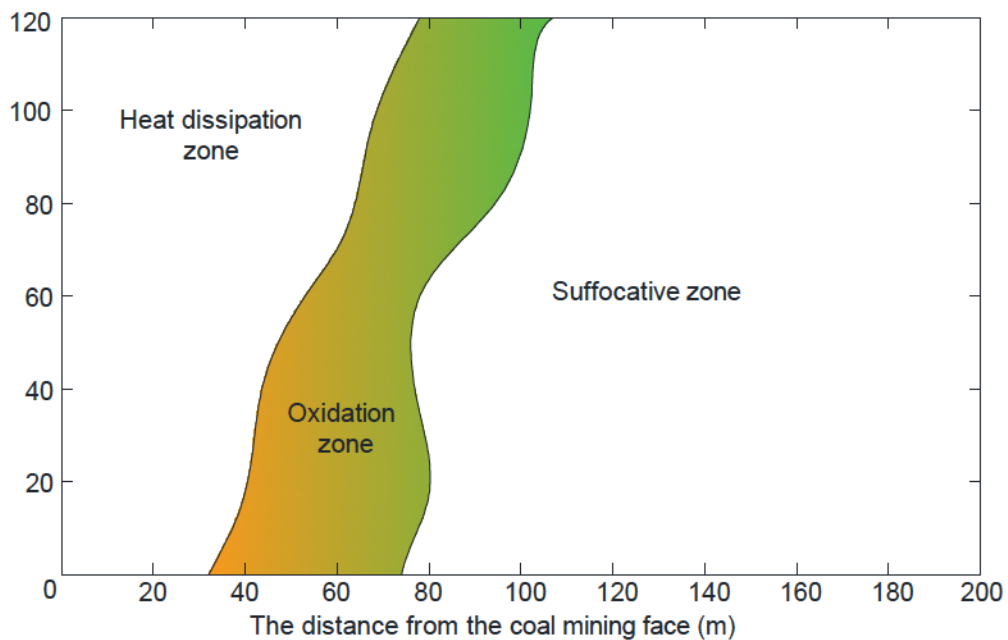
The distribution of oxygen concentration in goaf was obtained by the monitoring pipeline system. The change of oxygen concentration in goaf directly reflects the air leakage state in goaf and the oxidation environment of coal in goaf. When the temperature change in goaf is not obvious, the change of oxygen concentration is more accurate to reflect the location and area of dangerous area of coal spontaneous combustion in goaf. Before the coal mining face passes through faults,

the concentration of oxygen in the goaf measured by the monitoring pipeline system is shown in Figure 4.13.



**Figure 4.13 The monitoring data of O<sub>2</sub> concentration before passing through faults**

Based on the data collected from on-site monitoring and combined with the production situation of Dashe coal mine, the “three-zone” distribution of coal spontaneous combustion in goaf is shown in Figure 4.14. Distribution of coal spontaneous combustion zone: 78m~107m on the intake side; 53m~78m in the middle of goaf; 32m~74m on the air return side.



**Figure 4.14 Three zones distribution of coal spontaneous combustion in goaf before passing through faults**

After passing through faults, the measured O<sub>2</sub> concentration in the goaf is shown in Figure 4.15, and the three zones of coal spontaneous combustion are shown in Figure 4.16. Through the comparison and analysis of measured data and numerical simulation results, it is verified that the simulation can reflect the results of monitoring to a certain extent. It can be seen that the oxidation zone moves to the depth of goaf after passing through faults, and the width of oxidation zone is widened, so the risk of coal spontaneous combustion increased.

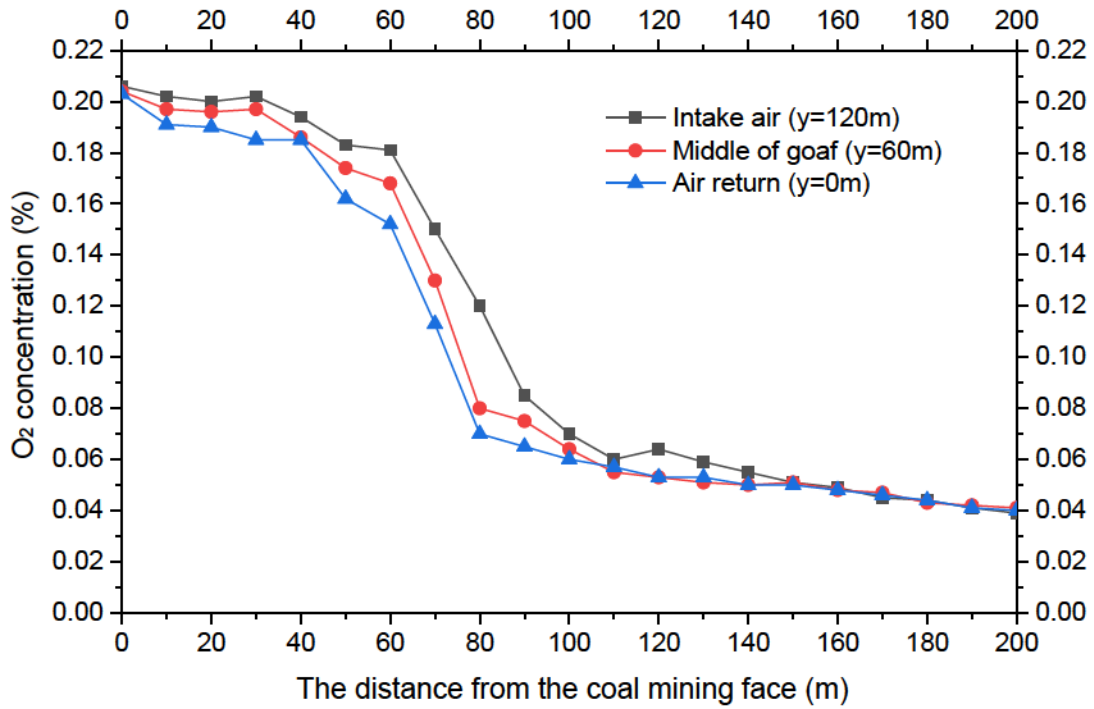


Figure 4.15 The monitoring data of O<sub>2</sub> concentration after passing through faults

