Theories and techniques of coal bed methane control in China

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Abstract: Coal bed methane control with low permeability is a hot issue at present. The current status of coal bed methane control in China is introduced. The government-support policies on coal bed methane control are presented. This paper proposes the theories of methane control in depressurized mining, including methane extraction in depressurized mining, simultaneous mining technique of coal and methane without coal pillar, and circular overlying zone for high-efficiency methane extraction in coal seams with low permeability. The techniques of methane control and related instruments and equipments in China are introduced. On this basis, the problems related to coal bed methane control are addressed and further studies are pointed out.

Key words: coal bed methane control; depressurized mining; low permeability; coal seams; simultaneous mining technique of coal and methane without coal pillar; circular overlying zone

1 Introduction

China is one of the largest coal producers in the world, accounting for 37% of the global coal production. As the major energy in China, coal accounts for 76% and 69% of primary energy production and consumption, respectively [1]. The State Energy Long-term Development Plan states that China will uphold the energy strategy that coal and electricity are used as the main resources; oil, gas and new energy are developed in all-round way. The National Energy Development Strategy 2030–2050 issued by Chinese Academy of Engineering (CAE) points out that the annual demands of coal will be up to $3.8 \times 10^7$ t (ton), which still accounts for 50% of the energy-consuming structure in China. Therefore, the present status and prospect of energy development and the coal resources sustainable supply dominate the important situation and prominent role of the coal industry in economic and social development in China [2]. It is evident that the coal as one of the dominant energy resources in China cannot be replaced in a long period of time.

According to prediction results of the 2nd national coal field investigations, the total reserve of coal resources in China is approximately $5.57 \times 10^{18}$ t, in which the predicted reserve of coal resources at depths of 0–600 m accounts for 26.8%, 600–1 000 m for 20%, 1 000–1 500 m for 25.1%, and 1 500–2 000 m for 28.1% [3]. Meanwhile, the abundant coal bed methane in China proves that geological reserve of coal bed methane is approximately $1.023 \times 10^{11}$ m$^3$, recoverable reserve is about $4.7 \times 10^{10}$ m$^3$, and the coal bed methane resources within the depth of 2 000 m is $3.68 \times 10^{10}$ m$^3$, ranking the third in the world [4]. In 2009, China’s coal production reached $3.05 \times 10^9$ t, accounting for 45.6% of the global coal production. In 2010, China’s coal production reached $3.25 \times 10^9$ t, accounting for 45% of the global coal production. The amount of methane extraction is $9.1 \times 10^9$ m$^3$, and the amount of methane utilization is $3.6 \times 10^9$ m$^3$, with a death rate per million tons (DRPMT) of 0.725 [5, 6]. Most coal mines in China are rich in methane, and more than 70% of state-owned major coal mines are methane-rich or coal and methane outburst-prone mines. The permeability of most coal seams is relatively low, which is basically less than 1 mD, averaging 0.002–16.17 mD. The coal seams with the permeability less than 0.1 mD accounts for 35%, 0.1–1 mD for 37%, larger than 1 mD for 28%, and more than 10 mD is scarce. Even for coal mines with larger permeability, such as mines of Shuicheng, Fengcheng, Huogang, Kailuan and Liulin, permeability is only 1–18 mD,
about two or three orders of magnitude lower than those in the United States and Australia [7, 8]. Coal Bed Methane Drainage Engineering Design Specification (GB50471-2008) indicates that the methane in coal seams with permeability less than 1 mD is difficult to be extracted. The geological conditions in Huainan mining district are very complicated, roughly characterized by (1) large overburden depth of 400–1 500 m, (2) 8–15 layers of coal seams, (3) methane-rich coal seams with methane content of 12–36 m³/t, (4) very soft coal (robustness coefficient $f = 0.2–0.8$), (5) low coal seam permeability of 0.001 mD, (6) high gas pressure (up to 6.2 MPa), and (7) complex geological structures [7].

