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# Research on the Technology of Rapid Outburst Elimination Strip by High-Pressure Nitrogen Injection Displacement in Bottom Extraction Roadway for Promoting Flow and Enhancing Permeability

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## Abstract

**To address the challenges of difficult gas extraction and outburst elimination in "three-soft" low-permeability outburst coal seams, a rapid strip outburst-elimination technology is proposed, which combines high-pressure nitrogen injection displacement in the bottom drainage roadway for promoting flow and enhancing permeability. This technology was experimentally studied in the upper bottom drainage roadway of 14205 working face in a coal mine. The experimental results show that after nitrogen injection displacement, the total gas flow rate from boreholes increases by an average of over three times compared to conventional conditions, with a peak increase of over six times. The gas content in the coal seam within the displacement area decreases from an average of 6.80 $m^3/t$ and 7.56 $m^3/t$ to 5.58 $m^3/t$ and 4.98 $m^3/t$, respectively, while the gas content outside the displacement area is 7.76 $m^3/t$ and 7.5 $m^3/t$. There is a significant difference in gas content between the inside and outside of the displacement area, indicating that nitrogen injection displacement can enhance gas extraction and achieve rapid outburst elimination.**

## Keywords

**Gas Extraction; "Three-Soft" Coal Seam; Nitrogen Injection Displacement; Rapid Outburst Elimination.**

## 1. Introduction

In China's coal resource distribution, coal reservoirs in most areas have unique engineering geological traits. Typically, coal strength in these reservoirs is low, hindering the formation of large scale, interconnected coal seam fracture networks. Additionally, many Chinese coal seams are buried deep [1-2]. In deep mining, in-situ stress on coal seams rises significantly. There's a strong link between in - situ stress, coal strength, and fracture development. Higher in-situ stress compresses internal coal fractures, reducing coal reservoir permeability, a key parameter for fluid flow and crucial for gas extraction efficiency. Low permeability is a major obstacle to efficient gas extraction in most production scenarios [3]. To enhance gas extraction and reduce gas outburst risks, "permeability-enhancing measures" have become a core focus in China's gas research. Many researchers and engineers have explored ways to improve coal reservoir permeability [4-5].

Outburst mines under Zhengzhou Coal Industry (Group) Co., Ltd. have made positive attempts in gas control. The widely used hydraulic punching pressure relief gas extraction technology in floor rock roadways is based on "permeability - enhancing measures". It uses high pressure water jets to impact coal in the target extraction area, disturbing the coal structure and reducing in-situ stress. This promotes fracture dilation, creating more gas flow channels for "pressure relief and permeability enhancement" and stronger gas extraction. However, in practice, this technology has issues. Due to low coal seam permeability, gas migration is difficult, resulting in low gas extraction concentration and poor extraction effects. The hydraulic punching process is complex, involving multiple steps like high pressure water equipment installation and parameter control. Any problem can affect the overall punching effect. Moreover, high - pressure gas in the coal seam may be suddenly released during punching, causing gas ejection. This threatens operator safety, damages equipment, and slows construction. These problems hinder the implementation of regional outburst prevention measures, restricting mine safety and normal operations.

Safe mine production and operation are vital for coal enterprises' sustainable development. Currently, poor gas extraction and difficult outburst prevention measures lead to long pre - extraction times and tight mine succession. Long pre-extraction times increase production costs and may disrupt mining excavation balance, reducing overall efficiency. Thus, there's an urgent need for a rapid outburst elimination technology for outburst - prone soft coal strips to shorten pre-extraction times and ease mine succession while ensuring safety. This paper proposes an innovative gas control technology: injecting high pressure nitrogen into coal seams through pre-extraction boreholes in floor rock roadways. After injection, nitrogen's "flow-promoting and permeability-enhancing" effect can significantly increase coal seam gas flow. As an inert gas, nitrogen diffuses well in coal seams, displacing adsorbed gas, the main form of gas in coal seams that affects gas pressure and outburst risk. By reducing gas content and pressure, it can quickly eliminate outburst risks in front of the driving face in a strip - like manner. This technology offers new solutions for gas control in outburst - prone soft coal strips, with important theoretical and practical value.

