Research on Electrochemical Composite Energy Fracturing Coal Seam Gas Treatment Technology

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Abstract

Using the 2608 transportation roadway of Zhangcun Coal Mine in Lu'an Mining Area as the engineering background, this study compared the differences between gas extraction using electrochemical composite energy pulse fracturing technology and conventional methods. Experimental results showed that after coal seam permeability enhancement treatment, both gas concentration in fracturing holes and auxiliary extraction holes within the affected zone increased significantly. The gas extraction concentration in treated areas reached up to three times higher than that in untreated original extraction holes, with the optimal fracturing influence radius being approximately 5.0~7.5m. Field gas extraction results demonstrated that electrochemical composite energy fracturing effectively modifies multi-scale pore-fracture structures in coal seams, facilitating gas desorption, diffusion, and migration. The gas permeability enhancement and extraction mechanism of electrochemical composite energy fracturing may involve: When shock stress waves penetrate coal seams, they generate stress at both ends of existing fractures, expanding their length and width while creating new fractures. Simultaneously, the stress induces tensile damage to coal matrix particles, causing fracture propagation. This process connects new fractures with existing ones, forming a complex fracture network that enhances gas migration and production capacity.

Keywords

Electrochemical Composite Energy; Gas Extraction; Extraction Efficiency.

1. Introduction

Gas disasters have consistently accounted for a significant proportion of coal mine safety accidents in China, severely constraining the efficiency of underground roadway excavation and coal mining face recovery [1]. However, methane itself is a high-efficiency clean energy source, and its resource utilization represents a crucial pathway to enhance the comprehensive value of coal mine production. Consequently, safe and efficient methane extraction technology has become a core element in ensuring mine safety and improving economic benefits, as well as a key challenge in underground mining operations. Against this backdrop, the "extract first, then mine" principle has emerged as the fundamental guideline and consensus for methane management in China[2]. In recent years, various enhanced pre-extraction technologies-such as pre-split blasting, hydraulic fracturing, and CO_2-induced fracturing-have been widely applied and developed in mines with diverse geological conditions [3-5]. Among these, electrochemical composite energy pulse fracturing has been recognized as an effective method to improve coal seam permeability, increase methane extraction volume, and optimize reservoir pore structure[6-8]. This technology offers advantages including easy operation, low cost, simple management, safety reliability, and reusability. Given the varying applicability and effectiveness of different technical solutions, this study selects Zhangcun Coal Mine in Lu'an Mining Area as a case study to systematically investigate the field application of electrochemical composite energy pulse fracturing technology. It evaluates its practical benefits for mine production and analyzes technical challenges encountered during implementation, aiming to provide practical experience and engineering references for methane management in similar mines.

2. Geological Background

The Zhangcun Coal Mine is located in Changzhi City, Shanxi Province, with its mining area spanning Zhangcun Village in Xibatu Town (Luzhou District), Shiku Village in Dianshang Town (Luzhou District), Xihuiyuan Village and Angou Village in Houpu Town (Xiangyuan County), as well as Xiangshuitou Village in Yuwu Town and Dongnao Village in Luchun Township (Tunliu District). The industrial square is situated in Zhangcun Village, Xibatu Town, Luzhou District. To the north lies the Wuyang Coal Mine, while to the south are the Changcun Coal Mine, Wangzhuang Coal Mine, and Yuwu Coal Mine. The geographical layout of its surrounding areas is illustrated in Figure 1.

The mining area is located in the southeastern limb of the Qinshui syncline, characterized by a broad single-fold structure with bedding dip angles ranging from 5 to 15 degrees. Key structural features include: 1. **Folds**: Secondary broad folds are well-developed, forming small anticlines or synclines locally, though these have not significantly impacted coal seam continuity. 2. **Faults**: Predominantly medium-small normal faults, such as the F1 fault (NE-trending with 10-20m dip), show some influence on coal seam continuity. 3. **Caving Pillars**: Karst development in Ordovician limestone has created localized caving pillars, requiring enhanced exploration during mining. The Shanxi Formation (P1s), containing the No.3 coal seam (the main mining seam), has a thickness of 60-80m with an average 5.5m thickness. This simple-structured coal seam is classified as stable, ranging from low-rank (PM) to lean (SM) with ash content 15%-20%, sulfur 0.5%-1.2%, and calorific value 25-28 MJ/kg [9-11].

