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Environmental treatment technology for complex coalfield fire zone in a close distance coal seam—A case study

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Abstract
To achieve fast and effective control of complex coalfield fire areas in close-distance coal seams, proposals regarding "blocking air leakage, reducing oxygen, eliminating high temperature, and preventing re-ignition" were put forward. Combined with isotope radon measurement, infrared thermal imaging and ground drilling construction technology, the exact location of coalfield fire source was outlined. According to the characteristics of coalfield fire areas in Liujiamao and Qian'an mines, a set of economical and efficient coalfield fire control and extinguishing plans have been developed, which include the isolation of the production system, treatment of slope, injection of fly ash composite colloid, and excavation. The results show that the combined application of multiple detection technologies can accurately determine the location of fire source and divide three regions according to the temperature distribution. In addition, we developed a set of coalfield fire detection, fire-fighting equipment, fire-fighting materials and data monitoring as one of the coalfield fire control and extinguishing technology. Through the implementation of the plan, the coalfield fire disaster of Liujiamao and Qian'an mines was successfully solved. The successful application of this technology provides theoretical and technical support for similar coalfield fire control and extinguishing.

Keywords Coal · Close distance coal seam · Coalfield fire zone · Fire source detection · Fire extinguishing technique

Introduction

China is one of the largest producers of coal with abundant coal resources, and provides an adequate amount of materials for rapid economic development. However, the large-scale coal mining is also accompanied by some secondary disasters, such as those attributed to fire, water damage, gas, coal dust, and roof collapses. Among these, coalfield fires have always been the focus of the coal mine industry. Coalfield fires have the characteristics of large fire areas, high temperature, long burning time, and strong destructive force. Coalfield fire will not only destroy the surface ecology, cause coal resources losses, but it will also produce a lot of greenhouse gases (CO_2 and CH_4) [1–6], toxic and harmful gases (CO, SO_2, H_2S, N_2O, NO_x, etc.) [7–9], radiation gases (Rn) [10, 11], and trace elements (As, F, Se, Hg, etc.) [12, 13]. In addition, coalfield fires also seriously threaten the health and safety of workers and restrict normal mine productions [14]. The Nineteenth National Congress of the Communist Party of China pointed out that economic development must establish and practice the concept of "lucid waters and lush mountains as invaluable assets," and adhere to the harmonious coexistence of man and nature [15]. Therefore, the prevention and control of coalfield fire are an important task of environmental management in areas rich with coal resources.

Coalfield fire prevention and control mainly consists of fire location detection and fire control and extinguishing technology. Current fire source location detection technologies include measurements of temperature [16], magnetic detection [17], resistivity [18], gases [19], isotopes [20, 22], radiowaves [21], geological radar detection [23], remote sensing [24], and computer numerical simulations [25, 26]. Coalfield fire control and extinguishing technology mainly includes excavation [27], water injection [28], grout injection [29], gel injection [30–33], inert gas injection [34–36], foam or three-phase

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foam injection [37–41]. Many scholars have reported on fire control and extinguishing technologies in coalfields. Excavation is the most direct and effective method for shallow seam coalfield fires, but the technology is limited by environmental conditions [27]. If the coalfield fire is less than 15 m above the surface, water injection is the most effective measure for the reduction of temperature within the fire zone [28]. When the water injection is located in the undisturbed coal seam, water can penetrate in the combustion center with high permeability, which is conducive to the cooling of the fire area [42]. In areas with poor water sources, compound colloids have become the main means of coalfield fire control. It can be mixed with fly ash, sand, loess, and other materials, and has a remarkable effect on water fixation and on the elimination of leakages [30]. In summary, the choice of coalfield fire prevention and control technology needs to be determined in combination with the supply of the location of the fire area resources and characteristics. In addition, there are few reports on the current technical guidelines for coalfield fire management systems.

We proposed a technical plan of coalfield fire control and extinguishing aiming to "block air leakage, reduce oxygen, eliminate high temperature, and prevent re-ignition." Based on the treatment of the coalfield fire area in the Liujiamao-Qian'an coal mine, we obtained the range of the accident fire area based on radon detection, and drilled a hole for verification. The production system isolation, open-fire-area landfill, fly ash glue injection, fire source excavation, and other measures were adopted to successfully control the fire area.

Accident overview and technical idea of coalfield fire control and extinguishing

Accidentoverview

Both the Liujiamao and Qian'an coal mines are located in the Shenmu County, Yulin City, Shaanxi Province, China. The eastern and southeastern parts of the Qian'an coal mine are adjacent to the Liujiamao coal mine, of which the Liujiamao mine is mine-exploited and the Qian'an coal mine is an open-pit mining site. The accident occurred at the boundary between the two mines, as shown in Fig. 1.

