2008

# Gas Drainage Practices and Challenges in Coal Mines of China

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# GAS DRAINAGE PRACTICES AND CHALLENGES IN COAL MINES OF CHINA

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*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 $m^3$. 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 $Mm^3$. 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 inseam gas drainage is practiced; for seams in hardly drainable category, inter-crossing inseam 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 inseam 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 technque 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 $m^3$/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**

<table>
<tr><th colspan="4">Technique of gas drainage</th><th>Applicable conditions</th></tr>
<tr><td rowspan="8">Working seam drainage</td><td rowspan="4">Drainage without de-stressing</td><td>Pre-drainage of seam roadway development</td><td>Cross-measure boreholes drilled from rock roadway<br>Inseam boreholes ahead of inseam roadway development</td><td>Outburst prone seam<br>Gassy seam</td></tr>
<tr><td rowspan="3">Pre-drainage of working face</td><td>Inseam boreholes</td><td>Outburst prone seam<br>Gassy seam</td></tr>
<tr><td>Cross-measure seam boreholes drilled from cross measure roadway, rock roadway or roadway in adjacent seams</td><td>Drainable seam<br>Outburst prone seam</td></tr>
<tr><td>Surface boreholes</td><td>Gassy and easily drainable seam<br>Relatively shallow seam</td></tr>
<tr><td rowspan="4">Drainage with de-stressing</td><td>Drainage while developing seam roadway</td><td>Boreholes ahead of development headings</td><td>Outburst prone seam<br>Gassy seam</td></tr>
<tr><td rowspan="2">Drainage while face retreating /advancing</td><td>Boreholes ahead of mining face</td><td>Outburst prone seam<br>Gassy seam</td></tr>
<tr><td>Cross-measure or inseam boreholes drilled from rock roadway ahead of mining face</td><td>Outburst prone seam<br>Gassy seam</td></tr>
<tr><td>Inter-crossing pre-drainage (measures taken to increase seam permeability)</td><td>Inseam boreholes<br>Boreholes drilled from rock roadway or surface</td><td>Gassy and hardly drainable seam</td></tr>
<tr><td rowspan="3">Adjacent seam drainage</td><td rowspan="3">Drainage with de-stressing</td><td rowspan="3">Drainage of overlying and underlying seams</td><td>Cross-measure boreholes to adjacent seam</td><td>High gas emission from adjacent seam.</td></tr>
<tr><td>Tunnel in adjacent seam for gas drainage</td><td>High gas emission from adjacent seam and normal boreholes can not cope with gas emission</td></tr>
<tr><td>Surface boreholes</td><td>When surface borehole is considered to be a better option than underground borehole.</td></tr>
<tr><td rowspan="3">Goaf drainage</td><td rowspan="3" colspan="2"></td><td>Pipes placed in goaf</td><td rowspan="3">No sponcom risk seam<br>Sponcom risk seam where measures taken to mitigate sponcom risk</td></tr>
<tr><td>Boreholes into goaf</td></tr>
<tr><td>Surface boreholes</td></tr>
</table>

*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 $10^0$-$18^0$, away from the return at an angle of $15^0$-$20^0$, 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 Tiefa 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.

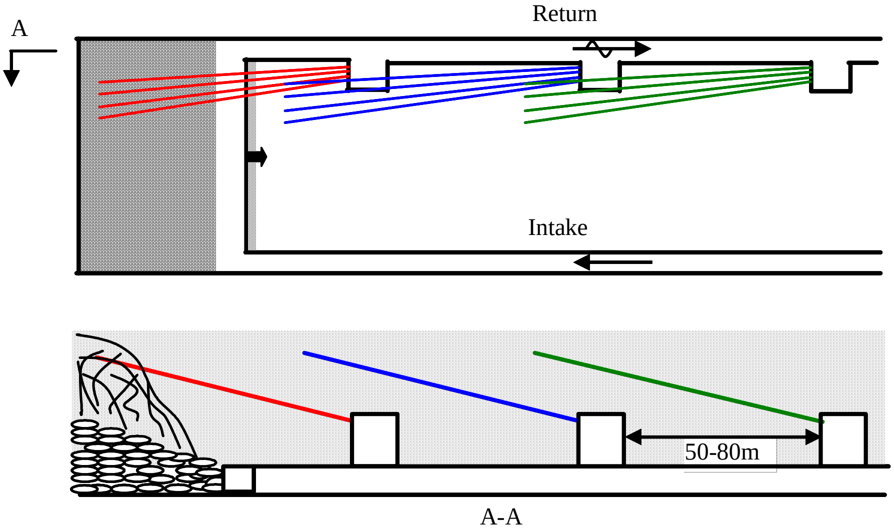


**Figure 1 - Goaf gas drainage with cross-measure boreholes into fractured roof strata**

*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, inseam 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.

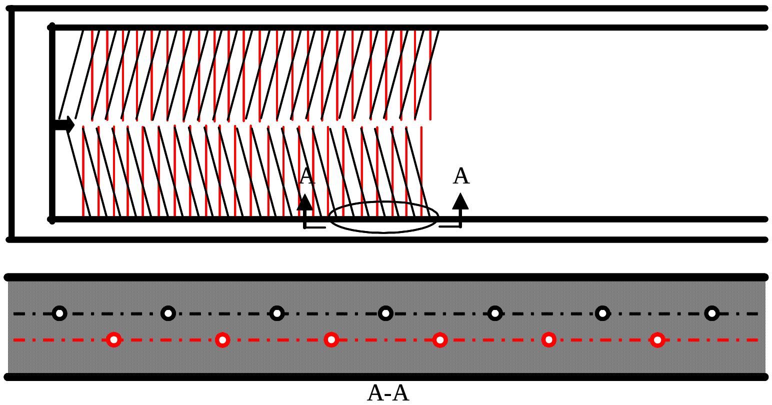


**Figure 2 - Inter-crossing boreholes for inseam gas pre-drainage**

Results of inseam 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 borehole ($q=q_0e^{-Bt}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Thickness, m | Dip, ° | Gas content, $m^3t^{-1}$ | Gas pressure, MPa | Permeability, $m^2MPa^{-2}d^{-1}$ | Diameter, mm | Spacing, m | Initial flow rate, $q_0$ ($m^3min^{-1}hm^{-1}$) | 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 | | 0.56 | 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 inseam 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 inseam 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 inseam 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 inseam borehole.

**Improving borehole sealing**

Gas purity of inseam gas pre-drainage is a major issue. Of all working faces where inseam 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, Tiefa 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, ($m^2MPa^{-2}d^{-1}$)/ 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 $B$, ($^{-1}$) | 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 | 125 | 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 | | | | 0.504 /3.03 | 191-256 /49-71 | 90 | 5-8 | ($t$≤100d) 0.811 | 0.193 | 1.399 |
| | | | | | | | | ($t$>100d) 0.1953 | 0.020 | |
| Hydraulic coal cracking | Hebi No.4 mine | 4.5-9 /<10 | 14.6-15.1 /- | 0.04 /0.36-0.96 | | | | Before treatment 0.025 | | |
| | | | | | | | | After treatment 0.065 | | |
| | Baishatan mine | 6.5 /30 | 14.3 /1.6 | 0.24-0.4 /9.8-55.2 | | | | Before treatment 0.21 | 0.007 | 4.32 |
| | | | | | | | | After treatment 0.611 | 0.009 | 9.36 |

## 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.

**ACKNOWLEDGEMENT**

This project is supported by National Natural Science Foundation of China (No.50404016, 50534090) and Fok Ying Tung Education Foundation (No.101050). The authors would also like to acknowledge China Scholarship Council for its support.

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