Physical Experiment and Numerical Simulation of the Depressurization Rate for Coalbed Methane Production

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ABSTRACT: The influence of the depressurization rate on coalbed methane desorption and percolation was studied using physical experiment and numerical simulation. First, low-field nuclear magnetic resonance technology provided a new approach to conduct desorption experiments with different depressurization schemes and obtain the compressibility (C) of coal samples. Then, the productivity calculation of different depressurization schemes was carried out via numerical simulation. The results showed that the first-slow-then-fast (FSTF) depressurization scheme had the highest desorption efficiency (94%), followed by one-stop desorption (85%), first-fast-then-slow desorption (79%), and uniform depressurization desorption (61%). Td cut-off values and the corresponding compressibility were obtained by the saturation–centrifugation method and spectral morphology method, and a high-precision permeability expression for dynamic evaluation of numerical simulation was established by the historical production data fitting approach. Through numerical simulation, high production efficiency can be achieved using depressurization rates of medium (15 kPa/d) and FSTF schemes (8 & 50 kPa/d), and depressurization funnel expansion in the single-phase water flow stage plays a decisive role in stable and high-yield production in the later stage. Thus, the FSTF pressure reduction strategy could be advocated to promote gas production. Slow depressurization should be applied in ineffective desorption and the slow desorption stage for saturated coal seam or single-phase flow stage for undersaturated coal seam, given the higher single-phase water permeability. During the rapid and sensitive desorption stage, rapid depressurization is recommended because of large desorption capacity and low water phase permeability. This paper provides a possibility for the optimization of coalbed methane field production management.

1. INTRODUCTION

Coalbed methane (CBM) mainly exists in coal reservoirs as an adsorption state. As the reservoir pressure drops below the critical desorption pressure, CBM begins to desorb and migrate to the wellbore through diffusion and seepage.1–4 It is of great significance to control bottom hole pressure (BHP) in the whole life cycle of CBM well production.5,6 The slow depressurization rate will prolong the development time and increase the production cost, while rapid drainage will lead to depressurization rate will prolong the development time and increase the production cost, while rapid drainage will lead to a pressure drop below the critical desorption pressure of 8 MPa and an initial methane equilibrium gas pressure of 2.5 MPa. The results show that the greater the pressure difference, the better the gas desorption, and thus, the rapid depressurization was recommended to extract coalbed gas resources. However, the equilibrium pressure used in the research was only 2.5 MPa, facing a challenge to reflect the complete desorption and migration process of a deep coal reservoir. Zhang et al.9 studied the influence of depressurization control on methane desorption through the one-stop desorption and uniform pressure drop schemes. The results showed that the desorption efficiency was significantly improved using the uniform depressurization scheme, and desorption gas content of samples was nearly doubled in 24 h. Although few comparison experimental schemes were limited in Zhang et al.’s research, it has proved that effective control of gas pressure under experimental conditions can significantly improve desorption efficiency.9

It is complex and difficult to simulate desorption under in situ conditions. Traditionally, the volumetric method depends
on the gas equation of state, and the shrinkage effect of the coal matrix leads to an increase in free space. Meanwhile, the change in gas compressibility factor makes the calculation and correction more complicated.10,11 In recent years, low-field nuclear magnetic resonance (LF-NMR) technology has been extensively used in reservoir fluid analysis, adsorption characteristics, and stress sensitivity. The dynamic changes of the coal reservoir during gas exploitation can be quantitatively characterized by the hydrogen-bearing fluid (e.g., CH₄ and H₂O) relaxation time.12−16 The quantitative identification of polymorphic methane during adsorption in coal and shale reservoirs was studied using LF-NMR technology by Guo et al.12 and Yao et al.,13,14 respectively. Yao et al.13 classified methane in the coal reservoir into the adsorption state (<7 ms), free state (7−240 ms), and free state (240−2000 ms) by direct detection of the hydrogen nuclear T₂ spectrum and found a linear relationship between the amplitude of the T₂ spectrum and the mass of methane. Based on the abovementioned linear relation, the dynamic process of one-stop desorption of anthracite was studied by Liu and Wu17 using LF-NMR technology. Therefore, LF-NMR technology provides a new approach for the desorption simulation under different pressure drop rates with the characteristics of being synchronous, nondestructive, and convenient.