On January 6, 2016, at 9 a.m., an explosion occurred at the Liujiamao coal mine in the Shenmu County, and 11 people were killed in the accident. The explosion caused large-scale coal combustion and produced a large amount of toxic and harmful gases. The location of the explosion point was located near the protective coal pillars of the 1st coal seam, and was 50–60 m away from the surface that caused the coal pillars of 1st coal seam to catch fire. The 2nd coal seam was located at the lower part of 1st coal seam, and was 80–90 m away from the surface. The 1st and 2nd coal seams were connected through a coal pass and a return air connection lane, as shown in Fig. 2. After the accident and during the rescue process, the rescue team found that the smoke in the roadway of the Liujiamao coal mine was heavy, and the highest CO concentration measured underground was 4.204 $\times 10^{-3}$ %. On January 11th, ambulance crews found two open flames in the underground parts of the Qian'an coal mine. On January 13th, smoke emerged from the open pit of the Qian'an coal mine (Fig. 3a and b). On January 17th, an open flame appeared in the open-pit (Fig. 3c). According to the

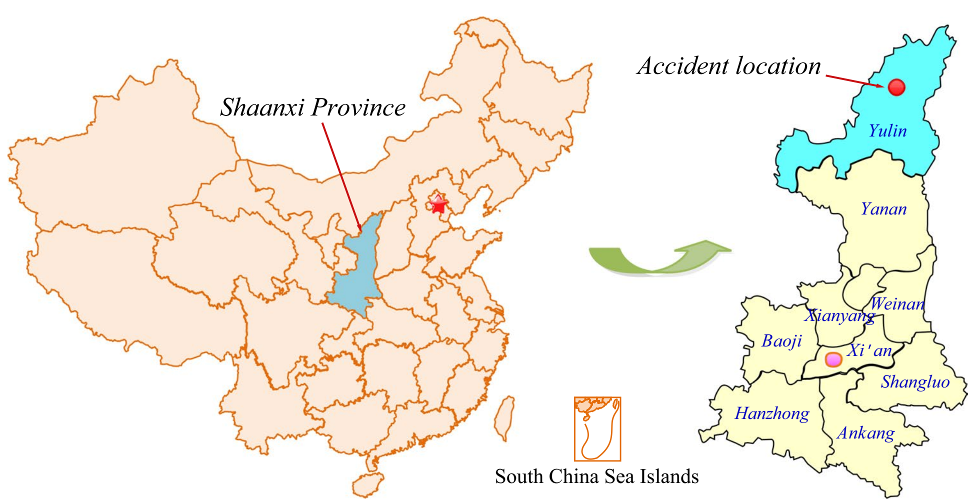


Fig. 1 Accident location

onsite situation, a long-distance, rapid closure plan were formulated. From January 18 to 21, all the wellheads of the Liujiamao mine, the open pits of the Qian'an coal mine, and the fire area, were closed to prevent the expansion of the fire area. Based on the onsite gas observations on February 26th, the CO concentration outside the closed wall of the main shaft was 3.05×10^{-3} %, and the CO concentration at the main fan of the air shaft was 7.5×10^{-4} %. In mid-April, the CO concentration outside the closed wall of the main shaft occasionally reached 1.0×10^{-3} %, and the CO

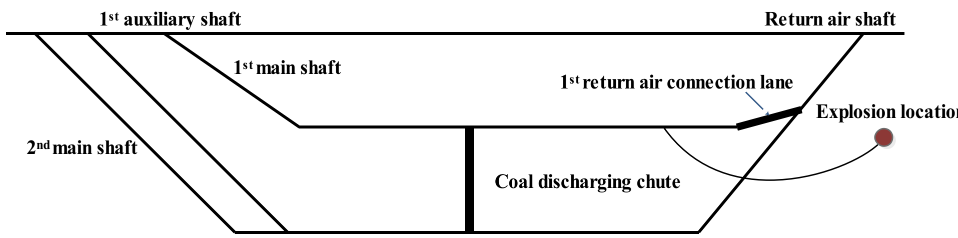


Fig. 2 Explosion point location

(a) Open -air outcrop smoke (b) Increasing smoke volume in open -pit mouth (c) Open fire appeared in open pit mouth

Fig. 3 Outcrop smoke in the Qian'an coal mine

Fig. 4 Ground condition after accident

concentration showed an upward trend. After the explosion, the original surrounding rock was destroyed, and the surface was cracked. As shown in Fig. 4, the ground surface of the goaf had a serious air leakage, and the coal fire situation become increasingly serious.

Characteristics of the fire area in the Qian'an and Liujiamao coalfields

It had been two months since Qian'an and Liujiamao coalfield fire started. Owing to the large heat capacity of coal and the large volume of the high-temperature coal body, a large amount of heat energy had been stored in the coal body and surrounding rock. As a large amount of heat accumulated in the fire area, it facilitated the continued spread of the fire over a wider area, subject to high-temperature and poor-oxygen conditions. Some spontaneously ignited coals can maintain the coal oxygenation with O_2 concentration in the range of 2 to 3% at 200 °C and prevent the coal temperature from falling. With sufficient oxygen supply, the heated coal will ignite in less than a day. The coal seam got some air supply through the ground fissures. This fissure air leakage, supported the spread of the fire over wider area (Fig. 4). Below the surface, the working space of the disaster relief personnel and the room for maneuver was small. This imposed a significant threat to the disaster relief personnel. In addition, there were detonators and explosives of unknown types within the fire area and the high temperatures from smoldering coal could detonate the explosives at any time. In summary, the coal body had stored significant amounts of heat energy, and the temperature of coal and rock around the fire was very high. The challenge was to reduce the temperature of coal and rock in such a large area. High-temperature coal has a high-oxidation activity and the air-leakage channel provided oxygen supply that sustained and fueled the spread the fire over a wider area. Extinguished coal fire can easily reignite upon sufficient supply of oxygen, this posed a risk to the isolated areas where fire had been extinguished.

