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Key technologies for extinguishing large-area goaf fires in closely spaced shallow coal seams

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ABSTRACT
The present study examines the spontaneous combustion fire in large-area goaf of the 22305 fully caving face at the Bulianta coal mine in north-western China. The cause of the spontaneous combustion in the goaf of closely spaced shallow coal seams is analysed. To deal with the problem of serious air leakage combined with a large fire area and a hidden fire source that could easily re-ignite, a proposed set of key techniques for extinguishing goaf fires is put into practice. This mainly comprises sealing the air leakage cracks, high-flow injection of liquid nitrogen, and infusion of a large quantity of foam inhibitor. The results show that these measures rapidly extinguished the goaf fire, lowered the CO concentration from 43,051 ppm to less than 25 ppm, and reduced the temperature in the goaf to about 20°C. The 22305 face was subsequently safely reopened and quickly put back into production within three months.
KEYWORDS: coal seam; spontaneous combustion of coal; goaf fire; liquid nitrogen; foam inhibitor

1. INTRODUCTION

Coal is the main energy source in China, accounting for about 70% of the production and consumption of primary energy (Tang and Li, 2013). The Chinese coal mining industry is mainly concentrated in the north-west (Fan, 2016). The Shendong mining area, located in north-western China, is China's largest coal production base, with a 250 million tonne output in 2012. However, the coal seams in the Shendong area are prone to spontaneous combustion. Contributing to this problem is the shallow burial depth (30-200 m) and the close spacing between the two coal seams (30–50 m), both of which are factors that lead to severe air leakage during the mining process. Thus, spontaneous combustion occurs very frequently in this mining area, threatening mineworkers' safety and producing large amounts of toxic gases, as well as sulfur, mercury, selenium and other harmful substances that cause significant local atmospheric pollution (Luo and Liang, 2003; Gu and Zhang, 2012; Kuenzer et al., 2007; Wang, 2009). Therefore, it is of great importance to take effective measures to prevent and extinguish spontaneous combustion fires in closely spaced shallow coal seams.

At present, coal mines in Shendong usually use conventional technologies, such as water injection, clay grouting, nitrogen injection and so on, to control spontaneous combustion fires. However, the effectiveness of these conventional technologies is unsatisfactory, since water injection and clay grouting commonly encounter the problems of small diffusion range, easily drained water and slurry, and a weak cooling capacity of nitrogen (Wang et al., 2012; Wang, 2008). For example, in June 2012, a serious spontaneous combustion fire occurred in the goaf of the 22305 fully caving face in the Bulianta coal mine, which is the largest mine in the Shendong area. The peak concentration of CO was detected to be in the tens of thousands of parts per million. Initially the mine used water injection and clay grouting in an attempt to extinguish the fire, but the CO concentration showed no obvious decrease and the fire zone continued to spread. This caused the closure of the 22305 face, cutting off abundant coal resources and trapping expensive mining machinery. Clearly, a more positive and effective fire control technology was urgently needed.

This paper takes the Bulianta fire as a typical case. By analyzing the characteristics and causes of spontaneous combustion in this shallow coal mine where the coal seams are closely spaced. A set of efficient fire prevention and extinguishing techniques is proposed and practiced.

2. METHODS AND SCHEME

2.1 Analysis of causes of coal spontaneous combustion

The 22305 face was put into operation on 16 June 2012. At 2:00 p.m. on 23 June, blue charcoal smoke was detected coming from the goaf alongside

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the return airway. The CO concentration was up to 1600 ppm in the upper corner and reached 300 ppm in the return airway. The coal face stopped production during the morning shift of 24 June when the face had advanced only 47 m. As mentioned above, water injection and clay grouting did not control the fire in time, and on 24 July the coal face was sealed off. The reasons for the goaf fire were as follows:

(1) About 2.0 m of top coal was not mined out, so abundant broken coal remained in the goaf. The 12 goafs of the Bulianta mine, together with the adjacent Shangwan mine, formed a total goaf area of 19.7 million square metres. The coal seams are prone to spontaneous combustion, and the shortest spontaneous combustion period, between the date of coal seam exposed to air and the date of occurring spontaneous combustion, was only 30 days. Adding to the problem, the porosity of the coal increased dramatically when soaked in water (Figure 1), rapidly raising its oxygen absorption rate and further increasing the risk of spontaneous combustion.

