

# Summary of Development and Utilization Status and Prospect Enlightenment of Coalbed Methane

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**Abstract:** Coalbed methane is an important hazard source in the process of coal mine production, and it is also an important clean energy source with multiple ways of power generation and civil use. This paper summarizes the present situation of the development and utilization of coalbed methane, and discusses its prospect. Through the systematic review of the distribution of domestic coalbed methane resources, mining technology, policy environment and market demand, it is revealed that the importance of coalbed methane as a clean energy in the transformation of China's energy structure is increasingly prominent. This paper analyzes the main technical paths in the current coalbed methane development and the application effect in improving the recovery rate. At the same time, the challenges faced in the development and utilization of coalbed methane are pointed out, such as complex geological conditions, water resource consumption, environmental pollution risk and economic benefit fluctuation. Furthermore, based on the existing research and practice, the paper looks forward to the innovation trend of coalbed methane development technology. In addition, the potential contribution to achieving the goal of carbon neutrality is also discussed. In summary, the development and utilization of coalbed methane is entering a new stage of rapid development. Technological innovation and policy guidance will be the key factors to promote its sustainable development, and provide strong support for the optimization of energy structure and environmental protection.

**Keywords:** Coalbed methane; Coalbed methane development and utilization of coalbed methane development; Development direction of coalbed methane mining technology; Carbon neutral.

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## 1. Introduction

Coalbed methane is a gas resource associated with coal. It refers to the hydrocarbon gas stored in the coal seam. It is an unconventional natural gas with methane as the main component. Coalbed methane is mainly composed of hydrocarbon gases adsorbed on the surface of coal matrix particles, partially free in coal pores or dissolved in coal seam water. Coalbed methane is an associated mineral resource of coal. As a new type of clean energy, coalbed methane is a kind of unconventional natural gas. It is a clean, high-quality energy and chemical raw material that has risen internationally. The exploitation of coalbed methane can not only optimize and improve the existing energy structure, but also protect the atmospheric environment, and ensure that the whole production process of coal mine is safer and more reliable.

China is rich in coalbed methane resources. However, this advantage has not been fully converted into actual production. The reason is that a large number of resources are concentrated in low-rank and deep coal seams, and mining technology in these areas has not yet made breakthrough progress. In addition, the problem of insufficient universality of CBM development technology, coupled with the shortcomings of high investment cost and long return period, has led to the embarrassing situation of 'large reserves and low production'.

It is the only way to solve these problems to establish an exploration and development technology system suitable for the geological characteristics of coalbed methane in China. In view of this, the author discusses the development status and development trend of coal seam gas mining technology at home and abroad, in order to provide a useful reference for China's coalbed methane reservoir reconstruction technology research.

## 2. Development and Utilization Status of Coalbed Methane at Home and Abroad

### 2.1. Coalbed methane formation conditions and accumulation mechanism

Coalbed methane is closely related to coal seam, and coal seam is the source and storage layer of coalbed methane. In the process of coalification, the organic matter in the coal seam generates coalbed methane, which is mainly adsorbed in the coal pores. Coalbed methane has energy value, and its development and utilization are of great significance to the coal industry and energy field.

In the process of coalbed methane generation, the early biogenetic stage is mainly manifested in the relatively shallow buried strata of the coal seam. Specifically, it is usually located within 400 meters underground. The occurrence of this stage is mainly attributed to the promotion of microbial activity in the shallow environment. Subsequently, the secondary biogenic stage often dominates in the later uplift process of the coal seam. This process is significantly affected by a variety of environmental conditions, such as temperature and humidity. These environmental factors work together on the microbial community, thereby regulating the formation of secondary biogas. As for the thermogenic stage, it is closely related to the gradual evolution of coal rank and constitutes one of the key paths for the formation of coalbed methane. At this stage, with the increase of coal seam burial depth and temperature conditions, organic matter undergoes pyrolysis and generates a large amount of thermogenic coalbed methane. This process is of great significance for the evaluation and development and utilization of coalbed methane resources. Table 1 briefly summarizes the

accumulation mechanism of coalbed methane at different stages, which is helpful to understand the generation and

accumulation process of coalbed methane.