Unlike the physical simulation method carried out in the laboratory, numerical simulation of CBM can predict the productivity performance from large scales such as a single well, well pattern, and gas field. Mathematical operation in the numerical simulation technology of CBM wells is usually completed by mature commercial software, such as CMG, COMET3, and Eclipse. Previous reservoir simulation studies have been focusing on productivity prediction and optimization of the CBM well group.5,19 To the best of the authors’ knowledge, few researchers have studied the influence of different depressurization rates based on dynamic permeability coupling reservoir depressurization behavior. Accurate models and parameters are critical to the success of numerical simulation, and permeability is one of the most promising reservoir parameters because of stress dependence.19−23 The decrease in BHP leads to significant damage in permeability, which is mainly affected by the stress compression effect in pore and fracture systems.24 There are many models to describe the relationship between permeability and effective stress, among which the exponential model is the most widely used.22

\[ k = k_0 e^{-3C_f(\sigma - \sigma_0)} \]

where \( k \) is permeability at effective stress \( \sigma \), mD; \( k_0 \) is permeability at effective stress \( \sigma_0 \), MD; and \( C_f \) is fracture compressibility, MPa⁻¹.

Therefore, \( C_f \) is one of the key parameters to describe the dynamic change in reservoir permeability, which is difficult to be obtained directly in the field.25 Coal has a typical dual pore structure, and its fracture system determines reservoir permeability. However, directly measuring fractures and their compressibility by conventional experiments was time consuming and inaccurate.26,27 Zhang et al.15 used dynamic LF-NMR compression experiment to calculate \( C_f \), and the results were consistent with other experimental methods; also, LF-NMR technology showed the advantage of characterizing the compression deformation of both the adsorption pores and fractures. Nevertheless, Zhang et al.’s method to divide pores and fractures according to wave trough needs to be verified, and he has not yet established the permeability model.

Therefore, to formulate a reasonable surface drainage scheme for CBM wells, the effect of the depressurization scheme on methane production was investigated based on an inefficient CBM well (S2 well). First, physical simulation
experiments of different pressure drop schemes were conducted under confining conditions. Then, based on the dynamic permeability model acquired by LF-NMR technology, a numerical simulation approach was utilized to explore the productivity performance of different pressure drop schemes on the scale of gas field. Finally, the influence of methane desorption and seepage in the coal reservoir under varying depressurization schemes was analyzed through the comparison of the abovementioned two methods. This paper aims to provide a set of effective physical experiments and numerical simulation methods to predict the productivity performance concerning different pressure reduction rates and also provide innovative insights for CBM drainage management.

2. CBM WELL DESCRIPTION AND MATERIALS AND METHODS

2.1. Geological Setting and Well Descriptions. The S2 well used for physical experiments and numerical simulation in this paper is located in the Laochang CBM Pilot Area in the eastern part of Yunnan Province (Figure 1), which is one of the hot CBM exploration and development areas in China. The S2 well is a production test in the southeast wing of the Laochang anticline. The target coal seams are no. 14, 16, and 18, with a buried depth of 687.40–703.60 m. The CBM was commingled from the three layers, and field production data could provide a basis for subsequent exploration and development.

Production data of the S2 well can be found in Figure 2, and the whole drainage process was divided into four stages (I, II, III, and IX) according to the relationship between the depressurization rate and gas production (Figure 3). Stage I was the initial stage for drainage testing (0–35 d), the average depressurization rate was 15 kPa·d⁻¹, and the CBM was not being produced. Stage II holds the characteristic of single-phase water flow, BHP decreased from 6.56 to 2.28 MPa with an average depressurization rate of 47 kPa·d⁻¹, and there was still no gas desorption. As BHP is falling below the critical desorption pressure (stage III), BHP decreased from 2.26 to 0.56 MPa, and the average depressurization rate was 12 kPa·d⁻¹. Methane was desorbed from the coal seam and the gas production increased steadily, reaching a peak daily gas production of 808.96 m³·d⁻¹ on the 283rd day. The last stage (stage IV) was characterized by a continuous decline of gas production and difficulty in declining BHP, with daily gas production gradually decreasing to 266.83 m³·d⁻¹.

