



Coalbed Methane: A Review of Key Mechanisms & Technologies

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ABSTRACT

As an important unconventional natural gas resource, in-depth research on coalbed methane (CBM) is of great significance. By synthesizing relevant literature, this paper expounds the concept, genetic types, and accumulation mechanisms of CBM, conducts a detailed analysis of the characteristics and distribution laws of CBM reservoirs, discusses the current status and challenges of CBM exploration and development technologies, summarizes the environmental impacts of CBM development and corresponding response strategies, and looks forward to future research directions. The purpose is to comprehensively sort out the research progress in the field of CBM and provide a reference for subsequent in-depth research and development practices.

KEYWORDS

Coalbed Methane (CBM); Accumulation Mechanism; Exploration and Development Technology; Environmental Impact.

1. INTRODUCTION

Coalbed methane is a hydrocarbon gas occurring in coal seams, with methane as its main component, and it is an important unconventional natural gas resource. With the growth of global energy demand and the pursuit of clean energy, the development and utilization of CBM have attracted widespread attention. China is rich in CBM resources; preliminary estimates show that the CBM resource volume at depths of 2000 meters and below exceeds 40 trillion cubic meters, among which the recoverable resource volume is over 10 trillion cubic meters. However, as the burial depth of CBM increases, its development faces many challenges, such as unclear phase transition and production mechanisms, complex geological conditions, high difficulty in development technologies, great challenges in beneficial development, and significant pressure on environmental protection. A literature review on CBM-related research is conducive to in-depth understanding of its accumulation laws and development technologies, thereby promoting the development of the CBM industry.

2. BASIC THEORIES OF COALBED METHANE

2.1. Concept and Characteristics of Coalbed Methane

Coalbed methane is a gas resource associated with coal. It is mainly adsorbed on the surface of coal matrix particles, while a part of it exists freely in coal pores or dissolves in coal seam water. Compared with conventional natural gas, CBM has the characteristics of self-generation and self-reservoir, low saturation, low pressure, and low permeability. Methane, its main component, is a clean energy source

that produces fewer pollutants after combustion. However, methane is also a potent greenhouse gas, with a greenhouse effect approximately 21 times that of carbon dioxide.

2.2. Genetic Types of Coalbed Methane

2.2.1. Biogenic Origin

Biogenic gas can be divided into early biogenic gas and secondary biogenic gas. Early biogenic gas is formed when coal seams are shallowly buried (generally below 400 meters in the stratum). At this stage, thermal effects are insufficient to cause changes in the structure of organic matter in coal seams to generate gas; instead, microorganisms decompose organic matter to form biogenic gas dominated by methane. Secondary biogenic gas, on the other hand, is generated during the later uplift stage of coal seams. Microorganisms carried by atmospheric precipitation metabolize wet gas, n-alkanes, and other organic compounds under relatively low-temperature conditions to produce this type of gas. In areas such as the Powder River Basin in the United States and the eastern margin of the Ordos Basin in China, secondary biogenic CBM accounts for a relatively high proportion.

2.2.2. Thermogenic Origin

From the perspective of source rocks, the coal rank evolution stage is divided into the low-maturity stage (peat-lignite), mature stage (long-flame coal-lean coal), and high-maturity stage (meager coal-anthracite). Thermogenic gas is truly formed in the long-flame coal-anthracite stage. With the increase in coal metamorphism, the organic matter in coal undergoes physical and chemical reactions, continuously deoxidizing, dehydrogenating, and enriching carbon, thereby generating a large amount of hydrocarbon gases such as methane and non-hydrocarbon gases such as carbon dioxide and nitrogen. Thermogenic gas can be further subdivided into thermal degradation gas (from long-flame coal to lean coal stage, $R_o=0.6\% \sim 2.0\%$) and thermal cracking gas (from lean coal to anthracite stage, $R_o > 2.0\%$).

2.2.3. Mixed Origin

In actual CBM reservoirs, biogenic gas and thermogenic gas often coexist in a mixed form, forming mixed-genesis CBM. The gas composition and isotopic characteristics of mixed-genesis CBM are affected by various factors, reflecting the mixing ratio of different genetic gases and the geological evolution process.