**Table 1.** Evolution of coalbed methane accumulation mechanism

Phase	Accumulation mechanism	Evolution of coalbed methane accumulation mechanism
Early biogenetic stage	Biogenetic gas	The coal seam is buried shallow, and the thermal effect is not enough to change the organic matter structure of the coal seam. The chemical reaction with the participation of microorganisms decomposes the organic matter. Various functional groups and side chains begin to degrade under the action of heat, forming a biogenetic gas dominated by methane.
Secondary biogenetic stage	Secondary biogenic gas	After the coal seam is uplifted, the environmental conditions are suitable for the survival of microorganisms. Microorganisms are brought in by atmospheric precipitation through the coal seam outcrop, metabolizing organic compounds such as moisture and n-alkanes to produce methane and carbon dioxide.
Thermal genesis stage	Thermogenic gas	When the coal rank evolves to the mature and high mature stages, the organic matter is pyrolyzed under high temperature and high pressure to generate thermogenic gas, which mainly occurs in the stage from long flame coal to anthracite.

## 2.2. Reserves, distribution and potential of coalbed methane resources in China

China's coal resources are mainly distributed in North China and Northwest China, from Mohe in the north to Hainan Island in the south, from Yining in the west, and from the east to the sea area. There are 39 coal-bearing basins in China, which can be divided into 60 main coal-bearing areas. The total amount of coal resources is about  $5 \times 10^{12}$ t, ranking third in the world [1].

There are more than 100 CBM enrichment zones in China, with a total reserve of about  $30.8 \times 10^{12}$  m<sup>3</sup>. CBM resources are mainly distributed in North China and Northwest China, of which 14 are above  $0.5 \times 10^{12}$  m<sup>3</sup>, accounting for 93.4 % of the resources. Among them, there are 9 basins with gas content greater than  $0.5 \times 10^{12}$  m<sup>3</sup>: Ordos, Qinshui, Zhungeer, Yunnan-Guizhou-Guizhou, Tuha, Erlian, Tarim, Hailaer, and Yili basins, respectively. The nine basins account for 83 % of the country's CBM resources. There are five basins with gas content of 5000-1 trillion cubic meters, including southern Sichuan and northern Guizhou, western Henan, Sichuan and Chongqing, Santanghu and Xuhuai. There are 10 ( $0.1 \sim 0.5$ )  $\times 10^{12}$ m<sup>3</sup>, accounting for 5.6 % of the total resources. There are 17 less than  $0.1 \times 10^{12}$ m<sup>3</sup>, accounting for 1.0 % of the total resources. In particular, the Qinshui Basin in Shanxi and the Ordos Basin in Inner Mongolia are important development bases for coalbed methane resources [2].

## 2.3. Present situation of coalbed methane exploration and development in foreign countries

Since the United States took the lead in the successful exploitation of coalbed methane from the late 1970 s to the

early 1980 s, countries around the world have competed to develop coalbed methane exploitation. After years of development, the coalbed methane industry is forming around the world. At present, more than 30 countries and regions in the world have carried out the exploration and development of coalbed methane, but only a few countries such as the United States, Canada and Australia have formed industrial scale mining.

The United States is the first country to develop coalbed methane in the world. The exploration process is divided into four processes: exploration, breakthrough, rapid development and shrinking period, as shown in Figure 1. In 1951, the United States drilled the first coalbed methane well in the San Juan Basin Basin in New Mexico, and then obtained industrial gas flow in Black Warrior, Uinta and other places. Since then, the large-scale exploration and development of CBM has spread throughout the United States. In the late 1980 s, the Black Warrior CBM field was completed, marking the modernization of CBM development in the United States. The Black Warrior, Jonah Field and other CBM fields have been put into production [3].

At present, it is common to use coalbed methane for power generation and civil fuel abroad. In the United States, coalbed methane is mainly injected into the natural gas pipeline system. The condition for coalbed methane to enter the natural gas pipeline is that the volume fraction of CH<sub>4</sub> is higher than 95 %. In addition, it is also used to produce automobile fuel, synthetic ammonia and methanol. Germany, France, Canada, Russia, Australia and Japan are mainly used for power generation. In India and the United Kingdom, coal bed methane is mainly used for power generation or vehicle fuel (CNG).

