RESEARCH ARTICLE

A gas outburst prevention and control strategy for single thick coal seams with high outburst risk: A case study of Hudi Coal Mine in Qinshui Basin

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Abstract
Coal and gas outburst is one of the most harmful natural disasters in coal mine production. The frequency and scope of outburst are closely related to the metamorphic degree of coal seam, the depth of coal seam, and the complexity of geological structure. In general, the use of traditional along-seam borehole or cross-seam borehole can meet the needs of gas control. However, for the coal seams with high outburst risk, these methods fail to meet the demands of high-yield and high-efficiency coal recovery as well as safe, green, and economical coal mining. Although pressure-relief gas extraction in the protective seam and coalbed methane (CBM) pre-extraction can eliminate outburst risk in coal seams, these methods can hardly help realize the green development trend of coal and CBM co-extraction because they cannot guarantee the current situation of highly mechanized mining. In this study, a three-dimensional coal and CBM co-extraction strategy was proposed. The strategy includes three levels of three-dimensional gas prevention and control methods. The first level is the combination of ground and underground gas extraction methods, to achieve joint extraction of ground and underground gas. The second level is the full-coverage extraction of the coal resources to be mined, to achieve joint extraction through upper and lower cross-seam borehole and along-seam borehole. The third level is the optimization of ground and underground extraction and utilization systems, to realize the full utilization of CBM and to achieve the goal of coal and CBM co-extraction. The three-dimensional gas prevention and control method constructs a new gas control model for single thick coal seams with high gas outburst risk and realizes the all-round coordination and unity of different gas control methods spatially and temporally. The gas control strategy completely eliminates the high gas outburst risk of a single thick coal seam and has been successfully applied in Hudi Coal Mine. The application results verify that the method can effectively guarantee the operation safety during highly mechanized mining, realize extraction and full utilization of separate-source gas, and provide guidance and direction for coal and CBM co-extraction with similar extraction conditions.
1 INTRODUCTION

China is the largest producer and consumer of coal. In 2018, with 3546 million tons of coal produced, nearly half of the world’s total coal production, it still needs to import 281.5 million tons of coal from other countries. Although China’s coal production is still growing at a rate of 4.5%-5%, it is faced with the severe situation where about 90% of the coal must be extracted underground. However, as China’s shallow coal resources have been depleted, coal resources have to be gained from deep underground, and the coal mining depth is increasing by 20-50 m per year. According to statistics, coal resources under 1000 m, about 5.9 trillion tons, account for 53% of the proved resources. Besides, 62 coal mines have reached a mining depth of over 1000 m, of which the biggest mining depth is 1501 m. Deep coal mining will not only be accompanied by more complex and harsh mining environments where coalbed methane (CBM) content and gas pressure increase significantly, but also bring about more dangerous natural disasters such as coal and gas outburst, impact pressure, highland stress, and strong groundwater.

Coal and gas outburst is one of the most destructive accidents that threaten underground production, because it can cause severe impact and spew out a large number of toxic and harmful gases. Strong airflow carries a large number of powdered coal particles and coal rock blocks which will instantly engulf the entire laneway and quickly occupy space for oxygen, inundating the workers and equipment. The strong airflow may reverse wind flows to other mining space. Along the way, a larger gas explosion or coal dust explosion accident may occur if the wind flow encounters sparks or external sources of fire. As a result, more serious secondary disasters may be caused, and even worse, the entire underground laneway can be destroyed. So far, coal or gas explosion accidents have taken place in nearly 1650 mines in China, among which nearly 98% occurred in coal and gas outburst mines. In 2004, the death toll caused by coal mine accidents reached a record high, 6027. China’s annual death toll caused by coal mine accidents accounts for more than 80% of the world’s death toll. Although the mortality rate per million tons of coal mine is declining year by year, and in 2018 the rate fell to below 0.1 for the first time, coal mine accidents still occur from time to time. In fact, 43 people died in gas accidents in 2018, accounting for 22% of the total number of accidents. It can be seen that the prevention of coal mine accidents is still the most important task of coal mine production.

In order to prevent coal and gas outburst accident, scholars have carried out researches for more than half a century. The relative mature gas control methods mainly include protective seam mining and underground gas pre-extraction. The former refers to the selection of a nonoutburst or low-outburst coal seam as the protective seam to be mined first under the geological condition of coal seam group storage. The outburst risk of protected coal seams can be efficiently and rapidly eliminated by releasing the stress and relieving the pressure of adjacent layers adjacent to the roof and the floor. The method has been widely applied and promoted in some coal-producing provinces such as Anhui, Shenyang, and Guizhou. For provinces where protective seam mining has not been adopted, such as Shanxi, Gansu, Inner Mongolia, and Xinjiang, measures such as cross-seam borehole extraction of original CBM and directed long borehole in the coal seam are used as regional gas control measures to prevent and control coal and gas outburst. However, the following problems still exist: The CBM cannot be extracted to the maximum. In addition, under highly mechanized production conditions, single thick coal seams still undergo frequent gas overrun and vast gas emission into the atmosphere for lack of stable extraction sources, thereby promoting the greenhouse effect.

It is well known that the greenhouse effect caused by methane is 75 times stronger than that caused by carbon dioxide. The Kyoto Protocol lists methane as one of the six major greenhouse gases. In 2012, methane concentrations in the atmosphere reached 1803 ppb, about 150% above the pre-industrial period. Studies show that China’s methane emissions grew by about 1.1 million tons a year in the period 2010-2015, with the growth of methane emissions by China’s coal industry accounting for 11%-24% of the world’s total growth of methane emissions. An article “North China plain threatened by deadly heat waves due to climate change and irrigation” published in the journal Nature Communications in 2019 stated that in 2015, China emitted 61.5 million tons of methane in total and can be assumed as the country with the most man-made emissions of methane in the world. In China, coal industry made the greatest contribution, 33%, to the total man-made emissions of methane. Due to their ample gas storage, mines with high outburst risk are the primary sources of methane emissions, and attention should be paid to efficient extraction and utilization of gas in these mines for the purposes of saving energy and reducing emissions. Chinese government has issued policies and plans related to the development, utilization, and regulation of CBM.
2016, China issued the “13th Five-Year Plan” for the development and utilization of CBM (coal mine gas) which said that by 2020, the amounts of CBM extraction and utilization should reach 14 billion m$^3$ and 7 billion m$^3$, respectively, with an utilization rate of over 50%. However, according to statistics from Statistics Department of State Administration of Work Safety, the CBM utilization rate in China is only 38.2%, far from meeting the target for CBM utilization made by Chinese government. Low efficiency of gas extraction and utilization is the main cause of poor effect of gas and greenhouse gas control.