Technical idea of coalfield fire control and extinguishing

In the process of making the plan, the comprehensive evaluation of each treatment measure is conducted according to the characteristics of the fire area, and the technical route is determined, as shown in Fig. 5. Owing to the presence of detonators and explosive hazardous materials within the fire area, the technical measure of direct excavation of the fire source was excluded from the evaluation of the measures to prevent the occurrence of secondary disasters.

Results and discussion

Coalfield fire area detection

Fire source detection based on isotope radon measurement

The α-cup radon detector is composed of an atmospheric pressure air-pulse ionization chamber, amplifier, a power

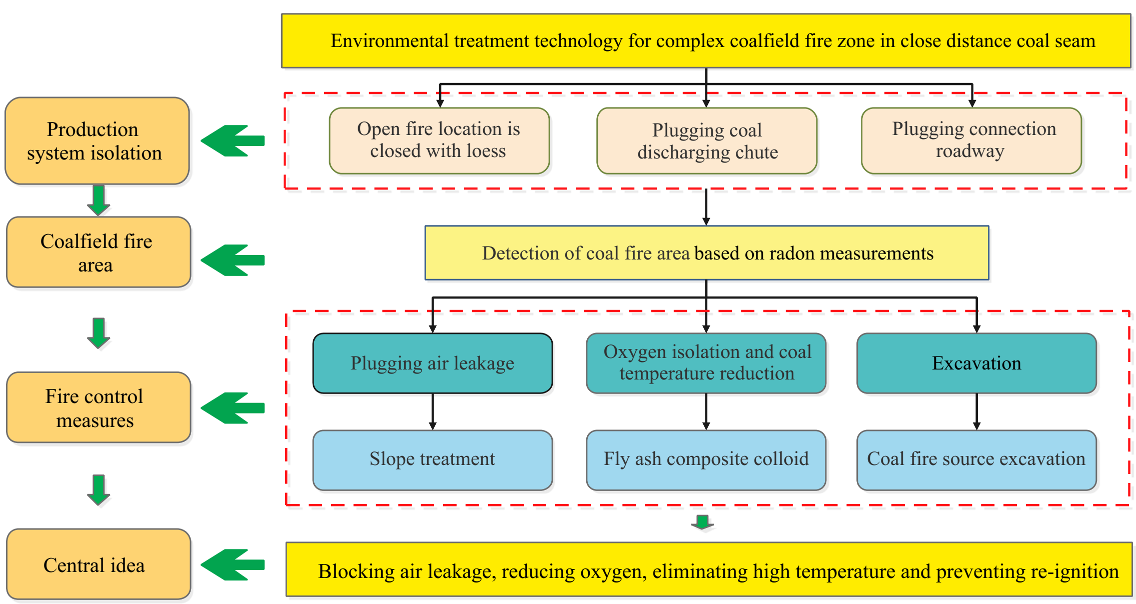
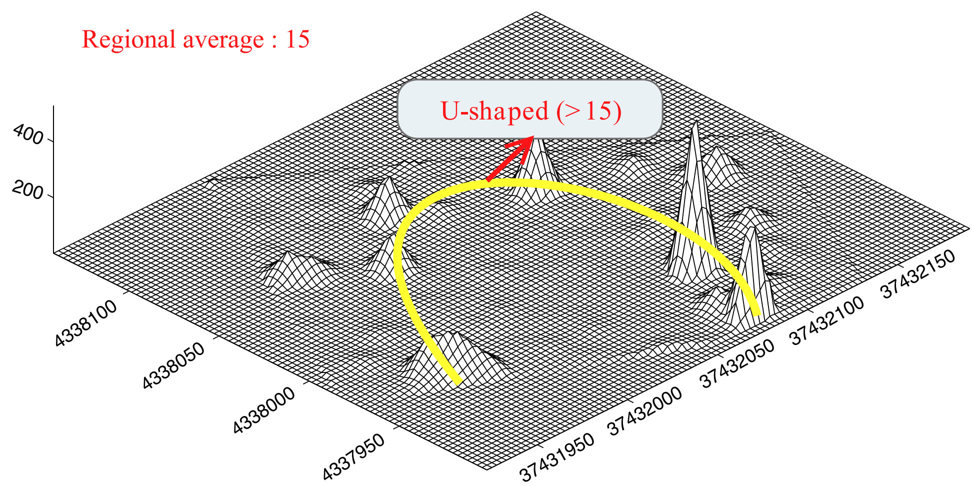


Fig. 5 Technical idea of fire area management

Fig. 6 Radon measurement device

Fig. 7 Stereogram of outliers [20]



supply circuit, and counter and control circuits. When the α-cup adsorbed with the radioactive radon daughters is put into the ionization chamber α-detector, the α-ray radiated by the radon daughters can make the air-ionization chamber produce positive and negative ion pairs, and form the pulse signal subject to the action of a high-voltage electric field in the ionization chamber. After the pulse signal is amplified by the low-noise pulse amplifier, the noise is removed by the pulse amplitude discriminator, and then recorded by the pulse counter.

