**INTRODUCTION**

Coalbed methane (CBM) is a companion to coal, which occurs differently from oil and natural gas, and is absorbed mainly in the coal structure. On the one hand, CBM is the primary cause of disasters in coal mines, and its presence can lead to disasters such as gas outbursts and explosions. On the other hand, CBM as an efficient and clean energy source has become a promising new resource and has attracted considerable interest from governments, scholars, and entrepreneurs. China’s high gas coal seam has the characteristics of complex geological structure, a dense coal matrix, high gas adsorption, and low permeability, which makes gas drainage difficult with low extraction efficiency. Therefore, measures to improve the permeability of the coal seam and achieve efficient extraction of the CBM are primary focuses of attention in the field of CBM exploitation.

**Abstract**

In coalbed methane (CBM) exploitation, liquid nitrogen (LN$_2$) fracturing has attracted much attention as a promising and effective means to enhance coal seam permeability. Considering the bituminous coal in the Xutuan coal mine of Anhui Province, China, the permeability characteristics of coal samples under different pressure and stress conditions, and a single LN$_2$ treatment and cyclic fracturing conditions were studied. Additionally, an evaluation of the macroscopic cracking behavior of coal was carried out. LN$_2$ treatment can be very effective in promoting the generation of macroscopic fissures in the coal, and the degree of damage increases with the number of fracturing cycles. The results of a single LN$_2$ treatment showed that under a constant confining pressure, the permeability increased exponentially with the increase in gas pressure. The cyclic LN$_2$ treatment showed that permeability first decreased and then increased with increasing gas pressure, which is consistent with the quadratic function distribution. The permeability of the coal sample increases exponentially with the number of cycles, but the growth rate gradually slows down. For the same absolute fracturing time, cyclic fracturing had a better fracturing effect than a single cycle, and the ratio of the permeability increment is 126.3%–213.8%. The research results provide some guidance for the development of the LN$_2$ freeze fracturing technology.

**KEYWORDS**

bituminous coal, coalbed methane, liquid nitrogen, permeability, seepage characteristics
Hydraulic fracturing technology is vital for the exploitation of unconventional oil and gas resources in the United States and elsewhere in the world.\textsuperscript{19,20} However, traditional hydraulic fracturing techniques consume large volumes of water, can pollute groundwater, and are difficult to implement in arid regions. Therefore, many studies have proposed waterless, low-temperature fracturing technology using LN\textsubscript{2} as the fracturing fluid.\textsuperscript{21-24} Compared with the traditional hydraulic fracturing method, LN\textsubscript{2} freeze fracturing has the advantages of being waterless, pollution-free, no liquid reflux problem, and no swelling of the coal body.\textsuperscript{25} The temperature of LN\textsubscript{2} is −196°C at atmospheric pressure, and it expands 696 times after gasification. The bituminous coal of Xutuan coal mine in Huaiabei coalfield in China was taken as research subject of the present study. On the basis of previous studies, the seepage characteristics of natural moisture content in coal at different stresses under a single LN\textsubscript{2} treatment and cyclic fracturing conditions were carried out. An evaluation of the macroscopic cracking behavior of coal was carried out, and the microcracking mechanism of coal was analyzed from the perspective of mineral composition. The results of this study provide some insight for the development of LN\textsubscript{2} freeze fracturing technology.

2 | METHODOLOGY

2.1 | Background

Xutuan coal mine is located in Mengcheng County, southwest of Suzhou City, Anhui Province, China. It belongs to the Huaiabei Coalfield, of the permian coal measures. The coal mine location and the borehole diagram of the 3\textsubscript{2} coal seam are shown in Figure 1. The mine is classified as a high gas mine (The relative gas emission is 22 m\textsuperscript{3}/t). The main coal seam of the mine is Coal Seam 3\textsubscript{2}, which has been characterized as “bituminous coal” in the international classification of hard coal. For the present study, coal samples were taken from the 3\textsubscript{2} coal seam. Appropriate raw coal was selected from the stope, packaged and sealed securely, and transported back to the laboratory. Before testing, the coal samples were prepared according to the Measurement Method of Physical and Mechanical Properties of Coal and Rock (GB/T23561.2-2009) to obtain a 50 mm × 50 mm cylindrical coal sample. The coal petrology parameters of the coal seam 3\textsubscript{2} are listed in Tables 1 and 2.
2.2 | Materials and methods

2.2.1 | Preparation of coal samples

The main instruments used for the coal tests included the Gas Flow and Displacement Testing Apparatus (GFDTA), the X-Ray diffractometer, an LN2 jar, an LN2 cup, a vacuum drying oven, electronic weighing scales, and an electronic Vernier caliper. Figure 2 shows the experimental instruments and procedure.