To solve the above problems, this paper presented a three-level three-dimensional gas control strategy for coal seams with high outburst risk. The main purpose was to (a) introduce effective coal and gas outburst prevention and control methods for coal seams with high outburst risk; (b) provide a coal and gas control strategy for single thick coal seams with high outburst risk; and (c) develop various ways for underground and ground gas extractions to realize coal and CBM co-extraction. Through the engineering practices of gas control and CBM utilization in Hudi Coal Mine, the efficiency of coal and CBM co-extraction strategy proposed in this study was verified.

## 2 | EFFECTIVE METHODS TO CONTROL COAL AND GAS OUTBURST

Coal-bearing basins in China have a complex history of evolution and structural deformation. Therefore, coals in China are mostly reserved in sophisticated reservoirs and characterized by high metamorphic degree, low porosity, and low permeability. Deep coal seams are generally prone to outburst. The proved effective methods to control gas include surface well extraction, protective seam pressure-relief extraction, and underground gas extraction.

### 2.1 | Surface well extraction

Coalbed methane reservoirs in China are characterized by high pressure, low permeability, and low gas saturation, and coal seams are of low coal seam permeability and high adsorption capacity. Thus, to promote the economic output of CBM wells, stimulation methods such as hydraulic fracturing, multigas replacement, and directional horizontal pinnate boreholes are always used to increase fractures in the original coal seam reservoir.\(^31\) The common practice is to inject large particles of solid support agent (quartz sand or ceramic sand) during the injection of high-pressure fracturing fluid. In this way, the width and height of fractures can be maintained for a long time so as to reduce the pressure of gas reservoir and raise the flow conductivity. However, the methane production rate of surface CBM well is related to multiple factors, including coal occurrence environment, coal metamorphic degree, and groundwater composition.\(^35,36\) In addition, coal seams in China have the characteristics of complex evolution process and low gas saturation. Hence, the surface CBM production is generally limited (lower than 1500 m$^3$/d). Nevertheless, surface well extraction has been confirmed by numerous researchers at home and abroad to be an effective measure to treat coal seams with high outburst risk. Surface well construction is independent from underground mining activities, not subject to the constraints of mining space, and easy to implement with little drilling risk. Through surface well extraction, CBM can be pre-extracted in original coal seams without affecting underground production activities.\(^37,38\) If the surface CBM is extracted earlier, the pressure, work, and cost of underground gas outburst control will be reduced, which is conducive to underground mining activities. Although surface CBM wells have been employed since 1967, mining practices in recent years prove that the amount of gas extraction from CBM wells is extremely limited. For most of the outburst coal seams, the method is unsuccessful and is even a failure.\(^39,40\) In 2016, China's CBM production reached 17.3 billion m$^3$, of which CBM production through drilling wells is less than 4.5 billion m$^3$ (less than 30% of the total output). The total number of CBM wells amounts to nearly 35 000, among which drilling wells in Ordos Basin and Yanshui Basin are still operating, while those in Guizhou, Huainan, Fushun, Jiaozuo, Fengcheng, etc, have ceased CBM extraction, mainly because the special coal quality, permeability, structure, and other features of outburst coal seams lead to difficulties in well completion, well cementation, and gas extraction. Qinshui Basin in Jincheng City, Shanxi Province, is one of the hot spots with high CBM yield in China. According to over 10 years’ experience of surface CBM extraction in Qinshui Basin, surface CBM extraction can basically guarantee a gas content decrease of 1-2 m$^3$/t per year. For original coal seam whose gas content exceeds 18 m$^3$/t, CBM extraction must be conducted at least 10 years in advance.

Given the advantages of early and easy implementation, surface well can be constructed in large scale on the surface above outburst coal seams to expand the impact area of transformed coal seam reservoir. In this way, the goal of shortening the extraction time while increasing extraction amount can be achieved. Although most surface wells in China can hardly achieve the extraction effect as Qinshui Basin does, the density of surface wells can be arranged as earlier as possible for reducing or eliminating the outburst risk of coal seams.
2.2 Protective seam pressure-relief extraction

For mines bearing multiple coal seams, protective seam mining is the most cost-effective gas control measure, and the selection of suitable coal seam as the first mining coal seam is crucial for successful implementation of this extraction method.\(^{41}\) If the first mining coal seam is a nonoutburst seam, a laneway can be directly developed for the recovery of it. If all the coal seams are outburst seams, it is necessary to judge the risk of seams first, and the thin or soft seam with the lowest outburst risk should be selected as the first mining coal seam. After the first mining coal seam is recovered, a stress release and gas transport space is formed. It will affect the upper and lower adjacent coal seams where gas and ground stress will be released in large quantities and coal seam permeability and fracture channels will increase notably. As a result, the outburst risks of the upper and lower adjacent coal seams will be significantly reduced (Figure 1A).

Many researchers have studied the pressure-relief effect of interlayer spacing on permeability changes. For example, when the upper adjacent coal seam is located at 20 times the height of the mining coal seam, the vertical stress of the overlying coal seam falls by 60%; the expansion and deformation rate reaches 60%; and the permeability rate surges by 3000 times.\(^{42}\) In contrast, when it is located at 40 times the height of the mining coal seam, the vertical stress of the overlying coal seam declines by 35%; the expansion and deformation rate is about 10-26%; and the permeability of the coal seam jumps by 1000 times. When the lower adjacent coal seam is located 20 m below the mining coal seam, the permeability of the coal seam will rise by 1000 times. In contrast, when it is located 50 m below the mining coal seam, the permeability will increase by 300 times (Figure 1B).