## 2. Principle of Nitrogen Injection Displacement for "Flow Promotion and Permeability Enhancement" Technology

From the perspective of coal seam gas flow mechanism, a coal seam can be regarded as a dual - porosity medium composed of matrix coal blocks and inter - block fractures. During the evolution of coal fields, gas molecules are mainly stored in the matrix coal blocks in an adsorbed state and reach a relatively balanced state with the free gas under a certain pressure in the inter - block fractures. Under the action of negative extraction pressure, an extraction borehole maintains a relatively low gas pressure inside the borehole, creating a certain gas pressure gradient (pressure difference) with the surrounding coal mass around the borehole. This gradient prompts the free - state gas in the inter - block fractures to flow towards the extraction borehole. As the extraction time prolongs, the gas pressure in the coal seam fractures gradually decreases, disrupting the dynamic equilibrium between the adsorbed - state gas and the free - state gas. The adsorbed - state gas then desorbs and diffuses from the matrix coal blocks into the inter - block fractures, acting as a compensation (gas source) for the free gas in the fractures. As the extraction process continues, the overall gas content in the coal seam continuously decreases, and the gas pressure gradient between the coal seam and the borehole also gradually reduces, leading to a continuous decline in the net gas extraction rate [6-8].

The relationship between coal seam gas pressure and coal seam gas content follows a typical Langmuir curve. The fitting parameters 'a' and 'b' of this curve represent the saturated adsorption capacity and the adsorption pressure at half of the adsorption capacity, respectively. The Langmuir adsorption characteristics determine that even if the extraction work can significantly reduce the coal seam gas pressure, for example, from 1 MPa to 0.5 MPa, the residual gas content remaining in the coal seam is still as high as about 7 $m^3/t$, and the gas content reduced by extraction is only about 2 $m^3/t$. It can be seen that only by reducing the coal seam gas pressure to an extremely low level can the coal seam gas content be significantly decreased, fundamentally eliminating the risk of coal and gas outbursts and reducing gas emissions during tunneling and mining operations. However, as the coal seam gas pressure gradually decreases, the gas pressure gradient between the extracted coal mass and the extraction borehole significantly reduces, resulting in insufficient "gas flow driving force". This is the reason why the net gas flow rate usually decreases significantly in the later stage of gas extraction, while the coal seam gas content remains high.

Gas extraction is a gas flow process influenced by both "driving force" (gas pressure) and resistance (coal seam permeability). Simply increasing the coal seam permeability to reduce the "resistance" can no longer meet the requirement of rapidly decreasing the coal seam gas content through gas extraction. From this perspective, some international scholars have proposed the technology of enhanced coal seam gas development by gas injection displacement, which involves injecting a foreign gas with relatively high pressure into the coal seam to maintain the "driving force" for gas flow within the coal seam. In addition, coal seam permeability is actually a dynamically changing parameter jointly determined by the stiffness of coal fractures, external stress (vertical and horizontal stress), and coal seam gas pressure. Specifically, external stress compresses the coal mass, reducing the coal seam permeability, while gas pressure expands the coal mass, increasing the coal seam permeability. Under normal conditions, as the coal seam gas pressure decreases, not only is the driving force for gas flow insufficient, but the coal seam permeability also decreases to a certain extent. On the contrary, by injecting high - pressure gas into the coal seam, in addition to promoting gas flow in the coal seam, it can also reduce the effective stress on the coal seam (i.e., the external stress minus the gas pressure) and improve the coal seam permeability.

In conclusion, gas injection displacement technology can achieve the dual effects of "flow promotion" and "permeability enhancement", showing significant advantages in its mechanism.

