Preface

Most coal seams in China have undergone complicated tectonic movements after they were formed through coalification processes. More than 80% of coal seams could be characterized as well-developed tectonic coal with low permeability, high gas contents and high stress. Among 105 coal mining districts in China, 58 coal districts or 55% of them are highly gassy and prone to outburst. These 58 coal districts have more than 60% of coalbed methane resources and 70% of coal output in China. The issue of mining highly gassy coal seams of low permeability has not been resolved and traditional gas control technologies are not meeting the current requirements of highly efficient and safe coal mining. Moreover, drainage gas is of low purity and low utilization ratio, with more than 65% of drained gas being ventilated into the air, resulting in environmental pollution and the waste of valuable energy.

Since 1996, the research team of coal mine gas control in the Huainan mining district has undertaken a systematic study on the dynamic process of stress field, fracture field and gas field in multi-seam mining operations through integrated approaches of field investigations, physical simulation and numerical simulation, and three basic models have been established, i.e., the distribution model of overburden de-stressing, the distribution model of overburden permeability, and the gas movement model in de-stressed overburden. Results of the studies provide a quantitative description of stress field, fracture field and gas field, which is fundamental for gas drainage design in coal mines. These results have gained wide recognition by coal mining industry, and have been widely used in Chinese coal mines. In fact, the coal production from mines adopting the above results makes about 50% of the total coal production in China. This book aims to provide knowledge of coal and gas co-extraction to undergraduates and postgraduates majoring in coal mining engineering and safety science and engineering. It describes the fundamental theory, methods and technologies of coal and gas co-extraction, covers the main achievements and advances in coal and gas co-extraction, and cases of coal and gas co-extraction in typical coal mining regions in China. This book strives to be scientific, systematic and easy to understand.

The contributing institutions of the book include China University of Mining and Technology (CUMT), National Engineering Research Center for Coal Gas Control, and China University of Mining and Technology-Beijing (CUMTB). This book has been reviewed by Prof. Zhou Shining, an academician of Chinese Academy of Engineering, Prof. Yu Qixiang of CUMT, Prof. Wang Jiachen of CUMTB, Prof. Zhang Guoshu and Prof. Meng Xiangrui of Anhui University of Science & Technology (AUST), Prof. Liang Bing of Liaoning Technical University, and Prof. Li Shugang of Xi'an University of Science and Technology. Those reviewers provided many valuable comments, which are greatly appreciated. The authors would also like to thank Prof. Zheng Chunshan and Prof. Tu Qingyi of AUST for their great work in word editing and graphic plotting.

Some of the standards in this book are not the latest versions, which is due to the timing of the original research. This is hereby noted.

The authors would like to thank the academicians Mr. Qian Minggao, Mr. Zhou Shining, Mr. Xie Heping and Mr. Peng Suping for their supervision and support in the long study and practice of coal and gas co-extraction. Our thanks also go to the publisher of this book for their great support and assistance provided in publishing this book.

The authors

2023.12

Contents

Chapter 1 Introduction

1.1 Basic Concepts of Coal and Gas Co-extraction

1.1.1 The concept of coal and gas co-extraction

Coal is the main energy source of China. In China's non-renewable energy consumption, coal accounts for approximately 66%, which is expected to be about 50% by 2050[1]. Coal seam gas refers to a hydrocarbon gas stored in coal seams, with methane as its main component. It mainly exists adsorbed on the surface of coal matrix particles, while part of it is in a free state in coal pores or dissolved in coal seam water. It is an associated mineral resource of coal, classified as unconventional natural gas, and is also known as coalbed methane. Coal and gas simultaneous extraction refers to a method that exploits both coal and gas as resources. By adopting the forms of coal mine gas drainage or coalbed methane extraction, it maximizes the amount of gas drained, thereby achieving the goal of developing and utilizing both coal and gas (coalbed methane) as resources in phased or simultaneous stages[2].

According to the sequence of coal mining and gas extraction, coal and gas co-extraction could be divided into the following three categories[3, 4].

(1) Gas extraction before coal mining. In the original coal, coal seam gas exists in the porous media of coal seam and its surrounding rocks. The adsorbed gas amount usually accounts for 80%−90%, and the free gas amount accounts for 10%−20%. According to Articles 2 and 7 of "Interim Provisions on the Standardization of Gas Extraction in Coal Mines", coal seams with high gas content and high proneness to coal and gas outburst must be effectively drained before mining.