Unfortunately, among nearly 5800 coal mines in China (according to 2018 Annual Report on the Development of the Coal Industry), 73% have not been subjected to protective seam mining for some reasons and are still adopting the method of upper-to-lower coal seam mining. The method of underground gas extraction is mainly adopted in single coal seams. On the other hand, under external force disturbance, the initial fractures of coal seam will further expand and turn into more secondary fractures, so that the permeability of coal seam will surge exponentially. At the same time, the permeability-enhancing measures can be implemented in the drilling channel in coal seams. By taking advantage of the destructive force of high-pressure liquid or gas to cause damage to coal seams that are tens of or even hundreds of meters long, the original reservoir borehole in coal seams is broken and more gas will flow along the fracture channel into the pumping pipeline. As gas flows out of coal seams, coal structure will shrink and coal hardness will be improved. Meanwhile, the comprehensive stresses (ground stress, gas internal energy, and coal expansion energy) that the coal suffers will be transferred to the undamaged deep coal. The hardened shallow coal will offset the comprehensive stress from the deep outburst coal seam, which greatly reduces the outburst risk of coal.\(^{20,44}\)

Gas pre-extraction is mainly realized by means of coal seam borehole and cross-seam borehole. In China, different gas control methods are adopted for coal seams of different deposit conditions. Along-seam borehole or directional long borehole is mainly applied to coal seams with big permeability coefficient and small gas flow attenuation coefficient, while cross-seam borehole is mainly adopted for gas pre-extraction in coal seams with low permeability and big gas flow attenuation coefficient.\(^{45}\)

During the drilling in coal seams, direct contact between human body and outburst coal seams is inevitable. Besides, problems such as gas spewing, drill sucking, and drill jacking tend to take place, posing difficulties in drilling to deep areas, especially to fractured high-outburst coal seams where vast coal powder is discharged by drilling and gas dynamic phenomenon occurs notably. In these seams, construction disturbance can easily induce coal and gas outburst accidents that pose great threat to fieldworkers. As for cross-seam borehole method, despite its great improvement to the extraction efficiency, extremely high gas content and long extraction time in coal seams with high outburst risk are still problems unable to overcome.

2.3 Underground gas extraction

For those single thick coal seams to which the method of protective seam mining is not applied, underground gas extraction is the most effective method to eliminate outburst risks. Coal seams with high outburst risk are generally facing problems such as low porosity, soft coal, and gas flow difficulties.\(^{43}\) On the one hand, by drilling in coal seams, the flow channel caused by external force disturbance can increase gas flow and significantly decrease gas resistance in coal seams. The above analysis reveals the most commonly used gas control methods for recovering coal seams with high outburst risk. However, surface well extraction, protective seam mining, and underground gas extraction are not universally applicable. For coal seams with high outburst risk, the use of a single gas control method or several gas control methods can neither completely eliminate the mining risks caused by high outburst risk, nor realize full utilization of CBM. In view of
this fact, a three-dimensional coal and CBM co-extraction strategy for single coal seam with high outburst risk was proposed in this study. The strategy consists of three levels of three-dimensional gas control methods and can achieve organized, scientific, and rational organization and implementation of various gas control methods (Figures 2 and 3).

3.1 The first level of gas control method

The first level of the three-dimensional gas control method is to achieve the joint mining of surface and underground coal seams. In this gas control strategy, the first thing is to plan for the coal mining areas 8-10 years in advance and to drill CBM wells in the planned working face for CBM extraction in advance. The layout of the surface CBM well should take into account the surface facilities, traffic, construction conditions, and other factors; avoid the influences of mining activities such as underground coal seam laneway development; and be arranged in the middle of the planned mining face or near the return airway. During the surface CBM extraction period after fracturing, the basic information of surface CBM and the dynamic condition of CBM extraction should be grasped in time to provide guidance for the development of coal mine laneway and the recovery work. Under the premise of extraction through big laneways in extraction areas covered by surface wells, laneways can be developed in areas where outburst risks

FIGURE 1 Pressure-relief effect of protective coal seam extraction; (A) the pressure-relief effect of upper and lower coal seams; (B) gas parameter changes after pressure relief

FIGURE 2 Diagram of the three-dimensional coal and CBM co-extraction strategy
have been eliminated. These laneways gradually become the main laneways of the mine and eventually create space for directional long borehole extraction (Figure 4). The strength of directional long borehole method is to drill from a certain small outburst-eliminated area to a huge outburst area and help eliminate the outburst risk of coal seams from dot to face. The specific construction method is to drill over-600-m-long boreholes to outburst areas with the aid of directional rigs in the developed laneway. The borehole should cover the next two or more working faces that are planned to be mined for eliminating the outburst risk of all coals in the area.

### 3.2 The second level of gas control method

The second level of three-dimensional gas control method is to combine the upper and lower spaces of coal seams by
developing rock laneways in both the upper and lower parts of the mining coal seam and conducting cross-seam borehole in the rock laneway. In this gas control strategy, the first step is to develop three rock laneways in the lower part of the mining coal seam (two for covering coal laneway development and one for covering the mining of mining face). The rock laneways for covering coal laneway development should be developed 1-3 years in advance so as to reserve enough time and space to determine the working face and ensure along-seam borehole extraction in the working face with shield support. During the construction of the two rock laneways, upward cross-seam borehole is conducted in the laneway, and boreholes should cover the areas where the laneways are to be arranged so as to eliminate the outburst risk of coal seams before the tunneling of laneway. The central floor rock laneway is located at the axis of the working surface. During the construction of this rock laneway, upward cross-seam borehole is conducted in the laneway to cover coal in the middle part of the working face. During the construction of coal seam laneway, along-seam boreholes are conducted to the coal in the working face to enhance gas extraction there. Meanwhile, the along-seam borehole and the cross-seam borehole of central floor rock laneway can intersect, thus eliminating the extraction blank belt of the working surface (Figure 5). During the mining period, multisource gas control methods such as roof high-level borehole and goaf area pipeline burying are used to intercept the gas that is flowing from goaf area to the upper angle position and to realize safe and efficient gas extraction (Figures 6 and 7).

3.3 The third level of gas control method

The third level of three-dimensional gas control method is to optimize the underground gas extraction system and surface utilization system to achieve the joint use of surface and underground gas extraction. In the method, a scientific and organized production plan is made for coal resource recycle within the coal mining area. In accordance with the order of production, the surface CBM well is arranged in advance for CBM exploitation. Facilities such as surface CBM transmission network, booster station, and delivery terminal should be constructed to transport CBM to gas power plant and other gas terminals. The gas extracted by underground extraction is pumped from the ground gas pumping station to the surface. With the support of ground gas storage tanks (usually 1000 m$^3$) and safety protection equipment for gas transport (antifire, antireflux, and anti-gas-explosive devices), high-concentration and low-concentration gases are transported through the ground gas pipe network to the gas power plant, realizing the integration of gas for civil and industrial use (see Figure 2).

