Academic Journal of Applied Sciences
ISSN: 3105-0549 (Print), ISSN: 3105-0557 (Online) | Vol. 1, No. 3, 2026

Experimental Study of Nitrogen Throughput for Decongestion of Low Permeability Coal Seams

Chenhao Liu

Henan Polytechnic University, Jiaozuo 454000, China

Abstract: China's underground coal seam geology is relatively old, and most of the reservoirs have low porosity, low permeability and low pressure. When a CBM well has been in production for a long period of time, the water production, gas production and formation pressure decrease over time. In order to achieve stable production or even increase production, multiple "nitrogen injection - pressure holding - release" operations can be implemented to achieve efficient development of CBM. In this paper, anthracite coal from coal seam 3# and coal seam 15# in Mabidong District was selected as the test sample for nitrogen throughput unblocking test to obtain the characteristics of permeability change after multiple throughput tests on coal rock samples. The test results show that: (1) in the process of nitrogen throughput, when the nitrogen injection pressure and holding time are fixed, the change in permeability is less related to the number of throughput repetitions, and the focus is on the i ncrease in pressure and the selection of holding time; (2) with the holding time fixed, the permeability gradually increases with the increase in nitrogen injection pressure and the number of throughputs, and there is a large increase in permeability when the nitrogen injection pressure reaches 12.6 MPa and above high pressure; (3) Under the condition of lower nitrogen injection pressure, extending the holding time and increasing the number of throughputs, the permeability has a slow increase until 36h of holding pressure, and after 36h, the permeability shows a significant decrease and is smaller than the original permeability; (4) Increase the nitrogen injection pressure and holding time at the same time, the overall increase of permeability is large r, the reservoir nitrogen injection pressure is 12.6~13.6MPa, and the holding time is 36~48h, not only the overall increase in permeability is larger by increasing the nitrogen injection pressure and holding time simultaneously.

Keywords: When Low Permeability Coal Seam, Coal Bed Methane, Unblocking, Nitrogen Injection Pressure.

1. Introduction

China is rich in CBM resources, with 30.05×10^{12} m^3 of CBM resources within a burial depth of 2000 m, ranking third in the world. Its exploitation and utilization are of great significance for improving the energy structure, alleviating environmental pollution, and reducing gas disasters. However, the development speed of China's CBM industry is slower than that of the United States and Australia, with a smaller scale and an overall development level lower than expected [1-2]. The main reason is the complex geological conditions of CBM, with reservoirs generally featuring low permeability, low porosity, and low saturation. The permeability of coal seams in most mining areas ranges from 10^{-7} to 10^{-6} μm^2, increasing the difficulty of CBM extraction [3-5]. Permeability is a key parameter for evaluating CBM productivity potential. Improving the permeability of original reservoirs and unblocking methane migration channels can realize efficient CBM development [6].

In 2014, Luo Peipei [7] conducted the first comparative experiment on coal sample permeability before and after N_2 soaking for permeability enhancement. After high-pressure N_2 soaking for 24 h, 48 h, and 72 h, the permeability of three coal samples increased by 7.49%, 2.74%, and 29.92% respectively compared with raw coal samples. In 2018, Gao Yuan [8] optimized construction parameters such as huff-n-puff cycles, soaking time, injection rate, and total nitrogen injection volume by simulating production data of the target block, concluding that nitrogen injection achieved remarkable stimulation effects. In 2019, Pang Feng et al. [9] concluded through laboratory experiments that increasing nitrogen soaking pressure positively impacts the permeability of high-rank coal seams, while soaking time has an optimal value for permeability improvement of high-rank coal seams. In 2019, Cao Yunxing et al. [10] carried out field tests of high-pressure nitrogen soaking in the Yuwu Minefield of the Lu'an Mining Area, achieving significant stimulation effects. Daily gas production of two test wells increased by 1.2-8.9 times, and that of three adjacent wells by 1.4-3.7 times. This sufficiently proves that high-pressure nitrogen soaking is an effective technology for stimulation and reconstruction of low-pressure and low-production CBM wells, with promotional value for such wells.

