Investigation on Key Parameters of N₂ Injection to Enhance Coal Seam Gas Drainage (N₂-ECGD)

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Abstract: Practice shows that CO₂/N₂-ECBM is an effective technology to enhance coalbed methane. However, there are few field tests in which the technology is applied to enhance the gas drainage in underground coal mines, and the effect is uncertain. In this study, firstly, the reasons for the decrease of gas drainage efficiency in the exhaustion period were analyzed based on the theory of fluid mechanics. Secondly, the mechanism of N₂ injection to enhance coal seam gas drainage (N₂-ECGD) was discussed: with the gradual decrease of gas pressure in the drainage process, coal seam gas enters a low-pressure state, the driving force of flow is insufficient, and the drainage enters the exhaustion period. The nitrogen injection technology has triple effects of “promoting flow”, “increasing permeability” and “replacing”. Thirdly, the numerical simulations of the nitrogen pressure on drainage effect were carried out based on the fully coupled model. The results show that the higher the nitrogen pressure, the greater the displacement effect between injection and drainage boreholes, the larger the effective range. Finally, a field test of N₂-ECGD was carried out in the Liu Zhuang coal mine in Huainan Coalfield, China. The results show that N₂ injection can significantly enhance the gas flow rate and CH₄ flow rate in the drainage boreholes, and the coal seam gas content decreased 39.73% during N₂ injection, which is about 2.6–3.3 times that of the conventional drainage. The research results provide an important guidance for promoting the application of N₂-ECGD in underground coal mines.

Keywords: coal; coal seam gas; gas drainage; nitrogen injection drainage; injection pressure

1. Introduction

Gas disaster is one of the main disasters that threaten coal mine safety [1,2], mainly including gas outburst, gushing, abnormal gushing etc. The gases associated with gas disasters are mainly methane and CO₂ [3–5]. Gas drainage is the fundamental measure to prevent and control gas disasters. For high permeability coal seams, conventional drainage can effectively reduce the gas content. However, the permeability of most coal seams in the world is generally low, especially in China, where 95% belong to low permeability coal seams. Conventional drainage takes a long time to reduce the gas content below the threshold, hence enhanced permeability technology to improve gas drainage efficiency is required [6,7]. For coal seam groups, pressure relief technology on the protective layer has positive results [8,9]. For a single low-permeability coal seam, local enhanced permeability technology is a better choice. Coal breaking media generally falls into two categories:
hydraulic technology and presplitting blasting technology, the latter has shown better performance in some Chinese coal mines [10–12].

Another typical feature of Chinese coal mines is low gas saturation. Even if the permeability increases, gas drainage still quickly enters the exhaustion period when the gas flow driving force is insufficient, and a great quantity of gas still exists in the micropores of the coal. CO\textsubscript{2}/N\textsubscript{2}-ECBM has been proven as an effective method in the coalbed methane industry [13–16]. Injecting other gases with a certain pressure into the coal seam can theoretically promote fracture gas flow and pore gas desorption. The United States first carried out the industrial test of CO\textsubscript{2}-ECBM on the ground in 2000, then China [17], Australia [18], Canada [19], Poland [20], and other countries also have successfully applied ECBM engineering practice.

In recent years, inspired by ECBM, from the perspective of enhancing gas drainage and reducing gas content, a few scholars have made a preliminary attempt of applying the injecting technology, such as enhanced coal seam gas drainage (ECGD), in underground coal mines. CO\textsubscript{2} has been verified as an outburst gas, but N\textsubscript{2} is less prone to outbursts, therefore, using N\textsubscript{2} as an injectant does not carry the same level of risk. Yang et al. [21] conducted an air injection and short-term N\textsubscript{2} injection field trial in the Northeast of the Qinshui Basin in China, which proved that the CH\textsubscript{4} flow rate was significantly increased. Fang et al. [22] carried out a mixture gas injection underground trial in the Southeast of the Qinshui Basin, and found that the air injection greatly increased the CH\textsubscript{4} concentration and flow rate compared with conventional drainage. Yang et al. [23] conducted continuous N\textsubscript{2} injection tests in low-gas coal seams, and the response characteristics of gas drainage parameters under different gas injection radii was investigated. Shi et al. [24] completed air injection tests based on the application of hydraulic flushing, which showed that even if the drainage entered the exhaustion period, the gas injection could still improve the drainage effect. As continuous air injection may induce the spontaneous combustion of coal and the mobile N\textsubscript{2} generators can provide a stable supply of gas, nitrogen is chosen as the optimal injectant for the field tests of ECGD [23].