4 STUDY AREA DESCRIPTION

4.1 Mine condition

Hudi Coal Mine is 2.3 km long (east-west) and 3.5 km wide (south-north). Located on the eastern edge of Qinshui Basin in southern Shanxi Province, China (Figure 8), the mine contains two main coal seams, both of which are with high outburst risk. Among No. 3, No. 9, and No. 15 coal seams which are located from the top to the bottom, No. 3 and No. 15 coal seams are the minable coal seams and No. 9 coal seam is the local minable coal seam. The thicknesses of the two main minable coal seams are 5.7 m and 2.6 m, respectively, and the space between them is 86 m. The mine adopts the from-top-to-bottom mining method. No. 3 coal seam whose inclination lies in the range of 2-10° and averages 5° is being mined currently. According to the measurement results, No. 3 coal seam has a maximum gas content of 25 m$^3$/t, a maximum gas pressure of 3.83 MPa, a maximum gas adsorption amount of 35.5 m$^3$/t, a coal seam permeability coefficient of 0.2-0.4 mD, and gas flow attenuation coefficient of 0.031 d$^{-1}$. No. 3 and No. 15 coal seams, both belonging to high-rank anthracite coals, share similar characteristics. However, No. 15 coal seam can adsorb more gas than No. 3 coal seam, and it possesses the highest metamorphic degree and the highest outburst risk among the three coal seams. At the beginning of the mining activities, coal and gas dynamic phenomenon and gas overrun accidents occurred frequently during borehole drilling period.

4.2 Coal quality characteristics

The macroscopic coal rock type of No. 3 coal mainly mined in Hudi Coal Mine is semibright to bright type, with relatively uniform physical properties; endogenous cracks are more developed, brittle, and fragile; apparent density is 1.45; and true density is 1.76. The content of organic microcomponents is relatively high, and the maximum reflectivity of the vitrinite group is 2.62 to 3.364%, with an average of 3.186%, which is a typical high-deteriorating anthracite.

The basic mechanical parameters of coal were measured using the HS-1000P microcomputer-controlled rock triaxial instrument. The mercury injection test was performed on coal samples using the AutoPore 9500 mercury injector, and the coal adsorption capacity was measured using the GAI-100 high-pressure gas isothermal adsorber test (Table 1).

The test results show that the elastic modulus of No. 3 coal seam is relatively low, which means that the stiffness of the coal rock is small, the compressive and tensile strengths are relatively low, and the Poisson ratio is high. The characteristics indicate that the coal seam is susceptible to deformation and has a greater impact on gas permeability. The pores
of coal are relatively developed, and the mercury removal efficiency can reflect the connectivity and morphological characteristics of the pores to a certain extent. The mercury removal efficiency of the test is higher, indicating that the pore connectivity is better. The results of isothermal adsorption test show that the maximum adsorption capacity of dry ashless coal samples can reach 42.56-42.70 m³/t under the condition of Lange pressure (P₁) of 1.95-2.71 MPa, which shows that coal has a strong adsorption capacity for methane.

The desorption characteristics of coal are usually characterized by the desorption rate, and the desorption rate is mostly expressed by the adsorption time. It is a quantitative index to measure the gas diffusion rate and an important technical parameter for intuitively evaluating the development potential of coal seams and the characteristics of coal reservoirs. The theory and practice show that the adsorption time plays an important role in controlling the gas production dynamics, and the CBM adsorption time of different coal ranks is very different. The shorter the adsorption time is and the faster the gas desorption rate is, the more likely the CBM well will reach its peak production capacity in the short term, which will help shorten the development cycle, but will not be conducive to the long-term stable extraction of the CBM well, and vice versa. According to the desorption experiment of methane in No. 3 coal seam of the study area, it can be known that the adsorption time of the coal seam is 8.89-14.08 days, with an average of 8.36 days. The overall adsorption time is higher than that of medium- and low-rank coals at home and abroad, which shows that high-rank coals have lower absorption times and lower desorption rates. It
makes the cycle of developing CBM in this coal seam longer, but it is beneficial to the long-term stable extraction of CBM wells.

### 4.3 Geostress state

The in situ stress is mainly composed of the gravity of the overlying rock mass and the residual stress of paleotectonic movement. Generally, the greater the sudden change of the thickness of the coal seam, the greater the buried depth, and the greater the influence of the structure or fault, the greater the horizontal and vertical stress, the greater the concentrated stress of the coal seam, the more intense the deformation of the coal seam, and the greater the safety risk of mining the coal in the stress concentration area. Under the compression of structural stress, the concentration of structural stress will be formed, and the permeability is often low, while under the tension state, the relaxation of structural stress will be formed, and the permeability is often high. Meng Zhaoping et al collected and analyzed 45 hydraulic fracturing test data in the study area. The study shows that the minimum horizontal principal stress in the study area is between 3.30 and 26.40 MPa, with an average of 11.391 MPa; the maximum horizontal principal stress is between 6.42 and 41.8 MPa, with an average of 17.21 MPa. In order to effectively characterize the stress state of a certain point in the coal reservoir, a lateral pressure coefficient $\lambda$ is proposed, which represents the ratio of the average value of the maximum horizontal principal stress to the minimum horizontal principal stress and the vertical principal stress at a certain point. It can be seen from Figure 9 that when the buried depth of coal seam $h$ in the study area is less than 650 m, the $\lambda$ value is relatively small, but the change range is large. For example, when $h$ is 600 m, $\lambda$ is in the range of 0.4-1.2, and the coal reservoir is in the state of extension; when $h$ is 650-1000 m, $\lambda$ value continues to increase, but the change range is narrow. For example, when $h$ is 1000 m, $\lambda$ is in the range of 0.80-1.15, and the coal reservoir is in the state of extension-compression transition. When $h$ is more than 1000 m, the coal reservoir is in compression state. From the extensional zone to the compression zone, the fractures tend to close and the permeability gradually decreases.

The No. 3 coal seam of Hudi Coal Mine is 500-700 m deep, and the coal reservoir is relatively shallow in the extensional

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**FIGURE 7** Diagram of roof high-level borehole

**FIGURE 8** Diagram of gas reservoir distribution of Hudi Coal Mine
zone, with good permeability, and relatively deep in the transition zone, with general permeability. The first mining face of Hudi Coal Mine is 600 m deep and located in the syncline structural zone. The results of laboratory mechanical tests of surface well and coal core drilling in face construction show that the maximum horizontal principal stress is 18.34 MPa, the minimum horizontal principal stress is 9.41 MPa, the vertical stress is 16.47 MPa, the pressure coefficient $\lambda$ is 0.84, the coal reservoir is in the transition zone, and the permeability is general.

