ISSN: 1813-4890

Research on the Current Status and Development Trends of Coal Seam Hydraulic Fracturing Technology

Jiangchun Fan [1,2]

[1]China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400039, China;

[2]State Key Laboratory of Coal Mine Disaster Prevention and Control, Chongqing 400039, China

Abstract

With the increase in mining depth of coal mines, the efficiency of gas drainage from low-permeability coal seams has become a critical factor constraining the safe and efficient production of coal mines. As an effective method for enhancing the permeability of coal seams, hydraulic fracturing technology has been widely applied underground in recent years. This paper systematically analyzes the current research status of hydraulic fracturing technology for underground coal seams in terms of theoretical models, laboratory experiments, numerical simulations, and field tests. It explores the development of coal seam hydraulic fracturing process technologies, equipment, and monitoring and surveillance technologies, identifies the current technical challenges, and proposes future development directions, providing a reference for the advancement of hydraulic fracturing technology for underground coal seams in coal mines.

Keywords

Underground coal mine; Hydraulic fracturing; Permeability enhancement technology; Gas drainage; Development trends.

1. Introduction

China is abundant in coal resources, but the majority of coal mines face challenges in mining high-gas and low-permeability coal seams [1-2]. Gas accidents pose a major threat to coal mine safety production, with coal and gas outbursts being particularly severe [3]. Traditional gas drainage methods are inefficient in low-permeability coal seams and fail to meet safety production requirements. In recent years, in addition to the relatively mature regional pressure-relief permeability-enhancement technology of protective layer mining (which is not applicable to single coal seams) for enhancing the permeability of outburst-prone coal seams, various in-seam regional pressure-relief permeability-enhancement technologies have been adopted, including hydraulic extrusion, hydraulic punching, hydraulic scouring, hydraulic slotting, rotary water jetting, hydraulic undercutting, deep-hole controlled pre-splitting blasting, and hydraulic fracturing. Among these, hydraulic fracturing exhibits the most significant technical and economic advantages in large-scale coal seam permeability enhancement [4-9]. By injecting water-based or chemical fracturing fluids at high pressure, hydraulic fracturing induces a fracture network in the coal seam, thereby improving its permeability and enhancing gas drainage effectiveness, making it an effective means to address this challenge.

2. Research Status of Hydraulic Fracturing Theory

2.1. Theoretical Models

The development of hydraulic fracturing theoretical models has evolved from simplicity to complexity. In the early stages, M. K. Hubbert and D. G. Willis proposed the theory of tensile failure induced by stress concentration at the borehole wall, laying the foundation for the mechanical analysis of hydraulic fracturing. Subsequently, B. Haimson, Eaton, and others introduced Poisson's ratio to predict formation fracture pressure, further enriching the mechanical models of hydraulic fracturing. Wang Li et al. [10] proposed a theoretical model of flow rate-fracturing effect, defined at the reservoir RVE (Representative Elementary Volume) scale, where the fracturing effect is characterized by volumetric aperture, pore fluid pressure, and matrix effective stress.

2.2. Laboratory Experiments

Laboratory experiments are a crucial means of studying the mechanisms of hydraulic fracturing. Through large-scale true triaxial testing systems, researchers can simulate the process of hydraulic fracturing in coal seams under different in-situ stress conditions, analyzing the initiation, propagation, and morphological changes of fractures. Experimental results indicate that hydraulic fractures in coal seams are often asymmetrically distributed and are influenced by various factors such as in-situ stress, coal and rock mechanical properties, and fracturing fluid performance. Ma Xingying et al. [11] conducted staged hydraulic fracturing experiments under conditions of in-situ stress difference, coal-rock interfaces, and pumping rates, analyzing the fracture development and stress variation laws during staged hydraulic fracturing.

2.3. Numerical Simulation

Numerical simulation methods play an important role in hydraulic fracturing research [12]. By establishing three-dimensional elastoplastic finite element models, researchers can simulate the initiation, propagation, and interaction of fractures during hydraulic fracturing, predicting fracture morphology and distribution ranges. Numerical simulation results provide scientific bases for optimizing fracturing parameters and designing construction schemes. Li Yanhui et al. [13] used RFPA-2D numerical simulation software to establish a numerical model of fracture development-stress field disturbance within coal bodies, simulating the evolution process of the internal fracture stress field in deep coal bodies under hydraulic fracturing.