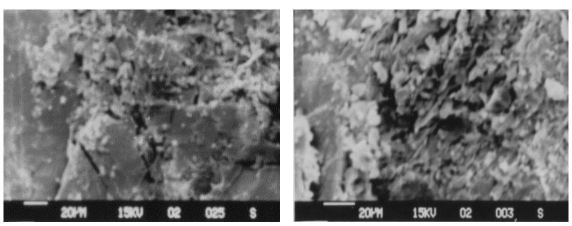

Figure 1: SEM image of pore structure of coal (a) before water soaking; (b) after water soaking.

(2) The coal seams in the Shendong mining area are very shallow, with a thick layer of loose overburden material that has very low strength in tension and compression, and low resistance to deformation, all of which make it vulnerable to the formation of mining-induced fissures and fractures. The roof rock of the goaf is very thin; consequently, surface subsidence and deformation is very difficult to control. As a result, pathways for air leakage between the goaf and the ground surface formed readily during mining, causing serious air leakage into the goaf (Figure 2). In addition, the Bulianta Mine has more than 90 connecting roadways between the goaf and the lower coal seam currently being mined, potentially providing a very large number of underground air leakage pathways.

Figure 2: Typical air leakage fractures in the Shendong mining area.

(3) When mining the upper coal seam, a great many mining-induced fractures form in the roof rock of the goaf and propagate to the ground surface (Figure 3), allowing surface water and underground water seepage to enter the goaf, with the result being that a large volume of water accumulates there. Then, when the underlying coal seam is mined, the accumulated water is discharged into the mine, causing large volumes of air to leak from the mine below the goaf to replace the lost water. For example, in the goaf above the 22305 face-originally the result of mining the upper seam (the 22304 face)-1.1 million m^3 of water was discharged. This amount, together with the 475,000 m^3 of water drained from the goaf of the 22305 face itself, greatly increased the air leakage.

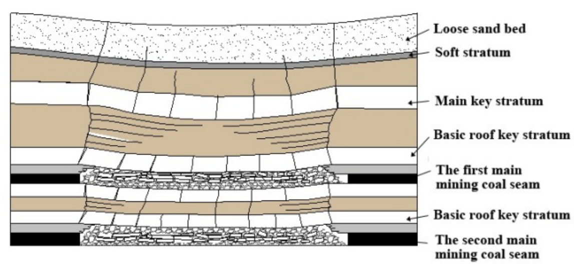

Figure 3: Schematic diagram of mining-induced fractures connected to the ground surface.

2.2 Plugging air leakage channels

At the surface, a combination of artificial and mechanical backfill was used to plug the leakage fractures and cut off the air leakage channels. To block the underground air leakage channels, shotcrete was used to reinforce the sealing walls in the connecting roadways.

As shown in Figure 4, sulfur hexafluoride (SF_6) tracer gas was used to investigate the distribution of the air leakage pathways and analyse the air leakage effect of fracture propagation over different periods.

Figure 4: Detection of air leakage pathways using SF_6.

2.3 Injecting liquid nitrogen

The temperature of liquid nitrogen is -195.8 °C, and its latent heat of vaporisation is 199 kJ/kg. Liquid nitrogen quickly evaporates into gaseous nitrogen at a temperature of -193 °C; one tonne of liquid nitrogen forms 780 m^3 of nitrogen gas. Thus liquid nitrogen absorbs more heat-in other words, has a greater cooling effect-than nitrogen gas (Yuan and Wan, 2013).