Gas extraction before coal mining is generally used in mining areas of coal seams with high permeability and shallow burial depth. The main methods of gas extraction in the case include pre-drainage with surface vertical wells and surface directional long borehole, pre-drainage with underground to in-seam (UIS) boreholes and pre-drainage with roof and floor cross-measure boreholes.

(2) Coal and gas co-extraction. Coal mining will break the balance of the original stress field, causing strata movement and stress redistribution of surrounding rocks,

forming stress relief zones and stress concentration zones, and leading to the generation, closure and expansion of cracks in the surrounding rocks. In the stress concentration zones, new cracks are generated. Meanwhile, the cracks may be closed and gas permeability is reduced, transforming part of the gas from a free state to an adsorption state. In the stress-relief zones, the cracks open and expand, and coal permeability is enhanced; gas is desorbed and moved in the mining-induced fractures, forming gas-rich zones. Coal and gas co-extraction is to make full use of the stress relief, the evolution of stress field and fissure field on gas, as well as the law of gas storage and transportation during coal mining, to establish two complete production systems of coal mining and gas extraction.

Coal and gas co-extraction is generally used in multi-seam environment with high gas content, low permeability and high coal and gas outburst potential. Gas extraction methods in this case mainly include roadway extraction, pillar-free drilling and ground drilling. The principles of these coal and gas co-extraction technologies are shown in Figure 1-1-1[5,6].

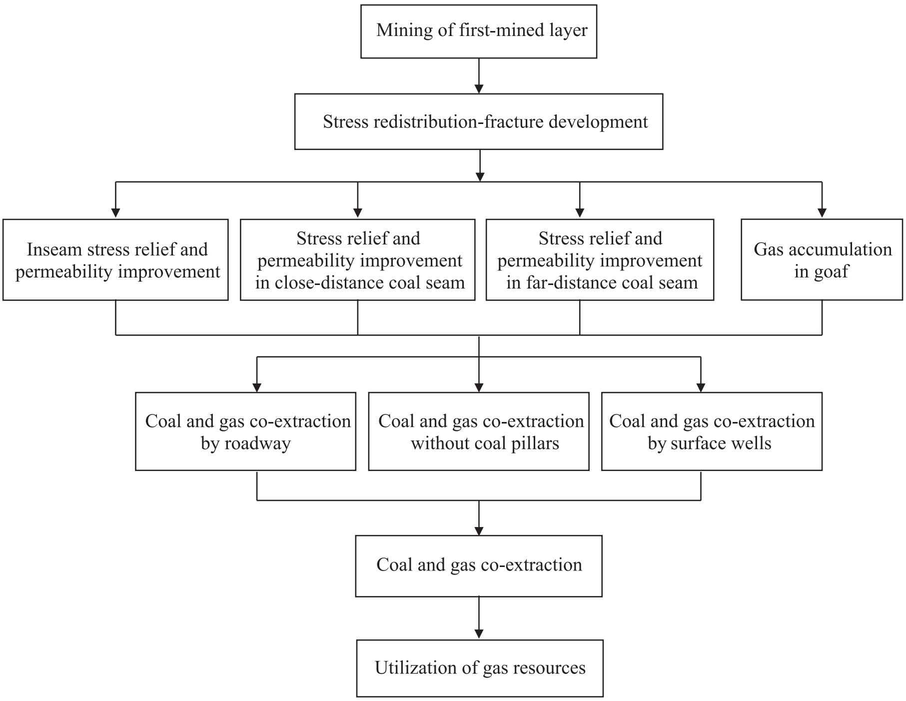

Figure 1-1-1 The principles of these coal and gas co-extraction technologies

(3) Gas extraction after coal mining. For coal seams with no coal and gas outburst proneness and high gas content in the adjacent strata, the method of coal mining

before gas extraction is often adopted. After coal mining is completed, the goaf is drained. Extraction methods mainly include roadway (drilling) extraction, sealed wall pipe extraction and ground drilling extraction.

1.1.2 The idea of coal and gas co-extraction

Coal and gas resources are characterized by co-existence. Extracting them separately will inevitably affect each other. When coal and gas in multiple seams of low permeability and high gas content are mined, it will be difficult to directly extract gas due to the low permeability, and it is difficult to eliminate the risk of coal and gas outburst in coal mining. If coal is mined directly and the gas content in the coal seam is not reduced prior to coal mining, the coal and gas outburst or gas explosion may occur [7-9].