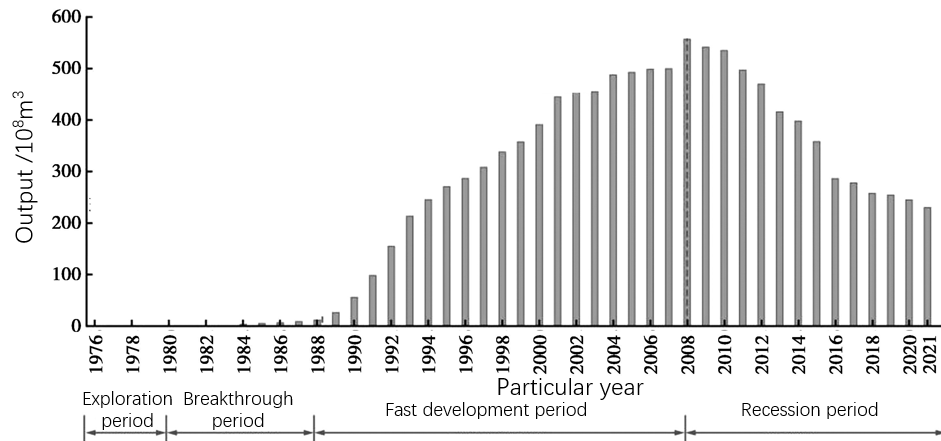


Figure 1. The development history of American coalbed methane industry

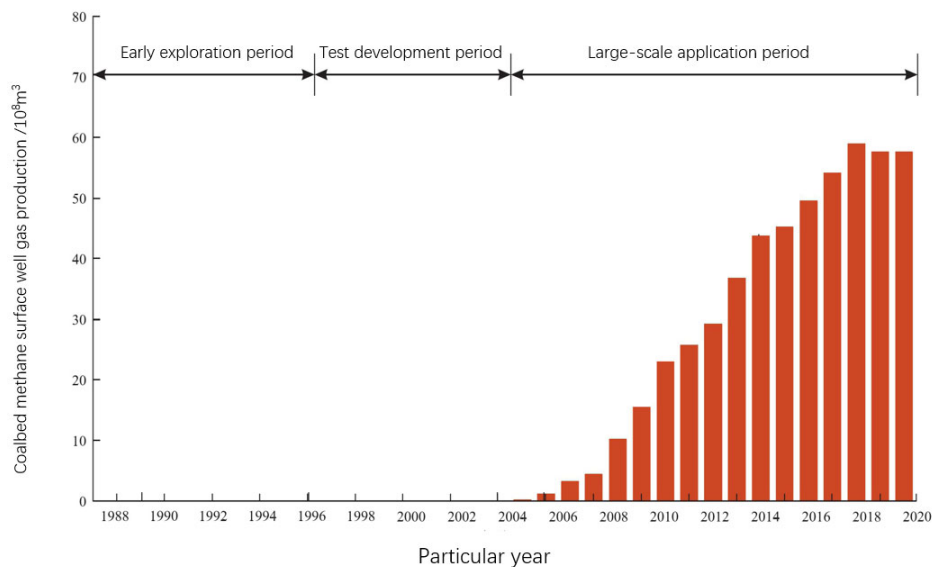


Figure 2. Gas production of surface wells under different development stages of coalbed methane in China

## 2.4. Present situation of coalbed methane exploration and development in China

There are many high gas, coal and gas outburst mines in China, which generally have the characteristics of broken and soft coal seam, low permeability, large gas content and difficult extraction. It is difficult to control gas in coal mines, which seriously affects the safe and efficient production of coal. In order to effectively control mine gas and utilize coalbed methane resources, coal enterprises have been carrying out ground coalbed methane development technology research and engineering tests for many years, and actively exploring new ways to extract and control gas on the ground.

The large-scale mines with high gas, coal and gas outburst in China are mainly distributed in Shanxi, Henan, Anhui, Shaanxi, Guizhou and other places. Among them, the development of surface coalbed methane is mainly carried out in Jincheng mining area in Shanxi, Jiaozuo mining area in Henan, Huaibei and Huainan mining areas in Anhui, Binchang, Jiaoping and Hancheng mining areas in Shaanxi, and Panting mining area in Guizhou. At present, the exploration and development of coalbed methane in China is facing the challenges of low resource exploration rate and low

average gas production rate of single well. The key to solve these problems is to establish an exploration and development technology system suitable for the geological characteristics of coalbed methane in China.

After years of hard work, China's coalbed methane exploration and development has made important breakthroughs, gradually from high-rank coal to low-rank coal, shallow to deep development. From the perspective of resource exploration rate and annual production scale, the exploration and development of coalbed methane in China is still in the growth stage. It is necessary to continue to tackle the following scientific problems and solve technical problems, further improve the effect of reservoir reconstruction, and promote the significant increase of single well production.

After decades of coalbed methane exploration and development practice, China has formed a theoretical and technical system for the exploration and development of medium-high rank shallow coalbed methane. Figure 2 shows the gas production of surface wells under different development stages of coalbed methane in China. The surface development of coalbed methane in China has experienced the early exploration stage, the experimental development stage and the large-scale application stage<sup>[4]</sup>.