## 3. Field Test of Nitrogen Injection Displacement in the Floor Drainage Roadway

### 3.1. Testing of Basic Gas Parameters of the Coal Seam in the Test Area

Zhaojiazhai Coal Mine is a mainstay mine controlled by Zhengzhou Coal Industry (Group) Co., Ltd. It has a designed production capacity of 3 million tons per year, with the No. $2_1$ coal seam in the Shanxi Formation as the main coal - mining seam. The average coal thickness is 4.5 m, the minefield area is approximately 49 $km^2$, and the remaining mineable reserves are 189 million tons. The mine was initially designed as a low - gas mine. In July 2015, during the construction of the coal bunker in the No. 14 mining area, a gas dynamic phenomenon occurred at an elevation of -300 m in the No. $2_1$ coal seam. In September 2015, it was upgraded to a coal and gas outburst mine. The measured maximum original gas content in the local area (lower part of the No. 14 mining area) of the No. $2_1$ coal seam is 18.11 $m^3/t$, the maximum original gas pressure is 0.48 MPa, the absolute gas emission rate of the mine is 12.03 $m^3/min$, and the relative gas emission rate is 1.95 $m^3/t$. The test area is located in the upper floor drainage roadway of 14205 in the No. 14 mining area of Zhaojiazhai Mine. To facilitate the comparison of the displacement effects before and after the test, it is necessary to measure the original gas content and gas pressure of the coal seam in the test area. There are a total of three test points in the test area: Test Point 1, Test Point 2, and Test Point 3. Test Point 1 is arranged in the No. 12 drilling site, Test Point 2 is arranged in the No. 14 drilling site, and Test Point 3 is arranged on the roadway of the opposite wall of the No. 15 drilling site. The layout of each test location is shown in Figure 1, and the measurement results of the gas content and gas pressure of the coal seam at each test point are presented in Table 1.

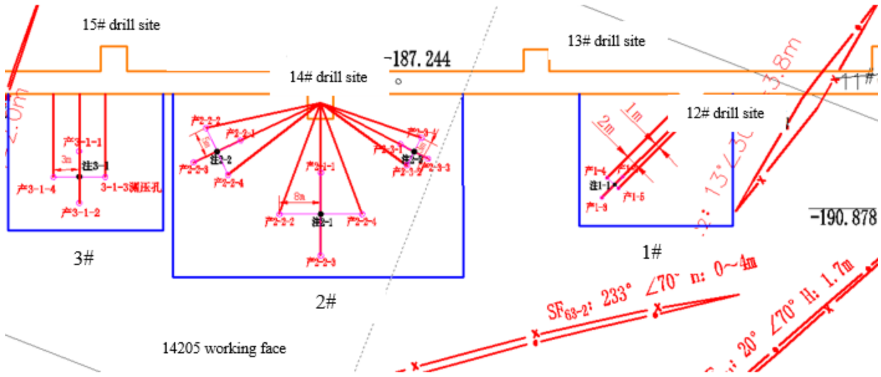


**Figure 1.** Layout of test points in the bottom pumping test area

**Table 1.** Coal seam content test results in the experimental area

| Test area | No. | Gas pressure(MPa) | gas content(m³/t) | Methane(m³/t) | Methane component(%) | Underground desorption capacity(ml) |
|---|---|---|---|---|---|---|
| Test point 1 (drilling site 12)) | Production 1-2 | | 6.07 | 4.89 | 80.58 | 204 |
| | Production 1-3 | | 8.36 | 7.64 | 91.39 | 380 |
| | Production 1-4 | | 6.08 | 3.95 | 64.93 | 152 |
| | Production 1-5 | | 6.7 | 6.04 | 90.09 | 264 |
| Test point 2 (drilling site 14) | Pour2-1 | 0.2 | 6.88 | 6.56 | 95.44 | 444 |
| | Production 2-1-3 | | 6.28 | 6.18 | 98.31 | 668 |
| | Pour2-2 | 0.15 | 9.42 | 9.18 | 97.41 | 752 |
| | Production 2-2-2 | | 9.25 | 8.89 | 96.17 | 710 |
| | Pour 2-3 | 0.12 | 11.46 | 10.75 | 93.89 | 630 |
| | Production 2-3-4 | | 5.09 | 3.99 | 78.36 | 78 |
| Test point 3 (drilling site 15) | Production 3-1-4 | | 7.56 | 7.09 | 93.74 | 720 |
| | Pour 3-2 | | 7.31 | 6.92 | 94.67 | 538 |
| | Production 3-2-4 | | 6.38 | 5.88 | 92.18 | 184 |