Separate operations of coal mining and gas extraction could either positively or negatively affect each other. Coal and gas co-extraction integrates independent coal mining with gas extraction. Coal mining causes the movement and stress redistribution of the coal seam, promotes gas desorption and flow, and creates favorable conditions for gas extraction. At the same time, the mining system and ventilation system provide space for gas extraction. In turn, the efficient gas extraction reduces the gas concentration in the working space and gas content in the coal seam, which could effectively prevent gas disasters and guarantee safe and efficient coal mining[10]. Coal and gas co-extraction is a resource-coordinated development approach that integrates coal mining and gas extraction. Furthermore, the efficient co-extraction of coal and gas can provide high-quality clean energy, by making full use of gas, and directly reduce greenhouse gas emissions (Figure 1-1-2).

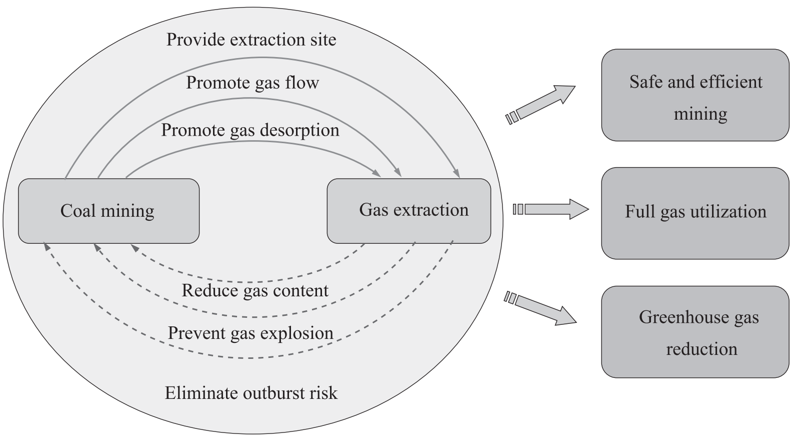

Figure 1-1-2 Idea of coal and gas co-extraction

1.2 Coal and Gas Co-extraction Models in China

1.2.1 Characteristics of coal and gas resources in China

1. The coal burial depth

China's coal reserves at depths of <600m, 600−1000m, 1000−1500m and 1500−2000m account for 26.8%, 20%, 25.1% and 28.1%, and geological gas resources in coal seams account for 38.8%, 28.8% and 32.4% at burial depths of <1000m, 1000−1500m and 1500−2000m, respectively. The amount of coal buried below 1000m is 2.95 trillion t, or 53% of the total coal resource, and coal seam gas in the same depth range is 1.42709 trillion m^3, or 61.2% of the total gas resource in China[11].

China's coal resources are mainly in thin and medium-thick coal seams, with few extremely thick coal seams. The amount of open pit mining is small, accounting for about 7% of the total reserves, and is mainly distributed in Inner Mongolia, Xinjiang and Yunnan. Therefore, more than 90% of the coal seams in China are mined underground. The average mining depth increases by 10−30m/a. At present, the average mining depth of large and medium-sized coal mines has exceeded 600m, and most of them are rapidly entering the deep mining stage. Most of the mines in Northeast and East China have a long mining history. According to statistics, China has 43 mining areas, such as in Huainan, Pingdingshan and Fengfeng. In these areas, there are more than 300 mines with a mining depth of more than 600m, of which nearly 200 mines have a mining depth of more than 800m. There are 47 deep mines deeper than 1000 m, with an average depth of 1086m and the maximum mining depth has reached 1501m[12].

With the increase of mining depth, the ground stress and the gas pressure of coal seams are increasing. Mining conditions of high gas content and high risk of coal and gas outburst also become challenging. It is more difficult to coordinate coal mining and gas extraction activities. The reduction in coal permeability with the increase of mining depth makes gas extraction even more difficult, increasing serious safety risks.