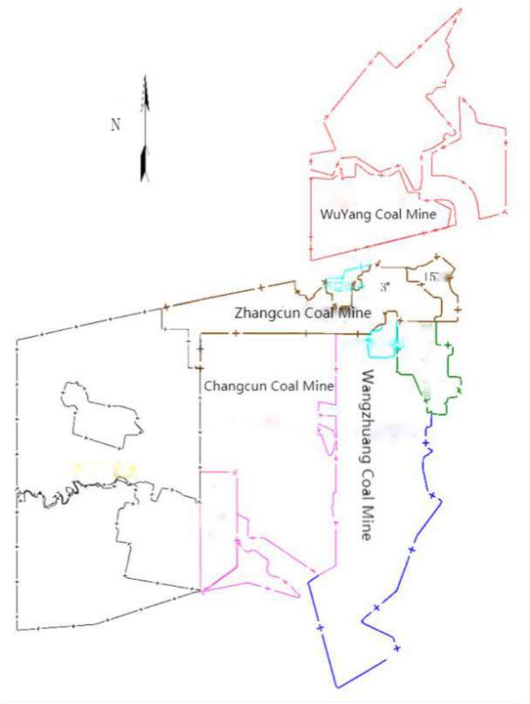

Figure 1. Neighborhood relationship diagram of Zhangcun coal mine

3. Electrochemical Composite Energy Pulse Transmittance Enhancement Construction Scheme

Based on the production conditions of the 2608 working face, seven boreholes were selected in the 2608 haulage roadway as pulse test holes, each with a depth of 90m. Several comparative enhancement holes were arranged between adjacent pulse test holes at 3m intervals, maintaining identical borehole parameters. This setup enabled determination of the pulse-enhanced reflectivity radius for electrochemical composite energy. The layout diagram of these pulse-enhanced reflectivity test holes in the 2608 haulage roadway is shown in Figure 2.

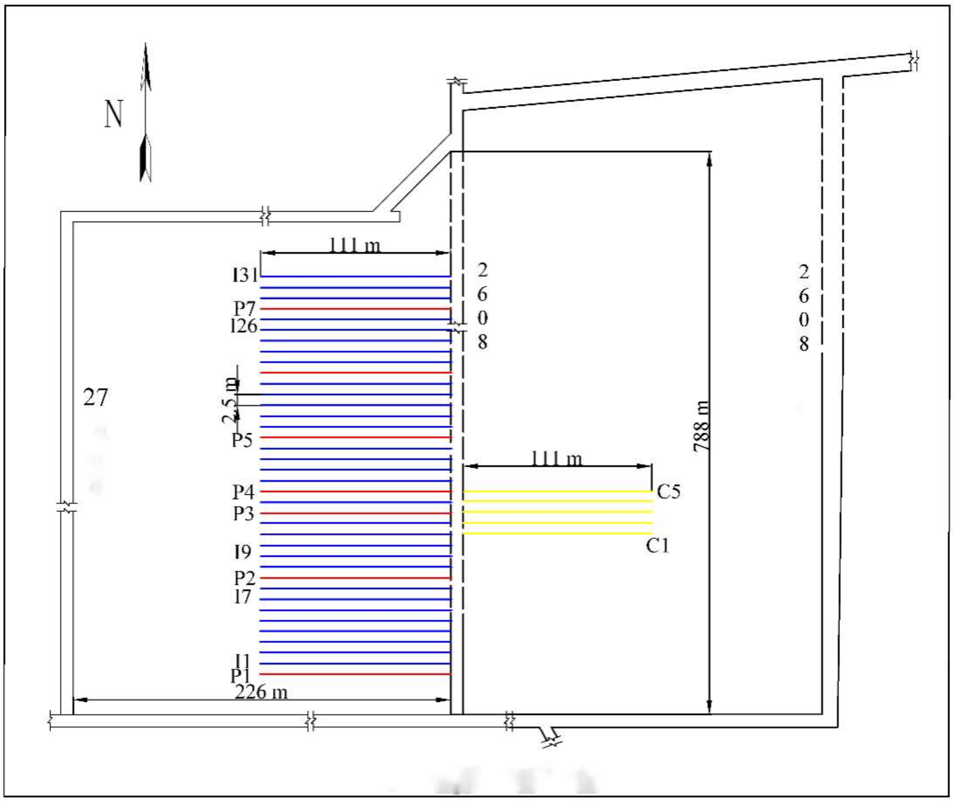

Figure 2. Electrochemical composite energy pulse transmittance enhancement scheme

Table 1. Electrochemical composite energy pulse fracturing scheme

Pore ID	Pore Depth	Pulse Count	Pulse Interval /m	Single-Point Count /f	Impact Density /(f·m^{-1})	Sealing distance/m
P1	40 m	12	4	3	0.3	20~25m
P2	35 m	10	3	3	0.3	
P3	50 m	20	2	3	0.4	
P4	45 m	18	4	5	0.4	
P5	50 m	25	5	5	0.5	
P6	45 m	16	3	4	0.35	
P7	60 m	21	3	4	0.35	

The construction process is as follows:

(1) Construction drilling: According to the pulse enhancement scheme, the first step is to drill the pulse hole. The inclination angle of the hole is 0, and the diameter of the hole is 133 mm. The specific hole depth is shown in Table 1;

(2) Installation of Wellhead Sealing Device: To facilitate water injection sealing at the wellhead and subsequent gas extraction parameter measurements, a steel pipe is embedded into the wellhead using the "two-seal-one-injection" sealing technique. The wellhead sealing steel pipe consists of two components: a welded flange and a sealing flange. The steel pipe has a diameter of 120 mm, the welded flange measures 160 mm in diameter, while the sealing flange features an inner diameter of 76 mm and an outer diameter of 150 mm.