From the Table 1, the gas content of the coal seams at the three test points ranges from 5.09 to 11.46 $m^3/t$, with an average of 7.45 $m^3/t$. The gas content is basically greater than 6 $m^3/t$, indicating a relatively high level. The maximum gas pressure in the coal seams at the three test points is 0.2 MPa, which is relatively low. Combining this with the previous research on the pore structure and diffusion process of the No. $2_1$ coal seam, it further illustrates that the No. $2_1$ coal seam has well-developed microporous structures, poor gas diffusion and desorption capabilities, and low permeability.

In the upper floor drainage roadway of 14205, each drilling site is constructed with 80 - 120 cross seam gas extraction boreholes on average. The borehole length ranges from 20 to 70 m, and the coal section length is between 3 and 10 m. The average extraction cycle for each drilling site is 6 months. The spacing between gas extraction boreholes in the floor drainage roadway is 5 m. The coal seam thickness is approximately 3 - 5 m, with an average of 4 m. On average, each borehole controls a coal quantity of 109.9 tons. Through calculations, it is found that the

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average monthly decrease in gas content per ton of coal is 0.17 $m^3$/t, and the average decrease in gas content per ton of coal over 6 months is 1.01 $m^3$/t.

## 3.2. Field Test Results and Analysis of Nitrogen Injection Displacement

### 3.2.1. Borehole Design at the Test Point

This paper takes Test Point 1 as an example to illustrate the on-site engineering test conditions. At Test Point 1, a total of one gas injection borehole (Gas Injection Borehole 1-1) and four gas production boreholes (Gas Production Boreholes 1-2, 1-3, 1-4, and 1-5) were designed. The spacing between the gas injection borehole and the gas production boreholes is depicted in Figure 2. During the gas injection period, the injection pressure was maintained at 4 MPa.

On January 28, 2018, monitoring of the natural gas emission rate from the test boreholes commenced. The nitrogen injection at the test boreholes began on March 28 and ended on June 4, with the observation period at Test Point 1 lasting a total of 67 days. During this period, no gas flow was observed from Gas Production Borehole 1-5 as it was blocked during the process of hole sealing and grouting. The gas injection dates were as follows: intermittent injection for 11 days from March 28 to April 8; injection for 1 day on April 13 - April 14; injection for 9 days from April 23 to May 2; and injection for 7 days from May 6 to May 13. In total, gas injection was carried out for 28 days during the natural observation period.