Figure 2. Drainage curves for the S2 well. Note: GP is the daily gas production rate, WP is the daily water production rate, and BHP is the bottom-hole pressure.

![Diagram showing gas production rate, water production rate, and bottom-hole pressure over time](https://dx.doi.org/10.1021/acsomega.0c03439)

![Figure 3. Relationship between the BHP change and depressurization rate.](https://dx.doi.org/10.1021/acsomega.0c03439)

The abovementioned production data and well basic physical parameters (Table 1) show that the S2 well have

| Parameter                  | Unit  | Value   |
|----------------------------|-------|---------|
| Well type                  |       | vertical |
| Coal seam depth            | m     | 695.5   |
| Thickness                  | m     | 7.6     |
| Reservoir temperature      | °C    | 27      |
| Gas content                | m³·t⁻¹| 12.80   |
| Porosity                   | %     | 0.5     |
| Permeability               | mD    | 0.36    |
| Critical desorption pressure| kPa  | 2294    |

characteristics of high reservoir pressure, low gas saturation, long drainage and depressurization period, low peak production, and fast gas production decline rate. A fast first and then slow step-down depressurization strategy was applied in field production; however, CBM resources cannot be effectively released. Therefore, it is worth exploring and studying whether control of the pressure drop procedure can effectively improve gas production.

According to the unimodal characteristics of the gas production curve of the S2 well (Figure 2) and a small distance between the three layers, similar reservoir parameters (such as critical desorption pressure, reservoir pressure, gas content, etc.) were considered in this case. Therefore, the geological model of the reservoir was simplified as one combined coal seam because this research is focusing on drainage optimization. The basic reservoir parameters were obtained according to the adjacent CBM parameter well, as shown in Table 1.

2.2. Sample Collection and Testing. The samples used in desorption experiments were taken from the DG coal mine which is 1.5 km far away from the S2 well. The samples were obtained from a newly developed mining face (no.16), and there is 2.70 m thickness at the sampling point of the coal layer, and the buried depth is 612.00 m. After collection, the coal samples were wrapped with the preservative film to prevent oxidation and then sealed for transportation. Column coal samples were prepared for the LF-NMR desorption experiment. The diameter of the sample was 2.42 cm, the height was 5.02 cm, and the mass was 37.34 g. Before the desorption experiment, the sample was dried in an oven at 100°C, with a buried depth of 687.40–703.60 m. The CBM was commingled from the three layers, and field production data could provide a basis for subsequent exploration and development.
°C for 24 h and then saturated with heavy water (D₂O) to eliminate the interference of the hydrogen nuclear signal.

The vitrinite reflectance, coal industrial analysis, and element analysis were carried out for the remaining samples, as shown in Table 2.

2.2.1. Desorption Experiments of Different Depressurization Schemes.

LF-NMR experiment for CBM desorption was performed by MRI Rock & Core Analyzer MacroMR12-150H-1 produced by the Niuman Company in Suzhou, China (Figure 4). The instrument included the gas supply subsystem (Figure 4 Part A), pressure-regulating subsystem (Figure 4 Part B), and desorption and T₂ spectrum subsystem (Figure 4 Part C). Subsystem B was connected with a vacuum pump to remove air of the whole system. As an intermediate buffer vessel in the desorption process, the reference cell can maintain gas pressure at a constant value using the pressure reducing valve (PRV) device, while outlet pressure of the reference cell can be controlled using the back pressure valve (BPV). Therefore, the accuracy of desorption pressure can be well improved through combining the use of these two valves. The sample room in subsystem C has a variable volume space, and the confining pressure of the sample was added by changing the inner fluorine oil pressure of the double-layer holder. Meanwhile, the sample was restricted by rods in an axial direction; hence, the space occupied by the coal sample was equal to the size of the sample room. The coil was connected to the computer to provide continuous LF-NMR T₂ spectrum signal detection, and the main parameters included echo interval time (0.6 ms), waiting time (5 s), echo number (2048), number of scans (64), temperature (23 °C), and number of iterations (10,000).

