

Exploration Status and Prospects of Deep Coalbed Methane in China

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Abstract

Against the backdrop of the global energy transition and the advancement of China's "Dual Carbon" strategy, deep Coalbed Methane (CBM), as a highly promising unconventional natural gas resource, has become an important support for safeguarding national energy security. This paper systematically reviews the current status of deep CBM exploration and development in China, and conducts analyses from such dimensions as resource exploration achievements, key technological breakthroughs, and future exploration directions. Studies show that China possesses superior deep CBM resource endowments, with 100-billion-m³-scale gas fields discovered in basins such as Ordos Basin and Sichuan Basin. Innovations in exploration theories, drilling and completion, and fracturing technologies have broken through the traditional 1500-m development "depth limit". Future efforts should focus on low-rank coal, deep thin coal seams, and other frontier areas, strengthening technological research and industrial collaboration. This paper aims to provide theoretical references and practical guidance for the large-scale and cost-effective development of deep CBM in China.

Keywords

Deep Coalbed Methane, Exploration and development, Key technologies, Gas field

Introduction

With the sustained development of China's economy and society, the demand for clean energy has been rising steadily. Meanwhile, the proposal of the "Dual Carbon" goal has driven the energy structure toward a low-carbon, high-efficiency, and sustainable transition. As an unconventional natural gas associated with coal, Coalbed Methane (CBM) features high calorific value and low pollution. Its main component, methane, produces only water and carbon dioxide upon combustion, making it an ideal clean energy source.

For a long time, CBM exploration and development in China have been mainly concentrated in areas shallower than 1,500 m. However, with the gradual depletion of shallow resources, moving to deeper strata has become an inevitable trend for the sustainable development of the CBM industry. Deep CBM is generally defined in the industry as CBM buried at depths exceeding 1,500 m. China's CBM resources within 2,000 m burial depth exceed 30 trillion m³, of which deep CBM accounts for approximately one third, indicating enormous

development potential [1].

In recent years, China has achieved a series of landmark results in deep CBM exploration and development. These breakthroughs have not only overcome the traditional "forbidden zone" of development depth but also provided new directions for increasing reserves and production of unconventional oil and gas. Nevertheless, the challenges facing deep CBM development - such as complex geological conditions, high technical difficulties, and elevated development costs - cannot be ignored. In-depth research on the current status of deep CBM exploration and development in China is of great practical significance for clarifying industrial development directions, solving technical problems, and promoting efficient resource utilization [2].

Deep CBM exploration

Resource distribution and endowment characteristics

Deep CBM resources in China are widely distributed, mainly concentrated in major coal-bearing basins including the Ordos Basin, Qinshui Basin, Junggar Basin,

and Sichuan Basin. Among them, the Ordos Basin is the main battlefield for deep CBM exploration and development, where five 100-billion-m³-scale large gas fields have been successively discovered, including Daji Block, Linxing-Shenfu Block, and Daniudi Block, with proven reserves exceeding 900 billion m³. High-yield and industrial gas flows have also been tested in the southeastern Sichuan Basin and the Dongpu Sag of the Bohai Bay Rift Basin, continuously expanding the exploration territory [3,4].

Compared with shallow CBM, deep CBM exhibits unique endowment characteristics. Traditionally, it was believed that with increasing burial depth, CBM storage conditions deteriorate and adsorbed gas content decreases, resulting in low exploration and development value. However, recent research and practice have demonstrated that the total gas content per unit volume of deep coal is 2-3 times that of shallow coal, and coal-bearing strata are widely distributed [5]. The methane adsorption capacity of different coal ranks in deep strata under high temperature and pressure conditions is the key factor affecting gas content distribution [6]. CBM has gradually shifted from an associated resource in shallow zones to a major development target. The proportion of free gas in deep CBM can reach 20%-50%, enabling rapid and high production after fracturing without long-term dewatering, which significantly improves economic efficiency [7-9].

Exploration achievements and breakthroughs

In recent years, major breakthroughs have been made in deep CBM exploration in China. Several large-scale deep CBM fields with 100-billion-m³-scale reserves have been discovered successively. In 2023, China National Offshore Oil Corporation (CNOOC) discovered the Shenfu Deep CBM Field in the eastern margin of the Ordos Basin, with proven geological reserves exceeding 110 billion m³. Coal seams in this field are mainly buried at approximately 2,000 m, with single-layer thickness ranging from 6.2-23.3 m, average gas content of 15 m³ per ton of coal, and maximum daily gas production of 26,000 m³ per well [10]. In 2024, PetroChina CBM Company achieved efficient reserve growth and production enhancement in the Daji Block deep coal and rock gas block in the eastern margin of the Ordos Basin. Daily gas production exceeded 7 million m³, with an annual production capacity of 2 billion m³, establishing

China's first deep coal and rock gas field with a 10-billion-m³-scale annual capacity equivalent to 10 million tons of oil equivalent [11].