Many scholars have established fully coupled models that consider different factors, and have carried out the feasibility and effect evaluations of gas injection displacement. Wu et al. [25] proposed a dual poroelastic coupled model for CO\textsubscript{2}-ECBM. Liu et al. [26] established a fully coupled model for THM and simulated the influence of injection pressure on CO\textsubscript{2} injectability and CH\textsubscript{4} production. Fan et al. [27] developed a THM model for the displacement by CO\textsubscript{2} and N\textsubscript{2} and studied the response characteristics of key parameters in the displacement process. Lin et al. [28] conducted a numerical simulation study of N\textsubscript{2} injection-enhanced gas drainage in CO\textsubscript{2}-rich coal seams. Ren et al. [29] put forward a binary gas migration model, and the feasibility of N\textsubscript{2} injection to improve gas drainage efficiency under different initial permeabilities was studied. Vishal et al. [30] used the finite difference to evaluate the effect of CO\textsubscript{2} injection on enhancing coalbed methane recovery in the Jharia Basin. Connell et al. [31] evaluated the accuracy of numerical simulation results by comparing the experimental results with SIMED II simulation.

From the above analysis, there are few studies of underground N\textsubscript{2} injection to enhance gas drainage at present. There are also few reports on the numerical simulation and field tests on the key parameters of ECGD. In this paper, we first analyzed the mechanism of N\textsubscript{2}-ECGD and carried out the numerical simulation of the effect of gas injection pressure. Then the field trials of N\textsubscript{2}-ECGD were carried out in Liu Zhuang Coal Mine, Anhui Province, and the response characteristics of drainage parameters under different injection pressures were investigated, and the drainage effect was evaluated.

2. Mechanism of N\textsubscript{2}-ECGD

2.1. Mechanism of Gas Flow in Coal Seams

A coal seam is a dual-porosity system composed of matrices and fractures [32–34]. The gas molecules are mainly adsorbed by the matrices, where they reach a relatively balanced
state with the free CH$_4$ molecules in the fracture, which are at a constant pressure, as shown in Figure 1.

![Diagram showing free and adsorbed CH$_4$ molecules in coal matrix and fracture](image)

**Figure 1.** The original state of coal seam gas: (a) Schematic diagram of the gas equilibrium process; (b) Illustration of the mechanism.

The boreholes go deep into the coal seam, creating an environment that maintains a relatively low negative pressure, which forms a gas pressure gradient that promotes the free gas in the fractures to flow toward the borehole (step 1 in Figure 2b). With the extension of drainage time, the CH$_4$ pressure in coal seam fractures gradually decreases (step 2 in Figure 2b), and the dynamic balance between adsorbed and free CH$_4$ is broken. The adsorbed CH$_4$ desorbs and diffuses from matrices to fractures, which plays a supplementary gas source role for free CH$_4$ in the fractures (step 3 in Figure 2b). However, with the continuous drainage process, the total CH$_4$ content in the coal seam is decreasing, the CH$_4$ pressure gradient between the coal seam and the borehole is gradually decreasing, and the pure CH$_4$ drainage volume is decreasing. The process can be summarized as follows:

1. The gas pressure gradient promotes the fracture CH$_4$ to flow to the borehole and reduces the overall gas pressure of the coal seam.
2. The decrease of gas pressure causes desorption and diffusion of adsorbed CH$_4$, and the overall gas content of the coal seam decreases.
3. Coal seam permeability determines the gas flow rate under the same gas pressure gradient.