2. Complex geological structure

The geological structure is one of the key factors affecting coal and gas co-extraction. China is located in the southeast of the Asian continent. In the modern tectonic pattern, the coal field is a complex structure where the Eurasian Plate meets the Pacific-Philippine Sea Plate and the Indian Plate. Controlled by the three geodynamic systems in ancient Asia, Tethys and the Pacific Ocean, the Chinese mainland has formed five large blocks, including the Junggar–Songliao Block, the Tarim Block, the North China Block, the South China Block and the Qinghai–Xizang Block. After the formation of basin basement, the sedimentation of coal-bearing strata and the later deformation, five coal-bearing areas in Northeast China, North China, Northwest China, South China and Yunnan–Xizang have been formed. Coal-bearing areas in Northwest China and Yunnan–Xizang are basically under the effect of compression-convergence geodynamic system. Since the Triassic, the coal-bearing area in Northeast China has been mainly affected by the Pacific geodynamic system. The structure of coal field is extensional, and the combination of wide gentle folds and stepped and graben-horst faults is developed. Coal-bearing area in North China has been subjected to the action of three geodynamic systems, and its tectonic combination is diverse. Generally, the structural deformation strength of coal field is strong around and weak in the center. Except for the center of the Ordos Basin, the structure of coal field is relatively complex. Compared with the coal-bearing area in North China, the tectonic deformation intensity and structural complexity of the South China coal-bearing area are greater. The western part of South China is dominated by compact folds, while the eastern part of South China is more faulted.

3. Tectonic coal development

The late Paleozoic coal accumulating period in China was followed by multiple geological tectonic movements, which caused different degrees of damage to the coal seam. Because the coal formation occurred before tectonic movement, a large amount of tectonic coal or soft coal is formed in some areas. The tectonic coal is mainly developed in western Henan–Lianghuai, east of Taihang Mountains and most areas in Southwest and Northeast China. Geological resources of coal seam gas or coalbed methane (CBM) in the areas where tectonic coal occurs are 787 million m^3, and the recoverable resources are 235 million m^3, accounting for 21% and 12% of the total geological resources and recoverable resources, respectively[11].

The original structure of these coal seams is severely damaged. Coal seams are broken and crumpled, and their permeability becomes low, usually below 10^{-3}–10^{-1}mD ($1\text{mD} \approx 10^{-15}\text{m}^2$), which causes great difficulties in the extraction of CBM and safe coal mining. CBM resources in tectonically deformed coal development area can only be extracted during coal mining. In contrast, the surface well technology is not mature for this kind of resource, and it is difficult to carry out low-cost methane extraction.

4. Low permeability of coal seam

Coal permeability is a physical quantity which represents the difficulty of gas flow in the coal seam. The unit of permeability coefficient of the coal (rock) layers used in China is $m^2/(MPa^2 \cdot d)$. Its physical meaning is the gas (at 0℃ with a dynamic viscosity of 1.08×10^{-6}Pa·s) permeability coefficient under the conditions of pressure gradient being 1MPa/m, through the cross section of $1m^2$ of coal (rock) layer and the flow rate being 1m/d. Permeability is a physical quantity that characterizes porous media, the unit of which is m^2, and the internationally accepted unit is D (Darcy) (1D=1000mD≈ $1\mu m^2$). For gas, 1 $m^2/(MPa^2 \cdot d)$ is equivalent to 0.025mD.

Coal permeability in China is generally low. Permeability value in typical coal mines is less than 0.1mD (generally between 10^{-4}–10^{-2} mD), except for a few of mining areas such as the Jincheng mining area. The low permeability of coal seam is the main factor that hinders gas development. For the coal seam with low permeability, the gas could only be effectively extracted after stress relief or an artificial increase in permeability coefficient.

5. High gas content in coal seam

Most coal seams in China have a high gas content. According to the survey results of "1 ∶ 2000000 Geological Map of Coal Seam Gas in China" on 105 coal mining areas nationwide, there are 43 mining areas with a gas content of more than $10m^3/t$, accounting for 41%. There are 29 mining areas with 8–$10m^3/t$, accounting for 28%. There are 19 mining areas with 6–$8m^3/t$, accounting for 18%. There are 14 mining areas with 4–$6m^3/t$, accounting for 13%. In these mining areas, there are a total of 79 coal mines with coal and gas outburst threat[13].

Due to the structural evolution of coal fields and the variation of gas generation and preservation conditions in China, the gas content in coal varies greatly. On the whole, the gas occurrence shows a trend of being high in the south and low in the north, and high in the east and low in the west of China. In the northeast area, the average relative gas emission of the mines is $14.53m^3/t$, and the mines generally enter deep mining conditions. The average relative gas emission in the northwest area is $4.50m^3/t$, and the gas hazard degree is relatively small. In particular, the gas hazard in Xinjiang has only begun to emerge in recent years. In the central-eastern North China Plate region, the average relative gas emission is $8.43m^3/t$, and the coal seams gradually enter deep mining, resulting in serious gas disasters. The Southwestern Yangtze Plate areas have complex geological structures and serious gas disasters, and the average relative gas emission is 19.89m^3/t. The combined disasters of gas outburst and rock burst begin to appear in deep mining.