With further development in coal mining, there is a trend to mine at depth. The coal mining depth in China increases 10–20 m per year on average, coal bed methane pressure increases by 0.1–0.3 MPa per year, and methane emission quantity increases by about $1.5 \times 10^8$ m³ per year. As the mining depth increases, the geological structures are complex or extremely complex. The threat of natural hazards in coal mine gradually increases. Most key state-owned coal mines are turned to be methane-rich mines, and treatment of mine-out coal seams becomes more and more difficult [4, 7, 8].

At present, China is one of the countries with the severest coal and methane outburst disasters in the world. Since the problem was not properly solved for a long period of time in the past, the methane outburst disasters occurred frequently, and the production efficiency was considerably low. Consequently, the safe and efficient mining could not be achieved.

2 Summary of coal bed methane disasters in China

According to the statistics [9–13], the DRPMT of China’s coal mines reduced from 2.811 during the 10th Five-year to 0.749 during the 11th Five-year, and the overall operation was going well. However, due to the technical and management bottleneck problems, the safe situation of coal mines in China is still discouraging.

During the 11th Five-year, both of the methane outburst disasters and death toll were gradually reduced. Compared with 2006, the methane outburst disasters in 2010 were reduced by 182 (accounting for 55.7%) while the death toll was reduced by 696 (accounting for 52.8%). But the particularly severe methane outburst disasters occurred time and time, and the severe methane outburst disasters with life loss over 50 cannot be avoided, as shown in Table 1 [9–13]. Therefore, the coal bed methane control is still the key issue for mining safety.

3 Key issues and techniques in coal bed methane control

3.1 Key issues

As the mining depth increases, the methane outburst accidents occur frequently. At present, 95% of coal mines in China are underground mines. The average mining depth of middle- and large-scale mines is about 456 m, and the deepest mining depth is 1 365 m. The coal production of mines at mining depth over 600 m accounts for 28.5% of total coal production at present. The amount of mines with depth larger than 1 000 m are up to 20. The mining depth is gradually increased. As the mining intensity increases, the content of methane in coal seams increases by 1 m³/t per year. Gas pressure and coal-methane outburst incidents in coal mines also increase. Accordingly, coal bed methane control becomes more difficult.

In order to improve the safety level of coal mines in China, coal resources integration and massive mergers and acquisitions in coal mines are carried out. However, the mining information of small coal mines is not sufficient, thus the coal resources integration programs may bring risks to mining safety.

The key techniques and equipments for coal bed methane control in deep gassy multi-seam with low permeability are urgently needed. The multi-coupling issues of stress, fracture and gas field during mining...
need to be solved.

3.2 Key techniques

With the technical advance in coal industry, the methane extraction technique in China was quickly developed. From the 1980s, methane emission in panel faces increased dramatically with introduction of longwall mining, in particular of longwall top coal caving (LTCC) mining. To control the methane emission, integrated methane extraction methods have been used.

In the late 1990s, some new methane pre-extraction techniques, such as methane extraction in coal seams with 200–500 m long horizontal boreholes and controlled pre-split blasting, were used in Pingdingshan mining district. The methane extraction ratio was increased by 20%.

In the early 2000s, extensive researches in prediction, prevention, monitoring and control of hazards associated with methane and coal dust were carried out in the Huainan mining district. Various techniques were developed to extract methane from coal seams with low permeability. During the 11th Five-year, Huainan mining district continued to conduct extensive researches on safety technology and equipment development in deep mining. High-efficient coal bed methane exploitation and utilization techniques were developed, and the key techniques and theories for simultaneous mining of coal and methane without coal pillar were proposed, where multi-seam with abundant methane and low permeability was observed. The coal seams in China are basically featured with complex geological structures, low permeability, high methane content and high outburst risks. 70% of mining districts in China have the same geological conditions as those in Huainan mining district, and these situations indicate that coal seams have to be depressurized before methane extraction. Thus, the emphasis of methane extraction should be put on the underground. Furthermore, the three-dimensional extraction pattern from surface to underground should be built to realize methane extraction by depressurized mining.

