Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 20, No. 1, 2026

Research Status and Development Trend of Gas Extraction and Permeability Enhancement Technology in Coal Mine

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Abstract: Gas drainage constitutes the cornerstone of coal mine safety production, with permeability enhancement technology being pivotal to addressing challenges in managing gas in low-permeability, high-outburst coal seams. China's coal mines feature complex geological conditions, where 90% of high-outburst seams exhibit permeability levels ranging from 10^{-18} to 10^{-20} m², representing typical low-permeability coal seams. This paper systematically reviews the research status and applicability of traditional technologies such as mining release layers, hydraulic permeability enhancement, and loose blasting. It highlights the development progress and engineering applications of emerging technologies including controllable shock waves, dehydration-based permeability enhancement, and supercritical CO_2 jet technology. The study analyzes current technical limitations and outlines future trends toward intelligent, green, integrated, precise, and deep-layered solutions, providing technical references for efficient coal mine gas management.

Keywords: Coal Mine Gas; Gas Drainage and Permeability Enhancement; Low-permeability High-outburst Coal Seams; Dehydration and Permeability Enhancement; Intelligent Management.

1. Introduction

As the primary energy source in China, coal mines face the foremost threat of gas disasters in production safety. Gas drainage serves as the fundamental solution for addressing gas hazards at their source, with its efficiency directly determining the effectiveness of control measures. Nearly 90% of high-outburst coal seams in China exhibit permeability levels ranging from 10^{-18} to 10^{-20} m², classified as typical low-permeability coal seams. Conventional drainage methods struggle to achieve efficient gas desorption and seepage, making permeability-enhancing technologies—through artificial intervention to improve coal seam aeration—become the critical support for gas hazard management [1].

Over decades of research, both domestic and international studies on gas extraction and permeability enhancement have developed a comprehensive technical system, evolving from traditional pressure relief methods to advanced physicochemical approaches. The implementation of the "Coal Mine Safety Production Regulations" has imposed stricter national requirements for coal mine gas management. Concurrently, the coal industry's accelerated transition toward intelligent and green technologies has driven innovations in gas extraction and permeability enhancement, including intelligent equipment, eco-friendly processes, and integrated applications. Cutting-edge technologies such as controllable shock waves and supercritical CO_2 jets have been successfully applied in engineering. This paper systematically reviews the current research and application status of traditional and advanced gas extraction and permeability enhancement technologies, analyzes their developmental trends, and aims to provide references for precise prevention and control of coal mine gas disasters in China.

2. Research Status of Gas Extraction and Permeability Enhancement Technology in Traditional Coal Mine

The traditional gas drainage permeability enhancement technology, based on pressure relief and fracturing, has developed mature techniques including mining of liberated seams, hydraulic fracturing for permeability enhancement, and loose blasting through years of engineering practice. These constitute the fundamental technical approaches for coal mine gas control [1].

2.1. Mining of the Liberation Seam

The release seam mining technique is currently the most widely adopted and effective method for gas control in coal mining areas, leveraging the decompression effect after coal seam extraction to achieve efficient gas extraction [2]. This technique is suitable for multi-layer coal-bearing mines. By prioritizing the mining of release seams with lower outburst risks and better gas permeability, it releases the elastic energy stored in protected coal seams and surrounding rock, causing the protected coal seams to expand and deform. This process promotes the development of primary pore-fracture systems, significantly enhancing gas permeability coefficients.

China was among the earliest adopters of this technology. During the 1950s-60s, mining regions like Tianfu and Beipiao pioneered its application. From the 1970s to 1980s, domestic research institutes conducted theoretical and process optimization studies. In the 1990s to 21st century, large-scale mining areas such as Yangquan, Huaibei, and Huainan further promoted its adoption, establishing it as the core technology for gas control in high-risk mines [13].

The core advantage of this technology lies in its stable gas control efficacy, which can eliminate the risks of coal and gas outbursts at the source, with broad applicability. However, its limitations are evident: it is only suitable for mines with multiple coal seams and has no practical value for single-thin coal seam mines. Additionally, the technology requires substantial engineering work and high overall costs. The spatial-temporal coordination between the extraction of liberated seams and the pumping of protected coal seams demands strict precision, making its promotion in small and medium-sized mines challenging.

