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Methane and coal exploitation strategy of highly outburst-prone coal seam configurations

Hongxing Zhou [a, b, *], Rong Zhang [a], Yuanping Cheng [a, **], Hao Dai [a], Chungui Ge [b], Jiaxiang Chen [b]

[a] Key Laboratory of Gas and Fire Control for Coal Mine, School of Safety Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China

[b] Post-Doctoral Research Station of Huaibei Mining Corporation Limited, Huaibei, Anhui 235000, China

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ABSTRACT

Outbursts are the sudden and violent releases of coal and gas from a coalface, resulting in damage to excavations and equipment, loss of life and even disastrous gas explosion if an ignition source is present. The highly outburst-prone coal configurations are formed of outburst-prone coal seams and some of them have high outburst propensity. The direct applications of traditional outburst control methods on these configurations will lead to various problems in mining safety, technical implementation and economy. This article proposes a methane and coal exploitation strategy for highly outburst-prone coal configurations, combining surface coalbed methane (CBM) recovery with underground methane drainage. In this strategy, vertical surface wells are firstly performed to mitigate or eliminate the outburst hazard of the configurations and thereby creates suitable conditions for the following underground protective seam working or methane pre-drainage. Thus the methane of the configuration is exploited, the outburst hazards of the configuration are eliminated and the outburst-prone seams of the configuration are to be mined safely. It is predicted that the methane contents will decrease from 25 m^3/t to about 6 m^3/t, the outburst hazards will be eliminated completely, and clean and safe mining conditions will be secured by executing this strategy on the Nos. 8, 9 and 10 seams in the Luling mine.

1. Introduction

Coal and gas outbursts are sudden and violent simultaneous ejections of large amounts of coal and gas from a working coalface during underground mining (Shepherd et al., 1981). The ejected coal may damage the excavation, equipment and miners. The ejected gas may cause miners to be unable to escape and even result in suffocation deaths. Worst of all, a gas explosion that is much more damaging than an outburst may be triggered if an ignition source is present. Outbursts are one of the most dangerous hazards of coal production in the world.

Despite extensive research efforts of more than a century, the fundamental mechanisms causing coal and gas outbursts continue to elude the scientific community, but it is generally acknowledged that gas pre-drainage is effective in reducing or eliminating the outburst risk by decreasing the gas content of outburst seams (Noack, 1998). Generally, a gas content greater than 8 m^3/t or 9 m^3/t is considered sufficient to initiate an outburst if other conditions are favorable (Beamish and Crosdale, 1998; Lama and Saghafi, 2002). To reduce gas content and eliminate outburst hazards, the main methods are gas pre-drainage by using vertical surface wells or underground boreholes and, if possible, by pre-working a protective seam in combination with pressure-relief methane drainage (Cheng and Yu, 2007; Cheng et al., 2003; Díaz Aguado and González Nicieza, 2007; Flores, 1998; Hungerford et al., 2013; Hyman, 1987; Lama and Bodziony, 1998; Lunarzewski, 1998; Sang et al., 2010; Wang et al., 2014).

Highly outburst-prone coal seams have a high gas pressure (>5 MPa), high gas content (>20 m^3/t) or large amounts of ejected coal or rock (>10,000 tons). By definition, a 'coal seam configuration' is a formation of coal seams that overlie each other in a vertical depositional sequence. If all of the coal seams in the configuration

* Corresponding author. Key Laboratory of Gas and Fire Control for Coal Mine, School of Safety Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China.
** Corresponding author.
E-mail address: zhou12510@126.com (H. Zhou).

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are outburst prone and some of the seams have high outburst hazards, the configuration is a highly outburst-prone coal seam configuration. For this configuration, the direct operations of traditional methane drainage methods will face multiple challenges and uncertainties.

The purpose of this paper is (1) to present the general principles of outburst control of coal and gas outburst coal seams, (2) to propose an outburst control strategy for highly outburst-prone coal configurations, and (3) to verify the outburst control strategy by experiments performed in the Luling coal mine.

2. Methane drainage principles for highly outburst-prone coal configurations

Most Chinese coal strata experienced several strong tectonic movements that destroyed the original construction of the coal seams (Karacan et al., 2011). As a result, the coal became structurally complicated, soft, and highly impermeable to gas flow. Therefore, gas drainage from virgin outburst coal seams is very difficult. The main feasible methane drainage techniques are pre-working a protective seam, surface coalbed methane CBM recovery and underground gas pre-drainage in China.