It is worth noting that with the gradual decrease of gas pressure, the gas pressure gradient between the coal seam and the borehole is greatly reduced, which leads to a reduction in driving force of the gas flow. This is the reason that the pure CH$_4$ flow rate is usually greatly reduced in the exhaustion period, even though the gas content of the coal seam is still high.
2.2. Mechanism of N₂-ECGD

Gas drainage is a gas flow process that related to the interaction between the driving force (gas pressure) and the resistance (permeability). Improving the permeability exclusively can no longer meet the need of quickly reducing the coal seam gas content. The mechanism of N₂ injection to displace CH₄ mainly includes two processes. Figure 3 shows the physical process of nitrogen injection drainage, the N₂ flows into the fracture through the boreholes, and becomes a free mixed gas in the fracture. Therefore, the first process is to promote CH₄ flow in the fracture by increasing the gas pressure gradient. The concentration difference between CH₄ in the fracture (low concentration) and the matrix (high concentration) causes the CH₄ in the matrix to diffuse into the fractures. The availability of unoccupied sorption sites is a prerequisite for nitrogen adsorption. The second process is the replacement process. The increasing quantity of N₂ in fractures promotes N₂ diffusion into the matrix under the concentration gradient. The pressure of injected N₂ is higher than CH₄, and previous studies have proved that gas pressure has significant influence on adsorption capacity [35,36], therefore, the high pressure can further promote the N₂ adsorption and replace the absorbed CH₄.

In addition, the permeability of a coal seam is a dynamic parameter determined by the coal fracture stiffness, external stress, and gas pressure. External stress plays a role in compressing the coal and decreasing the permeability, while the gas pressure has the opposite effect. In general, with the decrease of gas pressure, not only is the driving force is insufficient, but also the permeability decreases to a certain extent. By injecting higher pressure nitrogen into the coal seam, in addition to promoting the gas flow, it can also reduce the effective stress on the coal seam and improve the permeability.

Figure 2. The process of coal seam gas drainage: (a) Schematic diagram of the gas migration process; (b) Illustration of the conventional drainage mechanism.
3. Numerical Simulation of N₂-ECGD

3.1. Fully Coupled Model

The process of N₂-ECGD is a complex physical process in which CH₄ desorption-diffusion-seepage and N₂ seepage-diffusion-adsorption occur simultaneously. Ren et al. [29] proposed a fully coupled Multiphysics model based on engineering practices, which considered the competitive adsorption of binary gas, variable mixed gas viscosity and gas diffusion coefficient. The model can better describe the essential physical process of N₂-ECGD. In this paper, this model was used to carry out numerical simulation on the effect of N₂ injection pressure to enhance coal seam gas drainage.

The literature [29] considers that the equation of gas state controls the free gas state in the pores and fractures; the adsorption equation controls the adsorption and desorption process of gas in matrix; the diffusion equation controls the diffusion process of free gas between pore and fracture; the Darcy law and Klinkenberg effect jointly control the seepage process of free gas in the fracture flowing to a free surface, and is caused by the interaction of adsorption expansion strain, mixed gas pressure in the fracture, and external stress; the equation of mass conservation links these processes. The detailed derivation process is shown in reference [29], and the governing equations are summarized as follows:

\[
\begin{align*}
\phi_m & \frac{\partial p_{m1}}{\partial t} + \rho c_{p1} \frac{V_{11} b_1 (1 + b_2 p_{m2})}{(1 + \sum b_i p_{m1})} \frac{\partial p_{m1}}{\partial t} - \rho c_{p2} \frac{V_{11} b_2 p_{m1}}{(1 + \sum b_i p_{m1})} \frac{\partial p_{m2}}{\partial t} = -D_1 \sigma M_1 \left(p_{m1} - p_{f1}\right) \\
\phi_m & \frac{\partial p_{m2}}{\partial t} + \rho c_{p1} \frac{V_{12} b_2 (1 + b_1 p_{m1})}{(1 + \sum b_i p_{m2})} \frac{\partial p_{m2}}{\partial t} - \rho c_{p2} \frac{V_{12} b_1 p_{m2}}{(1 + \sum b_i p_{m2})} \frac{\partial p_{m1}}{\partial t} = -D_2 \sigma M_2 \left(p_{m2} - p_{f2}\right) \\
p_{f1} & \frac{\partial f}{\partial t} + \phi f \frac{\partial p_{f1}}{\partial t} + \nabla \cdot \left(- \frac{p_{f1}}{\mu} \nabla \left(p_{f1} + p_{f2}\right)\right) = D_1 \sigma \left(p_{m1} - p_{f1}\right) \\
p_{f2} & \frac{\partial f}{\partial t} + \phi f \frac{\partial p_{f2}}{\partial t} + \nabla \cdot \left(- \frac{p_{f2}}{\mu} \nabla \left(p_{f1} + p_{f2}\right)\right) = D_2 \sigma \left(p_{m2} - p_{f2}\right)
\end{align*}
\]