In addition, China Petroleum & Chemical Corporation (SINOPEC) has realized commercial-scale development of medium-to-deep CBM in the Yanchuannan Block, with an annual CBM output of 400 million m³. These achievements fully demonstrate the huge resource potential and development value of deep CBM in China, providing important resource support for national energy security.

Meanwhile, the exploration depth limit has been continuously refreshed, extending from 1,500 m to deeper than 3,500 m. Coal seam thickness has expanded from thick seams of 5-15 m to thin seams of 1-5 m. Well Xinfu 1204 HF, targeting a 3-m-thick coal seam, tested a daily gas production of 80,000 m³, highlighting the great development potential of deep thin-layer CBM [12].

Key technologies

Innovation in exploration theory

Traditional CBM geological theories suggest that the adsorption capacity of coal matrix for methane decreases with increasing burial depth and formation temperature. Burial depths exceeding 1,500 m were regarded as a development forbidden zone due to low gas content and high development costs. However, continuous advances in theoretical understanding have overturned this view. By breaking through traditional perceptions and starting from first principles, researchers have reconstructed the theoretical understanding system. The coexistence of free gas and adsorbed gas in CBM has been revealed for the first time, improving and consolidating the theoretical understanding of accumulation and enrichment mechanisms of CBM [13].

SINOPEC proposed the "dual-factor" enrichment model (favorable coal-accumulating environment + good preservation conditions) for medium-high-rank deep CBM, confirming that medium-high-rank deep CBM in structurally stable zones is the major target for near-term exploration [14]. CNOOC innovatively put forward the "complementary" and "three-dimensional" exploration concept for tight gas and CBM, strengthening research on the accumulation mechanism of deep CBM and effectively accelerating the exploration process of deep coal seams [15]. These theoretical innovations provide important theoretical guidance for the exploration and

development of deep CBM. CO₂ injection technology, which is mature in tight sandstone gas reservoirs, also provides a new idea for Enhanced Gas Recovery (EGR) in deep CBM reservoirs [16]. The CO₂-oil interaction mechanism in sandstone reservoirs can also provide a reference for the research on CO₂-CBM reservoir interaction [17].

Drilling and completion technology

To address problems including long drilling cycles and wellbore collapse caused by strong heterogeneity, developed parting, and high clay minerals content in the roof of deep coal reservoirs, researchers have continuously developed optimized and rapid drilling and completion technologies. SINOPEC has established a safe and efficient well-construction technology for deep CBM horizontal wells, centered on “high-sealing and high-inhibition compound salt drilling fluid, geosteering and batch drilling, and precise prevention and control of mechanical disturbance”. This technology has drastically reduced the drilling cycle from 93.5 days to 28.9 days and achieved “one-trip drilling” for a 2,000-m horizontal section [18].

The drilling and completion technology system for CBM exploitation is constantly being optimized and improved to adapt to the complex geological conditions of deep coal seams [19]. The research on drilling and completion technologies for broken soft coal seams provides important technical support for the wellbore stability control of deep CBM wells [20].

Meanwhile, high-sealing drilling fluids, high-efficiency steering technologies and equipment, and customized PDC bits have been developed to continuously improve reservoir penetration rate and shorten drilling cycles. The DNS-2 well cluster deployed by SINOPEC North China Oil and Gas Company in the Ordos Basin achieved three pioneering breakthroughs, including large-scale application of fully electric drive equipment, multi-source pipeline water supply, and “zipper” fracturing. The daily gas production reached 132,000 m³, supporting a proven reserve area of more than 100 billion m³ [21].

Fracturing technology

In terms of fracturing technology, a series of fracturing processes suitable for deep CBM development have been innovatively established. SINOPEC took the lead in proposing the fracturing concept of “creating long

fractures and achieving distant propping” and developed an effective supporting fracturing technology featuring “high-rate fracture creation, increased prefluid volume+continuous fluid injection for fracture extension, and multi-particle-size strong proppant support”. This technology enabled effective stimulation and stable high production in deep coal reservoirs, extending the depth of CBM exploration and development from 1,500 m to deeper than 2,800 m [22]. To tackle production enhancement challenges in the Shenfu Block, CNOOC applied ultra-large-scale fracturing technology and continuously optimized fracturing and production procedures, forming a technical system suitable for deep coal seam development in this block [23]. These innovations in fracturing technologies have effectively improved the recovery factor and single-well production of deep CBM [24].