(3) Equipment assembly: In the dry and dust-free place underground, the battery compartment, power control and switch, capacitor and pellet feeding mechanism of the electric pulse equipment are connected, and the pipe wrench is used to tighten to prevent the phenomenon of tripping during construction;

(4) Equipment entry hole: The connected electric pulse equipment is sent into the hole together. The battery compartment connector is connected to two water injection and cable drilling rods. Then, the drilling machine is used to drill the cable drilling rods into the hole one by one. After reaching the predetermined drilling depth, the sealing flange is connected at the hole mouth;

(5) Connect the water supply joint to the last cable-carrying drill rod. First, clean the coal slurry in the drill rod with air pipe for about 5 minutes, then replace it with water pipe to inject water into the borehole. When a small amount of water returns from the hole, the pulse permeability enhancement operation can be started.

(6) Lead the pulse line to 50m away from the pulse hole, and arrange a person to guard and cut off power. After the guard is completed, start the pulse according to the plan.

4. Gas Extraction Data Analysis

Starting August 4, 2025, the planned pulse-enhanced permeability test was conducted in the 2608 haulage roadway of Zhangcun Coal Mine, with the pulse fracturing experiment concluding on August 22,2025. Concurrently, dynamic methane concentration monitoring was performed on both enhanced permeability boreholes and control boreholes. This monitoring required data collection from 7 pulse test boreholes, 31 enhanced permeability boreholes, and 5 control boreholes. To streamline data processing, the average values of enhanced permeability borehole data near pulse boreholes were calculated. For instance, the average methane concentration between P1 and P2 was denoted as $\overline{(P1,P2)}$.

The methane extraction concentration data from all pulse test holes, permeability enhancement holes, and control holes in the 2608 Yunnan Tunnel were collected, as shown in Figure 3. Due to the nature of bare-eye drilling, pulse test holes often experience issues like hole collapse and excessive water accumulation. Consequently, the methane concentration in the electrochemical composite energy pulse fracturing test holes gradually decreased over time.

As shown in Figure 3, the permeability-enhancing holes 2.5 m away from P1-P5 pulse holes generally exhibit low gas concentration. This is because dozens of electrical pulse fracturing operations have created numerous fractures at the fracturing center, exceeding the critical threshold of coal fragmentation and increasing coal seam fragmentation. Consequently, this hinders gas desorption and migration, resulting in suboptimal extraction efficiency. However, permeability-enhancing holes approximately 5 m and 7.5m away from P1-P5 pulse holes showed improved gas extraction concentration after secondary electrical pulse fracturing modification. Observations of permeability-enhancing holes I4 and I5 between P1 and P2 indicate that extraction data remains unsatisfactory at 10 m from these two pulse holes, with weakened fracturing effects. Engineering experiments demonstrate that the optimal operational radius should be controlled within the 5-7.5m engineering interval, which represents the best extraction radius for electrical pulse fracturing modification.

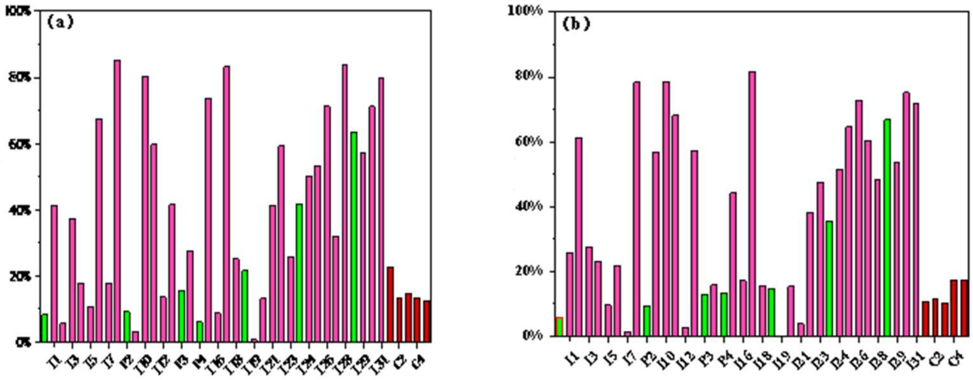

Figure 3. Pumping data from the 2608 Yunnan Tunnel's pulse drilling, enhanced permeability zone, and contrast borehole (a) September 13, (b) October 9

All extraction boreholes demonstrate enhanced methane recovery rates, with P6 and P7 achieving the highest concentrations. Compared to coal seams without electrochemical composite energy fracturing treatment, these boreholes exhibit approximately threefold improvements in methane extraction efficiency. This demonstrates that electrochemical composite energy fracturing effectively improves coal structure and pore-fracture systems, thereby influencing methane diffusion and migration processes. Notably, methane recovery rates remain relatively low when the electric pulse radius is around 2.5m, but show significant increases at 5-7.5m. This indicates that the optimal fracturing radius for Zhangcun Coal Mine treatment is approximately 5-7.5m.