2.3. Accumulation Mechanism of Coalbed Methane

2.3.1. Generation of Coalbed Methane

Abundant organic carbon is the material basis for CBM formation. The formation of biogenic CBM depends on the characteristics of microbial communities in coal seams. Its formation follows the four-stage theory of anaerobic fermentation, in which various microorganisms such as hydrolytic fermentative bacteria, acidogenic bacteria, acetogenic or hydrogen-producing bacteria, and methanogens work together to decompose the organic matter in coal into methane. The formation of thermogenic CBM, on the other hand, depends on the degree of coal metamorphism. During different coal rank stages, different types and quantities of gases are generated through chemical reactions such as the cracking of functional groups and side chains of organic matter.

2.3.2. Storage of Coalbed Methane

The adsorption-desorption mechanism is the basic theory for studying CBM storage. Coal has a large specific surface area and strong adsorption capacity for gases such as methane. The solid-liquid adsorption-desorption theory can better explain the gas adsorption-desorption phenomenon in water-bearing coal seams. The interaction force between water molecules and coal molecules is greater than

that between methane molecules and coal molecules, resulting in a lower methane adsorption capacity of coal samples with higher water content.

2.3.3. Migration of Coalbed Methane

Diffusion mechanism and seepage mechanism are the microscopic theories of CBM migration. In CBM reservoirs, gas migrates in coal matrix pores through diffusion under the action of concentration difference, and migrates in coal fractures through seepage under the action of pressure difference. The time-dependent diffusion model and non-Darcy seepage model are more suitable for explaining the migration process of CBM in low-permeability reservoirs in China.

2.3.4. Preservation of Coalbed Methane

The geological conditions for the formation of CBM reservoirs include sedimentary conditions, tectonic conditions, and hydrogeological conditions. Sedimentary conditions control factors such as coal composition, coal seam thickness, and roof and floor characteristics, which affect CBM accumulation. Tectonic conditions influence CBM accumulation through tectonic activities, coal seam burial depth, magmatic activities, and tectonic types. Hydrogeological conditions have a dual role in CBM accumulation: appropriate hydrogeological conditions are conducive to CBM preservation, while inappropriate ones lead to CBM escape.

3. CHARACTERISTICS AND DISTRIBUTION LAWS OF COALBED METHANE RESERVOIRS

3.1. Characteristics of Coalbed Methane Reservoirs

3.1.1. Physical Properties of Coal Reservoirs

Coal reservoirs have a dual-porosity structure, consisting of matrix pores and fractures. Matrix pores provide storage space, while fractures serve as channels for gas migration. The porosity of coal reservoirs is generally low, mostly ranging from 2% to 15%, and the permeability is also low, usually less than $1 \times 10^{-3} \mu\text{m}^2$. As the burial depth of coal seams increases, the in-situ stress increases, compressing the pores and fractures of coal reservoirs, further reducing permeability.

3.1.2. Composition and Structure of Coal Rocks

The composition of coal rocks includes vitrinite, inertinite, exinite, etc. Different coal rock compositions have an impact on the methane adsorption capacity and reservoir physical properties of CBM. Coal with a high vitrinite content has a stronger adsorption capacity. The coal structure can be divided into primary structural coal, fragmented coal, and mylonitic coal. Primary structural coal has relatively good reservoir physical properties. Fragmented coal and mylonitic coal have developed pores and fractures due to coal fragmentation, but they are prone to closure under high-stress conditions, affecting gas migration.

3.1.3. Reservoir Pressure and Temperature

Reservoir pressure is an important factor affecting the occurrence state and desorption of CBM. As the burial depth increases, the reservoir pressure increases. The reservoir pressure coefficient (the ratio of actual reservoir pressure to hydrostatic pressure at the same depth) is generally used to evaluate the reservoir pressure state, with a normal pressure coefficient ranging from 0.8 to 1.2. Reservoir temperature also increases with the increase in burial depth, which has a certain impact on the adsorption-desorption characteristics of CBM. As the temperature rises, the methane adsorption capacity of coal decreases.