To accurately obtain the range of coal seam combustion area, combined with the complexity of the terrain, the fire area is detected by the radioactive radon element testing method. The radon measuring device is shown in Fig. 6. Generally, the amount of radon exited from the soil is relatively stable. Subject to the same geological and stratigraphic conditions, when the local lower coal seam is oxidized or spontaneously ignited, the natural radioactive radon exited from the surrounding and overlying strata will increase. The α-cup method has a high-detection sensitivity and yields low-background measurements. It is easy to highlight the strength of α-radon rays and their daughters in the soil. Thus, the coalfield fire area can be obtained based on the abnormal radon range. Given that explosives and detonators are stored near the explosion site, it is necessary to control the fire area as soon as possible to avoid its spread and the risk of a secondary explosion. Therefore, clarifying the location and scope of the fire source in the fire zone is the

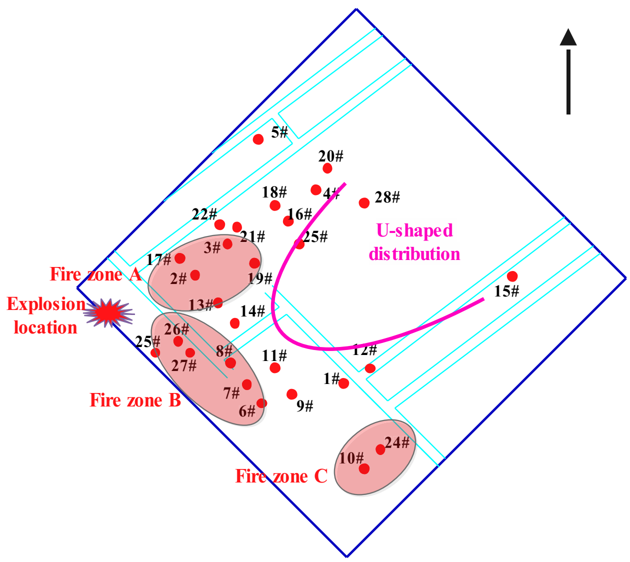


Fig. 8 Distribution map of borehole detection fire area

first major problem of the fire extinguishing project. According to the distribution of goaf areas in the Liujiamao coal mine, a total of 460 detection points were arranged, and 400 data of actual burial points were measured. The detection accuracy was controlled and was 10×10 m^2. The detection area was approximately 240 m long and 210 m wide, with a total detection area of 50,400 m^2. The three-dimensional diagram of the radon outliers in the fire area was obtained, as shown in Fig. 7.

The average radon level in the local area was 15. As it can be observed from Fig. 3, there are 14 high-temperature zones within the detection range, and the total area of the high-temperature fire zones was approximately 5050 m^2. The high-temperature area is a U-shaped distribution that conforms to the room-pillar mining mode and the roadway layout information provided by the mine. Radon anomalies usually exist on the upper surface in the mining affected area and coal fire covered area. The mine is a multiseam mine. It is impossible to judge at which coal seam the fire area is located at by measuring the radon on the surface. Therefore, it is difficult to judge the fire area directly by measuring the radon on the surface. Thus, an additional exploration is needed by surface drilling.

Borehole construction fire area verification

Based on the detection of the radon value and regional division, 32 holes were generated. As the Liujiamao coal mine adopts house-column mining, there is no detailed distribution map for the roadway and goaf, so the

