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GAS DRAINAGE PRACTICES AND CHALLENGES IN COAL MINES OF CHINA

Kai Wang^{1, 2}, and Sheng Xue²

ABSTRACT: A number of gas drainage techniques are developed and practiced in many coal mines of China mainly to minimize outburst risk and reduce gas emission. Dependent upon local geological and mining conditions, one or more techniques may be practiced in a coal mine. A detailed review of the gas drainage practices and challenges in coal mines of China is presented, with particular reference to gas drainage techniques applicable to coal seams of low permeability.

OVERVIEW OF GAS DRAINAGE IN COAL MINES OF CHINA

China is the biggest coal-producing country in the world and coal output reached 2,100 Mt in 2005. Coal production from underground mines contributes 95% of the total output and over 50% of underground coal mines are classified as gassy and/or outburst prone (Fu, 2005). Chinese coal mines have a high rate of accidents, among the incidents, gas-related disasters account for over 40%, and 82% of major incidents (over 10 fatalities in a single incident) are caused by gas explosion (Yuan, 2004).

Gas drainage is the most effective measure for mine gas control. By 2002, gas drainage systems were set up in 193 mines in China and total volume of gas drained reached 1.1461 billion m³. In 2002, average mine-wide gas drainage ratio was 26.6%, average panel-wide gas drainage ratio was 37.6%, average methane concentration of drained gas was 30.3%, and there were 35 coal mines with the amount of gas drainage exceeding 10 Mm³. Table 1 lists the volume of drained gas, ratio of gas drainage, and utilizing ratio of drained gas of these 35 mines (Fu, 2005; Wang, 2003).

GAS DRAINAGE TECHNIQUES

Seam classification in terms of ease of gas drainage

Based on ease of seam gas drainage, seams are classified into three categories, namely: easily drainable, drainable and hardly drainable. The classification is quantified by the decay rate of gas flow and seam permeability, as shown in Table 2 (Yu, 1992). For seams classified as drainable and easily drainable, conventional in-seam gas drainage is practiced; for seams in hardly drainable category, inter-crossing in-seam gas drainage and/or drainage after distressing measures are taken is practiced.

**Table 1 - Drainage volume, ratio, and utilization ratio of top
35 gas drainage mines in China in 2002**

No	Mine	Company	Drainage volume Mm ³	Drainage ratio %	Utilizing ratio %
1	Laohutai	Fushun	127.60	81.7	93
2	No.5	Yangquan	90.29	79.9	10
3	Houcun	Qinshui	47.86	54.6	-
4	No.2	Yangquan	33.92	29.5	90
5	No.1	Yangquan	33.82	47.9	64
6	Baijigou	Ningxia	30.80	53.0	100
7	Datong No.1	Songzao	27.66	43.5	95
8	Baijiao	Furong	26.58	26.5	100
9	Panji No.1	Huainan	25.16	38.0	-
10	Xinjing	Yangquan	23.73	48.8	100
11	Xieqiao No.1	Huainan	22.87	31.0	50
12	Luling	Huaibei	22.11	43.9	48
13	Tucheng	Panjiang	20.28	55.0	-

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14	Datong No.2	Songzao	18.96	48.0	90
15	No.3	Yangquan	18.07	24.0	93
16	Huopu	Panjiang	17.39	30.1	-
17	Songzao	Songzao	16.79	42.2	85
18	Daxing	Tiefa	16.53	39.7	41
19	Panji No.3	Huainan	15.70	36.0	11
20	Sihe	Jincheng	15.00	60.0	-
21	Hongling	Shengyang	14.64	41.3	21
22	Dalong	Tiefa	14.64	40.6	51
23	Dawan	Shuicheng	14.30	39.5	5
24	South	Zhongliangshan	14.24	56.0	100
25	Shihao	Songzao	13.30	41.5	98
26	Laowuji	Panjiang	12.68	44.7	-
27	Wangjiazai	Panjiang	12.66	34.2	13
28	Xinzhuangzi	Huainan	11.57	22.3	-
29	Nanshan	Hegang	11.39	35.0	66
30	Wulong	Fuxin	11.36	32.0	-
31	Moxinpo	Tianfu	11.06	44.1	97
32	Yonghong	Qinshui	11.01	22.7	-
33	Muchonggou	Shuicheng	10.64	44.4	-
34	Xiaoming	Tiefa	10.34	45.5	45
35	Yueliangtian	Panjiang	10.33	30.1	9
Total			83,544		
Average				44.7	51