All eight coal samples are drilled from the same coal block with an approximate diameter of 50 mm and an approximate length of 50 mm, as shown in Figure 3. The coal samples were divided into two groups for single LN2 fracturing experiments (A1, B1, C1, D1) and cyclic LN2 fracturing test (A2, B2, C2, D2), respectively. For the preparation of the coal samples with natural moisture, first, the coal samples were placed in a vacuum drying oven set to a temperature of 100°C and dried. The coal samples were taken out and weighed at intervals, and the drying was stopped when the mass of the coal samples no longer decreased. After 70 hours of drying, dry coal samples were obtained. Based on the mass of water and the mass of dry coal samples, the natural moisture content of coal samples can be calculated. Then, the coal samples were placed indoors for air-drying and weighed at intervals. After 120 hours of air-drying, the moisture content was very similar to the natural moisture content. The natural moisture content of coal samples is approximately 1.2% ± 0.1%.

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2.2.2 | Permeability test

In the present investigation, the permeability of the coal samples was measured using the GFDTA, which was developed by the research group, and the test gas was nitrogen. The GFDTA system is composed mainly of the following subsystems: the loading system (0-70 MPa), high-pressure kettle (0-20 MPa), circulating water bath system (−25 to 95°C ± 0.1°C), vacuum system, data acquisition and control system, strain test system, software system, safety system,
and related auxiliary systems. The flow meter had three range options: 100 sccm, 2 slm, and 15 slm. The pressure sensor had a test range of 0-25 MPa. The schematic layout diagram of the GFDTA is shown in Figure 4.

The test system uses the steady-state seepage method to perform an axial permeability test. The coal sample is placed into the colloidal sleeve, which is inserted into the closed high-pressure kettle. Liquid water is used to apply the confining pressure, and a fully automatic pressure pump applies the axial pressure. The circulating water bath system ensures that the temperature of the test environment is maintained constant at 25°C. At the bottom of the coal sample, there is a gas inlet, and at the top, there is a gas outlet. Transmission of the gas through the coal sample determines the axial seepage. During the test, the real-time monitoring of inlet and outlet gas pressures and flow rates is undertaken. The axial permeability of the coal sample is calculated using Equation 1:

$$K = \frac{2Q\mu L}{A(P_1^2 - P_2^2)}$$ (1)

where $K$ is the permeability of the coal sample, in md; $P_0$ is the atmospheric pressure, in MPa; $Q$ is the flow rate of the gas, in cm³ s⁻¹; $\mu$ is viscosity of the gas, in mPa s; $L$ is the height of the coal sample, in cm; $A$ is the sectional area of the coal sample, in cm²; $P_1$ is the inlet pressure, in MPa; and $P_2$ is the outlet pressure, in MPa.

The design values of pore pressure seepage test are shown in Table 3. According to the design values, the inlet pressure permeability test was carried out under hydrostatic pressure (confining pressure = axial pressure). In order to reduce the error caused by the experimental instrument, the permeability of each stress point was measured five times, and the average value was taken as the permeability. In
In order to prevent the colloidal sleeve from being opened by gas, the inlet pressure design value is less than the confining pressure value of 0.25-0.5 MPa. The confining pressure value in the following sections represents the hydrostatic pressure value.

2.2.3 | XRD test

A D8 Advance X-Ray diffractometer (manufactured by Bruker) was used for the study. The scan field of 2θ is 3-65°. The voltage and current of the X-ray tube are 40 kV and 30 mA, respectively. Pulverized coal with a particle size of 325 mesh (0.045 mm) was obtained using the grinding dish and sieve, as shown in Figure 2. The mineral composition was identified by analyzing the position (2θ) and intensity of peaks in the diffractograms.

2.3 | Test procedure

1. Photograph the prepared coal samples before LN₂ treatment.
2. Based on the design values shown in Table 3, a variable inlet pressure permeability test was carried out to obtain the original permeability of the coal samples.
3. Single LN₂ experiment.