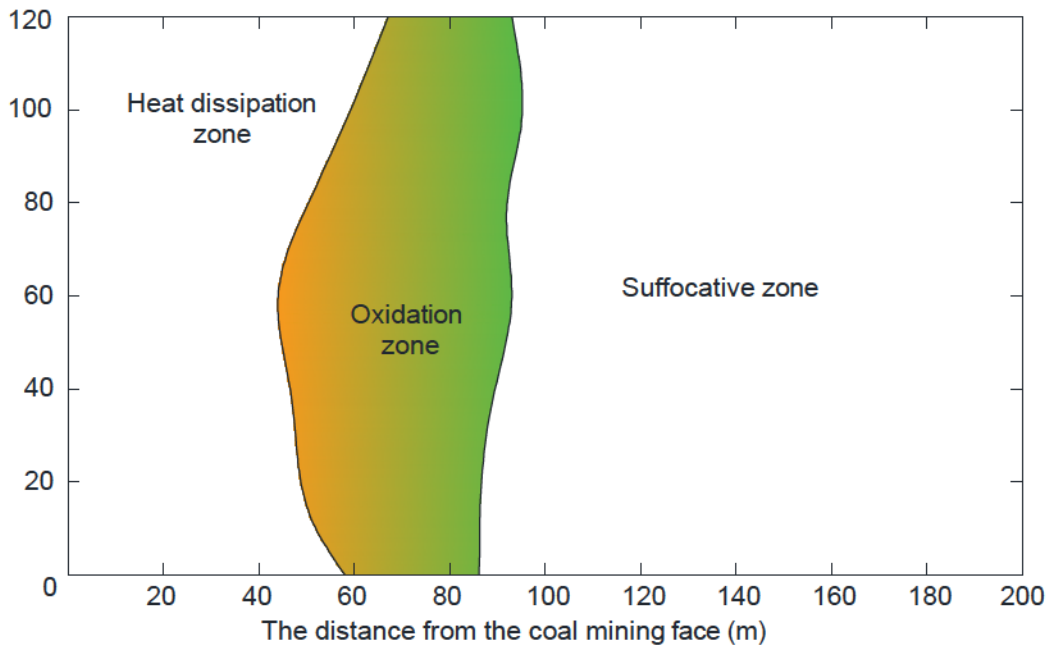


Figure 4.16 Three zones distribution of coal spontaneous combustion in goaf after passing through faults





## **5 Design and simulation of nitrogen injection in goaf**

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Under the condition of multi-faults, the conventional measures of coal spontaneous combustion prevention and control can not achieve satisfactory results of preventing coal spontaneous combustion in goaf, so it is necessary to make special measures to prevent coal spontaneous combustion. This chapter mainly studies the nitrogen injection fire fighting system in goaf under the condition of multiple faults in Dashe coal mine.

### **5.1 Principle of preventing coal spontaneous combustion by nitrogen injection in goaf**

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Nitrogen is stable in nature and has good fluidity, which can enter into the deep part of goaf and the range of other coal spontaneous combustion areas. In addition, nitrogen resources are easily accessible, the manufacturing process and nitrogen injection process are relatively simple, which can rapidly reduce the oxygen concentration in the oxidation zone, and the oxidation reaction of coal in the goaf can achieve cooling by absorbing the heat of goaf. Moreover, nitrogen injection can also reduce the strength of gas in goaf and prevent gas and coal dust explosion. In view of the above advantages of preventing coal spontaneous combustion by nitrogen injection in goaf, nitrogen injection has been widely used.

Nitrogen exists widely, accounting for about four fifths of the atmosphere, and its density at standard atmospheric pressure and room temperature is 1.25g/L. Nitrogen gasification is stable in chemical properties. Generally, it does not react with other substances, does not burn, does not support combustion, is colorless, non-toxic, has no decaying candle, and is not easy to dissolve in water. The principle of preventing coal spontaneous combustion by nitrogen injection in goaf is:

- (1) Nitrogen injection into goaf can significantly dilute oxygen concentration in goaf, inert oxidation reaction of coal in goaf, and effectively prevent spontaneous combustion and oxidation of coal in goaf.
- (2) After nitrogen injection, the gas pressure in the goaf rises, and the positive pressure in the goaf is formed relative to the coal mining face, which reduces the air leakage into the goaf.

(3) Nitrogen absorbs heat and reduces temperature of gas and coal in spontaneous combustion area or goaf, and slows down the speed of coal oxidation reaction.

(4) Nitrogen can transform explosive gas mixture of gas or coal dust in fire area or goaf into inert gas mixture without explosive tendency, effectively reducing the possibility of gas explosion.

## 5.2 Design of preventing coal spontaneous combustion by nitrogen injection in goaf

There is a nitrogen injection machine room on the ground of Dashe coal mine. The nitrogen injection equipment is made of DT-1000/8 coal mine carbon molecule nitrogen plant. The equipment can produce  $1000\text{Nm}^3/\text{h}$  nitrogen per hour. The nitrogen concentration can reach above 97%, and the outlet pressure of nitrogen injection equipment is 0.65MPa. Nitrogen from the ground along the shaft to the main roadway, through the Dg100 pipeline to the goaf of each coal mining face.

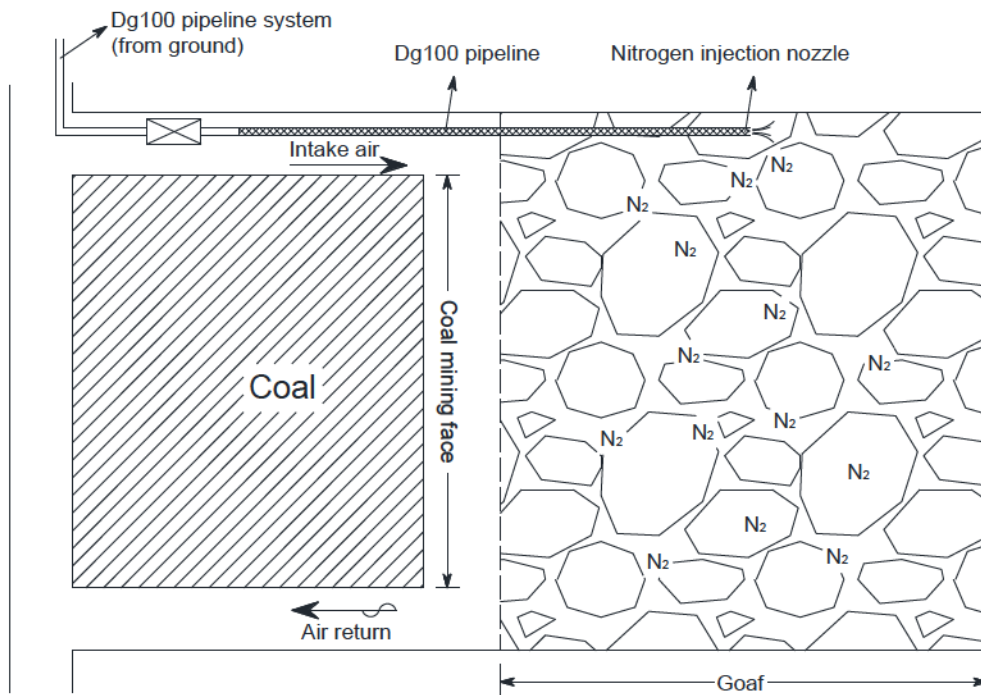


Figure 5.1 Nitrogen injection system in goaf

### 5.2.1 Calculation of nitrogen injection in goaf of Dashe coal mine

In calculating the quantity of nitrogen injection for fire prevention in working face, the geometry of goaf, the width of oxidation band, air leakage, roof condition and gas composition in goaf should be taken into account. In MT/T701-1997(China)

standard, it is recommended to calculate nitrogen injection according to oxygen content in oxidation zone of goaf, and refer to other calculation methods.