Table 2 - Seam classifications in terms of gas drainage ease

Category	Decay coefficient of gas flow from a in seam borehole of 100m in length, d^{-1}	Seam permeability* $m^2MPa^{-2}d^{-1}$
Easily drainable	< 0.005	>10
Drainable	0.005~0.05	10~0.1
Hardly drainable	> 0.05	<0.1

* $1 m^2MPa^{-2}d^{-1}$ is equivalent to 0.025 md

Gas drainage techniques and their applicable seam conditions

Based upon gas sources, gas drainage techniques are divided into working seam drainage, adjacent seam drainage, and goaf drainage. In terms of where gas flows through, the techniques are divided into borehole and tunnel techniques. Gas drainage techniques are also classified as drainage with and without de-stressing. Gas drainage can also be divided into underground drainage and surface drainage. Various gas drainage techniques are practiced in coal mines of China, and their applicable conditions are summarized in Table 3. Selection of appropriate gas drainage technique(s) for a coal mine depends mainly on site specific geological and mining conditions, such as seam permeability, seam gas content, seam hardness, sources of gas emission, as well as cost.

Gas drainage practice

Working seam drainage

Most coal mines extracting a single gassy or outburst prone seam adopt the technique of gas pre-drainage prior to mining, such as the mines in Jiaozuo, Hebi, Jincheng and Lu'an mining areas. Some mines which extract multiple seams also use this technique to drain gas in protective seams. Sometimes in order to overcome the problem of insufficient gas drainage lead time and increase drainage ratio, techniques of gas drainage while mining are also applied. To minimize outburst risk and control high gas emission during seam roadway development, some mines adopt the techniques of gas drainage while developing seam roadways.

Adjacent seam drainage

If gas emission at a mining face mainly comes from de-stressed adjacent seams and face ventilation circuit couldn't provide sufficient air quantity to dilute the high gas emission, then techniques of adjacent seam drainage are applied. In this case, most faces (70%) use cross-measure boreholes to drain gas from adjacent seams. Such technique is widely used in Yangquan, Tianfu, Songzao and Zhongliangshan mining areas, and the drainage ratio of these faces is usually over 50 %.

Technique of specially extracted gas drainage tunnel in an adjacent seam has been successfully tried in Yangquan No.1 mine (Bao et al., 1996). This technique is also been named as high position drainage tunnel which is capable of draining more gas than conventional boreholes. The drainage ratio of upper adjacent seam with this technique can reach up to 85 %, which is suitable to mining faces where gas emission from upper adjacent seam is over 30 m³/min.

It is well known that gas in adjacent seams can be effectively drained if the seams lie in a fractured zone (de-stressed). Recent practice in Huainan mining area indicates that if adjacent seams lie in a deformed and subsided zone, gas from the seam can also be effectively drained with high efficiency (Yu et al., 2004). Technique of adjacent seam drainage has been widely applied in many mining areas with satisfactory results.