2.1. Surface CBM recovery using vertical surface wells

Methane recovery using hydraulically stimulated vertical wells is a technique that has been applied successfully and widely in many industrial countries. The hydraulic stimulation involves fracturing a series of coal seams using high-pressure fluids pumped into a surface borehole. The fractures are held open by injecting fine sand. Thus, gas and other fluids that are able to flow through the coal seams can enter the borehole without being limited by the resistance of the surrounding coal. The surface CBM recovery includes three stages: methane desorbs from the surface of coal matrix pores, then methane spreads into the factures through matrix and micro-pores, and finally methane flows into surface wells through the sand layer in a mode of Darcy flow.

However, surface CBM recovery is not very successful for most outburst-prone coal seams and can even be called a failure in China (Yun et al., 2012). The special reservoir characteristics of outburst-prone coal seams cause great difficulty to the well completion and stimulation and, ultimately, restrict methane productivity. As a result, the methane yields are always lower than 1500 m^3 per day, which is not worth commercial exploitation.

Vertical surface wells are implemented from the surface, and methane recovery is carried out independently of underground operation; thus, these wells can be constructed and drain methane in advance of coal mining. Though methane recovery effects are poor from a business perspective, long duration recovery can gradually reduce the methane content and alleviate the outburst risk of outburst-prone coal seams.

2.2. Pre-working a protective seam and pressure-relief methane drainage

For a coal seam configuration, the first mining of one selected seam (protective seam) can reconstruct the other seams (protected seams). The idea behind this method is to mine the coal seam with the least stress and/or lowest gas content first so that the other outburst-prone coal seams can be over- or under-mined (Wang and Cheng, 2012). This is the most important and effective outburst control method in China.

The rock surrounding the mining area can be divided into several zones in section and plan views (Yu et al., 2004; Palchik, 2003). In the vertical section above the roof, the rock strata can be divided, working upward, into a caved zone, a fractured zone and a bending zone (Cervik, 1979; Singh and Kendorski, 1981). In the vertical section under the floor, the rock strata can be divided, working downward, into a floor fractured zone and a floor dilating zone (Wang et al., 2013a) (Fig. 1). Along the direction of the advancing working face, the upper and lower rock strata can be divided into three zones: a stress concentration zone, a stress relief zone and a stress resume zone (Fig. 2). The three zones move in advance of the working face, and the protected seams experience the three zones in sequence (Yu et al., 2004). The methane in the stress relief zones desorbs and flows easily, and the methane drainage efficiency is far better than in other zones. For eliminating the outburst hazards of the protected seams and ensuring worker safety, pressure-relief methane must be extracted properly and timely.

Unfortunately, all minable seams in a highly outburst-prone configuration are outburst prone. The selection of the protective seam should take these considerations into account, such as the relative position, thickness, outburst hazard, stability and protected effects (Wang et al., 2013b). The outburst hazard magnitude in the configuration may be quite different: some are highly hazardous, some are medium hazardous and some are only slightly hazardous. A less outburst-prone and minable coal seam and even a soft rock seam can be selected as a protective seam.

2.3. Methane pre-drainage using underground boreholes

In virgin outburst-prone seams, the fractures are generally compressed and the opening and connectivity of these fractures are poor, resulting in poor drainage. Drilling boreholes for methane drainage prior to coal mining is the most common outburst control solution (Diamond and Garcia, 1999). The drilling of boreholes discharges coal mass that helps to relieve local stress. Methane drainage reduces the gas pressure and content, which results in an increase of coal hardness. Stress relief and reduction of the gas content mitigate the triggering energy of outburst seams, increase the outburst resistance and then eliminate the outburst hazard.

Boreholes for pre-drainage may be cross-measure boreholes or in-seam boreholes drilled from underground entries (Cheng et al., 2009; Diamond, 1994; Zhou et al., 2014). In China, boreholes are commonly drilled from a rock tunnel measuring 20 m–25 m in thickness below the outburst-prone coal seams. The rock strata between the outburst seam and the entry are barriers to defending a possible outburst hazard, such as borehole drilling.