2.4. Field Tests

Field tests are a critical step in verifying the effectiveness of hydraulic fracturing technology. Field trials have been conducted in multiple mining areas both domestically and internationally, with results indicating that hydraulic fracturing technology can significantly improve the permeability of coal seams and increase gas drainage volumes [14-15]. However, field tests have also exposed some issues, such as difficulties in controlling the propagation direction of fracturing fractures and severe losses of fracturing fluids, which require further research and solutions.

3. Research Status of Underground Coal Mine Hydraulic Fracturing Technology

3.1. Research Status of Coal Seam Hydraulic Fracturing Process Technology

(1) Directional Hydraulic Fracturing Technology

Directional hydraulic fracturing technology involves constructing directional boreholes within the influence radius of hydraulic fracturing boreholes to guide and control the direction of fracture propagation. This technology enhances fracturing effectiveness and reduces the

ISSN: 1813-4890

occurrence of secondary disasters. In recent years, with advancements in drilling equipment, directional long-borehole hydraulic fracturing technology has become a research focus. This technology combines the advantages of directional drilling and hydraulic fracturing, achieving localized pressure relief and permeability enhancement in coal seams. Wang Zhengshuai [16] elucidated the mechanism of outburst elimination through directional long-borehole hydraulic fracturing and established a numerical model to study the coupling laws of seepage and stress fields during hydraulic fracturing, as well as the influencing factors on fracturing effectiveness. Guo Chaoqi et al. [17] proposed an efficient gas drainage technology using directional long-borehole hydraulic fracturing in coal seams, utilizing self-developed complete sets of hydraulic fracturing process equipment. They conducted engineering application tests at Huangling No. 2 Coal Mine in the Huanglong Coalfield. The test results indicated that after implementing hydraulic fracturing permeability enhancement measures, gas drainage effectiveness was significantly improved, and the extractability of coal seam gas increased, providing technical support for efficient gas drainage in low-permeability coal seams in similar mining areas.

(2) Pulsating Hydraulic Fracturing Technology

Pulsating hydraulic fracturing technology causes fatigue damage and failure to coal masses through dynamic pressure loads, leading to the expansion of fractures into a network. This technology reduces fracturing pressure and improves fracturing efficiency, particularly suitable for low-permeability coal seams. Research has shown that after pulsating hydraulic fracturing, coal sample porosity significantly increases, and gas drainage effectiveness markedly improves. Chen Hao [18] found that the transformation of coal masses through directional long-borehole pulsating staged fracturing is the result of multiple synergistic effects, including the auxiliary softening effect of water, the fatigue damage effect of pulsating pressure, the block-cracking effect of hydraulic fractures, and the combined crushing effect of abutment pressure, achieving effective control of top coal.

(3) Fracture Network Hydraulic Fracturing Technology

Fracture network hydraulic fracturing technology forms a networked fracture structure to achieve uniform fracturing of coal seams. This technology enhances coal seam permeability and increases gas drainage channels. Research has indicated that the development degree of fracture network fracturing is controlled by factors such as natural fracture distribution, in-situ stress, coal and rock mechanical properties, and fracturing construction parameters.

3.2. Underground Coal Mine Hydraulic Fracturing Equipment

Underground coal mine hydraulic fracturing equipment is a complex and precise system, primarily comprising key components such as fracturing pumps, water supply systems, high-pressure manifold systems, and specialized sealing systems. Among these, the fracturing pump serves as the core power source, responsible for injecting high-pressure water-based or chemical fracturing fluids into coal seams and is the key executor of hydraulic fracturing operations. The specialized sealing system ensures that fracturing fluids do not leak during the injection process, guaranteeing safe and effective operations. However, with the increasing depth of coal seam mining and the growing complexity of geological conditions, traditional high-pressure pump groups are struggling to cope with high in-situ stress and high gas pressure. Therefore, the new generation of fracturing equipment is advancing towards miniaturization and intelligence to adapt to harsher operating environments and improve operational efficiency and safety.

3.3. Monitoring and Surveillance of Underground Coal Mine Hydraulic Fracturing

The water pressure and flow rate during coal seam hydraulic fracturing are key indicators affecting fracturing effectiveness. Currently, microseismic monitoring and transient electromagnetic methods are widely used for monitoring fracturing effects. Microseismic monitoring technology observes and analyzes micro-seismic events generated during production activities to monitor the influence range of fracturing, featuring long-distance, long-term, dynamic, three-dimensional, and real-time monitoring capabilities. The transient electromagnetic method is sensitive to low-resistivity media and is suitable for detecting the diffusion and distribution states of fracturing fluids. However, existing monitoring technologies still face challenges in terms of accuracy and applicability, which require further improvement.