Table 3 - Gas drainage techniques and their applicable conditions

			Technique of gas drainage	Applicable conditions	
Working seam drainage	Drainage without de-stressing	Pre-drainage of seam roadway development	Cross-measure boreholes drilled from rock roadway Inseam boreholes ahead of inseam roadway development	Outburst prone seam Gassy seam	
		Pre-drainage of working face	Inseam boreholes	Outburst prone seam Gassy seam	
			Cross-measure seam boreholes drilled from cross measure roadway, rock roadway or roadway in adjacent seams	Drainable seam Outburst prone seam	
			Surface boreholes	Gassy and easily drainable seam Relatively shallow seam	
	Drainage with de-stressing	Drainage while developing seam roadway	Boreholes ahead of development headings	Outburst prone seam Gassy seam	
		Drainage while face retreating /advancing	Boreholes ahead of mining face	Outburst prone seam Gassy seam	
			Cross-measure or inseam boreholes drilled from rock roadway ahead of mining face	Outburst prone seam Gassy seam	
	Adjacent seam drainage	Drainage with de-stressing	Drainage of overlying and underlying seams	Cross-measure boreholes to adjacent seam	High gas emission from adjacent seam.
				Tunnel in adjacent seam for gas drainage	High gas emission from adjacent seam and normal boreholes can not cope with gas emission
				Surface boreholes	When surface borehole is considered to be a better option than underground borehole.
Goaf drainage			Pipes placed in goaf	No sponcom risk seam Sponcom risk seam where measures taken to mitigate sponcom risk	
			Boreholes into goaf		
			Surface boreholes		

Goaf drainage

In cases where gas emission into a mining face is mainly from goaf, the techniques of goaf drainage are usually adopted. These include cross-measure boreholes into roof strata, placing gas drainage pipes in goaf, and surface boreholes.

Cross-measure boreholes into fractured roof strata, as shown in Figure 1, have been proven to be quite effective. The boreholes are drilled from panel return side into fractured roof strata at an upside angle of 10° - 18° , away from the return at an angle of 15° - 20° , and 80-140 m in length. Two adjacent drilling insets are spaced 50-80 m. At each inset, 3 to 5 boreholes are drilled, and this leads to borehole overlapping around 40-65 m. With the layout of boreholes, amount of gas drained from the boreholes can be kept fairly constant when the face is mined through the inset. Borehole diameter varies from 50 mm to 127 mm, the larger a borehole diameter, the higher gas flow rate from the borehole. Field observations from Daxing mine in Tiefsa mining area show that when borehole diameter is 50 mm, 75mm, 89 mm, 108 mm and 127 mm, the respective gas flow rate from the borehole is 0.3-0.5, 1.5-2.0, 3.0-4.0, 5.0-7.0 and 7.0-8.0 m^3/min .

Placing gas drainage pipes in goaf is another technique in use in coal mines of China. In order to ensure a certain quantity of gas drainage, pipe diameter should not be less than 150 mm, and the pipe made of magnesite are used to reduce cost.

Surface borehole goaf drainage has been trialed in some mines in China with mixed results. If coal seams are more than 600 m below the surface, its application may be also complicated with borehole stability.

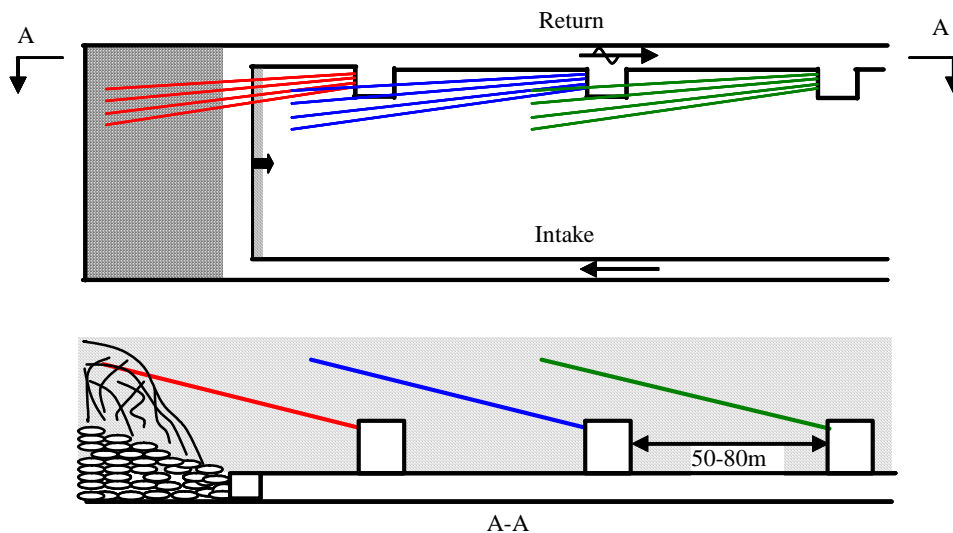


Figure 1 - Goaf gas drainage with cross-measure boreholes into fractured roof strata

