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REGIONAL GAS DRAINAGE TECHNIQUES AND APPLICATIONS IN CHINESE COAL MINES

Yuanping Cheng, Haifeng Wang and Lei Wang

ABSTRACT: With China's rapid and sustained development of economy, the demand for coal supply has resulted in the extraction of coal in deeper coal mines, particularly in China's economically developed Eastern region where many mines have started mining at depths between 800 and 1500 m. As the depth increases, the geo-stress, pressure and gas content of coal seam also increases, and the geological conditions become more complicated with lower-permeability and softer coals, thus coal and gas outbursts and gas explosions and other hazards become increasingly serious. In order to effectively prevent gas disasters, the National Engineering Research Centre of Coal Gas Control, together with the Huainan and Huaibei Mining Group, have developed a regional system of gas extraction technology and conducted theoretical and experimental research. The results include: a) under multi-seam conditions, a relatively low gas disaster-prone coal seams can be mined as the first key protective layer, which can lead to stress-relief, and increased permeability by 400 to 3 000 times, thus facilitating the desorption and accumulation of gas flow; b) in a single seam, the use of enhanced extraction boreholes (crossing boreholes and in-seam boreholes) combined with hydro-fracturing greatly increases coal seam gas extraction rates up to 50%. Engineering practice has proved that the regional gas drainage technology not only eliminates the regional coal and gas outburst threat, but also enables gassy seam mining with low gas emissions. The research results have been adapted by China's national safety codes of production technology. This paper introduces the technology principles, engineering practices as well as the key parameters of regional gas drainage for engineering applications.

SERIOUSNESS OF COAL AND GAS OUTBURST DISASTERS

With the rapid and sustained development of China's economy, the demand for coal is increasing. China's coal production increased from 0.999 bt in 2001 to 3.03 bt in 2009, a rise of 203.3% over nine years with average annual growth of 22.6%. This has led to the rapid expansion of mining to greater depths, particularly in the economically developed eastern regions, where coal exploitation has a long history, the shallow coal resources are nearly exhausted, and many coal mines have to start mining at depths of 800~1500 m. In China the coal resources within 800~2 000 m of overburden is about 3.25 tt, accounting for 63% of the total reserves. With the increase of mining depth, increased geo-stress, gas pressure and gas content, have lead to coal and gas outburst associated disasters becoming increasingly serious. Extremely serious coal and gas outburst accidents of over 1 000 t of coal have occurred nine times since 2000. Serious gas explosion accidents with more than a hundred fatalities have occurred eight times. Extremely large outburst accidents happened in Luling Coal Mine in 2002, Zhengzhou Daping Coal Mine in 2004 and Huainan Xieyi Coal Mine in 2006, all were caused by high gas outburst emissions during the extension to deep mining. An in-depth study of gas disaster prevention issues associated with deep coal development will be of great significance to China's deep coal resource exploitation.

Huainan and Huaibei mining areas, located in China's rapid economic development eastern regions have a long mining history, and both are gradually entering a deep mining stage. The depth of many coal mining faces is up to 800~1500 m. The maximum gas pressure is up to 6.4 MPa, and the maximum gas content up to 30 m³/t. Most coal seams are of low permeability in the magnitude of 10⁻³ md. The hardness of coal, i.e., the *f* value, is only 0.1 to 0.4. Coal and gas outburst disasters are very serious. Of the Huainan coal mines, 85% are coal and gas outburst prone as are 60% of the Huaibei coal mines. On April 7th, 2002, China's second largest coal and gas outburst accident occurred in the Luling Coal Mine, accompanied by 10 500 t coal and rock and 1.23 Mm³ of gas.

CONCEPT OF REGIONAL GAS EXTRACTION

Classification of gas extraction methods

There is no uniform classification of gas extraction methods in coal mines. The gas extraction methods have been divided into in-seam extraction in working seams, gas extraction from adjacent seams, and gas extraction in goaf and surrounding stata (Yu, 1992). A new classification of coal mine gas extraction methods with three levels is proposed, as shown in Figure 1. The first level is based on the time of coal mining, which includes pre-drainage, drainage during mining and post-mining drainage. The second level is based on the spatial sources of gas in relation to the mining seam, which includes gas extraction from adjacent seams, gas extraction in working face, gas extraction during development and from goaf. The third level refers to more specific methods of gas extraction, such as surface well gas extraction, cross-measure borehole extraction, and buried pipe in goaf gas extraction.