During the drilling of boreholes into outburst-prone seams, especially highly outburst-prone seams, drillers often note gas “kicks,” increasing gas flows and disproportionately large volumes of drill cuttings (Paul, 1980). Gas “kicks” mean miniature outburst events that occur in boreholes. The more outburst-prone the seam is, the more violent “kicks” will be encountered. Therefore, it is very dangerous to drill into coal seams that are highly outburst-prone. Only when their outburst hazards are greatly mitigated can the boreholes be allowed to drill.

3. Coal and methane exploitation strategy for highly outburst-prone coal configurations

The above analysis indicates that surface CBM recovery, pre-working a protective seam and underground gas pre-drainage have some difficulties when they are directly applied to a highly outburst-prone configuration. However, the orderly combination of the three techniques constitutes a complete technological system for the coal and methane exploitation of the highly outburst-prone configuration (Fig. 3). In this strategy, pre-working a protective seam is the core, so one proper coal seam should be selected as a

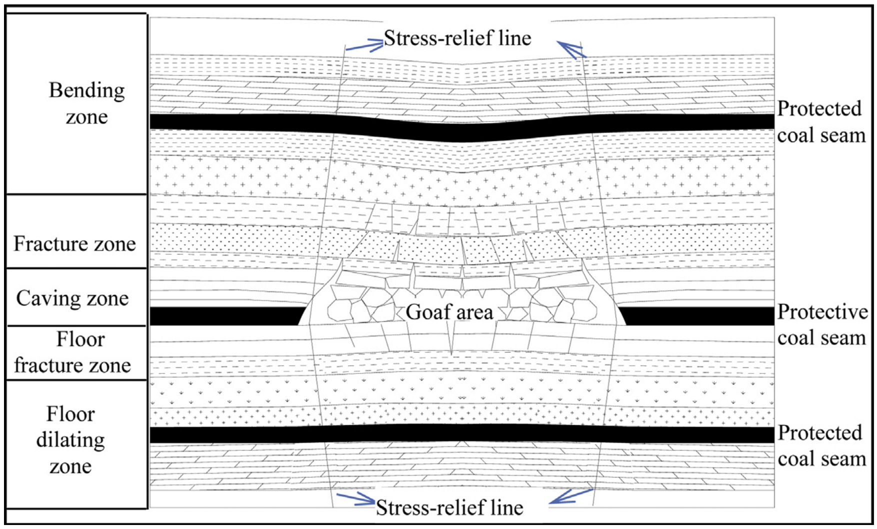

Fig. 1. The distribution of mining fractures in overlying and underlying rocks.

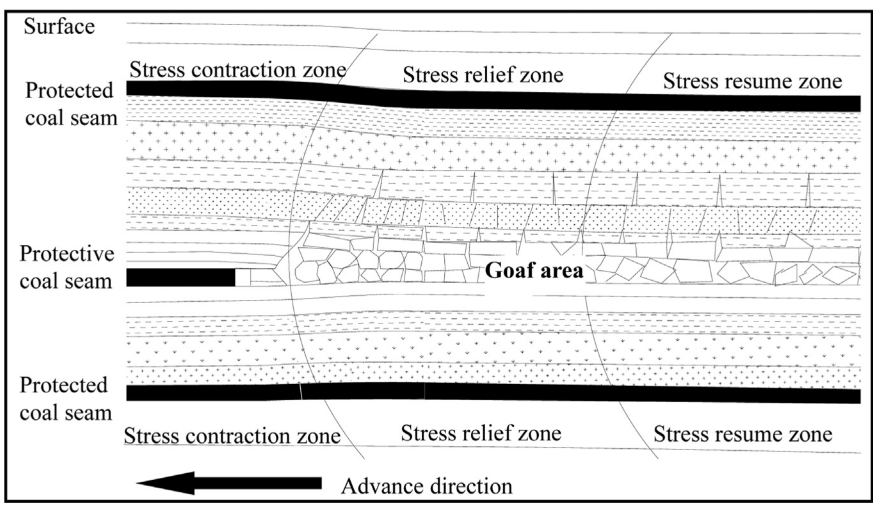

Fig. 2. Underground stope stress zoning in advance direction.