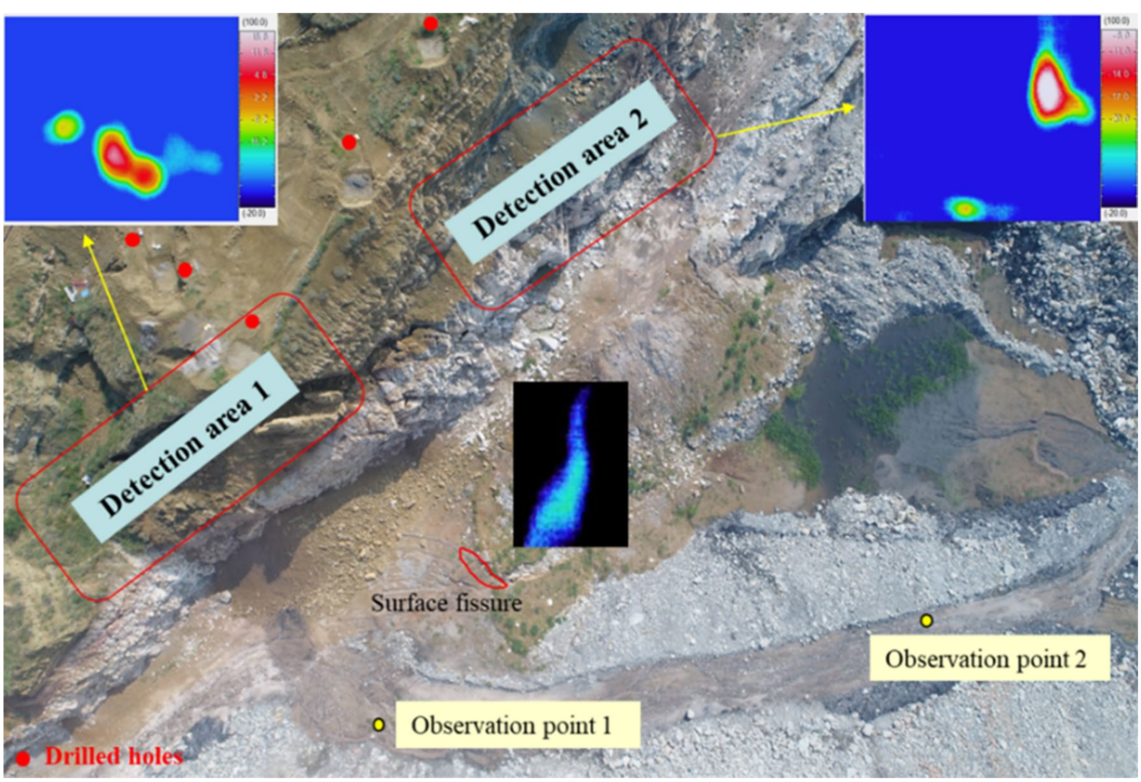


Fig. 9 Infrared thermal imaging detection results

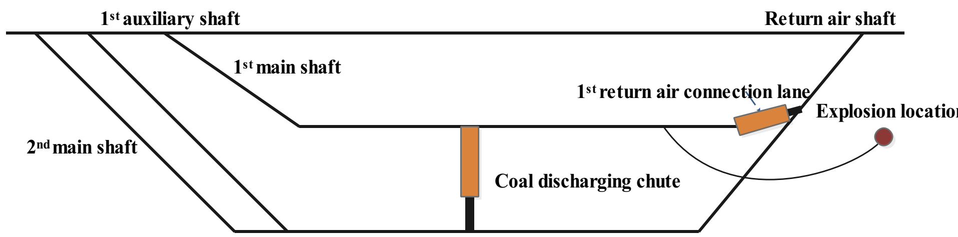


Fig. 10 Isolation of production system

Fig. 11 Slope treatment to prevent air leakage

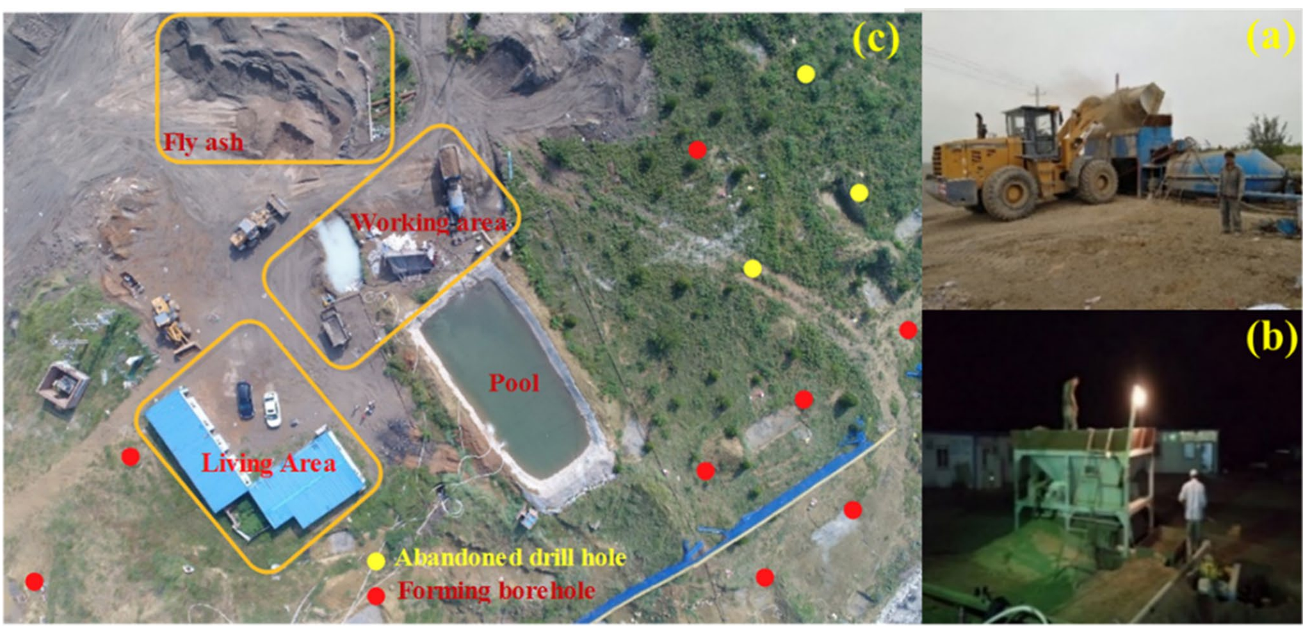


Fig. 12 Distribution of ground grouting system

pore-forming rate is only 51.61%. As it can be observed from Fig. 8, according to the temperature distribution, we divide the fire into three parts, namely A, B, and C. Among them, 18 fire holes are arranged in the A fire zone. These include 2#, 3#, 4#, 5#, 13#, 14#, 16#, 17#, 18#, 19#, 20#, 21#, 22#, 23#, 28#, 29#, 30#, and 31#. A total of 14 drill holes were arranged in the B fire area, and include 1#, 6#, 7#, 8#, 9#, 11#, 12#, 15#, 25#, 26#, and 27#. There are three boreholes arranged within fire area C and include 10#, 24#, and 32#.

Fire detection with infrared thermal imaging

The accident site is located at the junction of the two mines. The Qian'an coal mine is an open-pit mining. Therefore, the author held infrared thermal imaging to detect the cliff wall from two locations, as shown in Fig. 9, and obtained two main fire sources. Combined with geographical location analysis, the detection areas 1 and 2 correspond to the fire areas A and B in Fig. 8, respectively. The cliff at the fire zone C could not be detected owing to

Fig. 13 Coalfield fire monitoring

Table 1 Visual system monitoring results