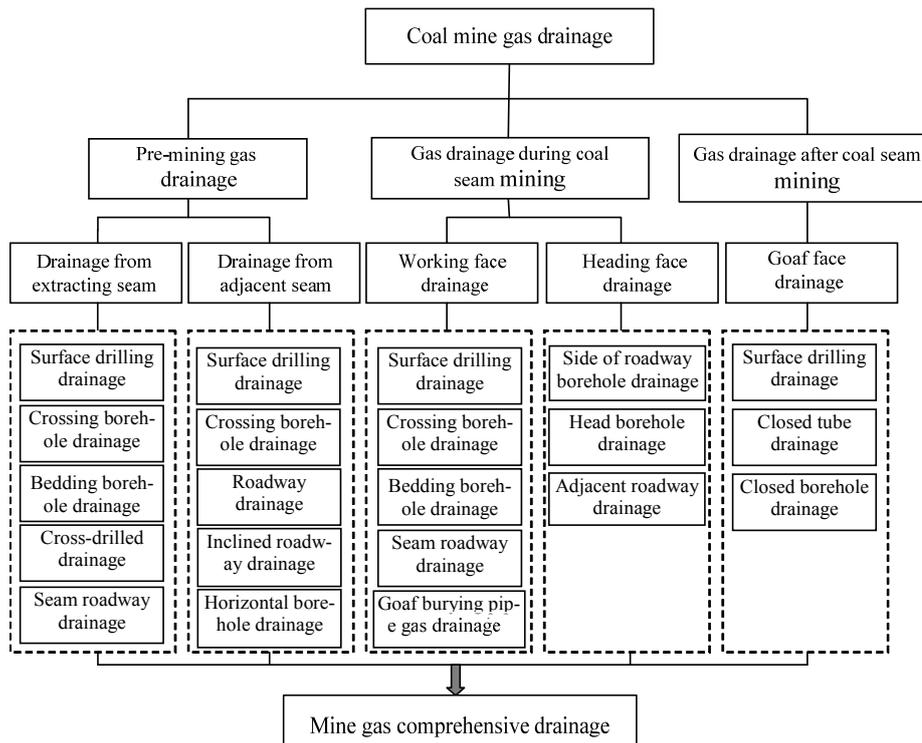


Figure 1 - Classification of mine gas drainage method

In coal mine production, the adoption of a single method of gas extraction usually could not solve mine gas problems. Instead, a combination of several of these methods has to be applied to achieve the goal of comprehensive gas extraction (Cheng, *et al.*, 2009).

Purpose of regional gas extraction

Regional gas extraction must be used in the dangerous zone of outburst prone coal seams before coal mining. After regional gas extraction, the gas content and gas pressure must satisfy the requirement of Chinese safety code *Basic Indexes of Coal Mine Gas Extraction*. Regional gas extraction is an outburst prevention program consisting of the setup of gas control projects from safe zones to unsafe zones during the mining process. It can reduce the gas content of unsafe areas, eliminating the regional risk of coal and gas outburst and making the unsafe zones to be safe.

Long-term theoretical research and outburst coal seam mining have proven that protective seam mining incorporating pre-drainage of seam gas is the most effective regional prevention approach to reduce coal and gas outbursts. This method can reduce the gas content of unsafe areas, minimizing the risk of coal outburst, improving the safety and reliability of controlling measures for coal and gas outburst, and increasing the level of safe mining of outburst coal seams. In addition, the regional gas extraction methods could drain a large volume of high purity gas and improve the utilization of clean energy, thus reducing the emissions of greenhouse gas.

Scope and standards of regional gas drainage

Protection area of the roadway in coal seams

When cross-measure boreholes or in-seam boreholes are used in coal roadways as outburst prevention measures, they have different protection effects in different coal seams. Considering the effect of gravity on outbursts, boreholes should control the upper side of roadway for at least 20 m, the down side for at least 10 m and the two sides for at least 15 m in inclined coal seams or half-edge coal seams (SACMS, 2009). As Figure 2 shows, the borehole control range is the distance along the coal seam.