2.2. Hydrotreating for Enhanced Transparency

Hydraulic permeability enhancement technology refers to a set of techniques that utilize high-pressure fluids to fracture, fissure, and perforate coal seams. Originating from the reservoir modification of oil and gas wells, it primarily includes three core processes: hydraulic fracturing, hydraulic fissuring, and hydraulic perforation. This technology is the mainstream approach for localized gas permeability enhancement in coal mine underground operations.

Hydraulic fracturing (HF) technology involves injecting fracturing fluid under high pressure into coal seams to create artificial fractures and a fracture network, thereby establishing pathways for gas permeability. First successfully tested in the United States in 1947, this method was pioneered by the Soviet Union in the 1970s for coal mine gas extraction. In China, Zhang Pengchong's underground HF experiments at Bao' an Mine achieved a significant leap in both coal seam permeability coefficients and gas extraction rates [3]. While widely applicable for large-scale permeability enhancement, the technique requires stringent parameters such as water pressure and pump flow rates. It is only effective for coal with low firmness coefficients, performs poorly on hard coal seams, tends to form unidirectional fractures, and is unsuitable for water-sensitive formations.

Hydraulic fracturing technology utilizes high-pressure water flow to directionally fracture the surrounding coal seam, creating controlled fissures that expand gas exposure areas. Field trials by Li Zhiheng et al. demonstrated its effectiveness in enhancing gas extraction efficiency and reducing coal seam gas content [4]. While this technique shows significant in-situ permeability improvement with low equipment investment and short construction periods, it has limitations including narrow effective coverage and short-lasting effects. It is primarily applicable to localized coal seam reinforcement in areas with low rock strength, while showing limited efficacy in treating hard coal seams.

Hydraulic perforation technology utilizes high-pressure water jets to impact surrounding coal within boreholes, creating localized pressure relief zones through coal fragmentation. This method serves as an efficient localized permeability enhancement technique for soft coal seams. Experimental studies by Li Lei et al. in "three-soft" coal seams demonstrated significant improvements in post-operation gas extraction parameters, including pure flow rate, extraction radius, and permeability coefficient. While the technology is operationally simple, it is exclusively applicable to coal seam reinforcement in areas with low regional coal strength. Precise design of high-pressure water jet parameters is essential to prevent issues such as borehole collapse [5].

2.3. Loose Blasting Technology

The loosening blasting technique is a localized gas permeability enhancement method for hard coal seams. By strategically positioning blast holes and control holes in front of mining operations, directional loosening blasting is performed. This technique utilizes shock waves and stress waves to disrupt the coal's original structure, creating a complex fracture network. Its core principle involves controlling blast energy to fragment the coal without causing large-scale fragmentation, thereby achieving dual effects of pressure relief and fracture development [6].

On-site construction results at the 1321 working face of Dingji Mine by Liu Zhi demonstrated significant improvements in coal seam permeability and gas extraction efficiency following blasting. This technology features simple construction procedures, effective permeability enhancement in hard coal seams, low equipment investment, and short construction cycles. However, it is only suitable for localized pressure relief and permeability enhancement in hard coal seams, as well as pressure relief and outburst prevention operations in coal seams exposed at stone doors and shafts. It is not applicable for large-scale construction in high-gas or outburst-prone coal seams, and the blasting process carries safety risks, as excessive energy may trigger coal and gas outbursts.

3. Research and Engineering Application of New Technology for Gas Extraction and Permeability Enhancement in Coal Mine

As mining depth increases, deep coal seams exhibit high gas content, high stress, and low permeability. Traditional permeability enhancement techniques show diminishing effectiveness, while hydraulic methods often cause issues like water jetting and hole collapse in soft, low-permeability coal seams. In recent years, innovative technologies such as controlled shock waves, water-free enhancement, and CO_2-based enhancement have effectively addressed these limitations by leveraging novel permeability enhancement principles.