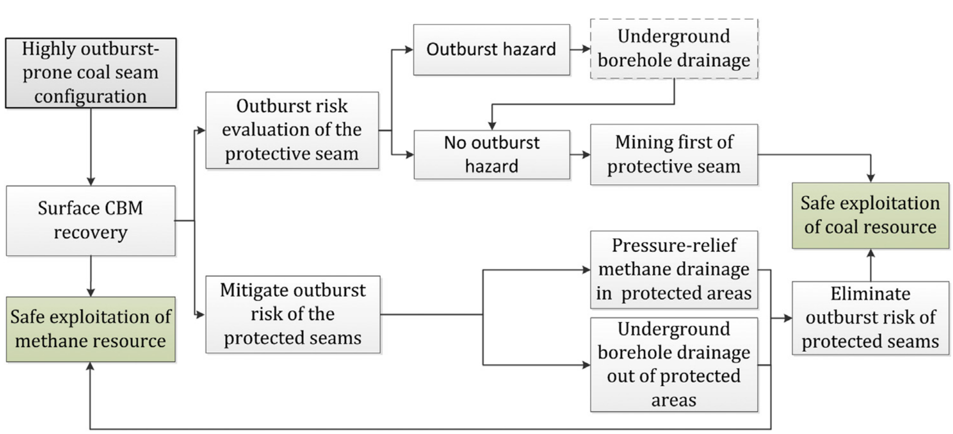

Fig. 3. Methane and coal exploitation strategy for highly outburst-prone coal configurations.

protective seam to mine first.

Vertical surface wells are first constructed to recover the methane stored in the configuration. Under current levels of CBM recovery development in China, the methane drainage effects are very poor in highly outburst-prone coal configurations. However, long duration of CBM recovery can gradually decrease the seam-gas pressure and seam-gas content of the configuration. Therefore, surface CBM recovery should be operated early enough, preferably more than 10 years in advance, so that sufficient time can be used to recover the methane.

When preparing to work the coal configuration, the remaining seam-gas content should be measured to judge the outburst hazard of the selected protective seam. If the protective seam is not outburst prone, underground borehole drainage is avoidable. Otherwise, boreholes should be drilled to drain the methane continuously until the outburst hazard of the protective seam is eliminated.

Then, the protective seam can be mined. Due to the mining influence, the methane desorption and migration is active in the protected areas. The pressure-relief methane of overlying protected seams can be drained using surface boreholes or underground cross-measure boreholes. The pressure-relief methane of underlying seams must be drained using underground cross-measure boreholes. The time of pressure-relief methane drainage depends on the actual drainage effects. Pressure-relief methane drainage should not only guarantee the elimination of outburst hazards, which is the minimum requirement but should also reduce the methane content as much as possible. Therefore, if the boreholes can obtain methane with stable quality and quantity, methane drainage should continue, even if the outburst hazard has been eliminated. This methane and coal exploitation strategy takes into account the drainage time, drainage effects and drainage requirements.

The protected areas are always smaller than the mine-out area (Fig. 1); thus, there are insufficient protected areas around the protected areas. Underground cross-measure boreholes are commonly drilled to relieve local stress, extract methane and thereby eliminate the outburst hazard of these areas. The long duration of surface CBM recovery mitigates the outburst hazard of the configuration so that the drilling of the underground boreholes is safe.

The spacing between wells or boreholes makes a huge difference on the effects of methane exploitation. The design of borehole or well spacing should take coal seam permeability, drilling work amount, drilling investment and expected gas extraction time into account. In China, the spacing between vertical surface wells is approximately 200 m; the spacing between surface boreholes for pressure-relief methane drainage is 150 m–200 m; the spacing between underground cross-measure boreholes should be 5 m–8 m (pre-drainage in virgin coal seams), 8 m–15 m (pre-drainage in less outburst-prone seams) and 15 m–40 m (protected areas).

By making these boreholes and methane drainage, all of the outburst coal seams in the configuration, including the high outburst prone seams, can be transformed into low-methane seams if the drainage parameters employed are reasonable and effective. The coal resource in the configuration can be exploited safely and efficiently.