5 | ENGINEERING APPLICATION

5.1 | The first level

Since the construction of Hudi Coal Mine in 2006, surface CBM extraction has been used. Surface wells were arranged in accordance with the mining plan. In the early stage, CBM wells were mainly arranged on the ground above the transport roadway and the return airway, in order to provide safe conditions for the construction of underground mining laneway. In the later stage, CBM wells were mainly distributed in the middle of the mining face and avoid the position of ventilation laneway of the working face, in order to eliminate the outburst risk of coal in the working face in advance. The surface wells can be classified into three types. The first type is used for the gas extraction of No. 3 main mining coal seam, that is, the pre-extraction of No. 3 coal seam. The second type is used for the joint gas extraction of No. 3, No. 9, and No. 15 coal seams, namely the pre-extraction of multiple joint-mining coal seams. The third type is used for the extraction of current goaf area and extracted old goaf area, namely the extraction of goaf area of No. 3 coal seam. Up to now, a total of 312 ground CBM wells have been constructed, of which 81 are for extraction of No. 3 coal seam, 226 are for joint extraction of No. 3, No. 9, and No. 15 coal seams, and 5 wells are for extraction of goaf area of No. 3 coal seam (Table 2).

During the construction of surface wells in Hudi Coal Mine, hydraulic fracturing was used to improve the reservoir. Specifically, it promoted the flow capacity from the coal seam to wellbore and expanded the range of water drainage and pressure reduction, thus effectively improving the yield and extraction rate of CBM. The first and second types of surface wells required the application of high-pressure hydraulic fracturing with conventional active water and sand ingress. Lanzhou quartz sand, in which the roundness and spherical degree are not smaller than 0.7, was adopted as the support agent for keeping the fracture unobstructed after reservoir fracturing. For the second type of surface wells, No. 3 and No. 15 coal seams were subjected to hydraulic fracturing, while No. 9 coal seam was only hydraulically perforated and not hydraulically fractured. Through manual fracture monitoring techniques such as microseismic method and potentiometry method, the mode of reservoir fracture caused by surface well was verified to be mainly horizontal fractures. The impact range of fracturing was elliptical, with the length of the long half-axis being 120-150 m and the short half-axis being 50-80 m. The gas flow of 100-m borehole in the coal seam affected by fracturing activity was 1.33-17.5 times that of the coal seam outside the fracturing-affected area, and the gas volume fraction increased by about 35%-60% on average (Figure 10).

The average daily CBM output of the first type of surface wells is 2600 m$^3$/d. Taking the five wells including H-027 as examples (Figure 11), till September 2019, after continuous extraction for 2300 days, the cumulative gas extraction volume is 5.98 million m$^3$/d and the current extraction volume remains 3700 m$^3$/d. The second type of surface wells is used for the continuous gas extraction from No. 3, No. 9, and No. 15 coal seams. Their extraction volume is greater than that of the first type, with the maximum daily CBM extraction being up to 14 200 m$^3$/min and the average daily gas output being 6000 m$^3$/d. From the gas extraction volume of H-32, it can be seen that after continuous extraction for 1800 days, the total amount of CBM extracted is about 11.34 million m$^3$. The third type of surface wells mainly extract gas in the current goaf area (L-type wells) and the old goaf areas (extraction wells) during and after the mining process. As the surface

| Sample number | Compressive strength/MPa | Tensile strength/MPa | Modulus of elasticity/MPa | Poisson’s ratio | Porosity/% |
|---------------|-------------------------|----------------------|--------------------------|----------------|------------|
| HD1           | 9.56                    | 0.43                 | 1120                     | 0.33           | 9.1171     |
| HD2           | 6.47                    | 0.56                 | 1044                     | 0.32           | 8.2444     |

FIGURE 9 The relationship between lateral pressure coefficient and buried depth

TABLE 1 Petrophysical parameters of coal
wells in Hudi Coal Mine expand to the original coal seam reservoir in the west and the north, the gas content of coal seam will be higher than that of the current first-panel production area, and the layout of surface wells will gradually change from the first type to the second type. Therefore, the daily methane production is expected to increase in the future. Through 12 years of extraction at a daily extraction volume of 4500 m³ since 2006, the CBM content of No. 3 coal seam has decreased from 30 m³/t (the highest level) to lower than 8 m³/t (the current level). The outburst risk of coal seams has been completely eliminated. At the same time, it can be foreseen that No. 9 and No. 15 coal seams can be jointly extracted in large quantity by the second type of surface wells, which will not only increase the yield of surface CBM but also solve the problems facing gas control in deep coal seams with high outburst risk 15-20 years in advance.

After using surface wells to eliminate the outburst risk of coal seams in the main laneway distribution area, directional long borehole was adopted to extract in coal seams on both sides of the main laneway and the coal seams where mining laneways were located. Directional long borehole was carried out in nonoutburst areas, while the extraction was conducted in outburst areas. In this way, the outburst areas could be transformed into nonoutburst areas, and a circular replacement relationship that realized the stride gas extraction could be achieved. The length of boreholes was 500-600 m; the drilling field spacing was 300-400 m; 8-10 boreholes were drilled in each drilling area; and final spacing between each borehole was 8-10 m. Residual gas content was tested for the coal seam laneway planned in the second working face before digging activity so as to determine whether outburst risk of the coal seam laneway had been eliminated. When the residual gas content became lower than 8 m³/t, it could be judged that the outburst risk of the coal seam laneway in the second working face had been eliminated and activities could be conducted in coal seam laneway. However, if the outburst risk had not been eliminated yet, extraction should be further carried out until the coal in this range is free of outburst risk. The gas control method of coal seam directional long borehole can avoid the dangerous direct contact with outburst coal seams and improve extraction efficiency of long borehole by improving the coal seam reservoir during the construction of surface well. In this way, the method succeeds in achieving the win-win results of surface and underground gas extraction.

| Mercury removal efficiency/% | Total pore volume/(mL/g) | Median aperture/nm | Langmuir volume/(cm³/g) | Langmuir pressure/MPa | Adsorption saturation time/day |
|-----------------------------|-------------------------|--------------------|-------------------------|-----------------------|-------------------------------|
| 80.43                       | 0.0614                  | 246.17             | 42.56                   | 1.95                  | 8.89                          |
| 75.86                       | 0.0758                  | 184.25             | 42.7                    | 2.71                  | 14.08                         |