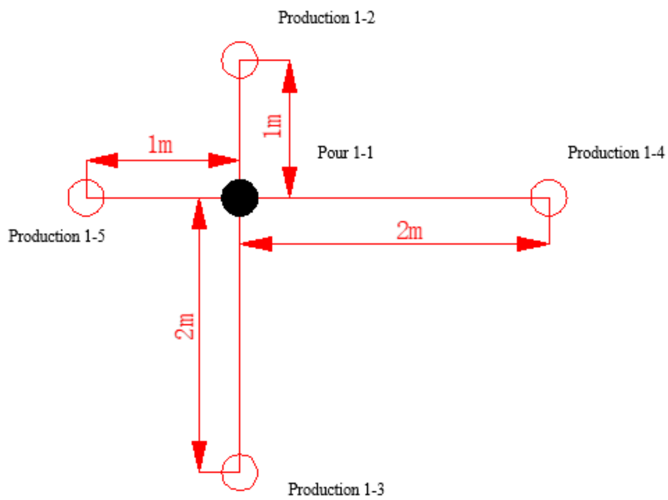


**Figure 2.** Schematic diagram of the final borehole layout for Test Point 1

### 3.2.2. Analysis of Nitrogen Injection Displacement Effects

(1) Gas Production Concentration and Net Volume

After gas injection commenced, the gas concentration at Gas Production Borehole 1-2 rapidly declined, with its changing trend being the opposite of that of the mixed flow rate. After gas injection stopped, there was a noticeable rebound in gas concentration, although it did not return to its original peak value. Despite the decrease in gas concentration following gas injection, there was a significant initial increase in the net gas volume during the injection period, which remained at a high level in the later stages. Similar to Gas Production Borehole 1-2, the gas concentration at Gas Production Borehole 1-3 also dropped significantly after gas injection. Unlike Borehole 1-2, the net gas flow rate at Gas Production Borehole 1-3 continued to rise in a stepwise manner until the final cessation of gas injection. The changing patterns of gas concentration and net volume at Gas Production Borehole 1-4 were intermediate between those of Boreholes 1-2 and 1-3. This indicates that the spacing between boreholes is not the sole determinant of gas injection effects, and that the heterogeneity of coal seam characteristics, such as permeability, also has a significant impact.

(2) Comparison of Mixed Flow Rate and Increase in Net Gas Volume Before and After Gas Injection

The comparison of the increase in gas purity of the mixed flow meter before and after gas injection at Test Point 1 is shown in Table 2. From Table 2, it can be observed that after nitrogen injection, both the mixed flow rate and the net gas flow rate of gas extraction from the production boreholes have significantly increased, achieving the effect of enhanced extraction.

**Table 2.** Comparison of gas flow and pure quantity increase before and after gas injection at Test Point 1

| Gas producing pores | 1-2 | | 1-3 | | 1-4 | |
|---|---|---|---|---|---|---|
| Internet traffic(L/min) | Mixed traffic | Gas purity | Mixed traffic | Gas purity | Mixed traffic | Gas purity |
| Before gas injection | 0.093 | 0.074 | 0.047 | 0.026 | 0.048 | 0.036 |
| After gas injection (peak value) | 2.03 | 0.311 | 0.423 | 0.16 | 0.896 | 0.225 |
| After gas injection/before gas injection | 21.8times | 4.2times | 9times | 6.2times | 18.7times | 6.3times |

(3) Comparison of Cumulative Net Gas Emissions from Boreholes

The change curve of the cumulative net gas emissions from Gas Production Borehole 2 is shown in Figure 3(a). As can be seen from the figure, under normal emission conditions, the conventional cumulative net gas emission from Gas Production Borehole 2 is 6.3 $m^3$. After the implementation of nitrogen injection displacement, the cumulative net gas emission reaches 21.9 $m^3$, with the gas emission volume during injection being 3.46 times that of the conventional emission volume. The change curve of the cumulative net gas emissions from Gas Production Borehole 3 is shown in Figure 3(b). As can be seen from the figure, under normal emission conditions, the conventional cumulative net gas emission from Gas Production Borehole 3 is 3.54 $m^3$. During the gas injection period, the cumulative net gas emission reaches 8.95 $m^3$, with the gas emission volume during injection being 2.53 times that of the conventional emission volume. The change curve of the cumulative net gas emissions from Gas Production Borehole 4 is shown in Figure 3(c). From the figure, it is evident that under normal emission conditions, the conventional cumulative net gas emission from Gas Production Borehole 4 is 3.82 $m^3$. During the gas injection period, the cumulative net gas emission reaches 12.55 $m^3$, with the gas emission volume during injection being 3.29 times that of the conventional emission volume.