With the progress of exploration technology and the continuous development of new wells, the proven reserves of coalbed methane in China have continued to grow, and the production has also increased year by year. At the same time, the proportion of coalbed methane in energy consumption has gradually increased, becoming an important force to promote the adjustment of energy structure. In terms of demand, the market demand for coalbed methane is also increasing, especially in the fields of residential gas, industrial production, power generation and vehicle fuel, the application of coalbed methane is more and more extensive.

### 3. Progress of Coalbed Methane Development Technology

In the process of coalbed methane development in China, reservoir stimulation technologies such as hydraulic fracturing, CO<sub>2</sub> injection displacement, and electric pulse controllable shock wave fracturing have played a significant role. According to the current technical maturity and wide application degree, CBM surface well reservoir reconstruction technology can be clearly divided into three categories: main application technology, experimental application technology and potential development technology. Through in-depth exploration of core scientific issues such as coal seam fracturing fracture propagation mechanism, proppant migration law, electric pulse rock breaking effect, microbial biochemical mechanism, and microwave heating coal and rock effect, remarkable progress has been made in the field of reservoir simulation technology. This series of studies have promoted the orderly evolution of the main application technology, experimental application technology to potential development technology, and laid a solid technical foundation for the large-scale development of coalbed methane in China.

At present, the reservoir reconstruction technology of coalbed methane surface mining shows a trend of evolution based on a single technological progress and towards the direction of integrated development. Therefore, it is necessary to further improve the optimal design scheme and accurate evaluation method of hydraulic fracturing technology, strengthen the experimental verification of pulse anti-reflection technology, and break through the key technical bottlenecks such as microwave equipment entering wells. At the same time, efforts should be made to develop reservoir stimulation technologies that can adapt to the geological characteristics of different coal seams, such as fracture-oriented fracturing technology for specific coal seam conditions, high-efficiency proppant system, and intelligent electrical pulse fracturing system, in order to achieve comprehensive upgrading and wide application of CBM reservoir simulation technology.

#### 3.1. In recent years, the development of coalbed methane mining technology in China

Efficient combined mining. The superimposed coal measure gas reservoirs are developed in the eastern margin of Ordos Basin, and commingled production is an effective method to solve the low productivity and poor comprehensive benefits of single layer<sup>[5]</sup>. The combined production of multi-layer and same wellbore can effectively solve the problems of small single-layer thickness, low productivity of separate development and poor comprehensive benefits, and improve

the gas production of single well and the utilization rate of underground resources. The efficient commingled production mode of coal measure gas is explored, which provides technical support for increasing the comprehensive exploration and development of coal measure gas in China.

Comprehensive exploration and development. Southern Sichuan-Northern Guizhou is also one of the areas with abundant coalbed methane resources in China. The distribution area of coalbed methane is about  $1.74 \times 10^4$  km<sup>2</sup>, and the resource volume is  $9.615 \times 10^8$  m<sup>3</sup>, which has the resource advantage of large-scale industrialization of coalbed methane. The Junlianshan coalbed methane field in the southern Sichuan Basin is the first coalbed methane field with commercial development value in southern China, and it is also the third coalbed methane industrial base in China except for the Qinshui Basin and the eastern margin of the Ordos Basin<sup>[6]</sup>. In view of the characteristics of high coal rank, thin coal seam and low permeability coalbed methane under the complex mountainous conditions of Yunnan-Guizhou-Sichuan, five major technical series of comprehensive exploration and development have been formed-structural transformation type mountain coalbed methane rich gas high yield optimization evaluation technology, ground and underground integrated deployment and rolling optimization design implementation technology, factory optimization, fast and efficient drilling and completion technology, integrated volume fracturing design and technology and digital intelligent fine drainage technology.

Ground extraction. Xinjiang is China's fourteen large coal industry bases, rich in coalbed methane resources. Xinjiang Fukang mining area is one of the main bases for the development and utilization of coalbed methane in Xinjiang coal mining area. The resource characteristics of Xinjiang coal mining area have the characteristics of 'large dip angle, many coal seams, low coal rank and high gas content'<sup>[7]</sup>. The exploration and development of coalbed methane in Xinjiang has made great breakthroughs. The coalbed methane exploration and development theory and drilling pressure drainage technology system applicable to the geological characteristics of Xinjiang have been further clarified and improved. Several pilot test projects for coalbed methane surface development have been built, and small-scale commercial development and utilization have been realized<sup>[8]</sup>. From the analysis of resource potential, gas production effect, market demand and other aspects, the development and utilization of coalbed methane in Xinjiang has the following advantages: First, coalbed methane resources are abundant, accounting for about 25.0 % of the total coalbed methane resources in the country; secondly, a number of high-yield wells have emerged in the exploration and development of coalbed methane, confirming the mining value of coalbed methane in Xinjiang. Thirdly, Xinjiang is an important energy base and land energy channel in China. The development and utilization of coalbed methane can not only supplement the increasing gap between supply and demand of natural gas inside and outside Xinjiang, help to achieve the goal of carbon peak carbon neutralization, but also fundamentally guarantee the safe production of coal mines.