In the meantime, there are two major patterns in methane control according to the difference in permeability of coal seams in different mining districts. One pattern is coal mining after methane extraction, named Jincheng pattern, which is suitable for mining districts with low saturation, low permeability, low reservoir pressure and high deterioration degree. Recently, a series of key techniques for methane control of different geological conditions were developed through technical innovation [7, 8, 14–16].

3.2.1 Ground boreholes

To extract methane in overlying depressurized coal seams, the methane extraction boreholes could be arranged in depressurized expansion crack development area or fully depressurized crack development area to get a higher gas extraction rate in a long range. In Huainan mining district, the methane extraction amount of single borehole in depressurized zone is up to 22,190 m³/d, averaging 14,943 m³/d. The extracted methane concentration is 95%, and the total methane extraction is 3×10⁶ m³ annually. In the mining district, the extraction radius of single borehole is normally 300 m, and the largest one is 500 m. The ground borehole can be used to extract methane in mining area and goaf.

3.2.2 Drilling techniques in roadways

(1) Long boreholes or methane extraction roadways in ring-shaped crack circle in roof of mined seams

High-elevation roadways or boreholes should be arranged in vertically wedge-shaped crack circle in roof of mined seams, and the opening position of boreholes should be arranged in vertically wedge-shaped crack circle formed by depressurized mining. In order to reduce the engineering quantity, the pre-arranged boreholes should be drilled as long as possible, normally above 100 m. The number of extraction boreholes is 6–8 in a drilling site, and the optimally negative extraction pressure is 16–20 kPa. According to the investigations of methane extraction from 39 panel faces, all the methane extraction rates exceed 50%.

(2) Methane extraction by grid-type upward crossing boreholes in floor of depressurized coal seams

In the rock strata of floor of protected coal seams, the roadways are arranged, and the crossing boreholes are drilled at proper intervals in the drilling fields towards the protected area of outburst-prone coal seams, as shown in Fig.1. After the mining of lower protected coal seams, the stress of protected coal seam is depressurized and the permeability is increased. A large amount of depressurized methane is extracted by pre-arranged grid-type upward crossing boreholes. In the depressurized process, the permeability of coal seam is increased by hundreds or thousands of times,
and the methane flow resistance is decreased, thus a large amount of depressurized methane is extracted and the outburst risk is reduced. Due to the long distance, the roadways and crossing boreholes will not be destroyed, and the extraction of depressurized methane in protected area will further reduce the methane concentration. The safe and high-efficiency mining can be achieved.

3.2.3 Drilling technique in retained roadways

(1) Methane extraction of goaf in roof of mined seams

2–3 extraction boreholes in dip direction are arranged at an interval of 20 m in retained roadways, and the final boreholes are arranged in the depressurized and vertically banded crack zone at the top of goaf. The desorbed free methane in goaf is extracted, which includes desorbed free methane in the depressurized and vertically banded crack zones at the top of goaf by mining-induced cracks in mined seam and depressurized seam. The depressurized and vertically banded crack zones are located in crack zones of separated strata above the caving zone of goaf roof, as shown in Fig.1.

(2) Depressurized methane extraction of the upper part of remote coal seams

After mining of the first coal seam, the range of depressurized seam in dip direction develops towards roof with a height of 130–150 m, and the gas coefficient of permeability of the depressurized coal seam at the upper part of the protected area will be multiplied by thousand times. Then the crossing boreholes for methane extraction, arranged with spacing of 20 m×20 m, are drilled towards the depressurized zones of remote coal seams in the retained roadways. The extraction boreholes are directly drilled through the upper remote coal seams, and the drilling angle is less than mining-induced depressurized angle. For gently inclined coal seam, the drilling angle is not greater than 80°; and for steeply inclined coal seam, the drilling angle is not greater than 75°, usually 50°–65°.