(1) According to the oxygen content in oxidation zone of goaf

According to the principle of this calculation method, the quantity of nitrogen injection used to reduce the oxygen concentration in goaf to below the inerting index is calculated. The calculation formula is as follows:

$$Q_n = 60Q_0k \frac{C_1 - C_2}{C_N + C_2 - 1} \quad (5.1)$$

$Q_n$ ——Quantity of nitrogen injection; m<sup>3</sup>/h

$Q_0$ ——Air leakage in oxidation zone of goaf (5 m<sup>3</sup>/min)

$C_1$ ——Average oxygen concentration in oxidation zone of goaf (14%)

$C_2$ ——Oxygen index of inert fire prevention (7%)

$C_N$ ——Concentration of nitrogen injection (97%)

$k$ ——Additional coefficient (1.3)

(2) According to the production of coal mining face

The principle of this calculation method is to calculate the quantity of nitrogen injection needed according to the volume of the goaf caused by the advancing of the coal mining face in a period of time. The calculation formula is as follows:

$$Q_n = k \frac{A}{24 \times \rho \times N_1 \times N_2} \left( \frac{C_1}{C_2} - 1 \right) \quad (5.2)$$

$Q_n$ ——Quantity of nitrogen injection; m<sup>3</sup>/h

$C_1$ ——Average oxygen concentration in oxidation zone of goaf (14%)

$C_2$ ——Oxygen index of inert fire prevention (7%)

$A$ ——Production of coal per day; t

$N_1$ ——Transport efficiency in pipelines of nitrogen injection (90%)

$N_2$ ——Efficiency of nitrogen injection in goaf (30%~70%)

$\rho$ ——Density of coal (1.3t/m<sup>3</sup>)

$k$ ——Additional coefficient (1.3)

Through calculation, the quantity of nitrogen injection calculated by the oxygen content in oxidation zone of goaf is  $682\text{m}^3/\text{h}$  and  $555\text{m}^3/\text{h}$  according to the production of coal mining face. The calculation result of the first method is taken as the main basis of quantity of nitrogen injection, and the second method is taken as reference. According to the calculation result, the safety coefficient is taken into account, and the quantity of nitrogen injection in goaf is designed to be  $700\text{m}^3/\text{h}$ .

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### **5.2.2 Technical requirements of nitrogen injection in goaf**

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Under normal production conditions, the monitoring pipeline system is used to collect the index gas and analysis the coal spontaneous combustion situation in the goaf. Generally, the coal mining face carries out intermittent nitrogen injection, when the air return or the upper corner of the wind index gas exceeds the normal standard, such as the concentration of CO is more than 24 ppm, or the monitoring temperature of the goaf is more than  $50^\circ\text{C}$ , 24 hours continuous nitrogen injection measures must be used to achieve better fire prevention and extinguishing purposes.

- (1) According to the actual production situation of the coal mining face, the quantity of nitrogen injection can be increased or decreased.
  - (2) In the process of nitrogen injection in goaf, the pressure of nitrogen injection pipeline is recorded regularly to obtain better nitrogen injection effect.
  - (3) When the quantity of nitrogen injection is increased, monitoring work of the change of oxygen concentration in coal mining face should be strengthened to ensure the safe production of coal mining face.
- 

### **5.3 Simulation of three zones in goaf under nitrogen injection condition**

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By using FLUENT software to simulate the goaf after nitrogen injection, the distribution of oxygen concentration in the goaf before and after nitrogen injection can be obtained, so the three zones of the goaf before and after nitrogen injection can be determined. The numerical models of the coal mining face before and after passing through the faults are built respectively, and only one fault is discussed here.

In order to determine the influence of location of nitrogen injection nozzle, the amount of nitrogen injection was determined as  $700\text{m}^3/\text{h}$  by calculation in the

previous section. The simulated location of nitrogen injection nozzle was set at  $x=10\text{m}$ ,  $20\text{m}$ ,  $30\text{m}$ ,  $40\text{m}$ ,  $50\text{m}$ ,  $60\text{m}$  and  $70\text{m}$  away from the coal mining face respectively. The other geometric parameters of numerical simulation were equal to previous sections. The changes of oxygen distribution in goaf before and after nitrogen injection at different distances were simulated.

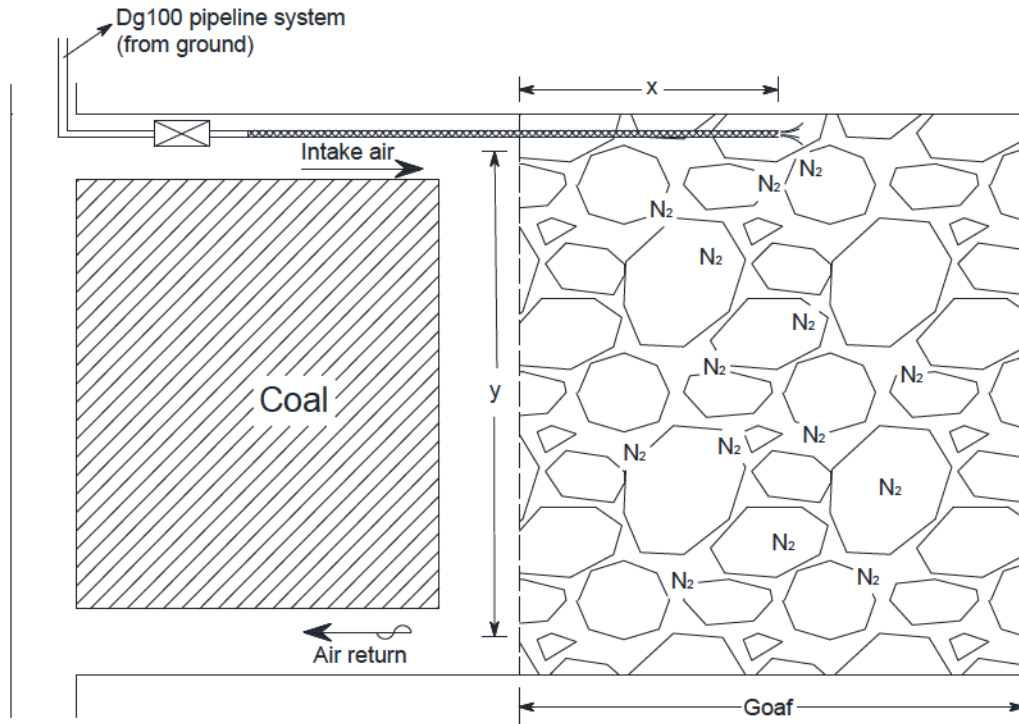


Figure 5.2 Location of nitrogen injection nozzle( $x/m$ )