3.2. Distribution Laws of Coalbed Methane Reservoirs

3.2.1. Global Distribution

CBM resources are widely distributed around the world, mainly concentrated in the Northern Hemisphere. Countries such as the United States, Russia, China, and Canada are rich in CBM resources. The United States is the most successful country in CBM development globally, with its CBM production mainly coming from the San Juan Basin, Black Warrior Basin, etc. Basins such as the Tunguska Basin and Kuznetsk Basin in Russia also have great CBM development potential.

3.2.2. Distribution in China

CBM resources in China are mainly distributed in four major coal-bearing areas: North China, Northwest China, Northeast China, and South China. The Qinshui Basin and the eastern margin of the Ordos Basin in North China are the key areas for CBM development in China at present. The Qinshui Basin is rich in CBM resources and has good coal reservoir conditions, realizing large-scale development. The eastern margin of the Ordos Basin also has a large amount of CBM resources, but its geological conditions are relatively complex. Basins such as the Junggar Basin and Turpan-Hami Basin in Northwest China have certain potential for CBM resources, but the degree of exploration and development is relatively low. CBM development is also gradually advancing in basins such as the Fushun Basin and Fuxin Basin in Northeast China. CBM resources in South China are scattered in distribution and have complex geological structures, resulting in high development difficulty.

4. EXPLORATION AND DEVELOPMENT TECHNOLOGIES OF COALBED METHANE

4.1. Exploration Technologies of Coalbed Methane

4.1.1. Geological Survey and Evaluation

Through surface geological surveys, the distribution of coal-bearing strata, structural characteristics, and coal seam development are understood. Coalfield geological exploration data are used to conduct a preliminary evaluation of CBM resources. At the same time, coal samples are collected for laboratory analysis to determine parameters such as proximate analysis, ultimate analysis, and isothermal adsorption-desorption of coal, providing basic data for resource evaluation.

4.1.2. Geophysical Exploration

Geophysical exploration is an important means for CBM exploration. 3D seismic exploration can clearly identify the structural shape of coal seams, changes in coal seam thickness, distribution of faults, etc., providing a basis for well location deployment. Electrical exploration, gravity exploration, and other methods can also be used to detect the occurrence state of coal seams and geological structural characteristics.

4.1.3. Logging Technology

Logging technology is used in CBM exploration to identify coal seams, determine coal seam thickness, and measure coal quality parameters and reservoir physical property parameters. Common logging methods include natural gamma logging, resistivity logging, acoustic logging, etc. Through the analysis of logging curves, information such as CBM content, porosity, and permeability of coal seams can be obtained.

4.2. Development Technologies of Coalbed Methane

4.2.1. Vertical Well Mining Technology

Vertical wells are a commonly used well type in CBM development. In CBM vertical well mining, stimulation measures such as hydraulic fracturing are usually adopted to increase the permeability of coal seams and improve CBM production. The selection of fracturing fluid and the optimization of fracturing process parameters are crucial to the fracturing effect.

4.2.2. Horizontal Well Mining Technology

Horizontal wells can increase the contact area between the wellbore and coal seams, improving CBM recovery. Horizontal well mining technology includes horizontal well drilling technology, completion technology, and drainage production technology. During the horizontal well drilling process, it is necessary to accurately control the wellbore trajectory to ensure that the wellbore runs through the coal seam. The selection of completion methods should consider coal seam characteristics and mining requirements, and during the drainage production process, drainage parameters should be optimized according to the production dynamics of CBM wells.

4.2.3. Multi-Branch Horizontal Well Mining Technology

On the basis of horizontal wells, multi-branch horizontal wells add branch wellbores to further expand the contact area between the wellbore and coal seams, improving the CBM mining effect. Multi-branch horizontal well technology is suitable for areas with large coal seam thickness and good continuity. However, this technology has high requirements for drilling technology and well pattern layout.

4.2.4. Fracturing Stimulation Technology

Fracturing stimulation technology is one of the key technologies to improve CBM production. In addition to conventional hydraulic fracturing, there are also CO₂ foam fracturing, nitrogen foam fracturing, etc. CO₂ foam fracturing can reduce the damage of fracturing fluid to coal seams, and the injected CO₂ can displace methane in coal seams, improving CBM production. Nitrogen foam fracturing has good sand-carrying capacity and flowback performance.