Multi-coal seam mining. Guizhou Province is a typical area where thin to medium-thick coal seams are developed. The characteristics of resource endowments such as large number of coal seams, thin thickness, low permeability, high ground stress, and multi-layer superposition of pressure systems have led to difficulties in the localization of mainstream coalbed

methane development technologies at home and abroad, and it is difficult to produce coalbed methane resources<sup>[9]</sup>. The particularity of the geological characteristics of multi- and thin-seam coalbed methane determines the obvious selectivity of coalbed methane development technology. Multi-seam combined mining has become the only way for the efficient development and utilization of coalbed methane resources in this area. By summarizing the exploration and development practice of coalbed methane for many years, the working system of "balanced drainage, staged depressurization and orderly development" suitable for multi-seam coalbed methane co-production in Zhijin block of Guizhou Province was established, and the economic and effective development of coalbed methane in Zhijin area of Guizhou Province was realized.

### **3.2. Progress of foreign coalbed methane mining technology**

Domestic and foreign scholars have studied the deformation characteristics of mining disturbed strata under the disturbance of single working face mining by B. A. Poulsen et al.<sup>[10]</sup>. Combined with the mathematical model, the pore size of the disturbed fracture is calculated, and the peak distribution of permeability is accurately calculated. It is found that the permeability of the overlying strata of the supporting coal wall in the middle and both sides of the mining coal seam increases to varying degrees. At the same height, the permeability of the upper strata of the supporting coal wall of the working face will increase by 3 ~ 6 times, while the permeability of the upper strata near the recompacked area in the middle will increase to a lesser extent. This shows that the re-compaction of overburden rock in the middle of mining disturbance area has obvious influence on the distribution of fracture field, which makes the mining-induced fractures in some areas of overburden rock close again, and then makes the seepage field in the disturbance area distribute differently.

Close the coal bed methane resources of the mine. C. Ö. Karacan et al.<sup>[11]</sup> took two adjacent working faces of a coal mine in southwestern Pennsylvania, the United States as the research object, and evaluated the development potential of the remaining coalbed methane resources after its closure. Based on the measured data of 278 coalbed methane exploration boreholes in the coal mine, it was concluded that the remaining coalbed methane resources in the study area within 700 days after the closure of the coal mine reached  $3.68 \times 10^6 \text{ m}^3$ , and the overall development cycle could reach 2 500 ~ 4 000 days.

Surface coalbed methane extraction in mining area. The ground extraction is carried out by using a large number of cracks and permeability of coal strata caused by the intense activity of coal seam mining<sup>[12]</sup>, which is mainly used for gas extraction during and after mining in the mining face. This method is generally negative pressure extraction, which has the characteristics of short time, large gas volume and low methane concentration.

Production water treatment of coalbed methane wells. With the large-scale development of the coalbed methane industry, the environmental benefits of the produced water from coalbed methane wells have attracted much attention. During the drainage process of coalbed methane wells, a large amount of groundwater in the coal seam and its surrounding rock will be pumped out, and the fracturing fluid injected during the fracturing process will also flow back together.

These large amounts of produced fluid are different from the original formation water and may have a certain degree of impact on the environment<sup>[13-17]</sup>. At present, Canada has improved the theoretical and technical system of coalbed methane development in the United States and realized the commercial development of coalbed methane. And in the development process, focusing on environmental protection and sustainable development, the use of advanced wastewater treatment technology and ecological restoration measures.

Multi-gas co-exploitation of coalbed methane and tight sandstone gas. Multi-gas co-mining of coalbed methane and tight sandstone gas is an innovative way of natural gas exploitation. It refers to the simultaneous exploitation of two different types of unconventional natural gas resources, coalbed methane and tight sandstone gas, in the same wellbore. Multi-gas co-mining can make full use of various resources in geological structure and avoid over-exploitation and waste of single resources. The mining cost is reduced, and the simultaneous exploitation of multiple gases in the same wellbore can reduce the cost of repeated operations such as drilling and completion and improve the mining efficiency. Since 2014, Australia has focused on multi-gas co-mining of coalbed methane and tight sandstone gas, which has greatly reduced the cost of exploration and development. Through technological innovation and international cooperation, Australia has become one of the world's largest producers of coalbed methane.