5. Mechanism of Increasing Permeability and Extraction Capacity of Coal Seam with Electrochemical Composite Energy Pulse Fracturing

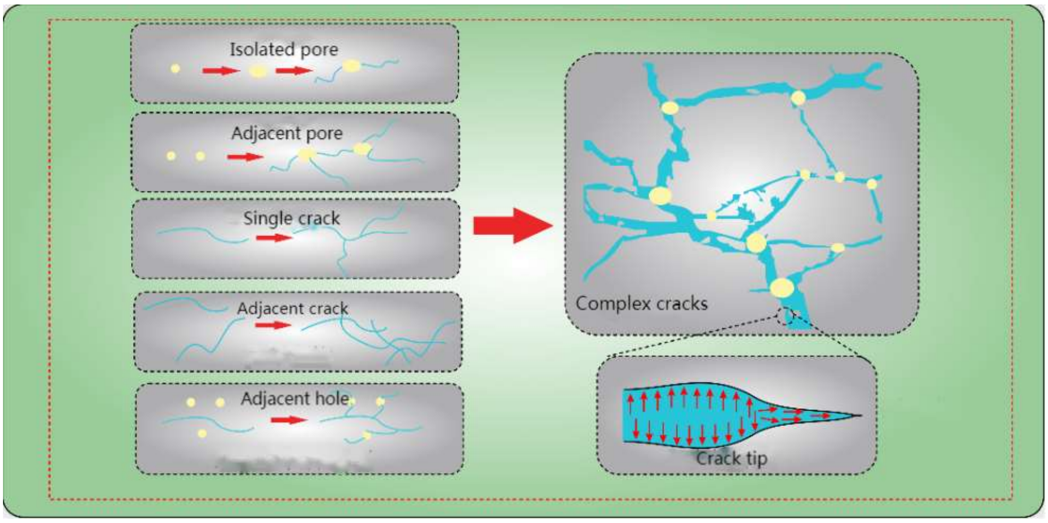

Figure 4. Mechanism of electrochemical composite energy pulse wave osmosis

The experimental application of this technology in Zhangcun coal seam gas extraction project demonstrates its enhanced permeability and extraction mechanism. When electric-chemical composite energy pulse stress waves carry water jets into the coal seam, the porous medium induces stress concentration at crack tips. This stress concentration not only facilitates crack propagation but also generates hydraulic wedge effects at crack tips, effectively driving fracture development[12-14].

Under the combined effects of two mechanisms, the original pore-fracture system in coal seams may undergo the following transformations: ① isolated pores being fractured to form micro-fractures; ② adjacent pores becoming interconnected through coal matrix fractures, creating multiple fissures

– a phenomenon consistent with mercury intrusion test results. After undergoing electrochemical composite energy-induced fracturing, coal samples exhibit significant increases in total pore volume and macropore capacity ③ existing single fractures expanding into multiple branches; ④ interconnected fractures forming branched fissures, along with communication between isolated pores and fractures. These combined effects create a complex fracture network system that enhances gas desorption and migration processes within coal seams. The mechanism of electrochemical composite energy pulse wave enhancement is illustrated in Figure 4.

6. Conclusion

The electro-chemical composite energy fracturing technology was implemented in the 2608 roadway of Lu'an Zhangcun Coal Mine for engineering trials and gas drainage monitoring. Experimental results demonstrated that after coal seam permeability enhancement, both fracturing holes and auxiliary drainage holes in affected zones showed significant increases in gas concentration. Compared to original drainage holes without fracturing, gas extraction efficiency reached approximately three times higher, with the optimal influence radius of fracturing modification being 5.0~7.5m. Field data confirmed that this combined electro-chemical fracturing effectively reshapes multi-scale pore-fracture structures in coal seams, facilitating gas desorption, diffusion, and migration. The mechanism of enhanced gas permeability and drainage through electro-chemical fracturing may involve: When impact stress waves penetrate coal seams, they generate stress at both ends of existing fractures, extending fracture lengths and widths while forming new fractures. Simultaneously, these waves cause impact damage to coal matrix particles, creating tensile forces that fracture existing fractures and connect them with new ones. This process establishes a complex fracture network, thereby significantly improving gas migration capacity.

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