### 5.3.1 Oxygen distribution in goaf at different location of nitrogen injection before passing through faults.

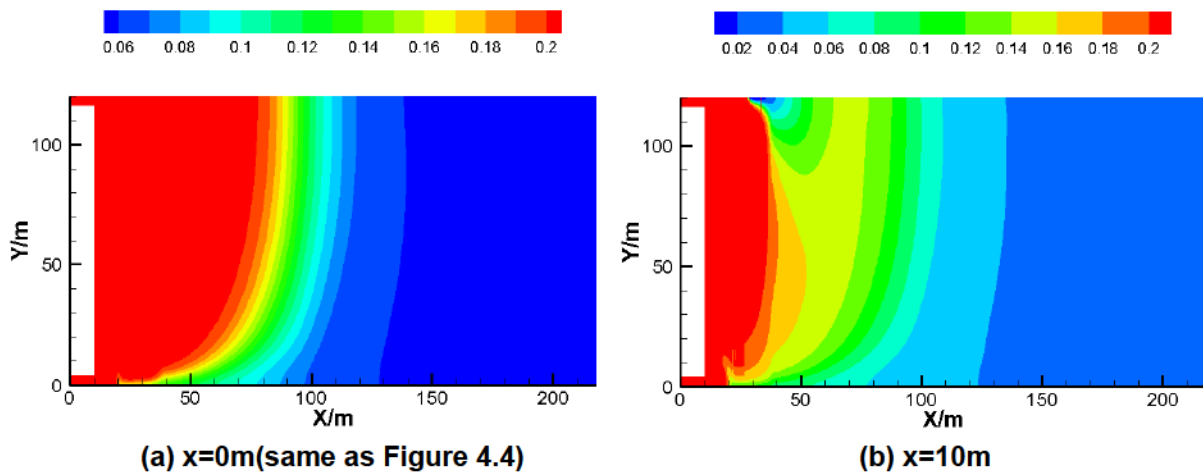


Figure 5.3  $O_2$  distribution in goaf at different location of nitrogen injection before passing through faults.

As shown in Figure 5.3, the effect of nitrogen injection from 10m away from the coal mining face( $x=10m$ ) is not good. Although the oxidation zone( $0.8 < O_2$  concentration  $< 0.18$ ) moves forward and close to the mining face, the area of oxidation zone increases significantly, which will make it more difficult to prevent coal spontaneous combustion in goaf, and the quantity of nitrogen injection into goaf will also increase significantly.

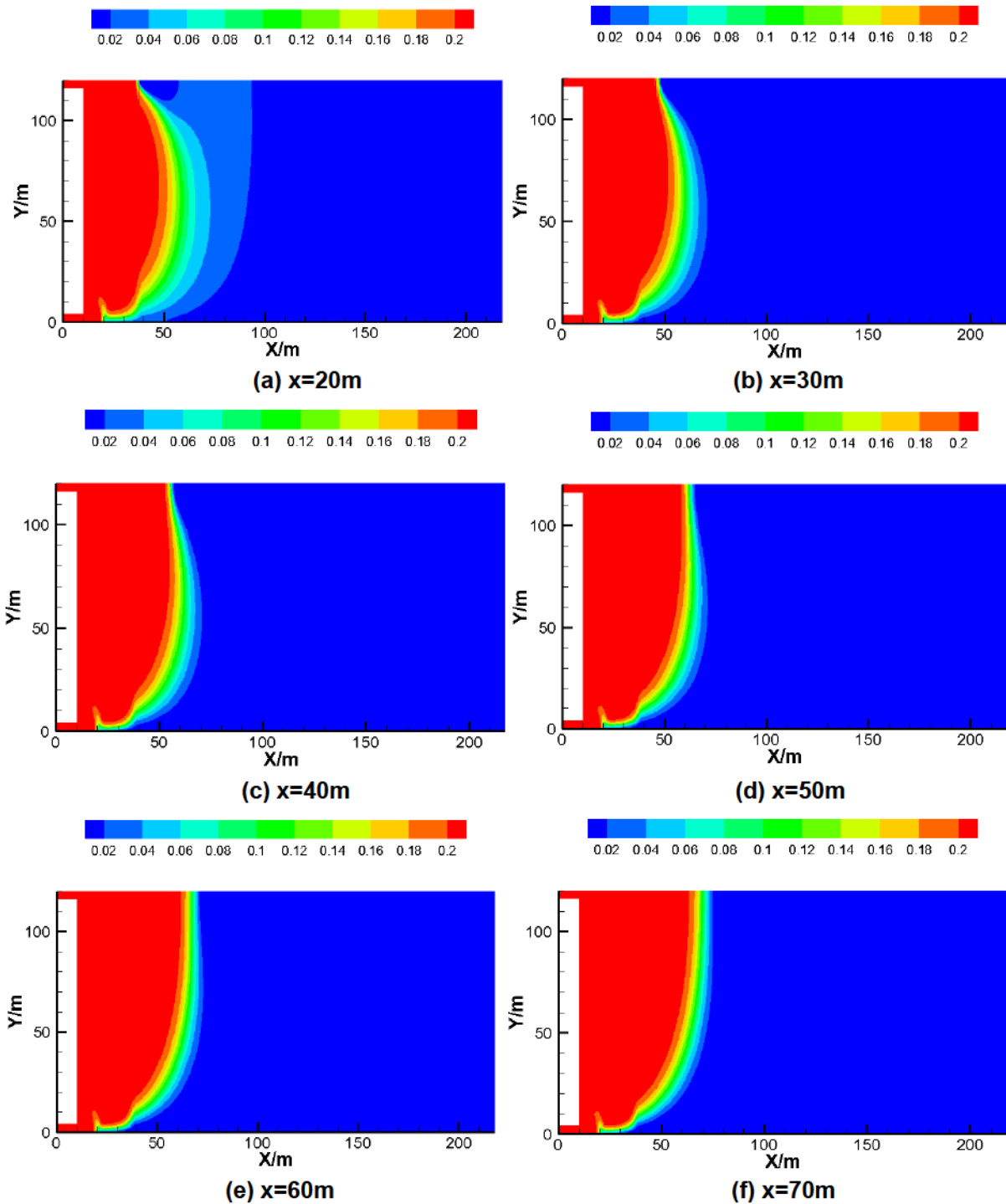


Figure 5.4  $O_2$  distribution in goaf at different location of nitrogen injection before passing through faults.