Firstly, carefully place a coal sample in an LN₂ cup, slowly inject LN₂, immerse the coal sample, cover the cup, and soak the sample in the LN₂ for 40 minutes. As the LN₂ volatilizes continuously, the sample should be observed continuously. When the LN₂ level is lower than that of the coal sample, the LN₂ should be replenished immediately. Secondly, after complete soaking, the coal sample is placed in a vacuum bag.
in order to prevent the moisture in the air from condensing on the surface of the coal body and placed in a room to return to ambient temperature. Finally, the coal sample was photographed again and the permeability test was carried out. Repeat the single LN₂ fracturing experiment according to the above steps.

4. LN₂ cyclic fracturing test.

The coal samples were soaked in LN₂ for 10 minutes and then placed indoors for 2 hours as one cycle. The coal samples were photographed, and the permeability was tested during each cycle. Due to the limitation of the range of the permeability test equipment, only four fracture cycles were performed.

3 | MACROSCOPIC FRACTURE EVOLUTION BEFORE AND AFTER LN₂ TREATMENT

3.1 | Contrast of macroscopic fractures

The observed phenomena and conclusions related to several groups were basically the same. Hence, in the present investigation, only the experimental data of A1 (single LN₂ fracturing) and A2 (LN₂ cyclic fracturing) were used to analyze the variation in macroscopic fracture and seepage characteristics of coal samples under LN₂ fracturing conditions. Observation of the macroscopic fracture changes of coal samples is the most intuitive method to judge the degree of damage caused to the coal samples caused by the LN₂ fracturing. Figure 5 shows the macroscopic fracture changes of the A1 coal sample. As shown in Figure 5A, under the effect of LN₂ cold soaking, the top surface of the A1 sample not only exhibits expansion and extension of the original fractures, but new fractures also were generated. However, neither the new nor old fractures penetrated very deep. It can be seen from Figure 5B that a polygonal mesh fracture was generated at the bottom surface of the A1 sample and a small number of coal pieces fell off at the edge. Figure 5C,D illustrates that a plurality of long fractures parallel to the bedding direction was formed on the side of the A1 sample, as shown by the red circle in the figure.

The macroscopic fracture changes of the A2 coal sample are shown in Figure 6. It can be seen that the degree of coal damage under the LN₂ circulation treatment is much higher than that of a single LN₂ treatment. As shown in Figure 6A,B, propagation of the original fractures and new fractures occurred in the upper and lower end faces of the A2 sample,
and the number of new fractures increased as the number of cycles increased. Figure 6C shows that side “A” had an original main fracture filled with minerals at an inclination angle of approximately 60° and several interconnected secondary fractures on both sides. When two fracturing cycles were applied, coal body spalling was very evident along the right side of the original main crack and the peeling range expanded continuously as the number of freezing cycles increased. Based on this, it can be inferred that the minerals in the primary fracture have a significant influence on the degree of damage sustained by the coal. After four cycles of fracturing, side “B” of the A2 sample exhibited a plurality of mutually parallel main fractures, as shown in Figure 6D. A plurality of secondary fractures penetrated the main cracks to form a grid-like fracture network. Expansion of the original fissures, the creation of new fissures, and the increase of the connectivity of the fissures, all enhanced the permeability of the coal samples.31

3.2 | Analysis of LN₂ fracturing factors

Four factors affect the expansion of coal fissures: external stress, the frost expansion force arising from water-ice phase change, coal matrix shrinkage, and the LN₂ vaporization expansion force.36 No external stress was applied during the LN₂ fracturing process. The vaporization expansion force produces only compressive stress on the coal sample that is constrained in a limited space, but the coal sample is unconstrained during the LN₂ treatment. Therefore, the influence of external stress and vaporization expansion force was not considered during the present investigation.

A schematic depiction of the analysis of factors that affect LN₂ fracturing is given in Figure 7. It can be observed from the diagram that under the joint effect of the water-ice phase frost heaving force and the shrinkage of coal matrix, not only the expansion and extension of the original fracture occurred but also new pores and fissures were formed. Coal samples with natural

**FIGURE 6** Comparison of main macroscopic fracture changes of the A2 coal sample
moisture content were used for this test. When the coal sample is in contact with the LN$_2$, water in the pores and fissures freezes rapidly to produce a volume expansion of 9%, which causes the extension of the pores and fractures. Moreover, the expansion force will produce a large tensile stress at the tip of the crack that is significantly larger than the tensile strength of the coal, causing the expansion and extension of the fractures.