3.1. Controlled Shock Wave Antireflection Technology

The controlled impact wave enhancement technology generates controllable shock waves within coal seams to disrupt the original structure of coal through dynamic forces, thereby promoting the development and expansion of pores and fractures, ultimately forming a complex fracture network. This technique is characterized by safety, reliability, high energy utilization efficiency, and controllable impact frequency and energy [7].

For soft and low-permeability coal seams, researchers have developed a controllable shockwave-based roof permeability enhancement technique. Simulation experiments reveal that discharge voltage and frequency are critical factors: high voltage induces dense and rapidly propagating cracks, while increased frequency promotes crack development into a "fan-shaped" network. The damage process is cumulative, with severe damage occurring at fracture-induced boreholes and coal-rock interfaces, forming fully damaged zones. This study elucidates crack evolution and damage mechanisms. The technology has been successfully implemented in field trials at selected mines, demonstrating promising results [7].

3.2. Dehydration and Antireflection Technology

Hydraulicization measures in soft and low-permeability coal seams are prone to issues like hole spraying, collapse, and blockage, making dehydration-based permeability enhancement a key solution. The air jet perforation and pressure relief technique utilizes compressed air as the driving force, where high-speed air jets impact the coal to decompress, fracture, and enhance permeability, effectively avoiding water lock effects and hole collapse.

Through theoretical calculations and experimental studies, researchers determined the key structural parameters of the nozzle: for a 73 mm drill string, the nozzle has a maximum length of 20 mm and an outer diameter of 13 mm. When the expansion ratio is 1.0, the jet achieves the longest isokinetic core length, the farthest target impact distance, and the highest pressure. Engineering tests demonstrated that under 0.6 MPa compressed air pressure, the perforation radius can exceed 0.56 m in soft coal seams with a f=0.3. The gas extraction flow rate is twice that of hydraulic perforation, the extraction compliance time is reduced by one-third, and the imbalance between mining and extraction is effectively resolved [8].

3.3. CO_2-based Antireflection Technology

CO_2-based antireflection technology utilizes CO_2 as the working medium, primarily comprising supercritical CO_2 jet technology and liquid CO_2 phase-change-induced cracking technology. It combines both physical cracking and chemical desorption effects, representing a green and highly efficient antireflection technique.

Supercritical CO_2 jet technology utilizes high-speed SC-CO_2 jets to fracture coal formations, with the dissolution and extraction properties of SC-CO_2 enhancing gas desorption from coal. Self-oscillating pulsed SC-CO_2 jets demonstrate advantages in low critical pressure and high coal fracturing efficiency. Researchers have developed an energy conversion efficiency calculation method based on the evolution of vortex structures within the nozzle. Their findings indicate that when the cavity-to-diameter ratio reaches 3.5, the jet energy conversion efficiency can reach up to 80.80%. Moreover, as the proportion of vortex kinetic energy at the nozzle outlet decreases, the jet becomes more concentrated, resulting in improved gas permeability enhancement [9].

Liquid CO_2 fracturing technology utilizes high-pressure liquid CO_2 injected into coal seams. Upon activation, the CO_2 rapidly vaporizes, expanding hundreds of times in volume to generate high-pressure shockwaves that disrupt coal structure [10]. Research demonstrates a significant linear correlation between vertical principal stress and coal fracturing pressure, with a 1 MPa increase in vertical stress corresponding to approximately 0.6 MPa in fracturing pressure. Tilted fractures significantly degrade coal mechanical strength, with permeability in overburden-pressurized samples containing such fractures increasing 12.7–14.9 times that of unfractured coal. This study reveals a three-stage synergistic mechanism of "dynamic fracturing—static expansion—geostress compression" for enhanced permeability. The technology has been successfully implemented in multiple deep, low-permeability coal seam mines .