4. Problems and Development Directions of Hydraulic Fracturing Technology

4.1. Problems in Hydraulic Fracturing Technology

(1) Insufficient Understanding of Hydraulic Fracturing Mechanisms

Existing hydraulic fracturing theories primarily rely on factors such as injection pressure, duration, and volume to control fracture propagation length, but they often overlook coal seam filtration conditions and lack in-depth research on fracture control mechanisms. Additionally, studies on fracture propagation tend to focus solely on mechanical energy transfer, neglecting the impact of rock mass deformation and fluid stress losses.

(2) Limited Accuracy and Applicability of Hydraulic Fracturing Range Monitoring Technologies

Conventional drilling methods are exploratory and blind, providing only point-based detection with significant limitations. Microseismic technology, while useful for monitoring the influence range of hydraulic fracturing, is susceptible to interference from underground factors. Transient electromagnetic methods offer high accuracy in determining fracturing ranges but involve complex procedures and potential safety hazards.

(3) Lack of Effective Safety Assessment Methods for Hydraulic Fracturing

There is currently no effective safety assessment method for hydraulic fracturing in China. Existing technologies and theories do not address the feasibility of on-site implementation conditions, the rationality of process parameters, or whether the desired effects have been achieved.

(4) Inadequate Safety Assurance Technologies and Systems for Hydraulic Fracturing

Although efforts have been made in areas such as hydraulic fracturing pump units, sealing, and safety management, there is a lack of research on establishing systematic and standardized implementation procedures for hydraulic fracturing, developing intelligent design software, creating intelligent monitoring and remote control systems for fracturing pump units, evaluating fracturing effects, and optimizing parameters.

4.2. Development Directions of Underground Coal Seam Hydraulic Fracturing Technology

(1) Conducting Multi-Methodological Basic Research on Hydraulic Fracturing

In the future, it is essential to integrate mathematical modeling, laboratory experiments, numerical simulations, and field measurement techniques to establish large-scale physical simulation systems for hydraulic fracturing. By employing technologies such as CT scanning, microseismics, and acoustic emission, the propagation of fractures can be monitored and analyzed in real-time, making the process visible. Additionally, a comprehensive hydraulic fracturing assessment system covering pre-fracturing, during-fracturing, and post-fracturing stages should be established to provide scientific guidance for on-site operations.

(2) Developing Diversified and Adaptive Hydraulic Fracturing Technologies for Various Coal Seams

To address the poor on-site application effectiveness of hydraulic fracturing technologies in soft coal seams, it is necessary to draw inspiration from the oil and gas industry for improvements. Segmented hydraulic fracturing technologies should be developed to solve issues such as borehole collapse and caving during directional long-borehole construction. Furthermore, integrating multiple permeability-enhancement technologies can create synergistic effects, improving the overall permeability enhancement of coal seams.

(3) Achieving Integration and Intelligence of Hydraulic Fracturing Equipment

Future development should focus on advancing hydraulic fracturing technologies and processes while enhancing the performance of fracturing equipment. By leveraging artificial intelligence, the Internet of Things, and big data technologies, real-time monitoring, autonomous parameter optimization, remote monitoring, and integrated operation of fracturing sites can be achieved. Additionally, real-time recording and monitoring of fracturing parameters, automatic data organization and analysis, and the generation of data models should be implemented to enable autonomous decision-making in abnormal situations.

5. Conclusion

This paper systematically analyzed the current research status of theoretical models, laboratory experiments, field trials, and numerical simulations related to underground coal seam hydraulic fracturing technology. It also explored the development of coal seam hydraulic fracturing process technologies, equipment, and monitoring and surveillance techniques. The paper identified existing problems in current technologies and proposed future development directions.

As the depth and scope of underground coal mining continue to expand, and coal seam geological conditions become increasingly complex and diverse, hydraulic fracturing technology will face greater demands and challenges. By strengthening basic theoretical research, developing diversified hydraulic fracturing technologies suitable for various coal seams, and achieving integration and intelligence of hydraulic fracturing equipment, the advancement of underground hydraulic fracturing technology will be promoted. These measures will provide strong support for ensuring safe and efficient coal mining operations.