6. Serious coal and gas outburst

According to statistical results of coal mine gas grade appraisal in 2012, China's coal mines are mainly gassy mines, which have two main characteristics. First, there are a large number of mines with high gas content and coal and gas outburst potential, approximately 3284 mines in most of the 26 major coal mining provinces. Second, 2865 of them are in Guizhou, Sichuan, Hunan, Shanxi, Yunnan, Jiangxi, Henan provinces and Chongqing municipality, accounting for 87.2% of the total number of mines with high gas content and coal and gas outburst potential in China[14].

According to the national gas geological map and related data, there are 79 coal and gas outburst mining areas in China. When the tectonic compression and shearing actions are extremely strong, coal is classified as type Ⅲ, Ⅳ or Ⅴ tectonic coal, and the coal is regarded as having serious coal and gas outburst potential, e.g., Yinggong and Dengfeng coal fields or mining areas. In addition, some other coal fields or mining areas are defined as coal and gas outburst areas, such as Yangquan and Jincheng.

According to the statistical data in 2010, the national raw coal output of mines with high gas and coal and gas outburst potential is 10.56×10^8t, accounting for 1/3 of the national coal output. Among the key state-owned coal mines, the number of mines with high gas and coal and gas outburst potential accounts for 49.8%, and the coal output accounts for 42% of the total output. Among them, there are 235 outburst mines, accounting for 19.3% of the total and 11.8% of the country's coal output. Among 45 key safety-monitoring enterprises, the number and output of mines with high gas and outburst threat account for 60.2% and 60.6%, respectively.

To sum up, most of China's coal seams have experienced complex geological tectonic movement during and after coal formation, and more than 80% of them are characterized by tectonic coal development, low permeability, high gas content and high ground stress. At present, among 105 coal mining areas in China, there are 58 high gas outburst mining areas, accounting for 55% of the country's coal mining areas. They host more than 60% of China's CBM resources and produce more than 70% of the country's coal output. Furthermore, gas disasters in these areas are also serious. With the expansion of China's coal mining industry, in particular the increase in the mining intensity and depth, there will be more and more high-gas mines, and the threat of gas to the safe production of coal mines will be more and more serious, which poses challenges to the safe production of coal mine and the safety of coal industry.

1.2.2 Coal and gas co-extraction models

Mining areas including Fushun, Tianfu, Yangquan, Jincheng and Huainan represent the coal and gas co-extraction models in different periods and under different occurrence conditions of gas in China. Practical coal and gas co-extraction technologies have been developed based on the characteristics of gas occurrence in coal seams in China.

1. Fushun model

The Fushun model refers to the coal and gas co-extraction technology used in extra-thick coal seam with high permeability and high gas content[15,16].

The main coal seam of the Fushun coal field is a single extra-thick coal seam rarely seen in the world. The maximum thickness of the coal seam is 130m (west of the coal field), the thinnest is 8m (east), and the average thickness is 50m. The coal seam is divided into four natural layers from top to bottom. This coal seam has well-developed joints, and has a high porosity (8.19%−17.32%) and good gas permeability (0.25−3.6mD). The burial depth of the seam is shallow and the degree of metamorphism is low. However, the seam gas content is high, which makes it a highly concentrated coalbed methane field. The relative gas emission quantity of gas grade appraisal of this mine in past years is all above 40m^3/t.

The Fushun coal field has a long history of mining. In 1952, the Longfeng Coal Mine carried out the first underground borehole pre-extraction of CBM in China, which was successful. The successful experience of the Fushun Coal Mine spreads rapidly in the coal industry and has wide reference values.

Aiming at the mining method of extra-thick coal seam and the severe risk of coal seam spontaneous combustion, in the Fushun Coal Mine, the comprehensive technology of gas extraction, reasonable ventilation and fire prevention measures in fully mechanized caving face has been scientifically implemented. Gas issues and spontaneous combustion have been solved. The methods of gas extraction mainly include pre-extraction in the drilling area through the strata of the floor roadway, extraction during mining excavation, pre-extraction before mining in two development headings, drainage in the goaf area and pre-extraction of gas by hydraulic fracturing in ground drilling.

With the increase of mining depth, the Fushun model encounters difficulties of preventing and controlling mine dynamic disasters. Since the 1990s, frequent occurrences of rock bursts in the Laohutai Coal Mine and increasingly serious disasters have brought great difficulties to the safe production in the mine.