(3) Depressurized methane extraction in floor

After mining of the first coal seam, the range of depressurized seam in dip direction develops towards floor with a depth of 80–100 m, and the gas coefficient of permeability of the depressurized coal seam at the lower part of the protected area will be multiplied by hundred times. The downward boreholes for methane extraction, arranged with spacing of 20 m×20 m, are drilled through the lower depressurized coal seam from retained roadways to extract the desorbed methane, and then the continuous and high-efficiency extraction of high-concentration methane can be realized. The angle of downward boreholes for methane extraction generally varies from −50° to −80°.

Based on the above discussions, methane outburst disasters of coal mine in China have been effectively controlled in the past few years. The amounts of methane extraction and utilization are increased significantly with a remarkable decrease in DRPMT, and coal production continues to grow. In 2010, China’s coal production reached 3.25×10⁹ t, and the amounts of methane extraction and utilization were 8.8×10⁹ and 3.6×10⁹ m³, respectively, with a DRPMT of 0.725. However, it should be noted that the methane control in low-permeability coal seams is a hot issue. Large numbers of experiments on safe mining under
such conditions have been conducted in the major coal mining countries worldwide, and various effective methane control methods and techniques were developed. However, it is still difficult to prevent the methane outburst in coal mines under such conditions. In recent years, a lot of effective efforts on coal bed methane control have been made in China, especially the scientific concept of simultaneous mining technique of coal and methane without coal pillar, making a breakthrough in the methane control technology. However, there are many types of disasters distributed widely in China’s coal mines with unfavorable mining conditions. So it is difficult to realize the safe mining policy of “methane extraction prior to mining” and energy strategy of “simultaneous mining of coal and methane” in a short period of time. Meanwhile, the theory and technique of simultaneous mining of coal and methane still need further improvement.

4 Methane extraction theory in depressurized mining

Mining practices in low-permeability coal mining areas in China indicate that the key issue of high-efficiency methane extraction is how to improve the permeability of coal seam effectively. The high-efficiency methane extraction should meet two basic conditions, i.e. steady high flow and high methane concentration. To achieve the high-efficiency methane extraction, the extraction boreholes should be arranged in the areas with high degree of methane desorption, high permeability and high methane concentration.

According to strata movement theory, during the coal seam mining, its roof and floor will fall, move and crack, resulting in the in-situ stress relief of adjacent seam. Moreover, coal dilatancy, gas permeability, methane desorption and methane extraction capacity will increase, and methane pressure will decline, thus the risk of outburst will be reduced. Mining practices also show that, once rock movement induced by coal mining occurs, the permeability will be increased by several hundred times, even for the coal seams with very low permeability, which is helpful for methane extraction. Therefore, the high stress in mining area can be transferred to surrounding areas through certain depressurized measures. The stress in the areas will be decreased, the stress distribution state will be improved, and the overlap degree of the stress increasing zones induced by repeated mining will be controllable for a smooth mining [2, 3].

4.1 The depressurized extraction technique of coal seams with low permeability

To solve the technical issues in safe mining of coal seams with low permeability and abundant methane, the depressurized mining scheme of loosening coal mass can be considered through improving the traditional top-to-bottom coal mining program, and the methane extraction principle to increase the gas permeability of coal seams by depressurized mining is put forward in this study. The traditionally natural methane drainage is changed to concentrative extraction, which highlights the scientific concept of simultaneous mining of coal and methane. As shown in Fig.2, a large quantity of desorbed methane is released in radial direction through the depressurized tensile cracks under negative pressures after the mining of first mined coal seam. In the coal seams, the safe and reliable coal seam should be mined first, resulting in swelling deformation, looseness and increase in gas permeability of the upper and lower coal seams. Meanwhile, the extraction roadways and boreholes are arranged at the roof and floor of depressurized coal seam. The theoretical findings are listed as follows:

(1) According to the laws of methane in goaf flowing towards the ring-shaped fractured zone, and methane in depressurized zones of roof and floor flowing towards the extraction boreholes, the reasonable positions of methane extraction roadways were determined.