4. Practice of methane and coal exploitation in the Luling coal mine

The Luling coal mine is 8.2 km along the strike and 3.6 km along the strip, with an area of 29.52 km^2. There are three main production seams, Nos. 8, 9 and 10 seams from top to bottom, and all of these seams have an outburst tendency (Fig. 4). The average

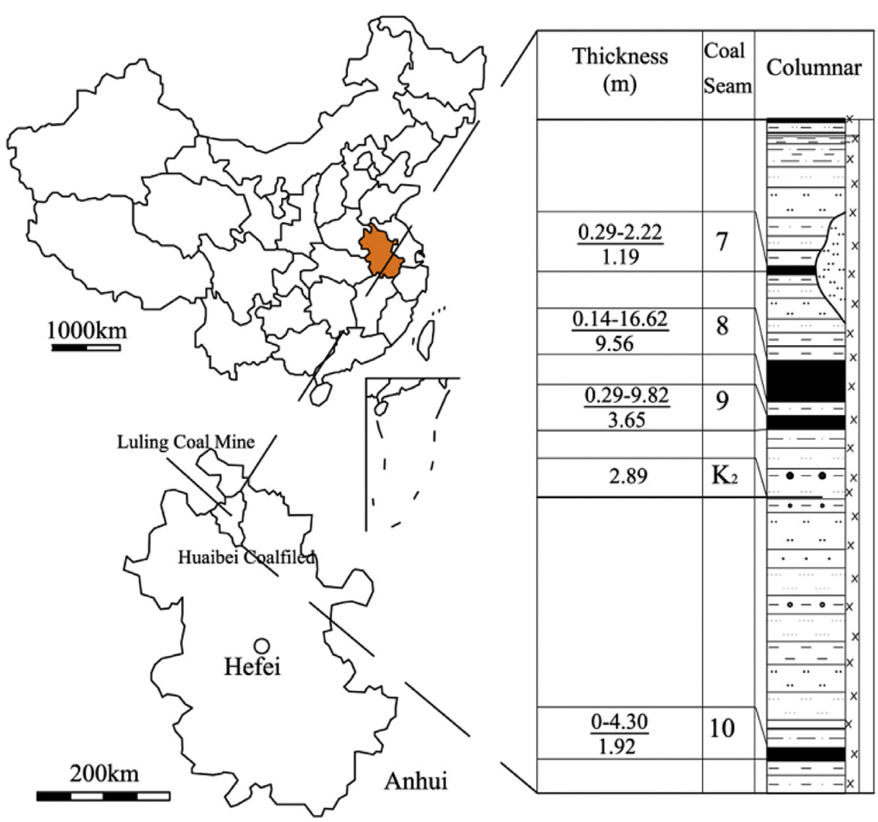

Fig. 4. Location and coal strata histogram in the Luling coal mine.

thicknesses of the three seams are 9.56 m, 3.65 m and 1.92 m, respectively. The spacing between the Nos. 8 and 9 coal seams ranges between 0 and 5.3 m, with an average of 3.2 m. The spacing distance between the Nos. 9 and 10 coal seams ranges between 60 and 110 m, with an average of 80 m.

The Nos. 8 and 9 coal seams have similar properties. The maximum adsorption capacity is 37.6 m^3/t, the maximum measured gas pressure is 5.0 MPa and the average methane content is 25.0 m^3/t at a mining level of −800 m. Twenty-six coal and gas outbursts were recorded in the No. 8 and 9 coal seams. An exceptionally large coal and gas outburst accident that occurred on April 7, 2002, released 10,500 tons of bursting coal-rock and 1.23 million m^3 of gas. The average methane content of the No. 10 seam is 12.0 m^3/t, which is relatively small. The Nos. 8, 9 and 10 coal seams constitute a multiple-seam configuration with a high outburst hazard. Among these seams, the Nos. 8 and 9 seams are more prone to outburst.