where the \( m \) and \( f \) denote coal matrix and coal fracture respectively, the \( CH_4 \) is defined as component 1 and the injected nitrogen is defined as component 2, \( R \) is the gas constant.
(m³ Pa/(K mol)), T is temperature (K), M is the molar mass of gas (g/mol), b (1/Pa) and \( V_L \) (m³/kg) are the Langmuir constants, \( p \) is the free gas pressure (MPa), \( D \) is the gas diffusion coefficient (m²/s), \( k \) is the coal permeability (m²), \( \phi \) is the porosity of coal (dimensionless), \( \rho_c \) is the density of coal (kg/m³), \( \rho_{SG} \) is the density of gas at standard condition, \( \mu \) is the gas viscosity coefficient (pa·s), \( c \) is the shape factor of cubic coal matrix blocks (1/m²).

### 3.2. Numerical Simulation

COMSOL Multiphysics is adopted to carry out numerical simulations. The simulation object is the Huainan coalfield, China. The permeability and gas (mainly CH₄) saturation of 11-2 seam in a coal mine are at a low level. The maximum buried depth can reach 500 m and the gas pre-drainage effect is poor. To evaluate the efficiency, the numerical simulation of N₂-ECGD is carried out based on the binary gas migration model established in Section 3.1 and the characteristic parameters of coal seam in Table 1. It has been demonstrated that the permeability and gas type are the main factors affecting the drainage effect. Considering the field engineering scale, the permeability and gas composition vary little in the same geological unit. Therefore, when the borehole spacing is constant, nitrogen injection pressure is the dominant factor affecting the drainage effect. Conventional drainage and nitrogen injection are simulated respectively. As shown in Figure 4, the borehole spacing is 5 m and the borehole diameter is 94 mm. When simulating conventional drainage, boreholes 1 and 2 will be taken as drainage boreholes. When simulating nitrogen injection, borehole 1 will be taken as the drainage borehole and borehole 2 will be taken as the injection borehole. The gas injection pressure is 0.5 MPa and 1.0 MPa respectively.

| Parameters                        | Value         | Source       |
|-----------------------------------|---------------|--------------|
| Seam thickness, m                 | 4             | Site data    |
| Young’s modulus of coal E, MPa    | 1980          | CCRI report  |
| Porosity of coal \( \nu \), dimensionless | 0.25          | CCRI report  |
| Density of coal \( \rho_c \), kg/m³ | 1400          | Lab measurement |
| Langmuir volume of CH₄ \( V_L \), m³/kg | 14.2 × 10⁻³  | Lab measurement |
| Langmuir volume of N₂ \( V_L \), m³/kg | 8.9 × 10⁻³   | Lab measurement |
| Langmuir pressure of CH₄ \( P_L \), MPa | 0.78         | Lab measurement |
| Langmuir pressure of N₂ \( P_L \), MPa | 2.12          | Lab measurement |
| Diffusion coefficient of CH₄ \( D_C \), m²/s | 2.8 × 10⁻¹³  | Lab measurement |
| Diffusion coefficient of N₂ \( D_N \), m²/s | 1.3 × 10⁻¹³  | Lab measurement |
| Porosity of coal matrix \( \phi_{fr} \), % | 5.6           | Lab measurement |
| Gas content of methane, m³/t       | 5.88          | CCRI report  |
| Seam gas pressure, MPa            | 0.45          | Estimation   |
| Initial permeability \( k_0 \), m² | 8.9 × 10⁻²⁰  | CCRI report  |
| Initial fracture porosity \( \phi_0 \), % | 1.8           | Estimation   |
| Vertical stress \( S_v \), MPa     | 10            | CCRI report  |
| Horizontal stress \( S_h \), MPa   | 19            | CCRI report  |