Previous studies have fully verified that N_2 soaking positively improves coal seam permeability and CBM production. In this paper, nitrogen huff-n-puff blockage removal tests are conducted on low-permeability coal rocks in the Mabidong Block. By adjusting nitrogen injection pressure and pressure maintenance time and performing repeated huff-n-puff cycles, permeability changes of coal samples after nitrogen huff-n-puff are tested to elaborate influencing factors of permeability enhancement via nitrogen huff-n-puff, thereby analyzing blockage removal effects under different conditions.

2. Mechanism of Nitrogen Huff-n-Puff for Blockage Removal

Nitrogen is chemically stable and rarely reacts with formation materials, making it suitable as a blockage removal gas. Coal has a lower adsorption capacity for nitrogen than for methane, so nitrogen does not compete with methane for adsorption in coal rocks. After continuous nitrogen injection, the main factors affecting reservoir permeability are effective stress and matrix shrinkage-swelling [11-12]. Nitrogen injection reduces the effective stress of methane in coal rocks, causing adsorbed methane to desorb as equilibrium pore pressure decreases.

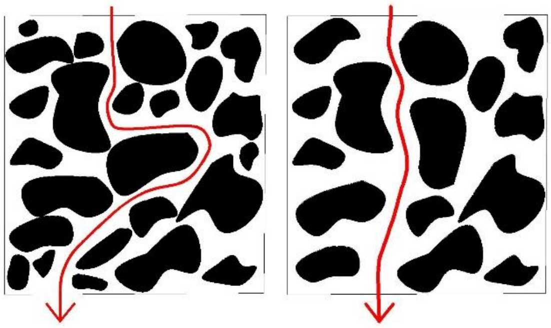

Figure 1. Simulation diagram of gas migration channels before and after nitrogen flushing unblock

Meanwhile, coal adsorbs nitrogen during methane desorption. Weaker gas adsorbability corresponds to lower adsorption volume, greater coal matrix shrinkage, and higher coal sample permeability [13-18]. Since nitrogen adsorbability is weaker than methane, nitrogen adsorption produces a permeability-enhancing effect [19-20], thus increasing permeability. As shown in Figure 1, after entering the formation, a large amount of nitrogen greatly increases formation pressure near the wellbore and invades numerous micro-fractures in coal seams near the wellbore, connecting fractures. During blowdown, nitrogen pushes coal particles blocking coal seam fractures into the wellbore, achieving blockage removal [8].

3. Experimental Apparatus and Scheme for Nitrogen Huff-n-Puff

3.1. Experimental Apparatus

The nitrogen huff-n-puff experiment adopts the TCQT-III low-permeability coal seam gas flooding stimulation test device jointly developed by Jiangsu Tuochuang Technology Co., Ltd. and Henan Polytechnic University. The device mainly consists of a gas pressurization and injection system, confining pressure (axial pressure automatic tracking) system, model system, temperature control system, vacuum system, back-pressure system, inlet-outlet metering system, pressure measurement system, and computer acquisition and processing system. The experimental apparatus flow is shown in Figure 2.

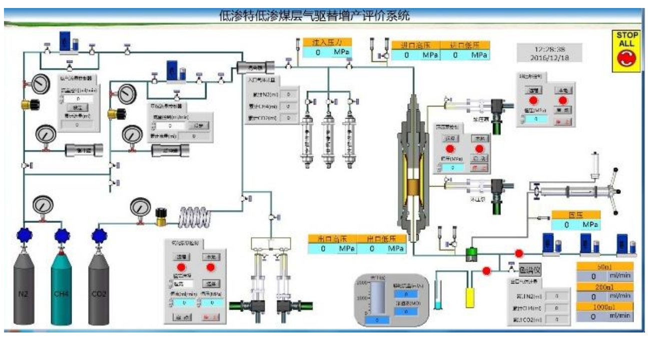

Figure 2. Nitrogen Adsorption-Desorption Experimental Apparatus Flowchart

Blockage removal effects of nitrogen huff-n-puff are mainly analyzed based on permeability changes. The apparatus is designed and manufactured in accordance with SY/T 6370-1998 Core Gas Permeameter. To improve the accuracy of core gas permeability measurement, reduce human errors, and automate the experimental process, data acquisition, and processing, modern computer technology is applied on the basis of the original permeameter testing principle to realize automatic data acquisition, processing, and database formation. The equipment features accurate measurement, small errors, and good repeatability.

3.2. Experimental Scheme

The nitrogen huff-n-puff experiment includes preliminary preparation and sample testing. Preliminary preparation mainly involves:

(1) Processing coal rocks into 10 standard test specimens of 50 mm × (50–70) mm using a wire-cutting machine.