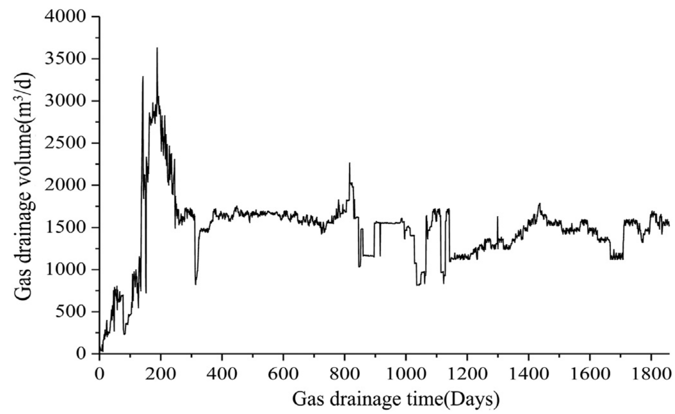

Fig. 6. Gas drainage volume of the WLG-6 well.

4.1. Methane pre-drainage using surface wells

The Luling coal mine launched the practice of ground fracturing well drilling for gas drainage in 2007. Seven surface wells with a spacing ranging from 200 to 300 m were constructed with the layout designed in a rectangular well pattern (Fig. 5).

Hydro-fracturing was constructed in two stages; the No. 10 seam was fractured in the early stage and the Nos. 8 and 9 seams were fractured in the later stage. Monitoring results revealed that the cracks were wedge-shaped and perpendicular to the seams. The height of the cracks was approximately 30 m at the No. 10 seam and 45 m at the Nos. 8 and 9 seams. The cracks extended unidirectionally along the seam flanks and measured 110 m–120 m at the No. 10 seam and 130 m–170 m at the Nos. 8 and 9 seams. Clearly, these wedge-shaped cracks defy methane recovery.

These wells yielded methane for more than 1800 days from April 2008 to June 2013. The methane output of the seven wells once reached 6700 m^3/d and remained stable at approximately 4700 m^3/d. However, the output of these wells was very different. The output of WLG-6 once reached 3700 m^3/d and stabilized at approximately 1500 m^3/d (Fig. 6), which was much higher than the outputs of the other wells. The outputs of the other wells were 500–700 m^3/d (WLG-3, WLG-4, WLG-5 and WLG-7) and 400 m^3/d (WLG-1 and WLG-2).

This experience serves as a guide for the following surface CBM recovery. With the development of multiple seam completion fracturing wells, the daily methane output can be expected to increase in the future. At a surface well spacing of 200 m and a daily output of 1500 m^3, after 12 years of recovery, the methane content of the No. 10 seam will be lower than 8 m^3/t and the content of the Nos. 8 and 9 seams will be lower than 18.0 m^3/t. The outburst hazard of the No. 10 seam will be eliminated completely, and it can be mined first to reconstruct the Nos. 8 and 9 seams.

4.2. Pressure-relief methane drainage using surface boreholes

The areas accepting surface methane recovery have not been mined until now at the Luling mine. However, the following practice of protective seam mining in the Luling mine can be used to predict the effect (Wu et al., 2011). The 1048 face was the first protective working face of the No. 10 seam. The working face has an upper level of −548 to −570 m, a lower level of −566 to −582 m, a length of 310 m, a length of the open-off cut of 220 m, and a 100-m stopping line (Fig. 7). The methane pressure and content of the Nos. 8 and 9 seams are 3.2 MPa and 18.2 m^3/t. The total thickness of the Nos. 8 and 9 seams is 13.0 m. One surface borehole was drilled nearly in the middle of the face to drain the pressure-relief methane.

According to the testing results, the original permeability of the Nos. 8 and 9 seams was only 0.0007 mD (millidarcy). After the

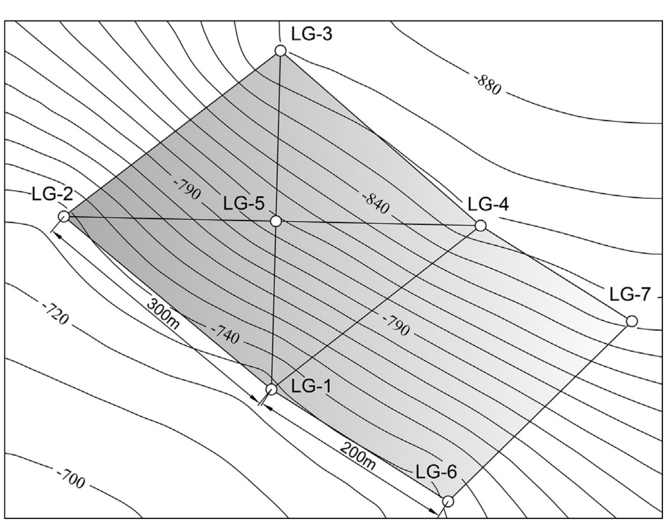

Fig. 5. Locations of the seven vertical surface wells.