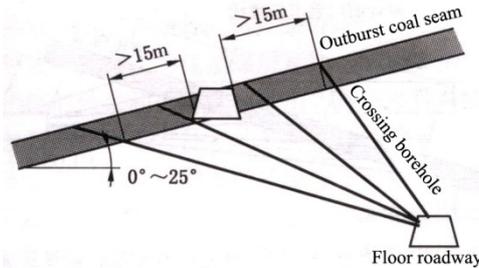


Figure 2 - Diagram show the protection area of the pre-drainage crossing boreholes for outburst prevention

Protection area of working face

When crossing boreholes or in-seam boreholes are used to pre-drain the disturbed (or the whole mining section) coal seam, they should control the whole mining coal block (or the whole mining section). The locations of these boreholes are shown in Figures 3 and 4. In Figure 3, the method of dense crossing borehole for pre-draining gas applies to the coal seam with high coal and gas outburst risk but without a protective layer. In Figure 4, this method is applied in the situation where there are roadways in a coal seam. For thick coal seams, pre-drainage boreholes should have a control extraction range within 20 m in the roof and within 10 m in the floor (SACMS, 2009).

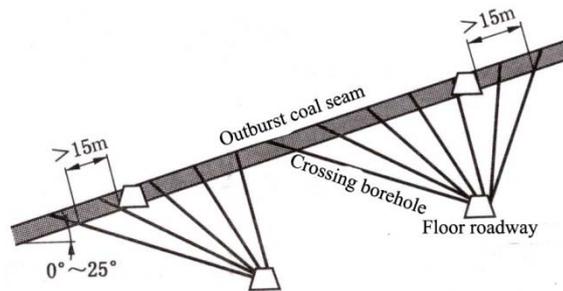


Figure 3 - The protection scope of dense crossing boreholes as regional outburst prevention measures

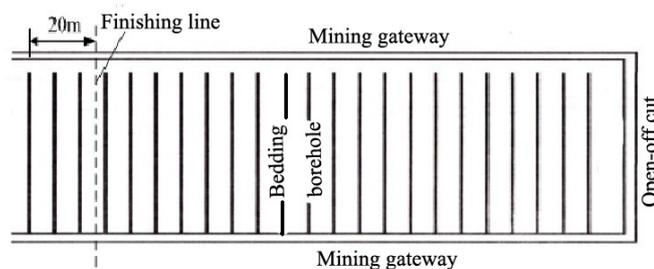


Figure 4 - The protection scope of in-seam boreholes as regional outburst prevention measures

Protection domain during cross-cut coal and shaft-sinking

When cross-measure boreholes are used for pre-drainage in the driving of main roadways or in shaft sinking (shaft and drift entry) before intercepting coal seams, the drilling should be completed at least 7 m (in vertical distance) between the drivage cut-through uncovering the working face and the coal seam. As shown in Figure 5, the lowest controlling ranges of boreholes are: 12 m beyond the boundary of the roadways which are intercepting the seam, at least 5 m for the distance between the edge of protection domain and the working level of the roadway. When the boreholes cannot penetrate the entire coal seam, a crossover distance of 15 m should be kept, and a distance of at least 12 m should be left for the pre-drainage of the coal gas beyond the working roadway and 15 m ahead the working face, otherwise, the work of drilling and inspection should be carried out without any delay.