Number	Total detection distance/m	Distance between the ground and the roof/m	Distance between roof and slurry level/m
4#	53.10	51.95	1.15
8#	53.40	53.00	0.40
5#	47.10	46.60	0.50
28#	56.55	54.90	1.65
20#	52.90	52.10	0.80
18#	53.10	52.50	0.60
14#	51.70	50.20	1.50
9#	57.50	55.00	2.50

the steep terrain. Therefore, the infrared thermography in Fig. 8 verifies the coalfield fire area distribution.

Coal fire extinguishing technology

Production system isolation

Based on the monitoring and analysis of the CO concentration at the closed point, after the accident, the high-temperature fire source was still at the development stage. At the same time, the CO will continue to spread to the 2nd mining coal seam. Conversely, to ensure the rapid recovery of the 2nd coal seam production system and reduce economic losses subject to conditions that ensure safety, the 1st coal seam production system was isolated promptly. According to the data, there may be three locations for the 1st and 2nd coal seams. These include the coal discharging chute, the 1st coal seam return air lane, the 2nd coal seam return air–well connection roadway, and the fissure between the caving zone of the goaf in the 2nd coal seam (first mining face) and 1st coal seam (Fig. 10).

Slope treatment

In view of the surface damage situation after the accident (Fig. 3), slope treatment measures were proposed to deal with surface fissures to reduce air leakage in the goaf, as shown in Fig. 11.