5.2 | The second level

5.2.1 | Gas pre-extraction before mining

For excavating coal seam laneways with high outburst risk, it is necessary to develop a floor rock laneway directly below two coal laneways 2-3 years in advance for extracting above unconstructed coal laneway with the support of shield, so as to eliminate the outburst risk efficiently and realize rapid excavation. For the mining working face, a floor rock laneway is constructed right below the central axis of working face in the dip direction. For coal in the middle of the mining face, a grid drilling is conducted to cover the whole coal and the coverage scope is 80-120 m. Short boreholes are created on both sides of the working face in the formed laneway space during the construction of air laneway and machine laneway. A full-width-coverage extraction is conducted in the working face whose length in the dip direction is 220-300 m. If only along-seam short borehole is constructed, the problems of gas overrun and coal and gas outburst may be caused by gas extraction blank belts in the working face due to the short borehole length. Fortunately, the above gas control method can completely avoid the problems. In China, the grid cross-seam borehole maintains a spacing of 5-8 m, so as to cover the coal lane and a 15 m scope on both sides of the laneway. In the middle of the working face, the bottom pumping lane is generally arranged in the central axis of working face in the dip direction, in order to eliminate the outburst risk in the 40-60 m scope on both sides of the working face. The distance between short boreholes in coal lane is generally 3-5 m; the borehole length is 60-100 m; and the along-seam short borehole and the cross-seam borehole in the middle of the working face should overlap for no less than 15 m.

5.2.2 | Extraction during mining

The extraction methods such as roof rock laneway, pipeline burying in goaf areas, and upper corner tube inserting are used to realize low gas gushing under the condition of highly mechanized mining of the working face. For the working face whose outburst risk has been eliminated, before coal mining, in order to avoid vast gas emissions and other problems caused by high degree of mechanization,
TABLE 2 Extraction conditions of some surface wells in Hudi Coal Mine

| Panel number | Name of gathering station | Number of wells under pumping | Extraction time | Well type | Daily average gas production/(m³) | Monthly cumulative pumping volume/(m³) | Annual cumulative water pumping/(Ten thousand m³) | Total accumulated pumping capacity/(Ten thousand m³) |
|--------------|---------------------------|-------------------------------|-----------------|-----------|----------------------------------|----------------------------------------|-------------------------------------------------|--------------------------------------------------|
| Production area | No. 30                    | 20                            | 2006            | First type          | 22,613.68                          | 701,024                               | 456.67                                           | 2,734.46                                          |
|               | No. 158                   | 13                            | 2010            | Second type         | 4099.87                            | 127,096                               | 114.95                                           | 2,165.33                                          |
|               | No. 66                    | 19                            | 2010            |                       | 16,193.35                          | 501,994                               | 342.09                                           | 5,721.6                                           |
|               | No. 130                   | 7                             | 2006            |                       | 8641.42                            | 267,884                               | 210.11                                           | 3,928.88                                          |
| Planning area  | No. 83                    | 15                            | 2007            |                       | 9602.84                            | 297,688                               | 200.25                                           | 7,862.16                                          |
|               | No. 184                   | 15                            | 2007            |                       | 22,034.58                          | 683,072                               | 455.63                                           | 5,104.2                                           |
|               | No. 220                   | 13                            | 2010            |                       | 7408.65                            | 229,668                               | 155.53                                           | 2,030.37                                          |
|               | No. 38                    | 24                            | 2006            |                       | 26,452.39                          | 820,024                               | 570.58                                           | 3,612.94                                          |
|               | No. 74                    | 18                            | 2007            |                       | 25,872.52                          | 802,048                               | 534.23                                           | 13,619.3                                          |
|               | No. 216                   | 23                            | 2007            |                       | 22,969.29                          | 712,048                               | 482.44                                           | 7,020.02                                          |
|               | No. 55                    | 13                            | 2007            |                       | 9280.58                            | 287,698                               | 212.57                                           | 6,874.85                                          |
|               | No. 114                   | 43                            | 2007            |                       | 45,492.39                          | 1,410,264                             | 889.85                                           | 7,047.78                                          |
|               | No. 223                   | 13                            | 2010            |                       | 8292.13                            | 257,056                               | 153.34                                           | 1,716.72                                          |
|               | No. 192                   | 18                            | 2010            |                       | 10,257.87                          | 317,994                               | 199.03                                           | 3,091.89                                          |
|               | No. 245                   | 18                            | 2010            |                       | 13,480.52                          | 417,896                               | 252.38                                           | 3,853.24                                          |
|               | No. 17                    | 9                             | 2006            |                       | 10,257.94                          | 317,996                               | 222.67                                           | 2,568.98                                          |
|               | No. 16                    | 5                             | 2006            |                       | 4904.71                            | 152,046                               | 106.09                                           | 1,391.84                                          |
| Mining area   | No. 6                     | 2                             | 2017            | Third type           | 3750.23                            | 11,206                                | 67.24                                            | 87.52                                             |
it is necessary to comprehensively control gas during the extraction period. The above-mentioned local gas control methods are primarily adopted for ensuring efficient mining. The first method refers to the method of constructing a rock laneway above the roof that is a certain distance away from the mining coal seam. In the construction process, a downward cross-seam borehole is drilled to extract gas in the working face, and phased closed extraction is conducted in the rock lane before the mining of the working face. High-level boreholes along the roof are drilled within the wind lane of the working face with a 200-300 m distance between each borehole. In the drilling area, directional long borehole is conducted for gas extraction in goaf area. Both the roof rock lane and the high-level boreholes are arranged in the fracturing belt of the goaf area to extract in accumulated gas in the roof fractures of goaf area. For the second method, pipelines are buried in the goaf area at the rear of the working face open-off cut for the purpose of closed extraction. The method can prevent the gas left behind in the mining area from migrating to the upper corner. The third method is independent of the high and low negative pressure extraction systems on the ground. It establishes a fixed gas pumping station underground and specially arranges an extraction system to strengthen the extraction in the upper corner. The pipeline is inserted into the upper corner triangle area for about 60-80 mm to intercept the gas that is about to flow to the upper corner.