Coal is a heterogeneous body composed of organic and inorganic components (mineral component). As can be seen from Table 1, the average proportion of organic and inorganic components in the 32 coal seam is 92.89% and 7.11%, respectively. Coal shrinkage can mainly be attributed to the shrinkage of organic components. However, as shown in Figure 6C, the mineral composition of coal is closely related to the coal damage in the process of LN$_2$ fracturing. The mineral composition of bituminous coal was tested using XRD, and the result is shown in Figure 8. The result shows that the mineral composition of bituminous coal mainly was kaolinite (60.8%), pyrite (16.2%), quartz (14.4%), and calcite (8.6%). A larger discrepancy in the thermal expansion coefficients between different minerals can induce more severe damage. The thermal expansion coefficient of quartz is 16.6-24.3 × 10$^{-6}$/°C, which is significantly higher than that of other minerals, as shown in Table 4. Due to the heterogeneity of mineral thermal expansion coefficients under the effect of temperature, when the coal comes into contact with LN$_2$, the coal body will undergo uneven shrinkage. However, considering the coal sample as a continuum, the mineral particles in the interior of the coal sample cannot be freely deformed according to their inherent thermal expansion coefficient. Therefore, a constraint is generated between the mineral particles, thereby causing thermal stress and resulting in the damage of coal body.

In summary, under the effect of the water-ice phase change expansion force and nonuniform shrinkage of the coal matrix, the original fractures expand and extend, and this is accompanied by the formation of new pores and microcracks. LN$_2$ cyclic fracturing will promote the expansion of the macroscopic and microscopic fissures in coal to form a fracture network, thereby increasing the permeability of the coal.

### TABLE 4 Mineral compositions and uniaxial thermal expansion coefficient

| Minerals     | Quartz | Kaolinite | Calcite | Pyrite |
|--------------|--------|-----------|---------|--------|
| Percentage   | 14.4%  | 60.8%     | 8.6%    | 16.2%  |
| Uniaxial thermal expansion coefficient (×10$^{-6}$/°C) | 16.6; 24.3 | 6.16 | 6.7 | 8.66 |

4 | Analysis of LN$_2$ fracturing results

#### 4.1 Analysis of single LN$_2$ fracturing

The main factors that affect the permeability during the change of gas pressure include the adsorption of coal, change
in effective stress, and Klinkenberg effect (i.e., the gas slippage effect) under low pressure. When the total stress is constant, the increase in pressure of the pore fluid will reduce the effective stress within the coal body (i.e., total stress minus the pore pressure), leading to the expansion of the pores and the opening of the fractures, thereby increasing the permeability. However, as the gas pressure increases, the amount of gas adsorbed into the coal also increases and the coal matrix expands, causing pore closure. The Klinkenberg effect was first proposed by Klinkenberg in 1941. It means that the molecular velocity at the wall of the channel is not zero when the gas flows in the channel and the gas exhibits a “slippage” phenomenon, increasing the gas flow rate and permeability. The Klinkenberg effect has a significant effect on the permeability of coal samples, especially in the low gas pressure range. Studies have shown that, with decreasing gas pressure, the effect of gas slippage becomes stronger because the mean free path of the gas approaches the characteristic length scale of the coal structure. In other words, the Klinkenberg effect diminishes as the gas pressure increases.

The permeability comparison before and after LN$_2$ treatment is shown in Figure 9. It can be seen that under constant confining pressure, the permeability increases exponentially with the increase in inlet pressure. Although there is a tendency for the permeability curve to first decrease and then increase, it does not affect the overall fitting. The permeability curve can be divided into two stages: the seepage stability stage and the seepage breakthrough stage. During the first stage, the negative effect of adsorption expansion of the coal body and the Klinkenberg effect, and the positive effect of the effective stress have the same degree of influence on the permeability. Therefore, at this stage, the change in permeability is not very evident. During the second stage, the effective stress decreases with the increase in gas pressure, causing an increase in the degree of crack opening and some nonconnected pores are penetrated. At this stage, the positive effect of the effective stress gradually dominates, resulting in a sharp rise in permeability.