(2) Connecting experimental instruments and testing their tightness. Maintaining the high-pressure holder at a nitrogen injection pressure of 14.6 MPa (1 MPa higher than the maximum experimental injection pressure) for 72 h of pressure maintenance. According to Reference [1], the pressure drop during pressure maintenance shall not exceed 0.2 MPa; to improve accuracy, this experiment ensures the holder pressure drop is no more than 0.1 MPa.

(3) Numbering samples and testing basic original parameters of coal rock samples, including length and diameter.

(4) Vacuumizing core samples to -0.1 MPa and stabilizing for 0.5 h.

(5) Loading core samples into the high-pressure holder, and setting confining pressure and axial pressure to the original in-situ stress of the formation. Coal samples from the Mabidong Mining Area are used in this experiment. Based on in-situ stress tests of 8 CBM wells in the study area, the maximum horizontal principal stress is 30.57 MPa, the minimum horizontal principal stress is 20.12 MPa, the vertical principal stress is 26.68 MPa, and reservoir pressure is 8.60 MPa.

(6) According to in-situ stress test results, setting axial pressure to 27 MPa, confining pressure to 30 MPa, and inlet gas pressure to 8.6 MPa to test original permeability.

(7) After completing preliminary preparation and original permeability tests of all samples, tests are carried out under the following four schemes. All schemes focus on adjusting nitrogen injection pressure and pressure maintenance time in multiple tests to explore permeability changes of high-rank anthracite and analyze blockage removal effects of nitrogen huff-n-puff on high-rank anthracite. The test scheme is shown in Table 1.

Table 1. Nitrogen Adsorption-Desorption Experiment Plan Test Form

Number of tests	Plan I		Plan II		Plan III		Plan IV	
	Nitrogen Injection Pressure	Holding time	Nitrogen Injection Pressure	Holding time	Nitrogen Injection Pressure	Holding time	Nitrogen Injection Pressure	Holding time
1	9.6MPa	0.5h	9.6MPa	0.5h	9.6MPa	12h	9.6MPa	12h
2	9.6MPa	0.5h	10.6MPa	0.5h	9.6MPa	24h	10.6MPa	24h
3	9.6MPa	0.5h	11.6MPa	0.5h	9.6MPa	36h	11.6MPa	36h
4	9.6MPa	0.5h	12.6MPa	0.5h	9.6MPa	48h	12.6MPa	48h
5	9.6MPa	0.5h	13.6MPa	0.5h	9.6MPa	72h	13.6MPa	72h

Notes during testing:(1) After each pressure injection, gas permeability is measured three consecutive times; the relative deviation must be less than 3% before subsequent pressure maintenance and blowdown steps.(2) To simulate permeability under real reservoir conditions, stable gas permeability is measured when pressure drops to 8.6 MPa during blowdown.(3) Recorded by the equipment data acquisition system, permeability uniformly adopts Klinkenberg permeability.(4) Since temperature has little influence on experimental results and all tests are conducted indoors, room temperature is adopted in this experiment.

4. Test Results and Analysis of Nitrogen Huff-n-Puff

4.1. Influence of Scheme I on Coal Rock Permeability

According to Scheme I, four groups of tests are conducted, with two groups of samples from the No. 3 coal seam and two from the No. 15 coal seam in the Mabidong Block, numbered MBD-1, MBD-2, MBD-3, and MBD-4 respectively. During testing, nitrogen injection pressure is 9.6 MPa and pressure maintenance time is 0.5 h for all four groups, with five consecutive repeated tests per group. The test results are shown in Table 2.

Table 2. Table of Coal Sample Permeability Test Results under Fixed Pressure and Multiple Time Intervals

	MBD-12 (10-3um2)	MBD-13 (10-3um2)	MBD-14 (10-3um2)
Initial state	0.045	0.062	0.088
9.6MPa/12h	0.034	0.049	0.069
10.6MPa/24h	0.012	0.078	0.117
11.6MPa/36h	0.060	0.159	0.417
12.6MPa/48h	0.098	0.171	0.495
13.6MPa/72h	0.112	0.187	0.606

Based on data in Table 2, a line chart of permeability changes affected by multiple nitrogen huff-n-puff cycles under fixed pressure and time is plotted (Figure 3).