Challenges

At present the main problem of gas drainage is low drainage ratio. The low drainage ratio is mainly caused by lack of effective pre-drainage technique for seams of low permeability and poor management of gas drainage practice. Nearly 95% of gassy and outburst prone mines in China are mining seams of 10^{-3} - 10^{-4} md permeability, and conventional gas pre-drainage is ineffective. Poor management of gas drainage practice include inadequate drainage lead time, insufficient number of boreholes, poor sealing of boreholes, lack of gas drainage monitoring system, and inappropriate gas drainage system (Wang, 2003).

GAS DRAINAGE IN SEAMS OF LOW PERMEABILITY

Targeted at highly gassy and outburst prone seams of low permeability, a number of technologies have been developed to enhance gas drainage over the last 30 years in China. These technologies include hydraulic or high pressure air fracturing or cracking of seams, high pressure water injection for borehole enlarging, blasting for coal loosening, controlled blasting in long boreholes for coal pre-fracturing, and inter-crossing boreholes drainage (cross-measure boreholes, in-seam boreholes, large diameter boreholes) (Fu, 2005; Yu, 1992; Bao et al., 1996; Wang, 1992; Wang, 2002). Among these technologies, inter-crossing borehole drainage, hydraulic coal cracking and controlled blasting in long boreholes for coal pre-fracturing are proven to be more effective and easy to implement because of simple equipments requirements.

Inter-crossing borehole drainage

In inter-crossing boreholes drainage, two groups of boreholes are drilled to increase the intensity of gas drainage. One group of boreholes is drilled in parallel and the other group intercrossing over or below the former, as shown in Figure.2.

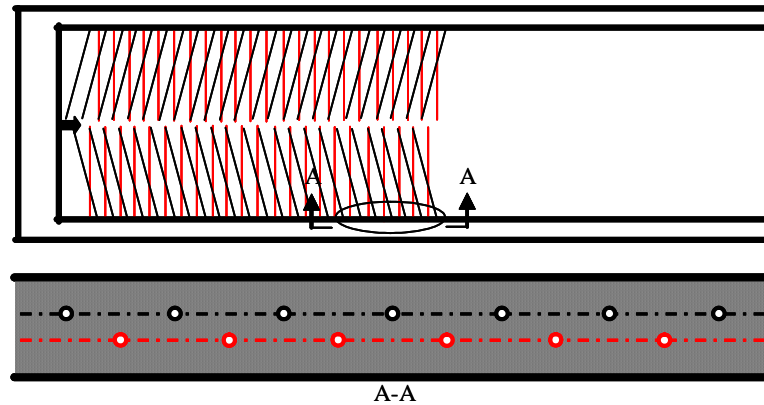


Figure 2 - Inter-crossing boreholes for in-seam gas pre-drainage

Results of in-seam gas drainage with parallel boreholes alone and inter-crossing boreholes at some sites are shown in Table 4. Results shown in Table 4 revealed that at the same site and with the same drainage lead time:

- amount of gas drained with large diameter (150 mm or 300 mm) parallel boreholes was 2.5 times more than that with normal diameter (65-75 mm).
- amount of gas drained with intercrossing boreholes is 1.5 - 2.0 times more than that with parallel boreholes alone with the same borehole intensity and diameter.