4.2.5. Drainage Production Technology

Drainage production is an important link in CBM development. By reducing the coal seam pressure, CBM is converted from the adsorbed state to the free state and produced. The drainage production process should follow the principle of slow and stable pressure reduction, reasonably control the drainage intensity, and avoid damage to coal reservoirs. At the same time, drainage parameters such as pump displacement and bottom-hole flowing pressure should be adjusted in a timely manner according to the production dynamics of CBM wells.

5. ENVIRONMENTAL IMPACTS OF COALBED METHANE DEVELOPMENT AND RESPONSE STRATEGIES

5.1. Environmental Impacts

5.1.1. Impact on Water Resources

A large amount of produced water is generated during CBM development. The discharge of produced water may pollute surface water and groundwater. Produced water contains a large amount of dissolved solids, heavy metal ions, and other pollutants. If not properly treated, it will cause harm to the surrounding water environment and soil environment. In addition, the drainage and pressure reduction during CBM mining may lead to a drop in the groundwater level, affecting the growth of surrounding vegetation and the ecological balance.

5.1.2. Impact on Atmospheric Environment

If not properly managed, methane leakage may occur during CBM mining. Methane is a potent greenhouse gas, and its leakage will exacerbate global warming. In addition, the combustion of CBM emits greenhouse gases such as carbon dioxide, which also has a certain impact on the atmospheric environment.

5.1.3. Impact on Land Resources

CBM development requires the construction of infrastructure such as well sites and gathering and transportation pipelines, occupying a large amount of land resources. At the same time, problems such as land subsidence during the mining process may lead to land collapse and surface deformation, affecting the normal use of land.

5.2. Response Strategies

5.2.1. Treatment and Reuse of Produced Water

A combination of physical, chemical, and biological treatment methods is used to treat CBM produced water to make it meet the discharge standard or reuse standard. The treated produced water can be used for fracturing water, irrigation water, etc., in CBM mining, realizing the recycling of water resources.

5.2.2. Methane Emission Reduction Measures

Strengthen the tightness inspection and maintenance of CBM mining equipment to reduce methane leakage. Advanced monitoring technologies are used to monitor methane emissions in real time. For leaked methane, treatment methods such as flare combustion can be adopted to convert it into carbon dioxide, reducing the greenhouse effect.

5.2.3. Land Reclamation and Ecological Restoration

After the completion of CBM development, land reclamation is carried out on the land occupied by well sites, gathering and transportation pipelines, etc., to restore the original function of the land. For problems such as land subsidence caused by mining, corresponding engineering measures are taken for governance, such as filling subsidence areas and reinforcing foundations. At the same time, ecological restoration measures such as afforestation are taken to improve the surrounding ecological environment.

6. CONCLUSIONS AND PROSPECTS

6.1. Conclusions

As an important unconventional natural gas resource, CBM has unique genetic types, accumulation mechanisms, and reservoir characteristics. CBM resources are widely distributed globally and in China, but the geological conditions and technical challenges faced by CBM development vary in different regions. At present, progress has been made in CBM exploration and development technologies, but there are still many challenges in deep CBM development, low-permeability CBM stimulation, and recovery improvement. At the same time, the environmental impacts of CBM development cannot be ignored, and effective response strategies need to be taken to reduce environmental damage.

6.2. Prospects

In the future, research in the field of CBM can be carried out in the following directions: First, conduct in-depth research on the occurrence mechanism and development technology of deep CBM to solve

problems such as complex geological conditions and high development costs faced by deep CBM development. Second, strengthen research on low-permeability CBM reservoir reconstruction technology to improve the production of low-permeability CBM. Third, carry out research on the coordinated development of CBM and other energy resources (such as coal, shale gas, etc.) to improve the comprehensive utilization efficiency of resources. Fourth, further improve the environmental impact assessment system for CBM development, develop more environmentally friendly mining technologies and environmental governance technologies, and realize the sustainable development of the CBM industry.

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