2. Tianfu model

The Tianfu model refers to the coal and gas co-extraction technology used in steep multiple seams with high gas outburst potential[17,18].

The Tianfu mine belongs to the Permian Leping coal series and is divided into three zones: south, north and Yangliuba. It is located in the southern part of the Guanyinxia anticline, which is a long belt. The structure of the anticline east wing is complex and is destroyed by a group of faults, thus showing no exploitation value. While the structure of the anticline west wing is simple and is in stable occurrence, and the dip angles of the coal seam are 60°–65°.

Coal seams are distributed in the first and third groups of coal measures. The coal seams in the third group from top to bottom are No. 1, No. 2,···, No. 6. The second group contained no coal. The first group consists of coal seams No. 7, No. 8, No. 9 and No. 10 from top to bottom. In the south zone, there are six coal seams or partial coal seams, i.e., No. 2, No. 3, No. 5, No. 6, No. 7 and No. 9. There are only three coal seams in the north zone, i.e., No. 3, No. 5 and No. 9. The No. 9 is a medium-thick coal seam with a stable thickness and good coal quality and the reserves in the zone account for more than half of the whole mine.

This mine is prone to coal and gas outburst risk. The absolute gas emission in the south zone of production level is 26–35m^3/min, and the relative gas emission is 48–54m^3/t. A total of 59 coal and gas outbursts have occurred in the mine, including 39 in the south zone and 27 in No. 9 coal seam, with a maximum strength of 5270t. The coal seam has both spontaneous combustion and explosion hazards. No. 7 coal seam also has an outburst near the +110m horizontal fault.

In the mid-1970s, the mine cooperated with China University of Mining and Technology and the Chongqing Branch of China Coal Research Institute to carry out gas prevention and control work in the mining of steeply inclined long-distance protective layer in Tianfu Coal Mine. This project has systematically and comprehensively investigated the gas pressure, gas flow, gas extraction effect, permeability coefficient, temperature, deformation and stress of coal seam after protective seam mining. Through this study, the basic principle of protective layer mining technology is developed, namely under the mining action of the protective layer, expansion deformation occurs, in-situ stress reduces, the coal seam permeability coefficient increases and the gas flow rate increases. This laid the foundation of theory and practice for the later application of protective layer mining technology.

3. Yangquan model

The Yangquan model refers to the coal and gas co-extraction technology suitable for the condition that the first-mined coal seam is a non-outburst coal seam, while its goaf and adjacent coal seams have high gas emissions[19,20].

Yangquan Mining Area is located in the northeastern part of the Qinshui Basin, Shanxi Province. Faults are not well-developed within the mining area, and the coal-bearing strata consist of the Taiyuan Formation and Shanxi Formation of the Carboniferous-Permian System. There are 16 coal seams in total. The main coal seams are No. 3, No. 12 and No. 15, and No. 6, No. 8 and No. 9 coal seams are partially recoverable. The average thickness of the coal seams is 1.01–5.20 m, and the maximum thickness is 11.26m. The coal is mainly anthracite with complete structure and well-developed fractures which are mainly small and micro fractures. Gas content is 5–30m^3/t, and the coal permeability is $(0.5–6.7)\times 10^{-3}$mD.

Combined with the main coal-mining strata, the coal-bearing strata can be divided into three gas reservoirs: the upper reservoir segment dominated by No. 3 coal seam, the middle reservoir segment dominated by No. 12 coal seam, and the lower reservoir segment dominated by No. 15 coal seam. No. 3 coal seam and No. 12 coal seam have high gas pressure and high gas content, while No. 15 coal seam has low gas pressure, low gas content and no outburst risk. It can be mined first as a protective layer. However, due to its great thickness, the amount of gas emission in the mining process is very large.

In 1957, the experiment of drilling boreholes to extract gas from the upper adjacent strata in No. 4 mine of the Yangquan coal field was successfully conducted for the first time in China, which solved the problem of a large amount of gas emissions from the first working face during mining of multiple seams. After that, the gas-drainage roadway in roof was developed and successfully drained gas from the adjacent layer with a drainage rate of 60%–70%. After the 1960s, this stress-relief gas drainage technology in the adjacent layer has been widely used in China.

Due to the large thickness of No. 15 coal seam in the Yangquan mining area, there are many adjacent layers. The influence of mining is great, resulting in a large amount