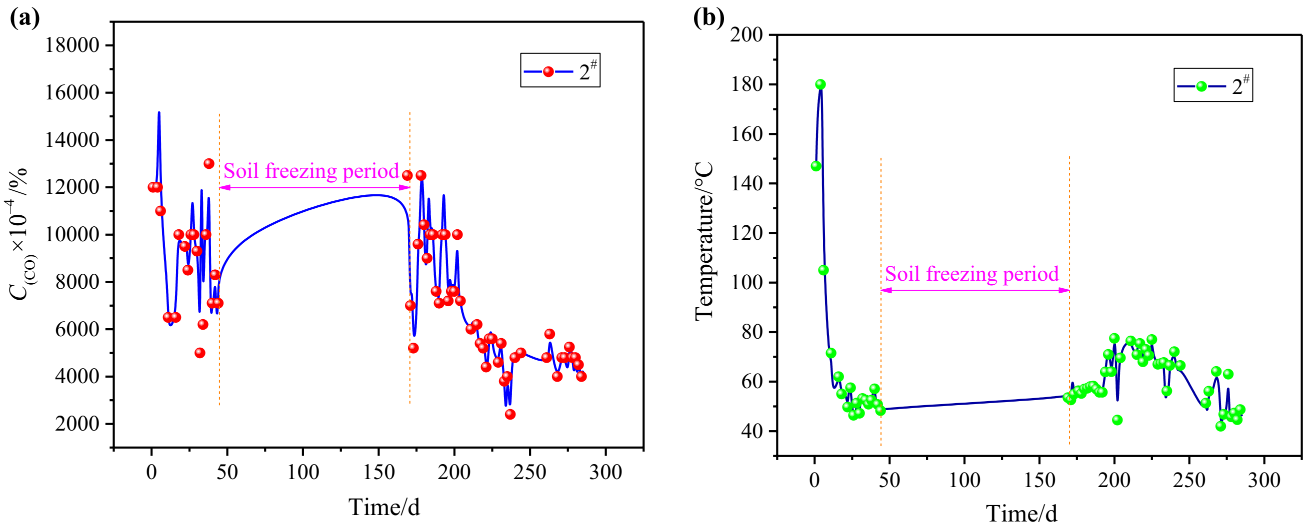


Fig. 14 2# Drilling effect analysis

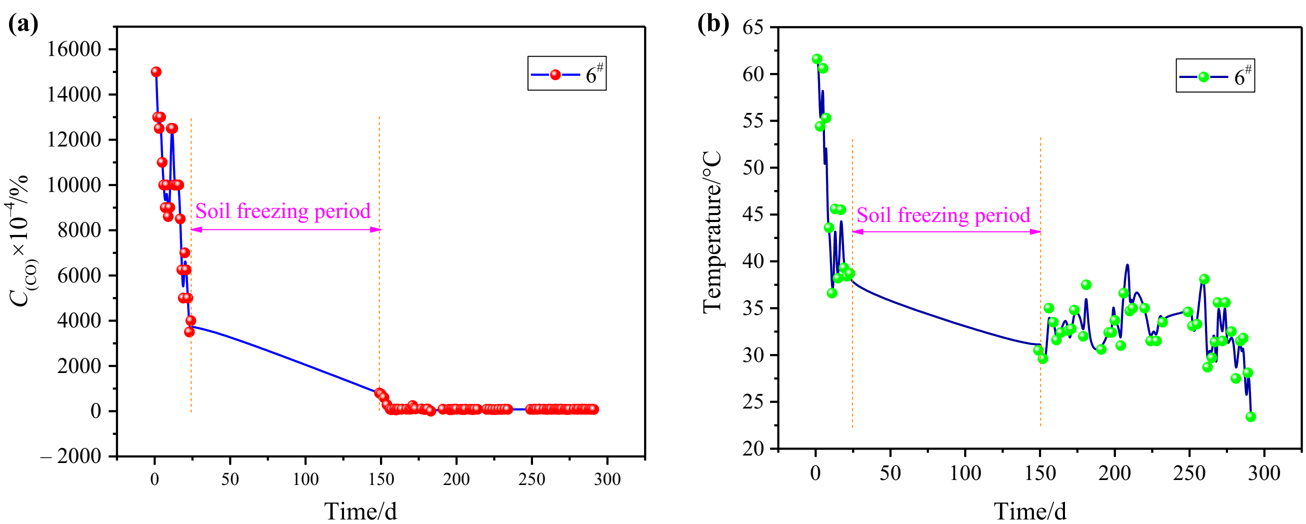


Fig. 15 6# Drilling effect analysis

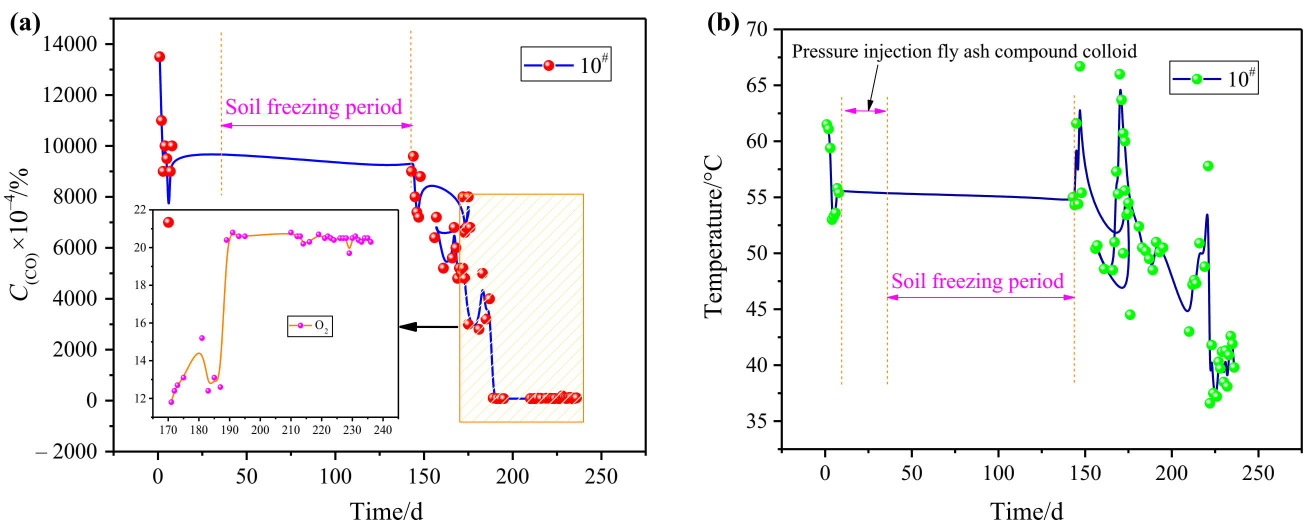


Fig. 16 10# Drilling effect analysis

Fly ash compound colloid

Water injection is the most effective measure used to eliminate high temperatures in the coalfield fire area. The accident was located at the boundary of the two mines, and it was difficult to obtain water. In addition, the fluidity of water was good, and the accident caused many cracks that were not conducive to water storage. There are many power plants in Shenmu City, and fly ash is abundant. Deng et al. [30] reported that the compound colloid had poor fluidity that was beneficial to the accumulation characteristics. Therefore, based on the characteristics of fire prevention and extinguishing materials, economics, and other indicators, we have proposed measures for injecting pulverized coal composite colloids. Figure 12c shows the regional layout of the fire extinguishing site that mainly includes four parts: living area, fly ash pile, working area, and pool. To speed up the progress of the project, a total of two sets of grouting equipment were invested, as shown in Fig. 12a and b. The grouting process has been described in detail in [30].