Figure 4. Configuration of the seam and drainage borehole.
Figure 5 shows the comparison of the CH$_4$ content between conventional drainage and nitrogen injection after two months. During the conventional drainage (Figure 5a), the CH$_4$ content between the two boreholes and its surrounding areas has decreased. For the injection case, when the injection pressure is 0.5 MPa, the CH$_4$ content in the area between the injection and drainage boreholes and near the right of the injection borehole has noticeably decreased (Figure 5b), which indicates that the free CH$_4$ in the fractures can be flushed, and the adsorbed CH$_4$ in the pores can be replaced by the injected nitrogen. The CH$_4$ content is significantly higher than that of conventional drainage case outside the effective displacement area at the right end of the seam.

![Figure 5](image_url)

**Figure 5.** Comparison of the gas content between nitrogen injection and conventional drainage: (a) Conventional boreholes drainage (2 months), (b) Nitrogen injection drainage (0.5 MPa, 2 months), (c) Nitrogen injection drainage (1.0 MPa, 2 months).
When the injection pressure is 1.0 MPa (Figure 5c), the gas content between the injection and drainage boreholes decreases more obviously, the effective displacement area at the right of the injection borehole further increases while the gas content outside the area is still higher than that of conventional drainage, and the gas content at the left end of the seam increases. It can be concluded that with the increase of nitrogen injection pressure, the displacement effect between the injection and drainage boreholes becomes more obvious, and the effective range also expands.

To describe the trends clearly, the changes of CH4 content on the central axis of the boreholes is shown in Figure 6. After 2 months of injection, the maximum CH4 content between two boreholes of conventional drainage is 4.4 m³/t, and the maximum CH4 content of injection drainage is 3.0 m³/t (0.5 MPa) and 2.3 m³/t (1.0 MPa), which are located at the right of the drainage borehole at 1.5 m and 1.35 m respectively. At the right of the injection borehole, the CH4 content is clearly lower than that of conventional drainage in a certain area, and it increases significantly beyond this area. At the right end of the seam, the CH4 content of the two injection drainage cases reaches 7.3 m³/t and 6.8 m³/t respectively, both exceeding the initial CH4 content of the seam.

![Figure 6. CH4 content on the axis of boreholes.](image)

4. Field Test

The feasibility of N2-ECGD has been preliminarily verified through theoretical analysis and numerical simulations. Based on this, the field trials were carried out in the Liu Zhuang coal mine in Huainan, China, the main purpose of which was to investigate the influence of injection pressure on gas drainage effect. The test site is in the belt roadway of the mining face. An N2 generator system equipped in the ground provides a stable nitrogen source for the trials. To pressurize the nitrogen supplied by the N2 generator, we have designed a pneumatic booster system.

4.1. Test System

The N2-ECGD test system is mainly composed of N2 generator, pneumatic pressurization system, high-pressure tank, gas pressure regulating valve, flowmeter, and high-pressure pipeline. The gas pressure regulating valve can regulate the pressure of injected nitrogen, and the flowmeter can monitor the gas flow in the drainage borehole. An optical
interference methane detector is used to measure the CH₄ concentration. The schematic diagram of the test system is shown in Figure 7.

Figure 7. Schematic diagram of N₂-ECGD test system.

4.2. Test Results

4.2.1. Drainage Parameters

The drainage parameters mainly include CH₄ concentration, mixture gas flow rate and CH₄ flow rate. Three groups of boreholes were designed, and named Group 1, Group 2, and Group 3. The schematic diagram of borehole design is shown in Figure 8, and the nitrogen injection pressure and borehole design parameters are shown in Table 2.

Figure 8. The schematic diagram of boreholes design.