FIGURE 10  Diagram of the surface well and fracturing impact; (A) diagram of hydraulic fracturing; (B) fracturing impact range

FIGURE 11  Diagram of the surface well extraction; (A) curve of the first type of CBM extraction; (B) curve of the second type of CBM extraction
5.2.3 Extraction after mining

A surface extraction well can generally meet the needs of pre-extraction, extraction during mining, and extraction in the goaf area, realizing the purpose of one well for three uses. Pre-extraction is mainly used for CBM extraction before recovery in mining areas. Extraction during mining mainly aims to disturb coal and rock through working face mining to improve the permeability so as to increase gas extraction rate and relieve ventilation pressure. Extraction in the goaf area mainly aims to deal with the gas in the goaf area. It helps reduce the amount of gas that pours from the goaf area to the mining face and solve the problem of gas overrun in the mining face. The position of surface extraction wells directly affects the extraction effect. On the premise of satisfying the overall extraction efficiency, the position of surface extraction wells should be selected in the central axis of mining face in the dip direction, with the drilling space between boreholes being 300 m, in order to maximize the serve time of the wells. For sloping coal seams, considering the gravity, it is better to set the surface extraction wells near the return airway, with the distance to the return airway being generally 1/3 the length of the working face. As for the vertical depth of the wells, the bottom of the wells is generally set in the fracturing belt above the caving zone, with the appropriate distance being 30-40 m to the mining face.

In Hudi Coal Mine, aiming at improving the utilization of low-concentration gas, raising the recovery rate of coal mine gas resources, and preventing the high-concentration gas stored in goaf area from flowing to the mining space, two mining wells are constructed, of which No. 13 extraction well serves the current production working face and No. 12 extraction well serves the closed goaf area adjacent to the working face. During production of the working face, No. 13 extraction well is used to extract gas for 112 d. In this period, it serves a production working face length of 208 m, maintains an extraction concentration of 75%-80%, and helps extract 913,000 m³ of gas in total (Figure 12). After recovery of the working face, gas extraction remains in the closed goaf area for 123 days, and a total of 354,000 m³ of gas in the closed goaf area is extracted. After the goaf area is closed, fractures in the goaf area are gradually closed due to the stress recovery of overlying strata. In this case, despite a high gas concentration of 96% in the goaf area maintains, the extraction rate still maintains 0.6 m³/min because the fracture channels are blocked (Figure 13).

After the second level of gas extraction in the three subsystems before, during, and after mining, the working face realized safe and efficient mining. The production data of a total of 220 days of working face from the beginning of mining to normal mining were counted (Figure 14). During the mining, the safety of the working face is ensured by along-seam borehole, cross-seam borehole through the floor rock tunnel, extraction roadway on roof, buried pipe in goaf, and directional long drilling on roof. Daily gas drainage volume of working face is 140,000 to 160,000 m³/d, gas drainage volume of rock roadway on roof is 38,000 to 72,000 m³/d, accounting for 45% -50% of the total gas drainage in the working face, and the ventilation gas emissions 25,000-35,000 m³/d.

5.3 The third level

China’s coal mine gas utilization rate is only at about 35%, mainly because the high-concentration gas in coal seams is
not extracted before coal mining. Therefore, although the outburst risk of coal seams is eliminated, about 40% of the gas stored in coal seams is released to the mining area under the impact of extraction stress. Accordingly, this part of gas becomes low-concentration gas (with concentration generally being lower than 1%) and is emitted to the atmosphere. To effectively improve the gas extraction concentration and gas utilization efficiency of coal seams with high outburst risk, Hudi Coal Mine has optimized the ground utilization system and underground extraction system.

5.3.1 Optimization of the underground gas extraction system

The process of underground coal production is rather complex. A variety of reasons may cause instability of underground gas extraction system and affect gas utilization. One of the reasons is that different work processes will interfere with each other. For example, adjustment of extraction system, connection of new pipeline, and continuous use of auxiliary devices like steam separator during drilling construction will allow a large amount of air to enter the pipeline system and to dilute the original high-concentration gas into low-concentration gas. Another reason is that boreholes with different concentrations co-exist in the same extraction system. Generally speaking, there are tens of thousands of boreholes underground, among which high-concentration gas can be extracted through newly revealed boreholes while low-concentration gas is extracted through the boreholes that have already served for more than 1 year. The co-existence of different boreholes with different extraction times in the same extraction system will cause instability of gas concentration and further affect the efficiency of gas utilization. Consequently, the gas is released to the atmosphere because its concentration is too low to reach the lower limit of utilization concentration. To this end, Hudi Coal Mine optimizes the underground gas extraction system. The main practice is to incorporate the processes that affect the stability of the high-concentration extraction system into a new extraction system, namely the medium-concentration extraction system, and to separate the original two systems into three systems (Table 3). The newly formed medium-concentration extraction system is mainly responsible for gas extraction through the boreholes under construction (50 rigs operating simultaneously) and the low-concentration boreholes which have been served for a long period (approximately 6000 boreholes, accounting for 45% of the total number of boreholes).

Before the renovation of the extraction system in 2017, the high-concentration gas power generation system in Hudi Coal Mine generated about 150 000 kWh/d. Besides, about 180 000 m³/d of high-concentration gas was released to the atmosphere, mainly because the high-concentration gas in the system could not be used after being diluted to lower than 30%. After system optimization in 2017, the ground pumping station with the original total extraction capacity of 320 000 m³/d is raised to 500 000 m³/d (by increasing 1200 m of new pipelines and two new pumping stations). High-concentration pre-extraction systems with extraction concentration of no less than 50% mainly serve for the high-concentration gas extraction areas such as the kilometer-deep module area, cross-seam borehole area, and the ordinary along-seam area. The medium-concentration extraction system with an extraction concentration of 10%-50% serves
for the old goaf area, the blowout prevention drilling system, and the common low-concentration gas extraction boreholes. The low-concentration extraction system with an extraction concentration of 3%-10% serves for pipeline inserting in the upper corner and pipeline burying in the rear goaf area.

### 5.3.2 | Ground gas utilization system optimization

Before the renovation of ground gas utilization system, Hudi Coal Mine mainly relied on the first-phase gas generator set completed in 2016 to carry out high-concentration gas power generation and to realize the field conversion of underground high-concentration gas. The gas source is mainly the ground CBM and the extracted underground high-concentration gas (concentration higher than 40%). The power generated by gas is mainly used for mine self-use and national grid power supply. Gas with concentrations being lower than 40% (approximately 150,000 m³/d) is released into the atmosphere, resulting in a waste of resources.

In order to improve the efficiency of coal mine gas utilization, Hudi Coal Mine established a low-concentration gas utilization system based on its adjustment of gas extraction system to achieve independent operations of underground high-concentration, medium-concentration, and low-concentration extraction systems. The system expanded the capacity of the original high-concentration gas generator set by installing 8 new 1.3 MW container-type low-concentration gas generator sets at the end of 2018. In this way, it can realize field conversion of underground low-concentration gas. The capability parameters before and after the transformation of Hudi gas power plant are shown in Table 2. Specifically, the low-concentration gas drainage decreased from 95 m³/min to 17.1 m³/min; the utilization efficiency increased by 90%; and the thermal energy efficiency increased by 26%. Both the mine and surrounding rural areas are benefited. At present, the total installed capacity of Hudi gas power generator has increased to 20.4 MW. The gas utilization system of Hudi Coal Mine, which realizes full utilization of coal mine gas, has become a benchmarking unit that takes the lead in officially operating “one-stop” high-concentration and low-concentration gas power generation in China.