## **4. Development Direction of Coalbed Methane Mining**

### **4.1. Low concentration coalbed methane mining**

The utilization of low concentration coalbed methane has always been a difficult problem. Due to the low concentration, the economic and technical feasibility of direct utilization are limited, resulting in a large number of low concentration coalbed methane being abandoned or discharged, which not only causes waste of resources, but also may aggravate environmental pollution. According to data, in 2020, China's coal mine gas extraction volume reached 12.8 billion cubic meters, but the utilization rate was only 44.83%. Among them, nearly 4.3 billion cubic meters of low-concentration gas with methane concentration less than 10% was almost completely emptied. In addition, nearly 20 billion cubic meters of coal mine ventilation air were discharged, and nearly 24.3 billion cubic meters of low-concentration coalbed methane in coal mine areas were discharged into the atmosphere due to the lack of effective utilization methods, resulting in serious waste of resources and environmental pollution<sup>[18-21]</sup>.

The main dilemma of low-concentration coalbed methane utilization is the complexity and high cost of its purification and concentration technology. Traditional coalbed methane purification methods, such as adsorption method and membrane separation method, are inefficient in treating low concentration coalbed methane and have high energy consumption. In addition, low-concentration coalbed methane often contains more impurity gases, such as nitrogen, carbon dioxide, etc., and the removal of these impurities also increases the technical difficulty and cost. From a geological point of view, the geological conditions such as the occurrence state, permeability and pressure of coalbed

methane also pose a challenge to the exploitation and utilization of low-concentration coalbed methane.

Despite many difficulties, the utilization prospect of low concentration coalbed methane is still broad. With the continuous progress and innovation of technology, it is expected to achieve efficient utilization of low-concentration coalbed methane in the future. On the one hand, the development and application of new purification technology will improve the purification efficiency and reduce the cost of low concentration coalbed methane, such as the use of advanced membrane separation technology, low temperature separation technology and so on. On the other hand, low concentration coalbed methane can be combined with other energy systems to achieve comprehensive utilization. For example, combining low-concentration coalbed methane with renewable energy such as solar energy and wind energy to build a multi-energy complementary energy system; or use low-concentration coalbed methane in power generation, heating and other fields to improve energy efficiency.

#### **4.2. Multi-coal seam combined mining technology**

The multi-coal seam combined mining technology can effectively develop the rich coalbed methane resources in the multi-coal seam area. However, due to the large span of the combined mining section, the permeability, fluid properties and reservoir pressure of each coal seam are different, which leads to the mutual interference of the inter-layer fluid flow, and then induces the inter-layer energy interference and reduces the development efficiency<sup>[22-25]</sup>.

Based on the production characteristic curve, the identification method and critical index of coalbed methane combined production interference are constructed. Combined with the analysis of gas production efficiency, the identification chart of combined production interference is formed, which has the function of production identification, and also provides ideas and methods for the efficient development of coalbed methane. The critical index has regional limitations, and the shape type of production characteristic curve has higher universality in indicating interference. The combination of the two can achieve efficient identification of coalbed methane combined mining interference for specific geological conditions in different regions. In the future, the application effect and applicability of this method in other regions should be further tested and optimized<sup>[26]</sup>.

#### **4.3. Coal seam pressure relief and permeability enhancement technology**

The coal seam permeability of most coal mines in China is low, the gas drainage is difficult, and the safety production of mines is seriously threatened<sup>[27]</sup>. Hydraulic pressure relief and permeability enhancement technology such as hydraulic punching, hydraulic slotting and hydraulic fracturing is the transformation of coal reservoir. It is an effective measure to realize safe and efficient gas extraction and prevent coal and gas outburst<sup>[28-31]</sup>. The principle is to use high-pressure water to impact and destroy the coal body around the borehole to form a cavity. The coal body migrates and produces cracks in the process of stress redistribution, which is conducive to gas pressure relief and discharge, so as to achieve the purpose of preventing and controlling outburst<sup>[32, 33]</sup>.