FIGURE 9  Comparison of different gas pressure permeabilities at the same confining pressure: (A) confining pressure 2 MPa, (B) 3 MPa, (C) 4 MPa, and (D) 5 MPa
correlated with the distribution and connectivity of fractures. Figure 9 shows that the permeability after LN$_2$ treatment is significantly enhanced. When the confining pressure is 2 MPa, the gas pressure is 1.75 MPa and the permeability is 2.74 md, which is 356% of the original permeability (0.769 md). Interestingly, the incremental increase in permeability under constant confining pressure is consistent with the increasing inlet pressure. For example, when the confining pressure is 2 MPa, the permeability increment increases from 1.43 md at a pressure of 0.5 MPa to 1.97 md at a pressure of 1.75 MPa. The probable cause is that the fracture width of the treated coal sample is larger than that of the untreated structure, and it is easier to reopen the fractures under the same stress condition. A comparison of permeabilities under different confining pressures under the same inlet pressure (0.5 MPa, 1.0 MPa, 1.5 MPa, 2.0 MPa) is shown in Figure 10. It is confirmed by curve fitting that the relationship between permeability and confining pressure at the same inlet pressure satisfies the negative exponential function. The main reason is that the effective stress increases with the increase in the confining pressure at constant inlet pressure, which causes the fractures and the pores to close and thereby reduce the permeability.

4.2 Analysis of cyclic LN$_2$ fracturing

The results of pore pressure seepage tests under a constant confining pressure with different numbers of fracturing cycles are shown in Figure 11. Contrary to the data from the single LN$_2$ treatment tests, the permeability in LN$_2$ cyclic treatment increases with the inlet pressure, showing first a decreasing trend and then an increasing one. The permeability curve shows a trend similar to the “V” type, which is consistent with a quadratic function distribution. At a constant confining pressure, there is a critical pressure value with increasing gas pressure. The critical gas pressure is the inflection point of the negative effect of coal adsorption expansion and the Klinkenberg effect, and the positive effect of effective stress. The permeability curves for each confining pressure were fitted and the critical gas pressure was calculated, as shown in Figure 11 and Table 5. The fitting formula is as follows:
where $a$, $b$, and $c$ are fitting parameters; $K$ is the coal sample permeability, in md; and $P$ is inlet pressure, in MPa.

As can be seen from Figure 11, when the gas pressure is less than the critical gas pressure, the permeability decreases as the gas pressure increases. This is mainly because the negative impacts of the Klinkenberg effect and coal matrix expansion dominate at this stage. Moreover, when the gas

$$K = aP^2 - bP + c$$

FIGURE 11  Results of pore pressure seepage at constant confining pressure: (A) 0 cycles, (B) 1 cycle, (C) 2 cycles, (D) 3 cycles, and (E) 4 cycles
TABLE 5  Fitting value of critical gas pressure

| Cycle number | Confining pressure/MPa | Critical gas pressure/MPa | Cycle number | Confining pressure/MPa | Critical gas pressure/MPa |
|--------------|-------------------------|---------------------------|--------------|-------------------------|---------------------------|
| 0 cycles     | 2                       | 0.94                      | 3 cycles     | 2                       | 0.73                      |
|              | 3                       | 0.93                      |              | 3                       | 0.98                      |
|              | 4                       | 1.38                      |              | 4                       | 1.19                      |
|              | 5                       | 1.62                      |              | 5                       | 1.45                      |
| 1 cycles     | 2                       | 0.76                      | 4 cycles     | 2                       | 0.74                      |
|              | 3                       | 1.16                      |              | 3                       | 0.69                      |
|              | 4                       | 1.14                      |              | 4                       | 0.92                      |
|              | 5                       | 1.39                      |              | 5                       | 1.16                      |
| 2 cycles     | 2                       | 0.82                      |              |                         |                           |
|              | 3                       | 1.12                      |              |                         |                           |
|              | 4                       | 1.29                      |              |                         |                           |
|              | 5                       | 1.65                      |              |                         |                           |

FIGURE 12  Permeability of different inlet pressures under constant confining pressure with different cycles: (A) confining pressure 2 MPa, (B) 3 MPa, (C) 4 MPa, and (D) 5 MPa
pressure is low, the pore pressure has a slight influence on the degree of opening of the coal body fractures. When the gas pressure is higher than the critical gas pressure, expansion of the pore spaces and fractures caused by the reduction in the effective stress plays a major role in the change in permeability and causes an increase in the permeability.