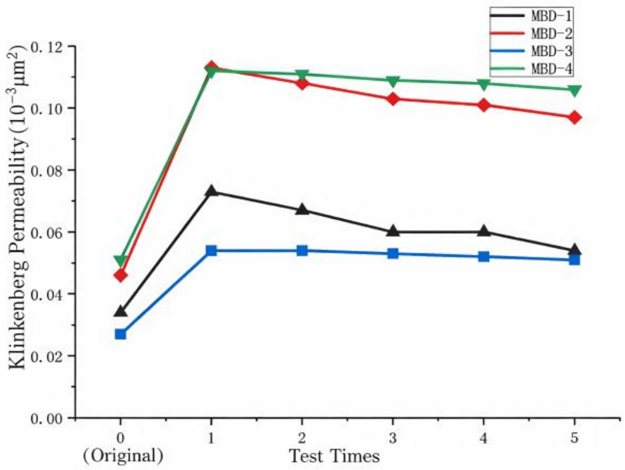

Figure 3. Effect of multiple injections at fixed pressure and time on coal sample permeability

It can be seen from Table 2 and Figure 3 that permeability of all four samples peaks in the first huff-n-puff cycle after implementing Scheme I. Permeability of MBD-1 increases by 114.71%, MBD-2 by 145.65%, MBD-3 by 100.00%, and MBD-4 by 119.61%, all more than doubling. Permeability then decreases slowly in subsequent cycles, but remains greatly improved after five cycles compared with that under reservoir conditions (outlet pressure 8.60 MPa). This also indicates that when nitrogen huff-n-puff pressure and time are fixed, permeability improvement has little correlation with the number of blockage removal cycles; the key lies in adjusting nitrogen injection pressure and pressure maintenance time during blockage removal.

4.2. Influence of Scheme II on Coal Rock Permeability

According to Scheme II, four groups of tests are conducted, with two groups of samples from the No. 3 coal seam and two from the No. 15 coal seam in the Mabidong Block, numbered MBD-5, MBD-6, MBD-7, and MBD-8 respectively. According to References [9, 22], the pressure increment gradient is 1 MPa in nitrogen soaking permeability tests; this experiment follows this setting. However, due to equipment range limitations, the maximum injection pressure in previous literature was only 8 MPa. To study the influence of higher pressure on permeability, the maximum injection pressure in this test is set to 13.6 MPa, with pressure maintenance time fixed at 0.5 h and five consecutive tests per group. The test results are shown in Table 3.

Table 3. Table of Permeability Test Results for Multiple Coal Sample Throughput Tests Under Different Pressure and Fixed Time Conditions

	MBD-12 (10-3um2)	MBD-13 (10-3um2)	MBD-14 (10-3um2)
Initial state	0.065	0.018	0.051
9.6MPa	0.099	0.051	0.104
10.6MPa	0.100	0.051	0.106
11.6MPa	0.100	0.052	0.108
12.6MPa	0.098	0.054	0.114
13.6MPa	0.065	0.018	0.051

Based on data in Table 3, a line chart of permeability changes affected by multiple nitrogen huff-n-puff cycles under variable pressure and fixed time is plotted (Figure 4).

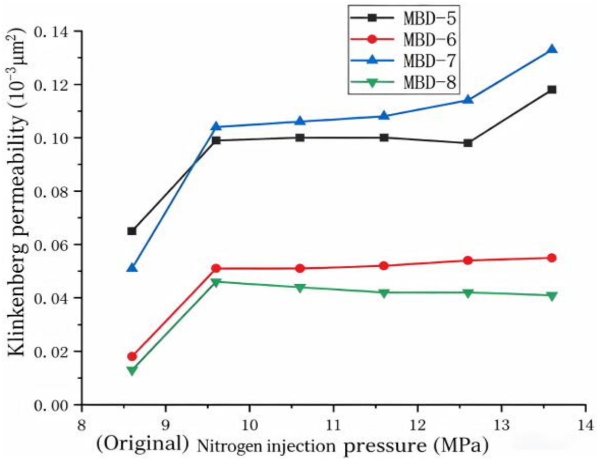

Figure 4. The Effect of Changing Pressure, Fixed Time, and Multiple Throughput on the Permeability of Coal Samples

Combined with Table 3 and Figure 4, after implementing Scheme II, permeability of all samples except MBD-5 increases by more than 90% in the first huff-n-puff cycle. Permeability of MBD-8 shows a gradual slow downward trend with increasing pressure from the second cycle. Permeability of MBD-5, MBD-6, and MBD-7 gradually rises with increasing huff-n-puff pressure. Permeability of MBD-6 increases slowly with rising pressure, while that of MBD-5 and MBD-7 rises slowly at 9.6–12.6 MPa and increases sharply at 12.6–13.6 MPa, with growth rates of 16.7% and 20.2% respectively. Permeability measured after Scheme II is significantly higher than that under reservoir conditions.