For the mining area with low coal seam permeability and

low gas saturation, it is necessary to explore the application of coal seam pressure relief and permeability enhancement technology in the future to improve the coalbed methane extraction rate. This kind of technology mainly includes pressure relief and permeability enhancement technology for protective layer mining, deep hole pre-splitting blasting technology, deep penetration perforation technology, high-energy gas fracturing technology and high-pressure hydraulic permeability enhancement technology.

#### **4.4. Closed coal mine goaf mining**

With the continuous exploitation of coal resources and the implementation of the 'double carbon target', a large number of coal mines will be closed in the optimization and adjustment of the whole industry. China has a long history of coal mining. From the end of the 20-th century to the beginning of the 21-st century, there were nearly 70,000 mines closed throughout the country. In the production process of coal mines in various regions, due to the restriction of recovery rate and geological conditions, it is estimated that 45 % to 50 % of the main coal seams and coal pillars are left in the underground, and these remaining coal resources contain a large amount of coalbed methane resources<sup>[34]</sup>.

These closed coal mines, including many high gas coal mines. The upper and lower adjacent coal seams, residual coal pillars, residual coal resources and underground goaf are rich in a large number of coal mine gas resources with development and utilization value. Taking Shanxi Province as an example, there are 2052 square kilometers of coal mined-out area with development and utilization value in Shanxi Province. It is predicted that the amount of coalbed methane resources in the residual mined-out area is about 72.6 billion m<sup>3</sup>, including seven mining areas with high coalbed methane content (Xishan, Yangquan, Wuxia, Lu 'an, Jincheng, Huodong, Liliu). The area of mined-out area is 870.92 square kilometers, and the predicted amount of coalbed methane resources is about 30.395 billion m<sup>3</sup>.

The gas extraction and utilization of coal mines in China is mainly based on gas pre-extraction and pressure relief gas extraction, and there are relatively few engineering examples of gas resource development and utilization with abandoned coal mines as the object. In the application of ground drilling and extraction of gas resources in abandoned coal mines, Shanxi Blue Flame Coalbed Methane Group Co., Ltd. put into operation the first abandoned mine ground gas extraction well in 2013, with a daily output of about 4500 m. At present, the company has operated more than 40 abandoned coal mine gas extraction wells.

The utilization of gas resources in abandoned mines is very wide, which can be used as fuel energy or chemical raw materials. Most of the existing utilization ways of coal bed methane in abandoned mines are domestic gas and gas power generation. At present, some companies in Germany, the United Kingdom and the United States have gained a lot of successful experience in gas power generation in abandoned mines. For example, Alkane Energy Company in the United Kingdom recovers gas from abandoned mines and directly supplies it to local users or on-site power generation. By 2014, it has built 24 green energy bases that have reached production; octagon Energy Company and StrataGas Company have successfully operated gas extraction and power generation projects. As the most successful country in the world for the scale of gas extraction and utilization of abandoned coal mines, by 2011, about 38 abandoned coal

mines in the United States had implemented surface extraction and utilization, with a total extraction and utilization of about  $1.6 \times 10^8 \text{m}^3$ .

The utilization of abandoned mines in China is still in its infancy. Up to now, only the abandoned mine gas extraction project in Shanxi Qinshui Coalfield has successfully achieved commercial operation.

#### 4.5. CO<sub>2</sub> displacement of coalbed methane production and CO<sub>2</sub> coal seam storage technology

CO<sub>2</sub> coal seam storage and coalbed methane development is a technology integrating environmental protection and energy development. This technology promotes the desorption and exploitation of coalbed methane (mainly methane) by injecting CO<sub>2</sub> into coal seams and utilizing the competitive adsorption of CO<sub>2</sub> on coalbed methane, and realizes the geological storage of CO<sub>2</sub>, which is helpful to reduce greenhouse gas emissions. In this process, the storage effect of CO<sub>2</sub> and the mining efficiency of coalbed methane are affected by many factors, including coal type, adsorption conditions, coal seam structure and injection parameters. In recent years, with the advancement of the 'double carbon' goal, CO<sub>2</sub> coal seam storage and coalbed methane development technology have received extensive attention and research, and have become an important way for clean and efficient utilization of coal.