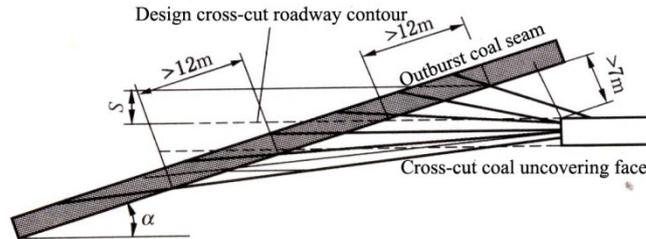


Figure 5 - The use of cross-measure borehole pre-drainage as regional outburst prevention measures

Codes compliance

When assessing the effect of pressure-relief gas extraction of the protective layer, the outburst prevention measures in the pre-drainage coal gas regional needs to be examined, firstly including whether the layout of boreholes complies with the design requirements. The assessment mainly uses the residual gas pressure test, residual gas content, deformation of coal seam expansion and other indicators and methods. It can also be combined with secondary indicators such as coal seam permeability. The key parameters to test coal seam gas pre-drainage area outburst prevention measures are the residual gas pressure and residual gas content. The critical index for regional outburst prevention measures is shown in Table 1.

Table 1 - Critical index of regional outburst prevention measures

Gas pressure (MPa)	Gas content (m^3/t)	Coal seam expansion deformation ($\%$)
< 0.74	< 8	>3

Implementation of regional outburst prevention measures

The implementation process of regional outburst prevention measures includes four steps, as shown in Figure 6. These are:

- Step one - carrying out outburst forecast of the regional coal seams, and according to the regional forecast, coal seams are divided into outburst risk and non-outburst risk regions.
- Step two - regional outburst prevention measures implemented prior to mining the outburst region to eliminate outburst risks. These measures include the exploitation of protective seam and the pre-drainage of coal seam gas. Wherever conditions permit, protective seam mining technology should be adopted as a priority.
- Step three - the effectiveness of regional outburst prevention measures are assessed. The main indicators are the residual gas pressure and residual gas content, which requires that the maximum residual value must be less than the critical value after prevention measures. If the residual gas content and pressure value are higher than the critical value, then the outburst prevention measures are insufficient and have to be enhanced further until the outburst risk is eliminated.
- Step four - regional validation will be carried out to ensure the safety of mining operations. If the working face is classified as in an outburst risk region, additional outburst prevention measures should be adopted to eliminate its outburst potential.

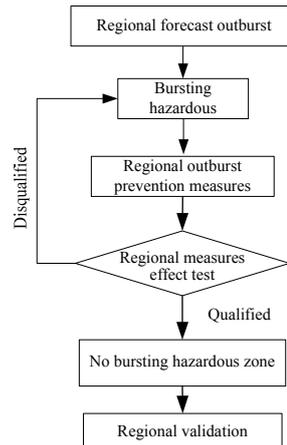


Figure 6 - Implementation process of regional outburst prevention measures

BASIC PRINCIPLES OF REGIONAL GAS EXTRACTION

Protective seam mining and pressure-relief gas drainage

As shown in Figure 7, after the protective seam mining, the overlying strata will form three zones, i.e., the caving zone, the fractured zone and the sagging (deformation) zone. The underlying rock will form two zones, i.e., floor heave fractured zone and floor heave deformation zone. The mining condition of the protected seam must not be damaged when mining the lower protective seam, so the protective seam should be in the fractured zone and sagging zone. The coal measure rocks in the fractured zone produce both parallel and vertical bedding fractures. Under the effect of drainage pressure, the pressure-relief gas can flow along these fractures. A range of efficient gas extraction methods can be used, including the roof or floor boreholes high level borehole along the panel, under or overlying gas drainage tunnels and vertical surface boreholes (Cheng, 2003a; 2003b; 2004; Yu, 2004; Liu, 2010; Wang, 2010 and Wang, 2010).

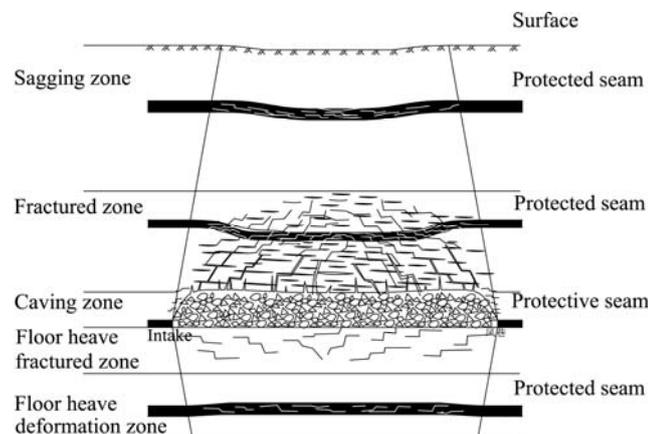


Figure 7- Development of fracture zones in the roof and floor of the working seam