The liquid nitrogen system consisted mainly of a moveable storage tank containing liquid nitrogen produced by Shenhua Coal Liquefaction Plant (as shown in Figure 5), a cryogenic centrifugal pump and stainless steel piping. Figure 6 illustrates the process of injecting the liquid nitrogen: first, the liquid nitrogen was transferred by the cryopump to the delivery pipeline; then, the liquid nitrogen was directly injected into the high temperature points of the fire zone through a series of 20 holes drilled from the ground surface. The liquid nitrogen extinguished the fire and suppressed the possibility of explosion, and also absorbed a great deal of heat as it vapourized.

Figure 5: Lorry carrying storage tank of liquid nitrogen.

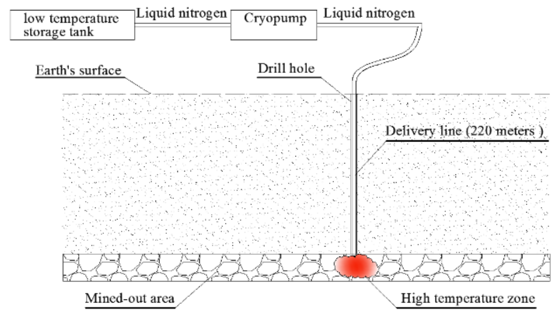

Figure 6: Liquid nitrogen injection process.

To rapidly reduce the temperature of the fire zone and displace the harmful gases accumulated in the goaf, the liquid nitrogen was poured into the goaf through 20 drill holes (MH26–MH45) from the ground surface, as show in Figure 7. Between 24 July and 7:00 a.m. on 20 August 2012, approximately 13,250 tonnes of liquid nitrogen were poured into the high-temperature zone.

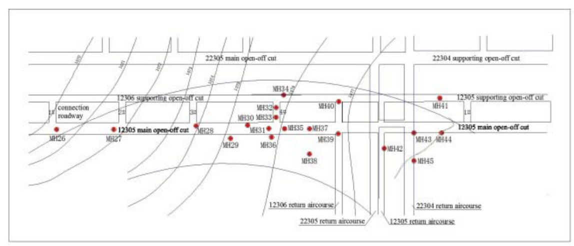

Figure 7: Location map of drill holes MH26–MH45 for liquid nitrogen injection.

2.4 Diffusion of foam inhibitor

The foam inhibitor was generated from slurry of yellow mud or fly ash, compressed air and a solution of foaming agent and retardant. The foam was generated at a rate of 600–1000 m^3/h, with a stability time of 12 h, and an effective diffusion radius more than 60 m. Using this volume of foam as the carrier, together with its wide diffusion characteristics, the retardant was carried to greater lateral distances and higher points in the fire area than could be reached by conventional liquid or solid fire-fighting mediums. The foam generating equipment mainly consisted of a metering pump, foam generator and foam delivery hose.

Figure 8 shows the fire extinguishing process of the foam. First, a metering pump adds the solution of foaming agent and retardant at a given ratio into the slurry of yellow mud or fly ash; then, compressed air is mixed with the slurry, producing a large volume of foam; finally, the foam is injected into the fire zone via a delivery hose and drill holes.

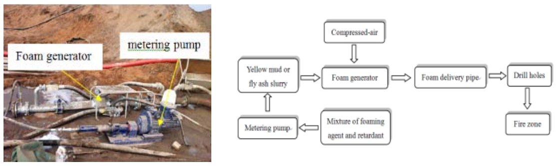

Figure 8: Preparation equipment of foam inhibitor.

Between 10 and 20 August 2012, a total of 770 tonnes of foam inhibitor was injected into the fire zone though 10 holes (ZJ5–ZJ14) drilled from the ground surface. The locations are shown in Figure 9.

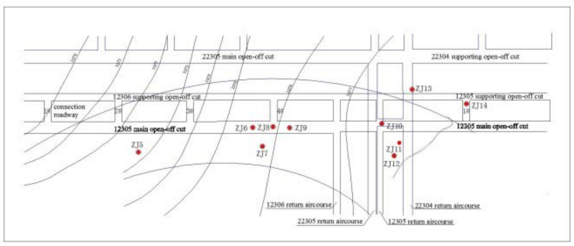

Figure 9: Location map of drill holes ZJ5–ZJ14 for foam injection.