From Figure 5.4, it can be seen that the width of oxidation zone of goaf decreases first and then increases with the moving of nitrogen injection nozzle. This shows that when nitrogen injection nozzle is located at a distance far from the coal mining face ( $x > 50\text{m}$ ), the dilution effect of nitrogen on oxygen concentration in goaf will gradually weaken, and when the distance is 50m from the coal mining face ( $x = 50\text{m}$ ), the width of oxidation zone appears to be the minimum, as shown in Figure 5.5. Therefore, the optimum nitrogen injection position is around 50m away from the coal mining face.

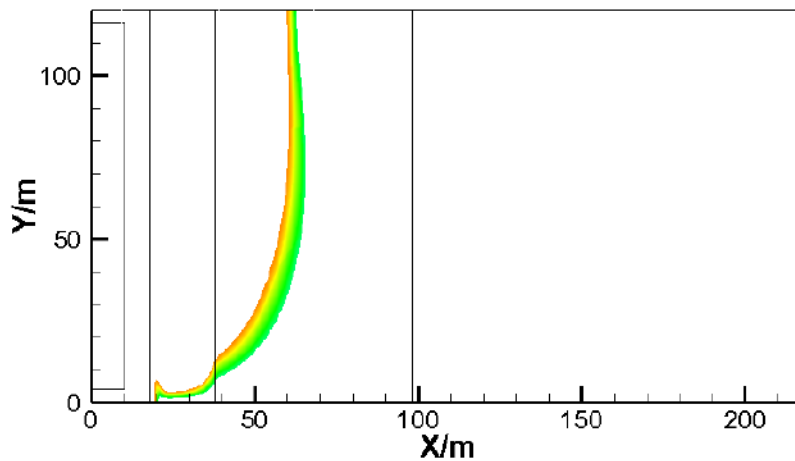


Figure 5.5 Oxidation zone after nitrogen injection at  $x = 50\text{m}$

According to the criterion of three zones of coal spontaneous combustion, the width of heat dissipation zone ( $\text{O}_2$  concentration  $> 0.18$ ) has not changed greatly after nitrogen injection, and the minimum width of oxidation zone has been reduced to  $6\text{m} \sim 12\text{m}$  ( $x = 50\text{m}$ ). Compared with that before nitrogen injection (Figure 4.4; Figure 5.3a), the width of oxidation zone ( $0.8 < \text{O}_2$  concentration  $< 0.18$ ) has been significantly reduced, and the suffocative zone ( $\text{O}_2$  concentration  $< 0.8$ ) occupies the remaining part of the goaf.

Table 5.1 width of three zones in goaf after nitrogen injection at  $x = 50\text{m}$

Location	Heat dissipation zone	Oxidation zone	Suffocative zone
Intake side ( $y = 120\text{m}$ )	0m~54m	54m~61m	61m~∞
Middle of goaf ( $y = 60\text{m}$ )	0m~59m	59m~68m	68m~∞
Air return side ( $y = 0\text{m}$ )	0m~19m	19m~21m	21m~∞

### 5.3.2 Oxygen distribution in goaf at different location of nitrogen injection after passing through faults.

In the case that only one fault(Fault No.1) is simulated, the simulated air leakage is set as 0.774kg/s. The simulated location of nitrogen injection nozzle was set at  $x=20\text{m}$ ,  $30\text{m}$ ,  $40\text{m}$ ,  $50\text{m}$ ,  $60\text{m}$  and  $70\text{m}$  away from the coal mining face respectively. The simulation results of oxygen concentration in goaf are shown in Figure 5.6.

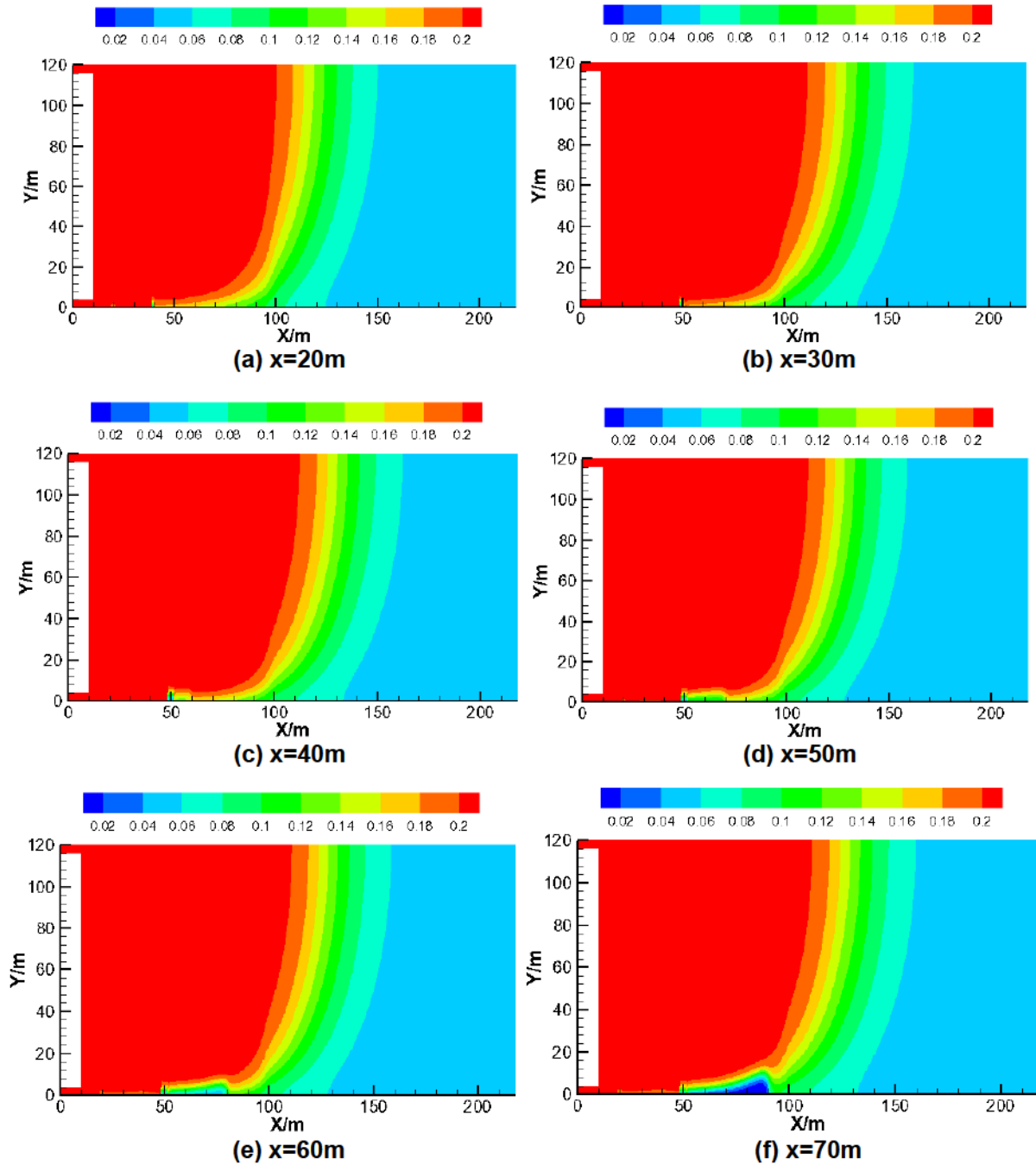
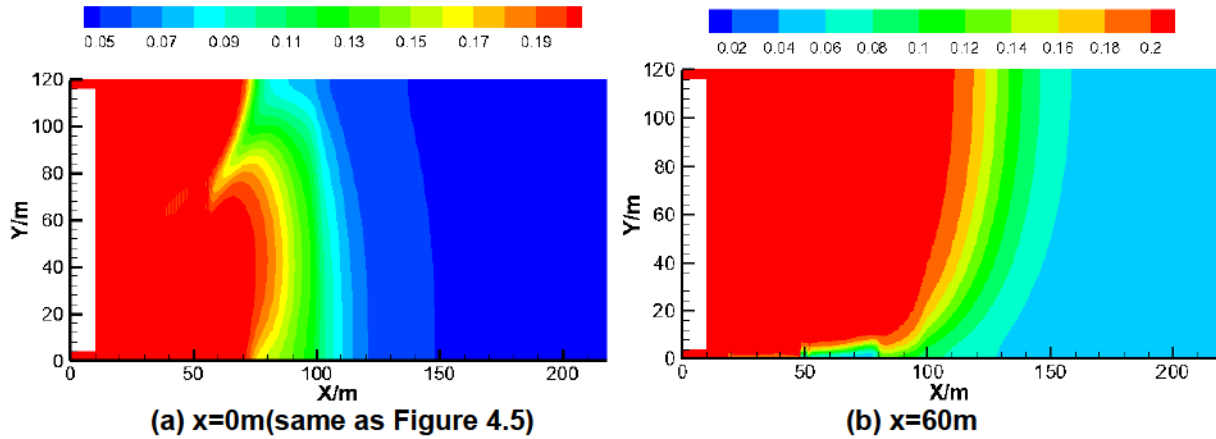