Enhanced gas extraction of a single seam

The enhanced gas extraction of a single coal seam refers to using intensive cross-measure boreholes and in-seam drainage to conduct high-intensity and longer term extraction of the *in situ* coal seam, through which to eliminate the outburst danger. China firstly carried out the enhanced gas extraction of a single coal seam in the Liangshan coal mine. From the analysis of the drainage results, the outburst prevention mechanism can be explained in the following three aspects (Li, 1981): (1) The shrinkage of coal caused a stress drop in the coal and the reduction of storage strain energy. Stress reduction can be up to 1.88~3.25 MPa, accounting for 23~40% of the total stress. The reduced amount of strain energy is 0.042~0.127 MJ/m³; (2) Through the extraction of coal seam gas, gas content and pressure can be dropped substantially, thus reducing the potential for outburst. Coal seam gas content is reduced from 20 m³/t to 10.1 m³/t, gas pressure reduced from 2.8 MPa to 0.4 MPa, and gas potential reduced from 0.77

MJ/t to 0.12 MJ/t; (3) The stiffness factor of coal is increased to 0.25-0.3 from 0.1 after extraction. The combined effect of increased coal hardness and reduced gas pressure gradient significantly minimise the likelihood of coal and gas outbursts.

To improve the single coal seam gas extraction effect, the water-powered induction nozzle technology can be used to enhance the coal bed permeability around the boreholes. This method uses the water pressured high power induction control nozzle in the drilling hole to form a number of fan-shaped boreholes. The coal around the boreholes flows to the adjacent holes, swells, and deforms, with pore fracture system expansion, forming a group of macro pores within the fracture network, with much increased permeability. Field results showed that the seam permeability increased 200 times, significantly reducing gas extraction lead time (Zhou, 2008). Hydraulic fracturing, and deep hydraulic cutting vibrating by blasting can also be used, but large-scale applications of these measures requires further study.

ENGINEERING APPLICATIONS OF REGIONAL GAS DRAINAGE

Gas extraction in Huainan coal seams

In the Huainan mining area, the coal measures system is Carboniferous-Permian with multiple seams divided into A, B and C groups. The B and C groups are the main mining groups, including 10 to 19 layers, and the total thickness is 23-36 m. The typical stratigraphic section is shown in Figure 8. With the increase of mining depth, the gas pressure and content of the main mining coal seams are increasing. With the increase of mining depths, the majority of the current coal mines are extracting outburst prone coal seams. The gas control issue of outburst coal seams has become the primary problem to be addressed in the Huainan mining area.

Thickness (m)	Rock columnar	Lithology
1.0		Seam C ₁₄
18.0		Mudstone, sandstone, siltstone
6.0		Seam C ₁₃
64.5		Mudstone, sandstone, siltstone
3.5		Seam B _{11 b}
3.8		Mudstone
23.0		Mudstone, siltstone
0.8		Seam B ₁₀
46.2		Mudstone, sandstone, siltstone
2.0		Seam B ₈
8.1		Mudstone, sandstone
5.3		Seam B _{7a}
11.3		Mudstone, sandstone
4.7		Seam B ₆
29.9		Mudstone, sandstone, siltstone
2.3		Seam B ₅
4.5		Mudstone
2.5		Seam B ₄
47.0		Mudstone, sandstone
3.2		Seam A ₃
8.1		Mudstone
2.0		Seam A ₁

Figure 8 - Histogram of Huainan Coal Mining

The Huainan mining area has a typical condition of coal seams that are suitable for protective seam mining. Firstly, the coal seam of non-outburst risk or low outburst risk is selected as the first key protective layer, mining of which eliminates the outburst risk of adjacent coal seams. Then, the coal seam whose outburst risk has been eliminated is selected as a protected seam, and the mining of this seam leads to pressure relief and increased permeability to eliminate the outburst risk. The protective seams can be repeatedly mined until safely mining the last coal seam.