Intelligent and digital technologies

With the rapid development of artificial intelligence (AI), big data, and other new technologies, their applications in deep CBM exploration and development have become increasingly widespread. Through geological modeling and numerical simulation, accurate characterization and prediction of CBM reservoirs have been realized, providing a scientific basis for formulating exploration and development plans [25]. Meanwhile, the application of such equipment as intelligent drilling rigs and remote monitoring systems has improved the efficiency and safety of drilling operations and reduced the risk of human operational errors [26].

For example, some enterprises use the Internet of Things (IoT) technology to monitor production equipment in real time, detect and resolve equipment failures promptly, and ensure continuous production. In addition, the application of AI algorithms in such areas as seismic data processing and reservoir prediction has improved the accuracy and efficiency of exploration [27].

Future exploration domains

Deep low-rank CBM

China is rich in low-rank coal resources, which are mainly distributed in basins such as the Junggar Basin and Turpan-Hami Basin. At present, the exploration and development of deep low-rank CBM are at a low level and still in the exploratory stage. Low-rank coal is characterized by well-developed pore structures and strong adsorption capacity, among other features.

However, it also faces challenges such as strong reservoir heterogeneity and large variations in gas content [28,29]. In the future, it is necessary to strengthen research on the accumulation mechanism of deep low-rank CBM and break through key technologies such as low-rank coal reservoir stimulation, so as to realize large-scale development of deep low-rank CBM [30,31].

For example, such technical means as developing fracturing processes suitable for low-rank coal and improving drilling and completion efficiency can reduce development costs and enhance resource recovery. Meanwhile, the exploration and evaluation of deep low-rank CBM should be strengthened to clarify resource potential and distribution patterns, providing a solid basis for exploration and development.

Deep thin-layer CBM

With the continuous increase in exploration depth, the development potential of deep thin-layer CBM has gradually emerged. At present, China has achieved exploration breakthroughs in deep thin-layer CBM with a thickness of 3 m in areas such as the Ordos Basin. Well Xinfu 1204 HF has tested a daily gas production of 80,000 m³. However, the development of deep thin-layer CBM faces challenges including thin reservoir thickness, strong heterogeneity, and great difficulty in fracturing stimulation.

In the future, geological research on deep thin-layer CBM should be strengthened to clarify its accumulation rules and enrichment characteristics. Drilling and completion, as well as fracturing technologies tailored for deep thin coal seams should be developed to improve reservoir stimulation effect and single-well production. For instance, horizontal well multi-stage fracturing can be adopted to increase the contact area between coal seams and fractures, thus enhancing recovery efficiency.

Offshore deep CBM

China's offshore areas contain abundant CBM resources, but the current level of exploration and development is extremely low. The development of offshore areas deep CBM faces difficulties such as high seawater pressure, complex geological conditions, and challenging operations. In the future, exploration and evaluation of offshore deep CBM should be strengthened to clarify resource potential and distribution. Drilling and completion, and fracturing technologies suitable for offshore environments should be developed to break

through technical bottlenecks.

Meanwhile, international cooperation should be enhanced to introduce advanced technologies and experience, reduce development costs, and improve efficiency. The development of offshore areas deep CBM will provide a new guarantee for China's energy security.

Coal-measure multi-gas co-production

Coal-measure strata host not only CBM but also various natural gas resources such as tight gas and shale gas. The implementation of coal-measure multi-gas co-production can improve resource utilization and reduce development costs. At present, experimental studies on coal-measure multi-gas co-production have been carried out in some regions of China, and certain achievements have been made.

In the future, theoretical research on multi-gas co-production should be strengthened to clarify the interactions and development rules of different gas reservoirs. Drilling and completion, and fracturing technologies suitable for multi-gas co-production should be developed to realize efficient and coordinated development of multiple natural gas resources [32]. For example, integrated drilling and completion, and fracturing technologies can be applied to reduce operational procedures and improve development efficiency.

Conclusion

China is endowed with superior deep CBM resources and has enormous exploration and development potential. In recent years, breakthroughs have been made in exploration theories and development technologies.

The discovery of several 100-billion-m³-scale deep CBM fields has provided important resource support for national energy security. However, deep CBM development still faces many challenges, including insufficient resource understanding, unbroken core technologies, high development costs, and overlapping mining rights.

In the future, efforts should be made to further strengthen scientific and technological innovation, enhance basic theoretical research, tackle key technologies and equipment, and promote deep integration of industry-academia-research collaboration. The policy system should be improved to increase support for deep CBM exploration and development, optimize mining rights management mechanisms, and strengthen financial

support. Industrial integration should be promoted to realize coordinated development of deep CBM with coal, new energy, and other industries. Through joint efforts, the large-scale and cost-effective development of deep CBM will be accelerated. Deep CBM will be built into an important component of China's clean energy system, supporting the high-quality development of China's energy industry and the smooth achievement of the "Dual Carbon" goal.

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Conflict of Interest

The authors declare no conflict of interest.

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