Figure 5.6  $\text{O}_2$  distribution in goaf at different location of nitrogen injection after passing through fault No.1.



It can be seen that the oxygen concentration on the intake air side is higher than that on the air return side, and the oxygen concentration decreases with the increase of the distance from the coal mining face. According to the criterion of three zones of coal spontaneous combustion, the width of oxidation zone is reduced to about 20m~30m, which is smaller than that before nitrogen injection(Figure 4.5), but the effect is not obvious, as shown in Figure 5.7.

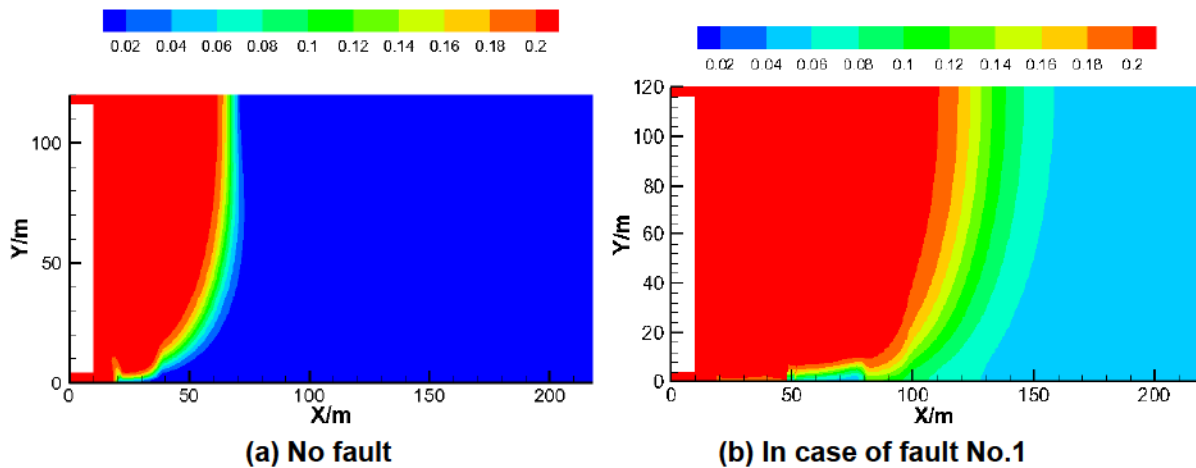


**Figure 5.7 Comparison of O<sub>2</sub> distribution in goaf before and after nitrogen injection in case of fault No.1 and air leakage 0.774kg/s**

When the distance is around 60m from the coal mining face, the width of the oxidation zone( $0.8 < O_2 \text{ concentration} < 0.18$ ) is the minimum, so it is the best nitrogen injection location at the distance of 60m from the coal mining face.

**Table 5.2 Width of three zones in goaf after nitrogen injection at x=60m in case of fault No.1 and air leakage 0.774kg/s**

Location	Heat dissipation zone	Oxidation zone	Suffocative zone
Intake side (y=120m)	0m~114m	114m~141m	141m~∞
Middle of goaf (y=60m)	0m~107m	107m~138m	138m~∞
Air return side (y=0m)	0m~50m	50m~102m	102m~∞