As shown in Figure 8, the thickness of B₁₀ coal seam is 0-1.85 m with an average of 0.9 m, and the outburst risk is relatively small compared with other coal seams. The interburden between the upper B_{11b} coal seam is 30 m, with the lower B₈ seam at 40 m. Through comparative analysis, the B₁₀ coal seam was selected as the first key protective layer to mine. After mining the B₁₀ seam, the upper caving zone can protect the safe mining of the B_{11b} coal seam, with the lower fractured zone protecting the safe mining of the B₈ coal seam. Then the B_{11b} protective seam at the top was mined to protect the mining of C₁₃ coal seam, and B₈ protective seam in the lower was mined to protect the mining of C₆ coal seam and so on.

Enhanced gas extraction for single outburst seams in Huaibei coal mine

Because all the mid-group seams in the Huaibei coal mining area are outburst prone seams and most of the mines do not have the conditions for protective seam mining, the use of intensified gas extraction technology to eliminate the danger of outburst is required. Cross-measure boreholes combined with in-seam drilling gas extraction technology is the most common method for enhanced gas extraction. Firstly a rock roadway is driven in the floor, then cross-measure boreholes are drilled from it to pre-drain the strip of coal roadway in order to ensure the construction safety of roadways; Secondly in-seam boreholes from seam roadways are drilled to extract the gas of the mining area so that the outburst danger can be eliminated. This method has been used to control the No. 7 coal seam in Qinan coal mine and achieved good performance. The No. 713 working face was selected as a testing face. The working seam has an average thickness of 3.5 m, an average dip of 5°, gas pressure of 2.42 Mpa and gas content of 12.3 m³/t. The drilling layout is shown in Figures 9 and 10. The spacing between crossing boreholes is 5 m, and 7 holes along the dip are arranged. The control width of coal strip is 35 m. The space between in-seam boreholes is 2-3 m.

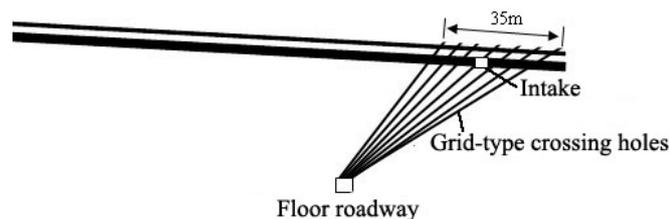


Figure 9 - Floor roadway network crossing holes layout diagram

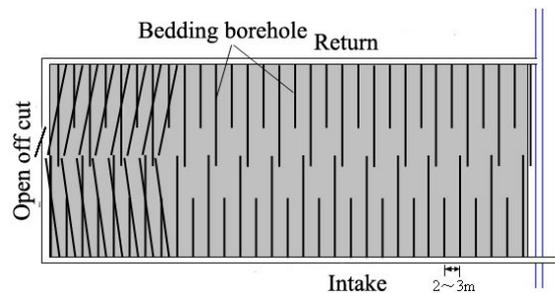


Figure 10 - In-seam borehole layout diagram

In this testing face, a total of 1230 cross-measure boreholes are drilled with a total length of 58 837.1 m, including 14 501.4 m of coal holes and 44 335.7 m of rock holes. The average gas extraction rate from cross-measure boreholes is 2.6 m³/min. A total of 1 700 500 m³ gas was extracted and the gas extraction reached an average of 63.4%. Average residual gas content was reduced to 4.5 m³/t, showing that the coal strip has eliminated the outburst danger.

CONCLUSIONS

Measures of regional gas extraction must be taken to eliminate the outburst danger before coal mining due to the seriousness of outburst danger in China's coal mines. Through the engineering practice in Huainan and Huaibei coal mines, regional gas extraction measures are shown to effectively reduce the gas pressure and gas content of the coal seams, and completely eliminate outburst danger, to achieve the mining safety of highly gassy seams with reduced gas condition.

Although the regional gas extraction measures have achieved remarkable results, there are still many technical problems need to be studied, such as the stress field caused by protective seam mining, fracture field development and the non-steady state desorption flow of pressure-relief gas, and enhancement of low permeability coal seams.

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