References

[1] Mi Hongwei. Application of hydraulic fracturing permeability-enhancing technology in gas control of low-permeability coal seams [J]. Energy and Energy Conservation, 2025, (02): 119-121.

[2] Zhang Wenke. Research and application of efficient gas control technology in mining high-gas and low-permeability coal seams [J]. Inner Mongolia Coal Economy, 2024, (20): 118-120.

[3] Cao Jie. Analysis of statistical patterns and dynamic effect characteristics of coal and gas outburst accidents in China over the past decade [J]. Mining Safety & Environmental Protection, 2024, 51(03): 36-42+49.

[4] Li Lei, Zhou Shaoxi. Analysis and evaluation of the permeability-enhancing effect of hydraulic punching in "three-soft" low-permeability coal seams [J]. Coal Technology, 2021, 40(09): 90-93.

[5] Li Lei, Li Wei, Chen Lei, et al. Experimental study on the permeability-enhancing extraction process of hydraulic cavitation in low-permeability coal seams [J]. Coal Technology, 2021, 40(09): 80-83.

[6] Zhou Yujun, Li Zhenhua, Li Jiacheng. Research on key technologies of combined pressure relief and permeability enhancement in low-permeability hard coal seams [J/OL]. Coal Science and Technology, 1-10 [2025-05-21].

[7] Xue Yanping. Research on multi-hole synchronous staged hydraulic fracturing permeability-enhancing technology in low-permeability coal seams [J]. Coal Engineering, 2024, 56(06): 111-116.

[8] Cao Yaolin. Current status and prospects of research on hydraulic technology for preventing and controlling coal and gas outbursts [J]. Coal Mine Safety, 2020, 51(10): 60-66.

[9] Cheng Yu. Current status of research on hydraulic technology for preventing and controlling coal and gas outbursts [J]. Coal and Chemical Industry, 2024, 47(05): 112-115+69.

[10] Wang Li, Hu Wenheng, Cao Yunxing, et al. Theoretical model of flow rate-fracturing effect in hydraulic fracturing [J]. Journal of Henan Polytechnic University (Natural Science), 2024, 43(03): 23-33.

[11] Ma Xingying, Cheng Xiaoyu, Cheng Cheng. Experimental study on fracture propagation and stress evolution characteristics of staged hydraulic fracturing in coal and rock strata [J]. Experimental Technology and Management, 2024, 41(09): 47-53.

[12] Yuan Chuan'ao, Nie Jialong, Long Gongbo, et al. Numerical simulation study on the perforation erosion effect during hydraulic fracturing [J]. Journal of Wuhan Institute of Technology, 2024, 46(01): 72-78.

[13] Li Yanhui. Numerical simulation study on the evolution law of fracture stress field under hydraulic fracturing in coal seams of kilometer-deep wells [J]. Energy and Environmental Protection, 2024, 46(04): 32-37+43.

[14] Chao Zhiguo. Technology and field experiment of hydraulic fracturing in Dongda Coal Mine [J]. Coal, 2024, 33(02): 76-79.

[15] Huang Xingli. Efficient extraction equipment and field test of directional hydraulic fracturing in deep mines [J]. Shaanxi Coal, 2022, 41(01): 15-18+36.

[16] Wang Zhengshuai. Research on hydraulic fracturing technology for enhancing gas extraction through directional long boreholes in fragmented and soft coal seams [J]. China Coal, 2023, 49(06): 46-52.

[17] Guo Chaoqi, Zhao Jizhan, Li Xiaojian, et al. Technology and application of efficient gas extraction through directional long borehole hydraulic fracturing in medium-hard and low-permeability coal seams [J]. Coal Geology & Exploration, 2020, 48(06): 103-108+115.

[18] Chen Hao. Research on the technology of weakening hard roof coal through pulsating staged hydraulic fracturing in directional long boreholes [D]. Xi'an University of Science and Technology, 2023.

[19] Fan Jichao, Jiang Qiping, Wang Yanbo, et al. Research on the fracture propagation law and controlling factors of hydraulic fracturing based on microseismic monitoring [J]. Mineral Resources Protection and Utilization, 2025, 45(02): 22-28.

[20] Weng Dingwei, Wei Ran, Sun Qiang, et al. Overview of hydraulic fracturing fracture monitoring technologies [J]. World Petroleum Industry, 2024,31(06):66-76.