Under different nitrogen injection pressures, the short-term upward permeability trend results from greater coal rock damage and new fractures caused by increased injection pressure. After long-term pressure maintenance, nitrogen adsorption and diffusion lead to a renewed permeability increase.

4.3. Influence of Scheme III on Coal Rock Permeability

According to Scheme III, three groups of tests are conducted, with two groups of samples from the No. 3 coal seam and one from the No. 15 coal seam in the Mabidong Block, numbered MBD-9, MBD-10, and MBD-11 respectively. According to References [7-9], soaking time is set to 24 h, 48 h, and 72 h in nitrogen soaking permeability tests. To obtain denser data, pressure maintenance time in this experiment is set to 12 h, 24 h, 36 h, 48 h, and 72 h. Nitrogen injection pressure is fixed at 9.6 MPa, with five consecutive tests per group. The test results are shown in Table 4.

Table 4. Table of permeability test results for coal samples with fixed pressure and varying time intervals of sampling and testing

	MBD-12 (10-3um2)	MBD-13 (10-3um2)	MBD-14 (10-3um2)
Initial state	0.083	0.021	0.749
12h	0.085	0.020	0.801
24h	0.088	0.023	0.813
36h	0.090	0.021	0.648
48h	0.070	0.017	0.539
72h	0.056	0.015	0.415

Based on data in Table 4, a line chart of permeability changes affected by multiple nitrogen huff-n-puff cycles under fixed pressure and variable time is plotted (Figure 5).

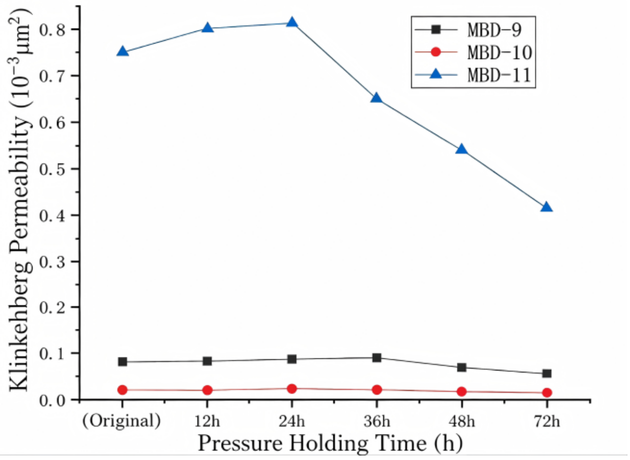

Figure 5. The Effect of Multiple Time-Dependent Fixed Pressure Fluctuations on the Permeability of Coal Samples

As shown in Table 4 and Figure 5, unlike Scheme I and Scheme II where coal sample permeability increases sharply in the first cycle, permeability of all three samples shows no significant growth after implementing Scheme III. Permeability of MBD-9 and MBD-10 increases slowly after 12 h, 24 h, and 36 h of continuous pressure maintenance and blowdown, with little difference from original reservoir permeability. However, permeability decreases significantly after 48 h and 72 h of pressure maintenance, falling below original reservoir permeability. Permeability of MBD-11 increases by 6%–8% after 12 h and 24 h of pressure maintenance, but decreases obviously after 24 h, far below original reservoir permeability.

This scheme reveals that under low nitrogen injection pressure, pressure maintenance time has little influence on coal sample permeability within approximately 20–30 h, but permeability decreases below original reservoir permeability after long-term repeated pressure maintenance and blowdown. It also verifies the conclusion in Reference [1] that there is an optimal pressure maintenance time for permeability improvement under fixed nitrogen injection pressure.