(2) Under the condition of coal mining, the key
depressurized coal seam was mined firstly. It increased the gas permeability of top and bottom coal seams rich in methane and the coal mining could be achieved after methane extraction. The methane extraction rate reached 65% or more. The methane-rich coal seams were pumped to a low-methane state to adopt safe and high-efficiency mining, coming up to the international advanced level in general.

(3) To efficiently solve the problem that the methane-rich coal seam in the first mined coal seam affected the safe mining, the methane extraction technique was developed to drain the methane in the roof of methane-rich working face. It made the daily production of coal in fully mechanized coal face be improved from 3 000 to 10 000 t.

(4) To reduce the methane outburst and avoid over-limit methane concentration during tunneling, a new pattern of drilling in methane extraction roadways, i.e. methane extraction in heading face and regional methane extraction, was established. The monthly drilling footage in methane-rich coal seams was raised from 70 to 150 m.

(5) To achieve the methane extraction of surface boreholes and reduce the quantity of underground methane projects effectively, a three-dimensional methane extraction pattern from surface to underground was proposed. The field tests were successfully conducted in more than a hundred working faces in Huainan, Jincheng, Xishan, Shaqu and Huabei mining districts.

4.2 Simultaneous mining technique of coal and methane without coal pillar

Although the methane extraction technique in depressurized mining is successful, there still exist some shortcomings such as the large number of methane extraction roadways and boreholes. For this reason, Huainan mining district proposed and implemented the simultaneous mining technique of coal and methane without coal pillar in 2004. According to the occurrences of coal seams, the key depressurized coal seam was mined firstly, and then the non-pillar continuous mining was implemented along the goaf edge. The mining roadways were retained to replace the methane extraction roadways in roof and floor through building a high-strength support body by rapid mechanization, changing the traditional U-shaped ventilation to Y-shaped ventilation. Of course, the retained roadway and the fully mechanized coal face should be advanced simultaneously. The upward (downward) and high-elevation (low-elevation) boreholes were arranged in the retained roadways to extract the methane from coal seam floor (roof) and goaf, and the methane extraction pipes were buried in the working face to prevent a large amount of methane emission in goaf. By using retained roadways instead of excavating various roadways to extract methane, the numbers of roadways and drilling projects can be substantially reduced, and the safe and high-efficiency simultaneous mining of coal and methane will be achieved, as shown in Fig.3.

![Sketch of simultaneous mining technique of coal and methane without coal pillar.](image)

The research findings have been used in more than 40 mining districts, nearly 200 mines, such as Huainan, Huabei, Tiefa, Songzao, Jincheng, and Fenxi, accounting for 60% of the methane-rich coal mines in China. The safe and high-efficiency mining of low-permeability and methane-rich coal mines is achieved. The technical issues of simultaneous mining of coal and methane are adequately solved under complex geological conditions in deep coal mines with abundant methane, low permeability and high in-situ stress, and the economic benefit and safety effect are very significant. The research findings are summarized as follows:

(1) The simultaneous mining technique of coal and methane without coal pillar is set up for coal seams with low permeability and abundant methane. Non-pillar continuous mining along retained roadways with Y-shaped ventilation is achieved and the methane accumulation in the corner is prevented. The extracted methane concentration is as high as 60%–100%, and the methane pre-extraction rate of depressurized coal seams reaches 70% or more, characterized by a long period of time and low cost for methane extraction.

(2) The number of roadways is reduced by 2–3, and
the temperature in working face is lowered. When the mining without coal pillar is implemented, a great amount of coal resources is saved.

4.3 The circular overlying zone theory for high-efficiency methane extraction in coal seams

According to the simultaneous mining characters of coal and methane, the high-efficiency methane extraction should be conducted in the areas with high methane desorption, high horizontal permeability and high methane concentration. Accordingly, based on the model of pressure-relief of surrounding rocks, the permeability distribution, the dynamic migration of extracted methane and the basically geometrical features of the high-efficiency methane extraction range can be plotted in Fig.4. It is of a circular structure in shape, overlying the goaf with certain width, and extending upward at a certain angle, so it can be called as circular overlying zone for high-efficiency methane extraction [16].