Overall, as the confining pressure increases, the critical gas pressure value also increases gradually, as shown in Table 5. It can also be observed that as the confining pressure increases, the permeability curve of the coal sample becomes more and more gradual, that is, the fitting parameter $a$ decreases, as shown in Figure 11. Interestingly, as the number of cycles increases, it is evident that the negative impact gradually weakens. When the confining pressures of the fourth cycle were 3 MPa, 4 MPa, and 5 MPa, the permeability curve exhibited almost no decline. The possible reason is that the greater the deterioration of the coal body as the number of cycles increases, the larger the fracture width and the porosity, resulting in a gradual weakening of the Klinkenberg effect.

The permeability of coal samples at different inlet pressures under a constant confining pressure with different cycles is shown in Figure 12, which visualizes the variation in permeability between different cycles. It is evident that the permeability of the coal sample increases as the number of cycles increases. Moreover, the permeability increased most significantly after the first cycle, which was obviously higher than the increase during the several subsequent cycles. The main reason is that after the first LN$_2$ treatment, damage to the coal structure was caused by the uneven shrinkage of the coal matrix and the water-ice phase change expansion. In each cycle fracturing process, the moisture content and the volume expansion rate of water-ice phase change were basically the same, and hence, the water-ice phase change expansion played a leading role only during the first cycle. However, damage during the next several cycles was caused mainly by shrinkage in the coal matrix, which results in the permeability increment of the several following cycles being less than that during the first cycle. It can also be observed that the increment in the permeability of the first cycle increases with increase in the gas pressure. Moreover, the permeability increment of subsequent cycles is basically consistent with the change in gas pressure.

**FIGURE 13** Permeability and permeability increment at constant inlet pressures under different confining pressures with different cycles: (A) inlet pressure 0.5 MPa, (B) 1.0 MPa, (C) 1.5 MPa, and (D) 2 MPa
The permeability and permeability increment of constant inlet pressures under different confining pressures for different cycles is shown in Figure 13. The histogram quantitatively reflects the increase in permeability between the different cycles. As shown in Figure 13, the permeability decreases with increasing confining pressure at the same inlet pressure. It can be deduced from the histogram that the increment in permeability between different cycle times decreases as the confining pressure increases. When the gas pressure is 0.5 MPa, the one cycle permeability increment decreases from 1.11 md at a confining pressure of 2 MPa to 0.467 md at a confining pressure of 5 MPa, as shown in Figure 13A. This is because, when the gas pressure is constant, the effective stress increases as the confining pressure increases, causing the coal fractures and pores to close again. It is worth noting that, as a whole, the permeability increment gradually decreases as the number of cycles increases. However, there are exceptions in that the permeability increment during the fourth cycle is higher than during the third cycle at confining pressures of 3 MPa, 4 MPa, and 5 MPa, as shown in Figure 13B. One possible explanation is that during the 3rd cycle permeability test, the increased porosity of the first two cycles is recompressed due to the external stress.

The change in permeability with the number of cycles under different stress conditions is shown in Figure 14. Through curve fitting, it can be observed that the permeability increases exponentially with the number of cycles, and the fitting formula is shown in Equation 3. As can be seen from Figure 14, the rate of increase in permeability gradually decreases with the number of cycles, within the scope of the test. Nuclear magnetic resonance (NMR) technology and the SDR model (also called the mean T2 model) were used to perform regression analysis on the permeability of different fracturing variables. The results showed that the NMR permeability of the coal body was related exponentially to the number of fracturing cycles. In contrast with the present findings, their fitting results showed that the growth rate of NMR permeability increased with the number of cycles. The possible reason is that their results were based on the change in the total porosity of coal.
without considering the effect of stress on the seepage rate. The application of stress caused the reclosure of the fractures and the pores, resulting in a measured permeability that was lower than the permeability when no stress was applied. It can be observed that under different confining pressures, the permeability curve at a gas pressure of 0.75 MPa, 1.0 MPa, and 1.5 MPa was lower than the permeability curve at 0.5 MPa. When the gas pressure was lower than the critical pressure, the permeability decreased as the gas pressure increased. When the confining pressure is 2 MPa, the permeability at a gas pressure of 1 MPa is higher than the permeability at a gas pressure of 0.5 MPa during 2-4 cycles. A similar phenomenon occurs when the confining pressure is 3 MPa and 4 MPa, and the gas pressure is 1.5 MPa. This is because the Klinkenberg effect gradually decreased as the number of cycles increased, resulting in a decrease in the critical gas pressure.

\[ K = -ae^{-bN} + c \]  

(3)

where \( a, b, \) and \( c \) are fitting parameters; \( K \) is the coal sample permeability, in md; and \( N \) is the number of cycles, \( N = 1, 2, 3, 4 \).