Under the same gas injection pressure, the short-term initial permeability increase may result from strong nitrogen expansibility: after first high-pressure nitrogen injection, coal body energy increases, and pressure release opens pre-existing micro-fracture systems in coal samples. Meanwhile, methane desorbs while nitrogen adsorbs and diffuses. Under long-term pressure maintenance, reduced effective pore pressure due to nitrogen adsorption cannot resist the set axial and confining pressures, causing pore channels to be compacted again.

4.4. Influence of Scheme IV on Coal Rock Permeability

According to Scheme IV, three groups of tests are conducted, with two groups of samples from the No. 3 coal seam and one from the No. 15 coal seam in the Mabidong Block, numbered MBD-12, MBD-13, and MBD-14 respectively. Nitrogen injection pressure is set to 9.6 MPa, 10.6 MPa, 11.6 MPa, 12.6 MPa, and 13.6 MPa, and pressure maintenance time to 12 h, 24 h, 36 h, 48 h, and 72 h, with five consecutive tests per group. The test results are shown in Table 5.

Table 5. Table showing the permeability test results of coal samples after multiple cycles of pressure and time variations

	MBD-12 (10-3um2)	MBD-13 (10-3um2)	MBD-14 (10-3um2)
Initial state	0.045	0.062	0.088
9.6MPa/12h	0.034	0.049	0.069
10.6MPa/24h	0.012	0.078	0.117
11.6MPa/36h	0.060	0.159	0.417
12.6MPa/48h	0.098	0.171	0.495
13.6MPa/72h	0.112	0.187	0.606

Based on data in Table 5, a line chart of permeability changes affected by multiple nitrogen huff-n-puff cycles under simultaneously variable pressure and time is plotted (Figure 6).

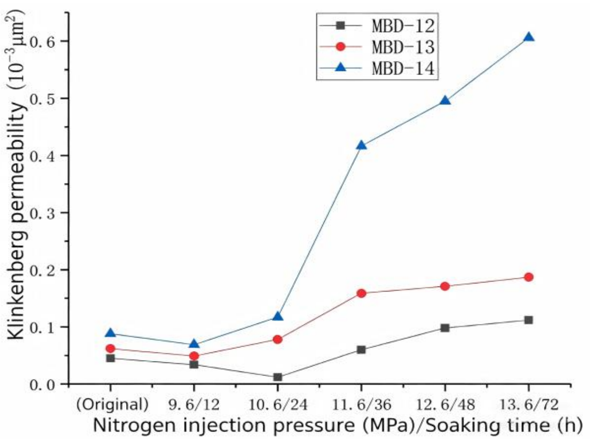

Figure 6. The Effect of Simultaneously Changing Pressure and Time on Multiple Throughput Operations on Coal Sample Permeability

After implementing Scheme IV, permeability of all three samples shows an overall trend of first decreasing and then increasing, with permeability decreasing after the first cycle. Permeability of MBD-12 starts to rise from the third cycle, while that of MBD-13 and MBD-14 increases from the second cycle, rising with extended pressure maintenance time and increased injection pressure. Permeability variation of MBD-14 is the most obvious, with an increase of 589% compared with original reservoir permeability, and permeability of MBD-12 and MBD-13 increases by more than 100%.

5. Conclusion

When nitrogen injection pressure and pressure maintenance time are constant, permeability improvement has little correlation with huff-n-puff cycles. 1–3 cycles are appropriate to maintain permeability at a relatively stable level.

With fixed pressure maintenance time, permeability increases significantly during the first huff-n-puff cycle and when injection pressure reaches 12.6 MPa and above. Increased pressure in the first cycle directly intensifies coal rock damage and forms new fractures; high-pressure nitrogen during blowdown also pushes fine coal particles in pores and fractures into the wellbore, achieving blockage removal.

When only pressure maintenance time is extended, permeability increases slowly within 36 h and decreases sharply below the original value after 36 h. Therefore, increasing nitrogen injection pressure is critical.

For samples from the Mabidong Block, simultaneous increase in nitrogen injection pressure and pressure maintenance time leads to a considerable overall permeability improvement. According to test results, injection pressure of 12.6–13.6 MPa and pressure maintenance time of 36–48 h maximize both blockage removal effects and economic benefits. Samples from different regions require corresponding injection pressures and pressure maintenance times.

The gas pressure drop rate controlled during each blowdown also significantly influences permeability variation; a faster blowdown rate leads to more obvious permeability changes.

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