The confining pressure was set as 15 MPa and remained unchanged to simulate the stress state of the coal seam with a buried depth of 695.5 m, and the initial equilibrium desorption pressure was 8 MPa. Four sets of desorption experiments were conducted to simulate the influence of different depressurization modes on CBM desorption (see details in Table 3 and Figure 5), which were one-stop desorption (scheme 1), first-fast-then-slow (FFTS, scheme 2) desorption, first-slow-then-fast (FSTF, scheme 3) desorption, and uniform depressurization desorption (scheme 4). The initial gas pressure of each group was the same before the start of the experiment, and the desorption time was 480 min. The specific experimental steps were as follows.

Table 2. Basic Parameters of the Coal Sample

| sample | Rₒ,max (%) | ultimate analysis (%) | proximate (%) | proximate (%) |
|--------|------------|-----------------------|---------------|---------------|
|        |            | C         | H         | O         | N         | Mₐd     | Aₐd     | Vₐdaf   | FCₐad   | ϕ       |
| DG-1   | 2.44       | 87.95     | 3.37      | 0.87      | 1.67      | 1.32     | 24.30    | 9.57     | 68.45    | 3.25     |

*Note: Mₐd is the moisture content in air-dried basis, %; Aₐd is ash yield in air-dried basis, %; Vₐdaf is the volatile content in dry ash-free basis, %; and FCₐad is the fixed content in air-dried basis, %.

Table 3. Table of Desorption Schemes (Unit: MPa)

| scheme | pressure | 1st h | 2nd h | 3rd h | 4th h | 5th h | 6th h | 7th h | 8th h |
|--------|----------|-------|-------|-------|-------|-------|-------|-------|-------|
| scheme 1 | 8−0.1    | 0.1   | 0.1   | 0.1   | 0.1a  | 0.1   | 0.1   | 0.1   | 0.1   |
| scheme 2 | 8−3.5    | 3.5−3  | 2.5−2 | 2−1.5 | 1.5−1 | 1−0.5 | 0.5−0.1| 0.1   | 0.1   |
| scheme 3 | 8−7      | 7−6   | 6−5   | 5−4   | 4−0.1 | 0.1   | 0.1   | 0.1   | 0.1   |
| scheme 4 | 8−7      | 7−6   | 6−5   | 5−4   | 4−3   | 3−2   | 2−1   | 1−0.1 | 0.1   |

Figure 4. Schematic diagram of the experimental device (photograph courtesy of Fangkai Quan. Copyright 2020).

Figure 5. Schematic diagram of desorption scheme setting.
First, the coal column was placed in the sample room, and the device was vacuumized. Then, the inlet gas pressure was controlled at 8 MPa through the PRV (see Figure 4). After the adsorption reached equilibrium, inlet valve V3 and balance switch V7 were closed. The back-pressure valve (BPV, also see Figure 4) was used to reduce the reference cell gas pressure, according to the scheme in Table 3. Finally, balance switch V7 was opened to simulate the depressurization and desorption process. The data acquisition interval was set as 10 min; meanwhile, outlet pressure data of the sample cell and NMR $T_2$ spectrum data were recorded.

2.2.2. Experimental Measurement of Compressibility by LF-NMR. Compressibility is the key to the numerical simulation of the field scale, and the determination of the movable water space representing fractures is the foundation for obtaining compressibility.32 The specific operation was as follows.

First, the coal sample was completely saturated with distilled water under vacuum conditions, and $T_2$ spectrum distribution of the coal sample was measured; also, the $T_2$ spectrum cumulative curve can be calculated.

Second, a CSC-12 super core centrifuge was used to centrifuge coal samples for 2 h to acquire the immobile water state of coal samples with a centrifugal force of 1.4 MPa,33 and the $T_2$ spectrum distribution and cumulative $T_2$ spectrum curve of immobile water were then detected.

Finally, samples were completely saturated with distilled water again under vacuum conditions, and $T_2$ spectral changes were detected every 10 min until the spectral signals remained unchanged at each pressure point.

The main test parameters of LF-NMR equipment were an echo interval time of 0.2 ms, a waiting time of 3 s, an echo number of 2048, scanning times of 64, a temperature of 23 °C, and an iteration number of 5000.

2.5. Geological Model and Numerical Simulation of the CBM Well. According to the buried depth contour line of the coal seam floor (Figure 6), a reservoir geological model with a side length of 1440 m was established for numerical simulation. Basic information (Table 1) obtained from parameter wells were input into the simulation software COMET3. The simulator automatically calculates the reservoir pressure distribution in each grid according to the reservoir fluid characteristics at the wellbore (Figure 7). The simulated gas production module was a dual-porosity and single-permeability model, Langmuir single-component adsorption model, and gas-water two-phase flow model.