4.3 | Analysis of the LN\(_2\) fracturing cycle

The comparison of the LN\(_2\) fracturing effect for single and multiple cycles is shown in Figure 15. Absolute permeability increments were used as a contrast condition between single and multiple cycle fracturing. The stacked histogram in the figure is the cumulative value of the multiple cycle permeability increments, and the black line is the permeability increment after a single LN\(_2\) treatment. The absolute cracking time is defined as the time for which the coal sample is in direct contact with LN\(_2\). The absolute duration of the single LN\(_2\) fracturing treatment was 40 minutes. The absolute duration of each treatment cycle was 10 minutes, and the absolute time of four cycles was 40 minutes. The red line is the incremental ratio of the cumulative permeability increment during four-cycle fracturing to the permeability increment of the single fracturing treatment for the same absolute time. The calculation formula is as follows:

\[ \eta = \frac{\sum \Delta n}{\Delta s} \cdot 100\% \quad (n = 1, 2, 3, 4) \]  

(4)
where \( \eta \) is the incremental ratio, \% ; \( \Delta s \) is the single-cycle permeability increment, in md; and \( \Delta n \) is the permeability increment of the different cycle, in md.

As shown in Figure 15, the cumulative permeability increment of multiple cycles increases as the gas pressure increases. The cumulative permeability increment corresponding to a gas pressure of 0.75 is less than that of 0.5 MPa at a confining pressure of 2 MPa, as shown in Figure 15A. This may have been caused by the presence of the Klinkenberg effect and coal matrix expansion. By comparing the black line with the stacked histogram, it can be seen that the single-cycle permeability increase was higher than the first cycle increment but generally lower than the first and second cycle cumulative permeability increment. In the case of the same absolute fracturing time, the cyclic fracturing had a better fracturing effect than the single fracture cycle, and the ratio of the permeability increment was 126.3%-213.8%.

In summary, single and cyclic LN\(_2\) fracturing are effective in enhancing the permeability of the coal body. However, cyclic fracturing LN\(_2\) has higher cracking efficiency than a single LN\(_2\) treatment. Therefore, in the practical application of the LN\(_2\) fracturing technology, it is possible to consider what should be an appropriate increase in the number of cycles, and the implementation of “less time and more cycles” can produce a more ideal fracturing effect.

5 | CONCLUSIONS

The seepage characteristics of coal with natural moisture content under different stresses under a single LN\(_2\) treatment and cyclic fracturing conditions were carried out. A brief evaluation of the impact of macroscopic cracks in coal was carried out. The main conclusions were as follows:

1. LN\(_2\) treatment is effective in promoting the generation of macroscopic fractures in coal and enhancing its permeability. Under the combined effect of water-ice phase frost heaving force and coal matrix shrinkage, the coal sample was subjected not only to the expansion and extension of the original fractures, but also to the generation of new fractures and the interpenetration between these fractures. The degree of damage to the coal structure under LN\(_2\) circulation was much greater than that associated with a single application and the degree of damage increased with the number of cycles.

2. The results of the single LN\(_2\) treatment showed that at a constant confining pressure, the permeability increased exponentially with increase in gas pressure. The permeability of cyclic LN\(_2\) fracture increased with the gas pressure, showing a trend first of decrease and then of increase, which is consistent with a quadratic function distribution.

3. Cyclic fracturing by LN\(_2\) can effectively enhance the permeability of coal. Under the same stress conditions, the permeability of coal increases with the number of cycles, but the rate of increase in permeability gradually decreases with the number of cycles.

4. LN\(_2\) cyclic fracturing has higher cracking efficiency than that of a single LN\(_2\) treatment. In the case of the same absolute cracking time, cyclic fracturing had a more efficient fracturing effect than a single treatment and the ratio of the coal permeability increment was 126.3%-213.8%. Therefore, in the practical application of the LN\(_2\) fracturing technology, it is appropriate to implement a “less time and more cycles” strategy to obtain a better effect on subsequent CBM production.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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