Table 4 - Results of gas drainage by parallel boreholes and intercrossing boreholes

Technique	Site	Seam parameters					Borehole parameters		Gas flow from 100m long boreholes ($q=q_0e^{-Bt}$)		
		Thickness, m	Dip, °	Gas content, m ³ t ⁻¹	Gas pressure, MPa	Permeability, m ² MPa ⁻² d ⁻¹	Diameter, mm	Spacing, m	Initial flow rate, q_0 (m ³ min ⁻¹ hm ⁻¹)	Decay coefficient $B, ^{-1}$	Drainage Quantity, 10 ⁴ m ³
Parallel boreholes	No.912 face of Yangquan No.1 mine	2.2	<10	18.3	1.3	0.015	73	1.7	0.005	0.004	0.204
Large diameter parallel boreholes							300	3.2	0.027	0.008	0.495
Parallel boreholes	No.42081 and 41041 faces of Jiaoxi mine	4.5 - 5.3	<10	17.7 - 14.9	1.2 - 0.8	0.55 - 3.6	75	4.8	0.084	0.009	1.426
Large diameter parallel boreholes							150	8.1	0.198	0.008	3.697
Parallel boreholes	No.13501 face of Jiaozuo Jiulishan mine	5.6	<10	16.9			65	2.4 - 3.0	0.040	0.008	0.711
Intercrossing boreholes								3.5 - 4.5	0.064	0.006	1.463
Parallel boreholes	E ₉₋₁₀ -20100 face of Pingdingshan No.10 mine	4.2	<10	13.5			75	2 - 4	0.028	0.029	0.139
Intercrossing boreholes								2 - 4	0.035	0.025	0.202

Hydraulic coal cracking and controlled blasting in long boreholes

Controlled blasting in long boreholes aims to enhance seam permeability through coal pre-fracturing. To control fracturing direction and increase free surface area, not all boreholes are filled with explosives and blasted, instead there are some boreholes left deliberately between two charged boreholes. Hydraulic coal cracking aims to increase seam permeability through cutting two 0.3-0.6 m wide cracks at both sides of an in-seam borehole by high pressure water injection.

Results of hydraulic coal cracking and controlled blasting in long boreholes at some sites are shown in Table 5. Results shown in Table 5 indicated that:

- Seam permeability was increased by 2 to 5 times by controlled blasting in long boreholes, and amount of gas drained after blasting was increased by 50 - 90%.
- Seam permeability was increased by 10 to 100 times by hydraulic coal cracking, and amount of gas drained after cracking was increased by 100-200%.

Discussion

By taking into considerations of equipment requirements, maturity of technology, effectiveness, practicality, operational safety and cost, the most feasible gas drainage techniques in seams of low permeability are inter-crossing boreholes and intensive parallel boreholes of large diameter. If underground conditions are suitable, hydraulic coal cracking technique can significantly reduce drilling operations and the technique can be used to replace intensive parallel boreholes. Technique of controlled blasting in long boreholes has the similar effect to that of inter-crossing boreholes, although its technical requirement is stricter because of drilling difficulty and operation of placing explosive charge in boreholes and blasting. As the borehole becomes longer, chance of successful blasting decreases, and safety risk of whole operation increases.

Technique of hydraulic coal fracturing/cracking requires specially complex and heavy equipment, and there are still issues to be resolved as how to control in-seam fractures and what kind of materials are more appropriate to support the fractures. Furthermore effectiveness of the technique has not yet widely demonstrated.

MANAGEMENT STRATEGY TO INCREASE MINE GAS DRAINAGE RATIO

Increasing borehole length

Borehole length is an important factor affecting gas drainage. In outburst prone seams of low permeability, drilling of long boreholes is difficult because the boreholes can be badly deformed, bursting can occur while drilling, and flushing cuttings can be problematic. Therefore more advanced and effective drilling equipment suitable for long-hole in-seam drilling should be developed as a matter of urgency. The drilling equipment should be directional, more powerful, and capable of removing cuttings and preventing bursting while drilling long in-seam borehole.