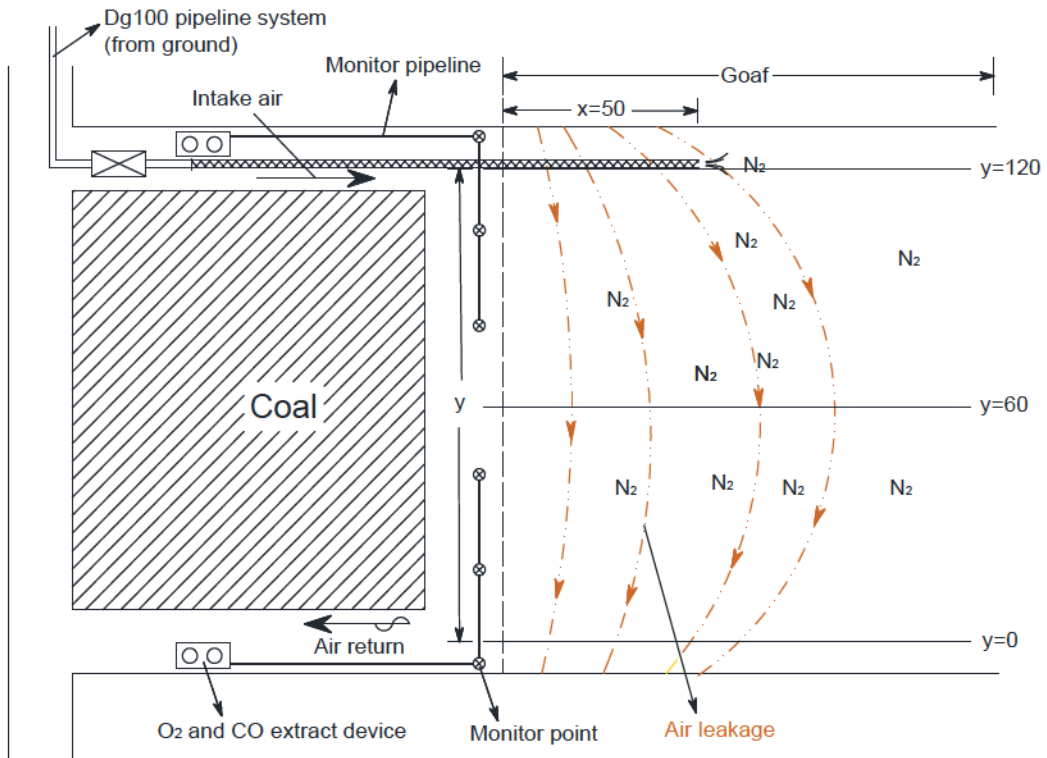


**Figure 5.8 The influence of fault No.1 on nitrogen injection (x=60m)**

As can be seen from Figure 5.8, fault No.1 have a great impact on nitrogen injection in goaf. The reasons can be summarized as two aspects: on the one hand, it is because the cracks at the fault make air leakage more easy, and increase the air leakage volume in goaf, keep the oxygen concentration in goaf at a high level, so widen the heat dissipation zone and oxidation zone, and it is more difficult to inject nitrogen. On the other hand, nitrogen may be lost through air leakage at fault, which makes it difficult to increase the concentration of nitrogen in goaf to prevent the coal spontaneous combustion.

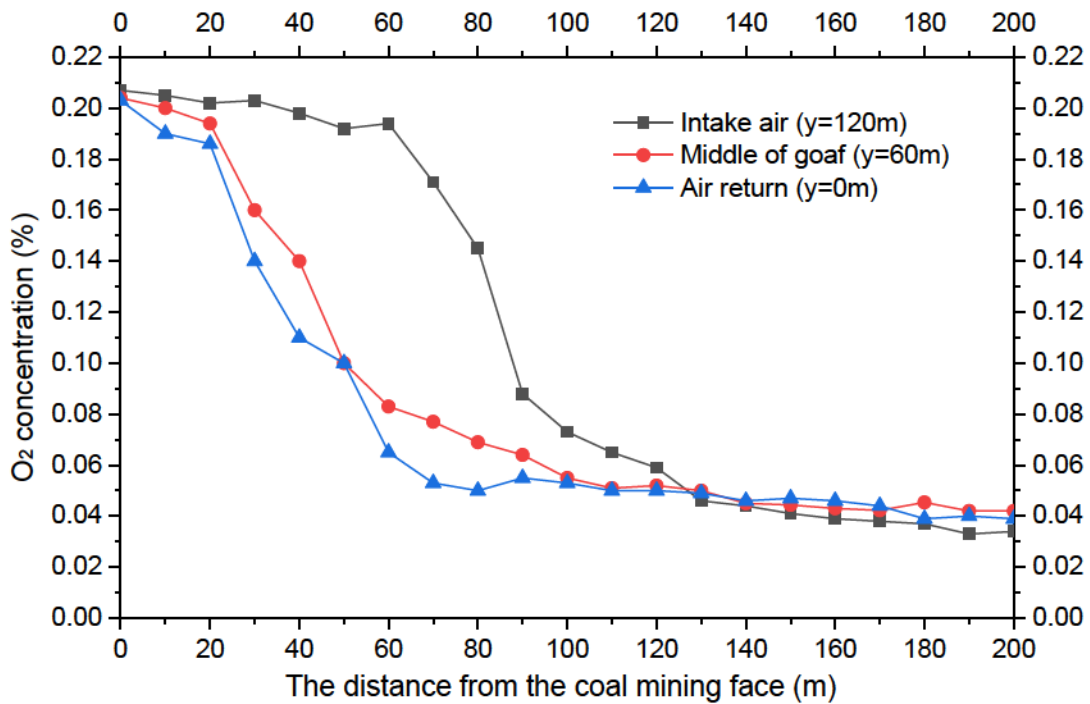
#### 5.4 On-site monitoring data of nitrogen injection

The change of  $O_2$  concentration in goaf after the nitrogen injection can also be monitored by the monitoring pipeline system. Before the monitoring process, it has already passed through a fault. The monitoring pipeline system installs monitoring device through the scraper conveyor behind the coal mining face . In order to reduce the pumping resistance of the pipeline and the power of the pumping pump, pipeline and conductors are laid in the intake side(y=120m) middle of goaf(y=60m) and air return side(y=0m) respectively, and the gas and temperature extract device that is 200m away from the coal mining face is used for controlling the pipeline. Dg100 pipeline is 250m away from the coal mining face. The layout of the monitoring pipeline system and nitrogen injection system are shown in Figure 5.9.