Excavation

According to the data provided by mines, the thickness of the coal seam in the fire area was 2 m on average, and the volume to be filled was calculated to be 40,000 to 60,000 m^3 based on a 50% porosity. In September 2017, the planned grouting volume was completed successfully. Based on temperature, gas data analysis, and visual monitoring results, it was concluded that coal spontaneous combustion had been effectively controlled, and no secondary disasters would occur. However, there were still dangerous materials, such as detonators and gunpowder in the explosion site, so it was decided to eliminate the fire sources and dangerous materials from the accident area to completely eliminate the risk for a disaster.

Fire area monitoring and effectiveness analysis

Coalfield fire area monitoring

During the implementation of fire-fighting project, the monitoring content mainly included two parts, namely the fire area and the change of injection slurry level. Therefore, onsite technicians monitored the drilling temperature and gas within the fire areas A, B, and C, at the same time every day, as shown in Fig. 13a and b. Moreover, the slurry levels in all boreholes in the fire area were regularly observed with the visualization system, as shown in Fig. 13c and d. Table 1 shows the height of the slurry level of some drilling holes detected in the construction process, and the distance between the slurry level and roof could be observed directly, thus providing reference for the implementation of the next project.

Analysis of fire extinguishing effect in coalfield fire area

To obtain the change of the fire area during the implementation of fire extinguishing technology, one drill hole was selected from the fire areas A, B, and C, namely $2^{\#}$, $6^{\#}$, and $10^{\#}$, respectively. The gas and temperature changes in the borehole are shown in Figs. 14–16. The construction of the $2^{\#}$ drill hole was completed in November 2016, the initial CO concentration in the drill hole was greater than

1% (Fig. 14a), and the temperature was 180 °C (Fig. 14b). Both variables exhibited a decreasing trend with respect to time. Affected by the climate in December, the ground was frozen, the project was temporarily suspended, and the boreholes in the fire area were all closed. In April 2017, the fire-fighting project continued. Compared with 2016, both CO concentration and temperature rebounded. The grouting pipe was moved to the fire zone A for drilling. After a period of grouting, the CO concentration and temperature gradually decreased, and were finally maintained at approximately 0.4% and 40 °C, respectively. At this time, based on visual borehole monitoring, all boreholes in the fire area A had been filled with a fly ash composite colloid. It was preliminarily determined that the fire area A was effectively controlled. As it can be observed from Figs. 15 and 16, the variation trend of the CO concentration and temperature in boreholes $6^{\#}$ and $10^{\#}$ is consistent with $2^{\#}$. At the end of the fire-fighting project, the CO concentration of $6^{\#}$ and $10^{\#}$ drill holes both decreased to 0.01% and the temperature dropped to 30 °C. This was consistent with the rock temperature. Combined with the visual drilling monitoring results, $6^{\#}$ and $10^{\#}$ boreholes have been filled with fly ash compound colloid. Thus, we judge that the fire area of B and C has been effectively controlled.

Conclusions

To achieve efficient control of coalfield fire area, our research group developed a set of coalfield fire control and extinguishing technology and carried out the implementation in Liujiamao and Qian'an mining areas. This study summarizes the coalfield fire control and extinguishing intervention of "blocking air leakage, reducing oxygen, eliminating high temperature, and preventing re-ignition." The main conclusions of this study are as follows: (1) On the basis of this guiding approach, combined with the characteristics of coalfield fire areas in Liujiamao and Qian'an mines, a set of economical and efficient coalfield fire control and extinguishing plan have been developed, which include the isolation of the production system, treatment of slope, injection of fly ash compound colloid, and excavation. (2) High temperature area was about 5050 m2 as determined by isotope radon measurement technology, and the distribution was U-shaped that conformed to the room-pillar mining mode and the roadway layout. Combined with infrared thermal imaging and ground drilling construction, the location of coalfield fire source was determined. According to the distribution of high temperature points monitored by boreholes, the fire area was divided into three parts for local treatment. The combined application of isotopic radon measurement method, infrared thermal imaging and ground drilling technology enabled the accurate determination of coalfield fire area and provides a foundation for the efficient implementation of fire control and extinguishing technology. (3) We have developed a set of coalfield fire detection, fire-fighting equipment, fire-fighting materials and data monitoring as one of the coalfield fire control and extinguishing methods. Through the implementation of the plan, the coalfield fire disaster of Liujiamao and Qian'an mines was successfully solved. The successful application of this method and technology provides theoretical and technical support for similar coalfield fire control and extinguishing.

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