Improving borehole sealing

Gas purity of in-seam gas pre-drainage is a major issue. Of all working faces where in-seam gas pre-drainage is practiced in China, about 65 % of them drain gas with its purity below 30%. One reason lies with borehole sealing, including sealing materials and sealing length. Clay and slurry of cement and sand are used to seal gas drainage boreholes in about 2/3 of mines. Recent practice indicates that polyurethane has high expansive coefficient, short coagulating duration, high sealing efficiency, small shrinkage and good sealing quality. It has been used in some mines to seal gas drainage borehole with good results. Sealing length is normally 4 – 6 m, and it needs to be increased.

Optimizing drainage system

Optimization of gas drainage system may include: (1) selection of suitable pumps to match gas volume and resistance of drainage reticulation system; (2) increasing the diameter of gas pipes; (3) installing automatic devices to discharge water in drainage reticulation system; and (4) regularly conducting leak check and maintenance of drainage system.

Increasing gas drainage lead time

For seams of low permeability (less than 10^{-3} md), drainage lead time must be over 6-8 months to realize moderate drainage ratio. In China, roadway development rate in outburst prone seams is usually less than 100 m per month, and schedule of roadway development and face retreating is fairly tight, which leaves little lead time for gas drainage. Data from Jiaozuo, Hebi, Pingdingshan, Huainan, Huaibei, Fushun, Tiefsa mining areas reveals that average gas drainage lead time in outburst prone seams is only 3-4 months. It is therefore necessary to optimize

mine planning to ensure sufficient gas drainage lead time, and at the same time to develop techniques to rapidly minimize outburst risk.

Table 5 - Results of gas drainage by controlled blasting in long boreholes and hydraulic coal cracking

Technique	Site	Seam parameters			Technique parameters			Gas flow from 100m long borehole, $q=q_0e^{-Bt}$				
		Seam thickness, (m)/Dip, (°)	Gas content, (m^3t^{-1})/Pressure, (MPa)	Permeability, ($m^2MPa^{-1}d^{-1}$) Before/after treatment	Explosive, (kg)/Length of explosive, (m)	Diameter of control Borehole, (mm)	blasting and control	Initial flow rate, q_0 ($m^3min^{-1}hm^{-1}$)	Decay coefficient B , (t^{-1})	Drainage Quantity, ($10^4 m^3$)		
Parallel boreholes	No.41041 face of Jiaoxi mine	5.3 /<10	14.9 /0.8	2.08 /2.08				0.0842	0.009	1.426		
Controlled blasting				2.08 /7.18	40 /30	12 /5	2				2.14	
Parallel boreholes	F ₁₇ -2228 face of Pingdingshan No.5 mine	5.9 /<10	10.3-16.6 /0.8-1.9	0.504 /0.504				0.2648	0.051	0.746		
Controlled blasting				191-256 /49-71	90	5-8	($\leq 100d$)	0.811	0.193	1.399		
							($> 100d$)	0.1953	0.020			
							Before treatment	0.025				
Hydraulic coal cracking	Hebi No.4 mine	4.5-9 /<10	14.6-15.1 /-	0.04 /0.36-0.96				After treatment	0.065			
								Before treatment	0.21	0.007	4.32	
	Baishatan mine	6.5 /30	14.3 /1.6	0.24-0.4 /9.8-55.2					After treatment	0.611	0.009	9.36
									Before treatment	0.07		

OUTLOOK

As coal seams become deep and coal production increases, gas emission will increase and gas-related risk will also increase. Moreover seam permeability will decrease further as seam overburden increases, and it will be more difficult to drill boreholes and effectively pre-drain gas. Therefore the following tasks should be targeted:

- A combination of gas drainage techniques must be applied to tackle multiple sources of gas emission at working face, the techniques include working seam drainage, adjacent seam drainage, and goaf gas drainage.
- Gas drainage technology should be further developed towards drilling large diameter (>150 mm), directional and long (200-500 m) intercrossing boreholes. Technologies to enhance seam permeability should also be further developed in terms of their effectiveness and practicality.
- De-stressed gas drainage techniques should be further developed with detailed understanding of mining-induced de-stressed zone(s).

In summary, development of effective gas drainage technology is vital to realize safe extraction of coal and gas and ensure sustainable development of coal mines in China.

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