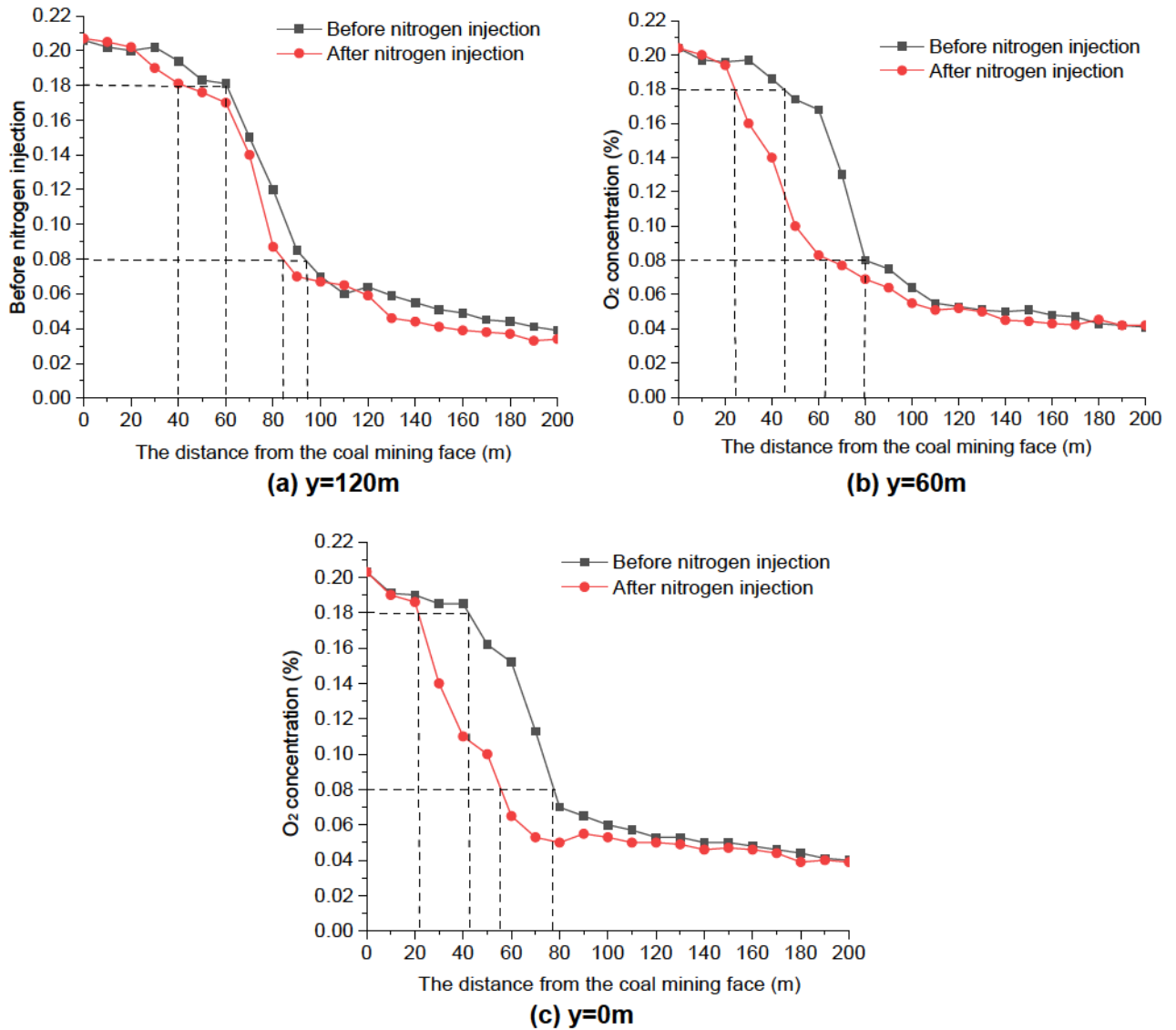
**Figure 5.9 The layout of the monitoring pipeline system and nitrogen injection system**

According to the simulation results, the effect of injecting nitrogen into goaf at  $x=50\text{m}$  after crossing fault is the most effective. Therefore, in actual production, the length of nitrogen injection pipeline in goaf is set to  $45\text{m}\sim 55\text{m}$ . The oxygen concentration in goaf monitored on site is shown in Figure 5.10.



**Figure 5.10 The monitoring data of O<sub>2</sub> concentration after nitrogen injection**

Compared with that before nitrogen injection, the oxygen concentration of monitoring data decreased faster, especially from 0.18 to 0.08, which was faster than that before nitrogen injection. This shows that nitrogen injection in goaf has an effect on oxygen concentration, and the oxidation zone ( $0.08 < O_2 \text{ concentration} < 0.18$ ) is more close to the side of coal mining face ( $x=0m$ ), as shown in Figure 5.11.



**Figure 5.11 The comparion of monitoring data of O<sub>2</sub> concentration before and after nitrogen injection**

## 6 Conclusion and outlook

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This thesis mainly studies the characteristics of coal samples of Dashe coal mine in the programmed-temperature heating experiment, and gives the temperature change curve of different gases released by coal samples before the temperature rises to 200°C, and simulates the influence of faults on the distribution of three zones (heat dissipation zone, oxidation zone and suffocative zone) in goaf with FLUENT. The simulation results of three zones are verified by monitoring data (oxygen concentration) of coal mining face. The paper also calculates the amount of nitrogen injection needed in goaf, and carries out numerical simulation of nitrogen injection in goaf. The main conclusions are as follows:

(1) The different index gases released from coal samples of Dashe coal mine in the programmed-temperature heating experiment all increase in the way of exponential function. The curve of CO concentration most obviously, and the rising process of CO concentration is divided into five stages. The concentration of oxygen will not change when the temperature rises around 150°C, and the exponential functions of CO<sub>2</sub>, CH<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> increase obviously. In addition, C<sub>2</sub>H<sub>4</sub> did not appear until about 150°C, and then it increased rapidly. Therefore, the coal spontaneous combustion in goaf can be monitored by detecting different kinds of index gases such as CO in goaf.

(2) The influence factor of coal spontaneous combustion in goaf under multi-fault condition in Dashe coal mine was discussed, which can be divided into internal factors and external factors. The oxygen concentration in goaf under no-fault condition and multi-faults condition in Dashe coal mine was simulated by FLUENT. Based on oxygen concentration classification criteria, the heat dissipation zone is from 18% to 21%, the oxidation zone is from 8% to 18% and the suffocative zone is less than 8%. The simulation results show that with the increase number of faults, the width of oxidation zone in goaf becomes wider and moves away from the coal mining face, which makes it more difficult to prevent coal spontaneous combustion in goaf.

(3) The nitrogen injection system to prevent coal spontaneous combustion in goaf was designed by using nitrogen injection equipment that is made of DT-1000/8 and Dg100 pipeline. According to two different calculation methods of nitrogen injection,

the quantity of nitrogen injection in goaf was calculated, which is  $700\text{m}^3/\text{h}$  considering safety factor. The simulation of oxygen concentration in goaf before and after nitrogen injection was made by FLUENT, and six different location ( $x=20\text{m}$ ,  $x=30\text{m}$ ,  $x=40\text{m}$ ,  $x=50\text{m}$ ,  $x=60\text{m}$ ,  $x=70\text{m}$ ) of nitrogen injection in goaf was discussed. Based in the simulation results,  $X=50\text{m}$  and  $X=60\text{m}$  are the best nitrogen injection positions in goaf before and after passing through the fault.

Although the distribution of oxygen in goaf is simulated by FLUENT, and the three zones of coal spontaneous combustion in goaf are determined, there are still some shortcomings because the actual geological conditions of Dashe coal mine are more complex and the simulation can not be completely consistent with the real geological conditions, more on-site monitoring data need to be obtained in the future.

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