3. RESULTS AND DISCUSSION

Following the injection of liquid nitrogen and foam into the goaf fire zone, sampling analysis of the fire index gases was conducted at eight measuring points (Figure 10) at ground level and underground. The continuous sampling test results showed that the concentration of fire index gases, O_2, CO, C_2H_2 and C_2H_4, declined continuously (Figure 11).

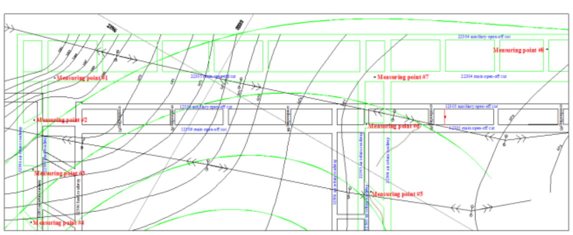

Figure 10: Location map of measuring points for fire zone.

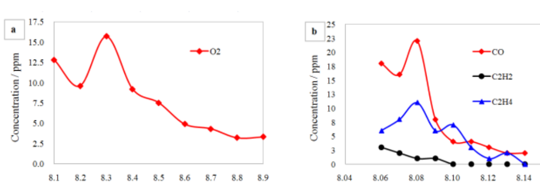

Figure 11: Change trend of different index gases.

Seen from Figure 11a and 11b, the oxygen concentration in the fire zone was below 5.0% from 6 August 2012, the acetylene (C_2H_2) concentration remained steady at 0 ppm from 9 August and the concentration of ethylene (C_2H_4) remained steady at 0-5 ppm from 11 August. In addition, the concentration of carbon monoxide (CO) gradually decreased during the period that the coal face was closed from a peak value of 43,051 ppm to a stable value of 5 ppm. The air temperature of the closed fire zone stabilized at around 20°C. According to Chinese Coal Mine Safety Regulations, these values indicated that the goaf fire at the 22305 coal face had been extinguished, and conformed to the conditions under which the face could be unsealed. The face was safely unsealed on 21 August and production smoothly resumed on 23 August.

After production was resumed at the Bulianta coal mine, the concentrations of index gases remained normal, with CO concentration steady at 6-7 ppm, the minimum concentration of O_2 was 19.8%, and the concentration of the other gases was 0.02–0.08%. This indicated that the foam inhibitor had effectively prevented the further fragmentation of coal in the goaf. From 8 October 2012, the 22305 coal face had safely advanced 558 m.

4. CONCLUSIONS

Spontaneous combustion fires in the goaf of fully mechanized caving faces mining two closely spaced shallow coal seams are characterized by a large volume of air leakage, a large fire zone and a hidden fire source. These conditions are highly prone to spontaneous combustion ignition and re-ignition, and conventional fire prevention and extinguishing methods such as water injection, grouting and nitrogen gas injection are largely ineffective in controlling such fires.

In these conditions, air leakage cracks are readily caused by the mining process, causing a high rate of air leakage into the goaf and providing a sustainable oxygen supply that is ideal for initiating spontaneous combustion of coal. Therefore, taking positive measures to block the air leakage channels is very important.

When low-temperature liquid nitrogen fills a sealed goaf, it quickly vaporises at normal pressures and temperatures. The cold nitrogen gas then quickly spreads to fill the entire fire area, displacing the other gases generated by the fire. The oxygen concentration drops rapidly, smothering the fire. The cold nitrogen gas also lowers the temperature of the fire zone by absorbing heat as it converts from the liquid to the gaseous phase, due to its latent heat of evaporation.

Foam inhibitor pumped into the goaf spreads widely throughout the fire-prone zone, transporting the fire retardant to areas that would otherwise be inaccessible to single liquid or solid fire-extinguishing materials. This makes it highly suitable for controlling fires occupying large spaces in the goaf, and/or hidden fires, and for preventing spontaneous combustion re-ignition.

5. ACKNOWLEDGEMENT

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