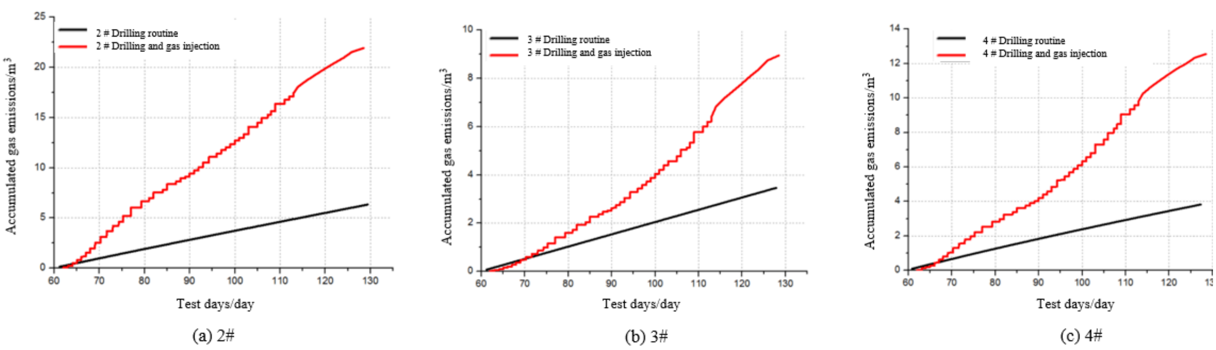


**Figure 3.** Accumulated pure gas emissions from gas producing pores

(4) Comparison of Coal Seam Gas Content Before and After Gas Injection

To evaluate the effectiveness of gas displacement in the test area of Test Point 1, six effect-assessment boreholes were arranged near the test area. The measured results of coal seam gas content after the displacement test are presented in Table 3. As indicated in Table 3, the gas content in Sample Points 1, 2, 4, and 5, which are located outside the displacement area of Test Point 1, generally exceeds the pre-displacement gas content. It is analyzed that the gas outside the displacement area may have been compressed by the injected gas, forming a gas accumulation zone and thus increasing the gas content. In contrast, the gas content in Sample Points 3 and 6, which are inside the displacement area, are 5.76 $m^3/t$ and 5.41 $m^3/t$, respectively, both lower than the original gas content and below the "double six" criteria stipulated by Henan Province.

**Table 3.** Determination of gas content in verification hole of Test Point 1

| Coal seam gas content /($m^3/t$) | | Gas content in coal seams within the displacement area /($m^3/t$) | Gas content in coal seams outside the displacement area/($m^3/t$) |
|---|---|---|---|
| Production 1-2 | 6.07 | 5.76 | 6.46 |
| Production 1-3 | 8.36 | 5.41 | 7.99 |
| Production 1-4 | 6.08 | | 8.64 |
| Production 1-5 | 6.7 | | 7.96 |
| Average | 6.8 | 5.58 | 7.76 |

## 4. Conclusion

(1) Nitrogen injection displacement has a significant effect on promoting coal seam gas extraction. At Test Point 1, with only 23 days of nitrogen injection displacement, the gas emissions from the three gas production boreholes during the injection period were 3.46 times, 2.53 times, and 3.29 times the conventional emission volumes, respectively. The maximum net gas volumes during the injection period for the three gas production boreholes were 4.2 times, 6.2 times, and 6.3 times the pre-test values, respectively.

(2) When the injection pressure exceeds 0.8 MPa, the injected nitrogen can break through from the injection borehole to the production boreholes in soft, low-permeability coal seams. As the borehole spacing increases, the time required for the displacement effect to take effect is prolonged. With an increase in nitrogen injection pressure, both the displacement mixed volume and net volume increase, but the gas production concentration decreases accordingly. There exists a "lag effect" in the injected gas displacement, meaning that after the cessation of injection, the net gas flow rate from the boreholes can still be effectively enhanced for a certain period.

(3) After the implementation of the gas injection displacement technology, the coal seam gas content within the displacement range in the test area significantly decreased (at Test Point 1, the coal seam gas content before injection ranged from 6.07 to 8.36 $m^3/t$, and after the test, it dropped to 5.41–5.76 $m^3/t$ within the displacement range), falling below the "double six" criteria stipulated by Henan Province and achieving a rapid outburst elimination effect. Outside the displacement range, since no injection or extraction boreholes were arranged, the displaced gas accumulated and formed gas zones due to compression, resulting in no significant decrease in gas content, with some areas even showing an increase.

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