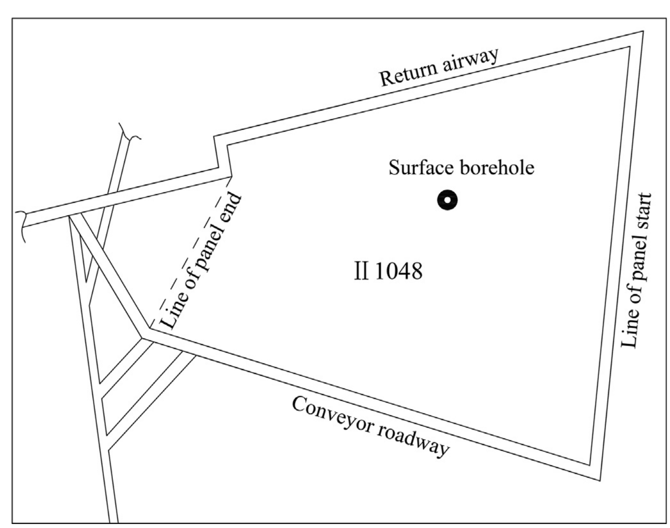

Fig. 7. Location of the protected face relative to the surface borehole.

mining of the No. 10 seam, the measured permeability increased by approximately 1930 times to 1.35 mD. The duration of methane production was approximately 291 days (Fig. 8). During methane drainage, the maximum methane concentration reached 98.3% and the maximum output reached 46,656 m^3/d. After 135 days of drainage, the daily output gradually abated. On the 191st day, the methane output and concentration were only 576 m^3 and 20.46%, respectively, which are too low for civil use. Thus, methane drainage was stopped. The total methane production was 2,484,000 m^3, and the methane content of the stress-relief area was reduced from 18.2 m^3/t to 5.2 m^3/t, which eliminated the outburst risk.

At the protective seam mining stage of the strategy, the Nos. 8 and 9 seams would have experienced surface well drainage and the methane content would have been lower than 18.0 m^3/t. Furthermore, the geological conditions of the Nos. 8, 9 and 10 seams are similar in the Luling mine. Therefore, similar pressure-relief methane drainage effects and outburst eliminating effects can be expected.

4.3. Methane drainage using underground cross-measure boreholes

Methane drainage using underground cross-measure boreholes was the major outburst control method used before 2005 in the Luling mine. The number of boreholes drilled was very large and much time was spent solving gas "kicks." On average, only one borehole could be finished per day. However, this method was very effective for draining methane and reducing the risk of gas outbursts.

The methane drainage at the 2884 coalface may well verify the drainage effects of the cross-measure boreholes. The coalface measured 195 m in the strike direction and 85 m in the dip direction. The methane pressure was 2.2 MPa, the methane content was 17.2 m^3/t, and the total thickness of the Nos. 8 and 9 seams was 11.8 m. The total methane reserves were 6,372,000 m^3.

Seven-hundred five cross-measure boreholes were drilled to drain the methane of the 2884 coalface. Borehole spacing was approximately 5 m. Each borehole was connected to the drainage system and began to drain methane. In total, 4,283,000 m^3 of methane was extracted over 28 months, indicating that approximately 60,000 to 400,000 m^3 of methane was drained monthly and 153,000 m^3 was drained every month on average. The methane drainage rate was 65.1%, the remaining methane content was only 6.0 m^3/t and the measured maximum methane pressure was only 0.65 MPa. These data indicate that the outburst hazards of the drainage area had been eliminated completely.