Table 2. Borehole design parameters.

| Group Number | Boreholes Number | Boreholes Depth/m | Sealing Length/m | Injection Pressure/MPa | Boreholes Spacing/m |
|--------------|------------------|-------------------|------------------|-----------------------|---------------------|
| 1            | Injection 1      | 100               | 20               | 1.2                   | 5                   |
|              | Drainage 1-1     |                   |                  |                       |                     |
|              | Drainage 1-2     |                   |                  |                       |                     |
|              | Injection 2      |                   |                  |                       |                     |
| 2            | Drainage 2-1     | 100               | 20               | 0.8                   | 5                   |
|              | Drainage 2-2     |                   |                  |                       |                     |
|              | Injection 3      |                   |                  |                       |                     |
| 3            | Drainage 3-1     | 100               | 20               | 0.4                   | 5                   |
|              | Drainage 3-2     |                   |                  |                       |                     |
Concentration of Boreholes

The CH$_4$ concentration with respect to time for three groups of boreholes is shown in Figure 9. In the process of conventional drainage, CH$_4$ concentration generally shows a downward trend. After nitrogen injection on the 52nd day, the CH$_4$ concentration noticeably increased. With increasing injection time, the CH$_4$ concentration began to decrease slowly. As shown in Figure 9a, when the injection pressure is 1.2 MPa, on the 34th day after nitrogen injection, the CH$_4$ concentration of drainage 1-1 was 1.4%, which is close to the concentration before injection. On the 30th day after nitrogen injection, the CH$_4$ concentration of drainage 1-2 was 1.2%, which decreased to the level before injection. The CH$_4$ concentration is a significant index to estimate the effect of single borehole drainage. If the CH$_4$ concentration is higher than the level before injection, this period is called concentration timeliness. Then the timeliness of drainage 1-1 is 34 days, and that of drainage 1-2 is 30 days.

Figure 9. Cont.
Figure 9. CH₄ concentration of drainage boreholes with respect to time: (a) Group 1 (Injection pressure is 1.2 MPa); (b) Group 2 (Injection pressure is 0.8 MPa); (c) Group 3 (Injection pressure is 0.4 MPa).

As shown in Figure 9b,c, when the injection pressure is 0.8 MPa, the concentration timeliness of drainage 2-1 and 2-2 is 22 days and 24 days, respectively. When the injection pressure is 0.4 MPa, the concentration timeliness of drainage 3-1 and 3-2 is 14 days. It can be concluded that the greater the nitrogen injection pressure, the longer the concentration timeliness.

(2) Drainage Parameters of Pipeline

The three groups of boreholes were connected to one confluence pipeline, which was equipped with a flowmeter to monitor the drainage flow rate. Figure 10 shows the variation of CH₄ concentration and instantaneous flow rate of the pipeline. The flow rate was about 0.25 m³/min before nitrogen injection, and rapidly increased after injection. The flow rate remained at about 0.40 m³/min after injection, which was significantly higher than before.

Figure 10. Drainage parameters of pipeline with respect to time.
Although the CH$_4$ concentration increased at first and then decreased slowly after nitrogen injection, the instantaneous flow rate remained at a high level. According to the analysis in Section 2.2, during the conventional drainage, the gas pressure gradient between the seam and the borehole gradually decreased, resulting in the continuous decrease of CH$_4$ concentration. After injecting nitrogen through the injection borehole, the mixture gas pressure gradient of the seam significantly increased. This resulted in the stagnant CH$_4$ molecules gaining kinetic energy. Therefore, when the injected nitrogen gradually breakthrough the drainage boreholes, the instantaneous flow rate showed a continuous increasing trend. The flow rate reached its maximum when all of the nitrogen had broken through, and then remained in a relatively stable state.

4.2.2. Effect Verification

The purpose of drainage is to reduce the gas content. It is indispensable to further investigate the CH$_4$ flow rate and gas content of the coal seam. The CH$_4$ flow rate can be calculated based on the mixture flow rate and CH$_4$ concentration. The gas content is the ultimate index to test the drainage effect, which can be tested based on China Coal Seam Gas Content Determination Standard (AQ1066-2008).

1) CH$_4$ Flow Rate

The CH$_4$ flow rate of a pipeline is shown in the Figure 11. The CH$_4$ flow rate showed a decreasing trend before nitrogen injection. The CH$_4$ flow rate was 0.51 m$^3$/min, it quickly increased to 1.61 m$^3$/min after nitrogen injection, which is 3.2 times increase. It reached the peak value of 1.77 m$^3$/min after 7 days, which was 3.5 times that of before nitrogen injection, and then gradually decreased. The flow rate was 0.84 m$^3$/min until the nitrogen injection ended after 35 days, which is still higher than before.