Based on the differences in structural characteristics of circular overlying zone in the strike direction, the circular overlying zone can be divided into three parts, i.e. front zone, middle zone and back zone, described as follows:

(1) The front zone, in the rear of working face within a certain distance, is located in effectively depressurized range, in which coal mass has high permeability, thus the adsorbed methane can be fast desorbed and gushed out. The front zone is the main area for desorption and emission of methane.

(2) As the overlying strata sink gradually, the overburden pressure in the middle of mining area with a certain width recovers gradually to the initial pressure, making the mining-induced fractures be re-compacted and permeability be decreased significantly. However, both sides of the mining area with a certain width still retain a higher depressurized degree, so the mining-induced fractures are not disturbed and the permeability of the middle zone is the same as that of the front zone. Both zones connect well with each other.

(3) Due to the deformation characteristics of overlying strata, coal rocks near the open-off cuts still remain a certain depressurized degree and a higher permeability during mining process, and can connect with the front zone through the middle zone, but the whole depressurized degree and permeability of the back zone are less than those of the front zone.

It can be seen from Fig.4 that the circular overlying zone with a certain thickness is distributed at a certain level above goaf, which is determined by requirements of the high-flow and high-concentration methane extraction. The methane of overlying coal seams flowing horizontally in high-permeability zone should be extracted efficiently. It is easy to drain the stope air out when extracting methane beneath the mining area, making the methane concentration decrease. The permeability of coal rocks is low, and the velocity and flow of methane desorption are slow. Thus the extraction flow quantity is small when extracting methane at a certain level above the mining area. The circular overlying zone extends upwards at a certain angle. The external extension angles at two sides of front zone are the similar (section I-I). Besides the external extension angle, it also has two internal extension angles, which are totally different from the external ones and influenced by the compaction characteristics of the mining area (section II-II).

Due to the large area with high connectivity beneath the mining area, the circular overlying zone is distributed at a certain level above goaf. The extension
pattern and mechanism in strike direction are the same as those in dip direction. It extends upward at a certain angle, and the external and internal extension angles are different in strike direction (section III-III). In terms of deformation time of overlying rocks, the external and internal extension angles in the back zone, which are different from those in the front zone, are similar to those in the middle zone.

According to the structural characteristics of the circular overlying zone, its range should be determined by the following geometrical parameters shown in Fig.4: (1) the heights of upper and lower bounds of the circular overlying zone, \( h_{\text{max}} \) and \( h_{\text{min}} \); (2) the projection length \( l \) of the circular overlying zone in strike direction on the goaf level, and the extension angles \( \alpha_1 \), \( \alpha_2 \) and their directions; (3) the projection width \( w \) of the circular overlying zone in dip direction on the goaf level, and the extension angles \( \beta_1 \), \( \beta_2 \) and their directions; and (4) the symmetrical characteristics of both sides of the circular overlying zone.

The theory of the circular overlying zone is applied to working face 1115(1) of Guqiao mine in Huainan mining district, Anhui Province, China. It clearly reflects the high-efficiency extraction range of high-flow and high-concentration methane [16]. It provides important significance for the simultaneous mining of coal and methane, and the control, prevention and utilization of methane.

The high-efficiency extraction of depressurized methane can ensure the safety of the first mined coal seam, reduce the outburst risks of nearby coal seams and convert them into low-methane coal seams, which can guarantee the mining safety of adjacent coal seams and realize the simultaneous mining of coal and methane. Therefore, the simultaneous mining of coal and methane is an important technical way for further exploitation of deep coal resources in China.