### 5.3.3 | Hudi Coal Mine gas control effect assessment

Before the gas utilization system was established, all the gas extracted from the mine was discharged into the atmospheric space except for bathhouses, dormitories and canteens. The utilization rate of gas was only 38%, and the annual volume of gas exhausted was about 15 Mm³. In 2015, With the optimization of the drainage system, the gas drainage volume increased from the original 10 Mm³ to 42 Mm³. Because the mine does not have a gas utilization system, about 45 Mm³ of gas is discharged into the atmosphere each year, causing serious waste of resources and environmental damage. In 2017, the high-concentration gas utilization system was operated, and the gas utilization rate increased from 6.6% to 55%. At the beginning of 2018, the low-concentration gas utilization system was operating, and the gas utilization rate further increased to 90%. Correspondingly, the amount of gas discharged into the atmosphere from the gas extracted from the mine has been reduced from 60 Mm³ to 9 Mm³ (Figures 15 and 16).
### Table 3: Comparison between the parameters of gas extraction and utilization system before and after optimization

| System | High-concentration pre-extraction system | Low-concentration extraction system |
|--------|-----------------------------------------|-------------------------------------|
| Before optimization | | |
| Number of pumps in operation | Two 2BCE72 | Two 2BCE72 |
| Negative pressure/kPa | 42.5 | 30.3 |
| Mixture proportion/(m³/min) | 289 | 520 |
| Scalar/(m³/min) | 115.6 | 47.8 |
| Concentration/% | 40 | 9.2 |
| Daily extraction amount/ (10 000 m³) | 35.5 | |
| Serving area | Boreholes on the pre-extraction area and in drilling period | Goaf area pipeline burying |
| Function | High gas concentration power supply, output, and self-use for mine | Drainage |
| Power generating system | | |
| Type | TCG2020v20 | — |
| Power | 10 MW | — |
| Concentration | 42.5% | — |
| Daily power supply/ (10 000 kWh) | 84.6 | — |
| After optimization | | |
| Number of pumps in operation | Two 2BCE72 | Two 2BCE72 |
| Negative pressure/kPa | 38 | 21 |
| Mixture proportion/(m³/min) | 186 | 300 |
| Scalar/(m³/min) | 93 | 60 |
| Concentration/% | 50 | 20 |
| Daily extraction amount/ (10 000 m³) | 63.7 | |
| Serving area | High-concentration areas by directional long borehole and common drilling | Low-concentration areas by BOP drilling and common drilling |
| Function | Power supply, output, and self-use for mine | Power supply, civil use, and self-use for mine |
| Power generating system | | |
| Type | TCG2020v20 | JGS420GS-S.L |
| Power | 10 MW | 10.4 MW |
| Concentration | >50% | 20%-50% |
| Daily power supply/ (10 000 kWh) | 178.2 | 65.24 |

6 | Discussion

Underground gas extraction should be scientific, normative, and efficient, and gas control should coordinate and unite the whole and the part. In the respect of macroscopic and overall gas control, on the basis of scientific coal mining plan for the next 5-10 years, it is necessary to formulate the corresponding gas control plans in detail, work out the phased tasks of gas control, and provide necessary personnel, equipment, and funds, in order to realize the effective conduction and connection of gas control. In the respect of local gas control, it is necessary to combine the three-level three-dimensional gas...
control strategy with permeability-enhancing measures, so as to maintain the extraction systems of three different concentration levels, adjust the gas concentration of each system in time, and exchange to the corresponding extraction pipe network.

During the construction of surface CBM wells, the second type of surface wells shall be arranged in priority to realize the advanced joint extraction of No. 3, No. 9, and No. 15 coal seams and realize the purpose of one well for three uses. In the utilization of CBM, the surface and underground extraction and utilization systems should be optimized in time, according to the principle of using high-concentration gas for utilization and low-concentration gas for power generation. While the extraction capacity should meet the demand, the stable concentration of extraction system and the lasting supply of extraction volume should be guaranteed. Meanwhile, the technology of purifying and capturing gas discharged by ultra-low-concentration airflow should be researched on to maximize the gas utilization efficiency.

7 | CONCLUSION

High outburst risk of coal seam is the main safety problem faced by coal mines in China at present and in the coming decades. The substantially increasing emission of greenhouse gas during coal production is also an environmental problem that must be solved. Although the methods of surface well and underground pre-extraction can effectively eliminate the outburst risk of coal seam, the CBM resource is still unable to be effectively utilized. It is a good way to achieve the maximum gas extraction of coal seams with high outburst risk by combining the coal reservoir improvement through surface well with the comprehensive underground gas extraction methods. Besides, the study aims to maintain stable gas extraction concentration and efficient gas utilization and realize coal and CBM co-extraction by optimizing the underground gas extraction system and the surface utilization system.

A strategy of three-dimensional coal and CBM co-extraction is put forward. The strategy consists of three levels of gas prevention and control methods. The first level is to combine the surface CBM extraction and underground directional long borehole extraction to realize the three-dimensional surface and underground extraction. The second level is to construct cross-seam borehole from the roof rock lane to the coal seams and carry out along-seam borehole in coal seams to realize the three-dimensional extraction which combines the upper and lower coal seams. The third level is to optimize the surface and underground extraction and utilization to realize the joint exploitation of coal and CBM.

Coal mining enterprises should make scientific plans for the next 5 or 10 years and make smooth deployment for extraction and mining work, so as to create space and specify position for the implementation of the first level. The second level will be carried out 5-10 years after the implementation of the first level. Different gas extraction methods will be used before, during, and after coal mining to maximize the amount of gas extraction in the coal seam, for completely eliminating the risk of coal seam outburst and ensuring the safety of coal mining. At the same time, the amount of gas discharged by airflow will be greatly reduced and the gas utilization efficiency will be significantly improved. The optimization of underground gas extraction system and surface utilization system is the fundamental guarantee to realize the green and safe mining of coal and CBM. The organized connection and good coordination among the three levels of gas
extraction and utilization methods in time and space are the future direction for coal mine development.

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest.

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