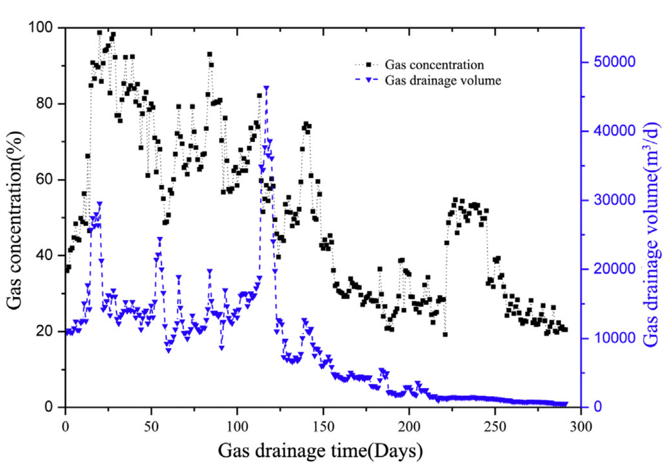

Fig. 8. Pressure-relief gas drainage volume of the surface borehole.

The methane drainage experience in the Luling mine shows that all three outburst control methods are effective. The proposed strategy, an orderly combination of the three methods, should also be effective for the deep Nos. 8, 9 and 10 seams in the Luling mine. By executing this strategy, the risk of gas outburst of the configurations will be eliminated completely and clean and safe mining conditions will be secured for all of the coal seams.

5. Discussion

The techniques of surface CBM recovery are widely used in the U.S., Australia and other countries. However, these techniques are not very successful for most Chinese outburst-prone coal seams. Generally, the benefits obtained in methane cannot meet the daily needs of operating these surface wells and the CBM recovery organizations depend mainly on government investment.

The main aim of methane pre-drainage is to mine coal resources in Chinese outburst-prone coal mines. The pre-drainage techniques are operated underground and have proved particularly successful. However, these techniques are difficult and costly and have security threats in highly outburst-prone coal seams. As a result, methane pre-drainage from underground will be very challenging in highly outburst-prone coal configurations.

For outburst-prone coal mines, the long duration of surface CBM recovery can reduce the methane content, relieve the workloads and costs of underground methane drainage, and benefit underground coal mining. To date, surface CBM recovery from highly outburst-prone seams is still not profitable in China. If the cost savings from underground drainage are paid to the surface CBM recovery, their financial difficulties can be partly alleviated. Therefore, if we combine surface CBM recovery and underground methane pre-drainage, coal mines can effectively enhance safety and the CBM recovery can obtain economic compensation, and thus, everyone will win.

Surface CBM recovery and coal mining belong to different administrative departments, and there are seldom substantive collaborations in China. Highly outburst-prone coal configurations offer opportunities for their collaboration. That is, surface CBM recovery reduces the outburst risks of the configurations and creates conditions for the exploitation of methane and coal resources. With deeper mining, the ground stress, gas pressure and gas content increase gradually and more highly outburst-prone coal configurations will appear. The combination of surface CBM recovery and underground pre-drainage is the general trend of exploiting methane and coal resources in the future.

6. Summary and conclusions

Methane and coal exploitation of highly outburst-prone coal configurations are very difficult. When directly applied to such configurations, the underground methane pre-drainage methods, such as pre-working a protective seam and methane pre-drainage, cannot meet the outburst control requirements. Pre-drainage using surface vertical wells can mitigate the outburst hazard of these configurations a decade ahead of coal mining operations and create conditions for the underground outburst control. Therefore, surface methane recovery and underground outburst control methods should be combined in an orderly fashion to solve the outburst hazard of highly outburst-prone configurations.

A methane and coal exploitation strategy for highly outburst-prone configurations is developed. Methane recovery by vertical surface wells is first performed as early as possible to mitigate the outburst hazards of highly outburst-prone seams and eliminate the outburst hazards of weak outburst-prone seams. Then a protective seam is mined and pressure-relief methane is simultaneously extracted to eliminate the outburst hazard of the protected areas. Lastly, underground boreholes are constructed to eliminate the outburst hazard of the insufficiently protected areas. Therefore, the outburst hazards of the configurations are eliminated completely.

Combining currently used underground outburst control methods with surface CBM recovery methods, the strategy proposed herein is a developing trend in methane and coal exploitation for future highly outburst-prone configurations. In these configurations, surface CBM recovery using surface vertical wells, pre-working a protective seam and underground methane predrainage are operated in an orderly fashion. The coordination of these techniques in time and space can completely eliminate the outburst hazards and thereby secure green mining conditions. The combination of surface CBM recovery and underground predrainage is the general trend of exploiting methane and coal resources in the future.

Acknowledgments

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