The combined development technology of CO<sub>2</sub> coal seam storage and coalbed methane shows a very considerable prospect in the future development of coalbed methane field. In recent years, domestic scholars have focused on the mechanism of multi-competitive adsorption, the law of displacement and replacement, and the change of coal rock porosity and permeability. In 2004, the field exploration test of CO<sub>2</sub> flooding coal seam methane was carried out for the first time in China. Since then, the field test of CO<sub>2</sub> flooding coal seam methane was carried out in different regions in China, which effectively promoted the engineering application of gas injection displacement technology<sup>[35]</sup>. This technology skillfully utilizes the strong adsorption capacity of coal seam to CO<sub>2</sub>. By injecting CO<sub>2</sub> into coal seam, it effectively promotes the desorption and recovery of coalbed methane, and realizes the geological storage of greenhouse gas CO<sub>2</sub>, which is of far-reaching significance for alleviating global climate change. With the acceleration of the global energy structure transformation, the demand for clean energy shows a continuous growth trend. As an efficient and clean energy option, the market demand for coalbed methane is also rising.

As a country with abundant reserves of coalbed methane resources, China has great potential for exploration and development. Under the continuous promotion of a series of supporting policies of the state and local governments, the joint development technology of CO<sub>2</sub> coal seam storage and coalbed methane has obtained a broader development space. Through continuous technological innovation and industrial upgrading, this technology has made significant progress in improving CBM recovery efficiency, reducing mining costs, and ensuring environmental safety. It is expected to play a more critical role in future CBM development and make important contributions to optimizing energy structure and promoting environmentally sustainable development.

#### 4.6. Increasing production technology continues to explore

Coalbed methane development is also facing some challenges. First of all, China's geological conditions are complex, and coal seams generally have the characteristics of 'three low and one high', that is, low saturation, low permeability, low reservoir pressure and high metamorphic degree, which increases the difficulty and cost of mining. Secondly, the exploration and development technology is difficult, and the universality of coalbed methane development technology under different geological conditions is poor, and the applicable technology for different coal seam geological conditions in China has not yet been formed. In addition, there are still some problems in the development of coalbed methane, such as long investment return period and high safety risk.

Due to the low permeability of coal seams in China, most coalbed methane wells have no production without fracturing. It is necessary to form an 'artificial fracture network' through fracturing to effectively exert the productivity of coalbed methane wells. In view of the three main coal structures of primary coal, cataclastic coal and crushed coal, combined with the mechanical characteristics of fracturing and the main controlling factors of diversion damage, variable displacement construction and multi-stage slug are comprehensively used in China. A number of support technologies such as composite fracturing has formed a high-efficiency support fracturing technology system for medium-high-order coal seams with the goal of extending main fractures, deep transformation, and improving distal support. At present, the commonly used coalbed methane reservoir reconstruction technology includes thin coal seam roof penetration, coal seam composite fracturing and repeated fracturing.

Active water sand-carrying fracturing is the mainstream technology for coalbed methane stimulation, and the active water sand-carrying fracturing process is constantly optimized for different reservoir properties, and it has become mature. For the multi-coal seam area, the combination of coal seam and rock layer staged fracturing technology can effectively improve the single well production and resource utilization efficiency. However, the injection of a large amount of water-based fracturing fluid in hydraulic fracturing will cause water sensitivity, water lock and solid phase damage of coal seams. Drainage and depressurization are mainly applicable to water-bearing coal seams, but the applicability to non-water-bearing or weakly water-bearing coal seams is poor<sup>[36]</sup>.

Heat injection technology is another effective method for increasing coalbed methane production, which is suitable for coal seams with low water content and difficult desorption. By injecting thermal medium into the coal seam, the activity of CH<sub>4</sub> molecules is increased, thus promoting the desorption and migration of coalbed methane. At the same time, the increase of temperature can also increase the permeability of coal seam<sup>[37]</sup>. Heat injection mining can also be combined with traditional mining methods to further strengthen the exploitation of coalbed methane. Therefore, it is also of great significance to strengthen the research on the method of increasing coalbed methane production by heat injection.

### 5. Conclusion

Coalbed methane, once regarded as the 'killer' of energy,

has been gradually transformed into an important strategic resource. After decades of development, China has formed some important CBM industrial bases and achieved phased technological progress. However, there are still many key technical bottlenecks to be broken through in terms of cost control, clean mining technology, and stable and increasing production strategies of coalbed methane wells. Compared with foreign countries with mature coalbed methane development, China still has a significant gap. Moreover, most domestic CBM fields are restricted by complex terrain and harsh reservoir environment, and it is difficult to directly apply the mature development model abroad. In the field of coalbed methane development in China, it is necessary to strengthen research from the theoretical level, strengthen the cooperation among enterprises, universities and scientific research institutions, and comprehensively consider various factors such as geological conditions, engineering technology, economic benefits and environmental protection, so as to promote the development of coalbed methane to be intelligent, economical and clean. Provide innovative ideas and technical means for the development of coalbed methane in China.

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