5 Prospect of coal bed methane control techniques in China

5.1 Theoretical development

The geological conditions of coal fields in China are very complicated because of several times of strong geological transformations. Therefore, the tectonic fields, evolution of stress and fracture fields in mining process, methane occurrence and methane flow fields are still not clear at present, and the researches on the multi-field coupling mechanism is few. Therefore, the structural features, dynamic mechanical behaviors and mining variation characteristics should be studied according to different geological and operative conditions of coal rocks containing methane, which is helpful for understanding the evolution mechanism of mining-induced stress and fracture fields of first mined coal seam, and for constructing the hydro-mechanical coupling and methane flow models of coal rocks under mining. Finally, the theoretical system of simultaneous mining of coal and methane can be improved and developed.

5.2 Relationship between geological structure and outburst of coal and methane

There is a close relationship between geological structure and outburst of coal and methane. The outburst accidents causing injuries and deaths are basically concerned with faults and folds. In deep mining, it is clear that none-outburst coal seam will turn into outburst-prone coal seam gradually. There are no regular and conclusive cognitions about the relationship between geological structure and outburst of coal and methane. The geological investigation is limited, and small structure detection is still in exploration stage due to the lack of effective techniques and equipments. The outburst regularity and sensitive index should be further studied.

5.3 Prediction of methane content

The methane content of coal seam is a very important index for predicting the methane emission quantity and outburst of coal and methane. Since the outburst mechanism of strong outburst-prone coal seams in deep mining is significantly different from that in shallow mining, the new outburst risk prediction technique such as prediction methods, sensitive indices and critical values should be studied. Meanwhile, with the development of coal mining mechanization level and increase in mining intensity in China, coal mines with high-efficiency and intensive mining activities are increasing gradually, and the previous outburst prediction methods cannot satisfy the requirements of high-efficiency mining at present. Therefore, new outburst prediction methods and techniques should be developed.

5.4 Drilling machines and techniques

Soft coal seams are of large proportion in the total coal seams in China, and drilling in soft and outburst-prone coal seams is a challenging problem.

(1) The key drilling techniques and advanced drilling equipments should be developed, among which the long-life bottom motor, reliable measuring system, etc., are very important. Meanwhile, the crawler drilling machine with automatic walk ability should be
developed urgently to solve the problem of frequent movement of drilling machines and to improve work efficiency.

(2) The key techniques of methane extraction and drilling equipments suitable for soft and outburst-prone coal seams should be developed.

(3) The safe, reliable and effective techniques of remote outburst prediction and high-performance remote control system should be developed.

5.5 Methane extraction techniques

In deep mines, as the methane emission quantity of strong outburst-prone coal seams is getting larger and larger, the outburst risk increases gradually. Therefore, technical innovation should be carried out to achieve safe and high-efficiency mining in China.

5.6 Monitoring of methane extraction

The methane monitoring system has been installed in all major state-owned coal mines. But the investment and construction levels differ considerably. In the near future, the digital, automatic and intelligent mine monitoring system should be fully utilized to realize data sharing.

5.7 Methane utilization

As a kind of clean energy, coal bed methane should be developed and utilized. However, due to the lack of safety management system and standards for quality control, methane utilization rates in different mining districts are diverse. In some mining districts, the methane utilization rate is below 30%. Furthermore, sometimes the low-concentration methane is discharged directly into atmosphere. It is a challenging problem.

6 Conclusions

(1) The simultaneous mining of coal and methane is an effective way for coal bed methane control, which is the most important mining method in China.

(2) Coal must be mined after methane extraction under complicated conditions. The ground coal bed methane extraction should be carried out in coal mining districts with high permeability, while the simultaneous mining of coal and methane should be fully used in coal mining districts with low permeability.

(3) Management is also a key factor for coal bed methane control. The techniques of depressurized mining and the simultaneous mining of coal and methane should be developed to achieve safe mining of methane-rich coal seams.

(4) The theory of circular overlying zone for optimal methane extraction can reflect the distribution and evolution rules of stress, fracture and methane fields in overlying rock strata, which provides a scientific and theoretical basis for methane control.

(5) The technology of coal and methane outburst prediction by methane content method was presented, and the development direction of coal bed methane control was put forward.

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