![Figure 11. CH$_4$ flow rate of pipeline with respect to time.](image)

2) Gas content of Coal Seam

After finishing the nitrogen injection trials, the measurement of the gas content in the test area was conducted. The design of sampling boreholes is shown in Figure 12, and the test results are shown in Table 3. Within 35 days of nitrogen injection, the coal seam gas content has noticeably decreased. During the nitrogen injection, the gas content decreased by 1.94 m$^3$/t, with a decrease of 39.73%, while the value is 12–15% in the conventional
drainage period. Compared with the conventional drainage, the efficiency of N₂-ECGD had increased by 2.6–3.3 times. The results showed that N₂-ECGD can effectively reduce the gas content and achieve the efficient drainage of coal seam with low gas saturation.

![Diagram of sampling boreholes design](image)

**Figure 12.** The schematic diagram of sampling boreholes design.

**Table 3.** The test results of coal seam gas content (m³/t).

| Status          | Measured Value | Mean Value | Decreasing Percentage |
|-----------------|----------------|------------|-----------------------|
| Before N₂ injection | 4.82 & 5.08 & 4.76 | 4.89       |                       |
| After N₂ injection  | 2.98 & 2.86 & 3.12 & 2.82 | 2.95       | 39.73%                |

5. Discussion

The simulation and field trial results show that the injection pressure has a great influence on the effective range and timeliness of N₂-ECGD. From the point of view of effective stress, nitrogen injection has the effect of increasing permeability. In fact, from the damage mechanics perspective, when the injection pressure reaches a certain value, under the effects of crustal stress and gas pressure, the coal will crack when the tensile stress exceeds the tensile strength, thus expanding the crack to increase the permeability. However, if the injection pressure is too high, the cracks between the injection and drainage boreholes will be connected to form a large-scale channel, which will play a negative role. The consumption of injected gas will increase sharply, and the pressure gradient between the injection and drainage boreholes will also decrease greatly. Therefore, it is necessary to investigate the coal damage mechanism in the process of gas injection displacement.

Secondly, after the formation of the large-scale channel, the nitrogen injected into the coal seam preferentially passes through the large-scale channel, and the flow-promoting effect of other tiny fractures is correspondingly weakened, so the injection pressure directly affects the proportion of this triple effect. In other words, when the injection pressure is less than a critical value, the larger the gas injection pressure, the more obvious the superposition effect. When the injection pressure exceeds the critical value, the excessive permeability increasing or flow-promoting effect may weaken the displacement effect. Therefore, it is necessary to explore the coupled mechanism of gas injection pressure on the triple effect of promoting flow, replacement, and increasing permeability.
6. Conclusions

In this paper, the mechanism of nitrogen injection to enhance coal seam gas drainage was analyzed, and numerical simulations and field trials of the N₂-ECGD were carried out. The main conclusions are as follows:

1. N₂-ECGD can play a triple effect of promoting flow, replacing, and increasing permeability, and it has obvious advantages in mechanism. The higher injection pressure can further promote the nitrogen adsorption and replace the absorbed CH₄.

2. The coupled mathematical model can quantitatively predict the effect of N₂-ECGD. When the distance between injection and drainage boreholes is constant, compared with the gas injection pressure of 0.5 MPa, the effective influence area is wider when the pressure is 1.0 MPa, and the CH₄ content between the two boreholes decreases more.

3. The nitrogen injection pressure has a significant influence on the concentration timeliness of the drainage borehole, and the timeliness of injection pressure at 0.4 MPa, 0.8 MPa and 1.2 MPa is 14 days, 23 days and 32 days, respectively.

4. N₂-ECGD can effectively improve the gas drainage efficiency of a low permeability coal seam. The CH₄ flow rate was greatly increased after the nitrogen injection. The gas content decreased by 1.94 m³/t during the injection, with a decrease of 39.73%. The efficiency was increased by 2.6~3.3 times compared with the conventional drainage.

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