4. Latest Progress of Gas Extraction and Permeability Enhancement Technology Equipment and Industry Management in Coal Mine

4.1. Innovation in Intelligent Technology and Equipment

At the National Coal Mine Gas Control Field Promotion Conference, the China Coal Research Institute showcased over 10 core technologies and equipment across four major categories for gas disaster prevention. The intelligent gas prediction and early warning system achieves a 30-minute in-situ measurement error of less than 5% for coal seam gas content, with a 40% improvement in gas outburst parameter testing efficiency and 100% accuracy in non-outburst warnings. The ZZY127 coal mine drilling debris detection system enables one-click operation for "drilling-mining-measuring-recording". The KJ1911 gas inspection system realizes full-process intelligence for inspection planning, gas detection, and abnormal alarms. These innovations drive the transition from "experience-based" to "precision-oriented" gas extraction permeability enhancement [11].

4.2. Sealing Process Optimization and Material Innovation

Yunding Coal Mine under Henan Energy Group's Yimei Company has implemented the "Three Blockages and Three Injections" sealing technology for downhole screens across all coal seams. This innovation has increased the average gas extraction concentration in single-row boreholes from 3.2% to 49.2%, with 85.7% of cross-layer boreholes achieving initial concentrations above 80% [14]. The Phase Change Gel Sealing Technology and Equipment, developed by the China Coal Research Institute, utilizes eco-friendly phase change gel sealing materials. This solution features low material consumption, reduced labor intensity, cost-effective sealing, and green biodegradability.

4.3. Upgrading Industry Management with Precision

Since the implementation of the "Coal Mine Safety Production Regulations", China's national mine safety supervision authorities have adopted a dual approach of "enforcement-driven measures and service guidance" to compel coal enterprises to enhance their gas control capabilities. For instance, the Henan Bureau of the National Mine Safety Administration established a dedicated task force for gas management in the "three-soft" coal seams of western Henan, conducting regular follow-up inspections to evaluate gas control effectiveness. Third-party institutions are tasked with measuring residual gas concentrations and pressure levels to ensure tangible results from the governance efforts [12].

5. Problems of Gas Extraction and Permeability Enhancement Technology

Despite significant progress in coal mine gas extraction and permeability enhancement technology in China, current techniques still face multiple challenges:

First, the technology lacks specificity, resulting in suboptimal governance effects under complex conditions.

China's coal mine geological conditions are diverse and complex, with certain technologies applicable only to specific coal seam conditions. Under complex conditions such as multiple coal seams overlapping, deep high-stress zones, and soft low-permeability strata, the enhancement of permeability shows significant attenuation [13].

Secondly, the level of equipment intelligence is not high, and the degree of automation in construction and management is low. Currently, construction still relies primarily on manual operations, with core equipment for some emerging technologies remaining at the laboratory stage. The intelligence and automation levels of engineering equipment are relatively low, and the precision of parameter monitoring is insufficient.

Third, the effectiveness of single-technology governance is limited, and the integration of multiple technologies is insufficient. Currently, coal mining enterprises still predominantly rely on single-technology applications, lacking coordinated design for the integration of different penetration-enhancing technologies. A comprehensive governance system combining 'regional governance + localized governance' and 'physical penetration enhancement + chemical desorption' has not yet been established .

Fourth, fundamental research remains underdeveloped, with the mechanism of gas permeability enhancement in deep coal seams still unclear. The insufficient understanding of pore-fracture evolution and gas desorption-seepage patterns under high-stress conditions in deep coal seams hinders the development of permeability-enhancing technologies.

Fifth, the level of greenification is insufficient. Traditional hydraulic fracturing technology consumes a large amount of water resources, while loose blasting technology pollutes the underground environment. Some sealing materials are non-degradable, which does not align with the green transformation requirements of the coal industry.

6. Development Trend of Gas Extraction and Permeability Enhancement Technology

In light of China's coal mine gas control requirements and the development trends of the coal industry, future gas extraction and permeability enhancement technologies will advance toward intelligent, green, integrated, precise, and deep penetration approaches.

6.1. Intelligence: Equipment Automation and Intelligent Control

Future research will focus on developing high-precision, automated anti-caking construction equipment to achieve integrated automation for drilling operations, anti-caking treatment, and parameter monitoring. Leveraging IoT, big data, and AI technologies, an intelligent management platform for gas drainage and anti-caking will be established to enable real-time parameter tracking, data analysis, and smart regulation. Additionally, an intelligent gas disaster prediction and early warning system will be developed to enable precise forecasting of gas outburst risks.

6.2. Greening: Application of Dehydration for Enhanced Transparency and Cleaning Media

Prioritize the development of dehydration-based enhancement technologies such as air jet perforation, controlled shock waves, and CO_2-based enhancement to reduce water consumption and avoid water lock effect and hole collapse issues; research and develop green, biodegradable sealing materials and auxiliary materials such as fracturing fluids; promote the resource utilization of gas to achieve dual benefits of "disaster control + resource recovery".

6.3. Integration: Multi-technology Convergence and Collaborative Governance

Based on the mine's geological conditions and gas characteristics, a multi-technology integrated design combining "regional control + localized treatment", "physical permeability enhancement + chemical desorption", and "pressure relief fracturing + sealed extraction" has been implemented to establish a comprehensive permeability enhancement management system. The approach emphasizes synergistic optimization of permeability enhancement techniques with sealing processes and extraction systems, thereby improving gas extraction efficiency throughout the entire workflow of "fracturing-sealing-extraction" [14].

6.4. Precision: On-demand Augmentation and Process Parameter Optimization

Based on precise detection of coal seam geological conditions and gas parameters, we implement tailored permeability enhancement designs. By selecting appropriate technologies and process parameters according to the gas content, permeability, and ground stress characteristics of different coal seams and regions, we achieve "one-zone-one-policy, one-hole-one-policy" precision permeability enhancement. Through integrated numerical simulation, laboratory experiments, and field trials, we accurately optimize key parameters.

6.5. Deepening: Research and Application of Technology for Increasing Penetration in Deep Coal Seam

Strengthen fundamental research on gas permeability enhancement in deep coal seams to elucidate the evolution of coal pore-fracture systems under high-stress conditions, gas desorption and seepage characteristics, and the mechanisms of permeability enhancement technologies. Develop novel permeability-enhancing techniques for deep, high-stress, low-permeability coal seams, such as ultra-high-pressure controlled shock waves and deep-well CO_2 phase-change fracturing. Design specialized equipment for deep coal seam permeability enhancement to improve its compressive and impact resistance.

7. Conclusion

Gas extraction permeability enhancement technology serves as the cornerstone for addressing China's challenges in managing gas in low-permeability, high-outburst coal seams. While traditional methods like mining release seams, hydraulic permeability enhancement, and loose blasting have matured through years of engineering practice and remain fundamental approaches, their applicability is limited in complex geological conditions [13]. Emerging technologies such as controlled shock waves, dehydration-based permeability enhancement, and CO_2-based permeability enhancement, which operate on entirely new principles, effectively overcome the limitations of conventional techniques and have demonstrated excellent engineering performance.

With the accelerated intelligent and green transformation of the coal industry and the implementation of the "Coal Mine Safety Production Regulations", innovations in gas drainage and permeability enhancement technologies and equipment have been continuously advancing. Industry management has evolved toward refined practices, further improving the effectiveness of gas drainage and permeability enhancement. However, current technologies still face challenges such as insufficient technical specificity, low levels of equipment intelligence, inadequate integration of multiple technologies, and lagging basic research.

In the future, gas extraction and permeability enhancement technologies will advance toward intelligent, green, integrated, precise, and deep-layer applications. By developing intelligent automated equipment, precise control of the permeability enhancement process can be achieved; advancing anhydrous permeability enhancement technology will drive the green transformation of gas management; strengthening multi-technology integration and collaborative governance will establish a comprehensive permeability enhancement governance system; enhancing fundamental research and technological development for deep coal seam permeability enhancement will meet the demands of extended coal mining depths. Through technological innovation, equipment upgrades, and multi-technology integration, the efficiency of gas extraction and the safety of gas management will be continuously improved, providing solid technical support for coal mine safety production and the high-quality development of China's coal industry.

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