Figure 6. Contour line and gridding of the coal seam floor.

Figure 7. Initial reservoir pressure distribution of the S2 well.

Figure 8. Depressurization schemes for numerical simulation.

30 m centered on the S2 well was set as the fracturing zone, and initial fracturing permeability was assigned as 5 mD. The $C_f$ characterized by LF-NMR was used to model the reservoir permeability. Besides, because of low gas saturation, long drainage depressurization period, and low gas production, the effect of coal matrix shrinkage on permeability was ignored during numerical simulation.

Based on the abovementioned numerical model, five groups of depressurization schemes (see Figure 8) were set up, in which scheme 1 represented rapid depressurization (50 kPa/d), scheme 2 represented rapid depressurization followed by slow depressurization (FFTS), which was adopted for field production history, scheme 3 represented medium speed depressurization (15 kPa/d), and scheme 4 represented slow depressurization (8 kPa/d); in scheme 5, the gas pressure was reduced slowly first and then rapidly (FSTF; 8 & 50 kPa/d). All final depletion pressures were set at 500 kPa to predict the 1200 d gas production performance. After numerical calculation, reservoir pressure and permeability of each grid were output for analysis.
3. THEORY AND CALCULATION

3.1. Theory and Data Processing Principle of LF-NMR.

3.1.1. Quantitative Calculation of Methane Content. LF-NMR was used to study CBM desorption and fracture compressibility based on the response of the hydrogen bearing fluid (methane and water) in the nucleus magnetic field, and the amplitude of $T_2$ was closely related to the number of hydrogen nuclei ($^1$H). Under a uniform magnetic field, the effect of diffusion relaxation is negligible, and then, relaxation time $T_2$ of the pore fluid can be expressed as follows: \[ \frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} \] (2)

where $T_{2B}$ is bulk relaxation time, ms and $T_{2S}$ is the surface relaxation time, ms.

The relaxation time of adsorbed methane is shorter than that of free methane, which is located at the left of the $T_2$ spectrum (Figure 9, dark area). In this paper, the spectrum distribution of initial time $T_2$ spectral area can be further calculated according to the variation of movable space wave spectrum under different confining pressures. The calculation method is consistent with eq 5.

$T_2$ cutoff values are most commonly determined by saturation—centrifugation and curve distribution morphology. The first method is obtained from saturation and centrifugal experiments (see Subsection 2.2.2 for details). The obtained $T_2$ spectrum distribution of saturated and immovable water is transformed into cumulative $T_2$ spectral integration. Then, a horizontal straight line is drawn from the maximum value of the cumulative distribution curve of movable water to the cumulative distribution curve of saturated water. The $x$-axis coordinate value corresponding to the intersection point is the $T_2$ cutoff value ($T_{2c1}$). The curve morphology method is relatively simple, and the $T_2$ spectrum can be directly divided into IPV and MPV according to the position of independent troughs ($T_{2c2}$). The applicability of the two methods is discussed in Subsection 4.2.

4. RESULTS AND DISCUSSION

4.1. Comparison of Physical Desorption Experiments of Different Depressurization Schemes. To compare the methane desorption efficiency under different depressurization schemes, four groups of physical desorption experiments were carried out according to the experimental method set in Subsection 2.2.1. The $T_2$ spectrum distribution of initial time and desorption for 8 h is shown in Figure 10. The dynamic changes in the desorption process were observed by $T_2$ spectra collected every 10 min (Figure 11).

The $T_2$ spectrum shows that FSTF has the least residual $T_2$ spectrum after 8 h of desorption (Figure 10), indicating that FFTS was the most favorable for methane desorption and

\[ A_i = A_0 e^{-c_i \Delta \delta} \] (5)

where $A_i$ is the saturated water spectrum area under different stress differences, p.u.; $A_0$ is the initial saturated water spectrum area under a given pressure, p.u.; and the rest of the variables keep the same meaning as mentioned above.

Permeability is generally considered to be only related to seepage pores and fractures, that is, the occurrence space of movable water in coal characterized by LF-NMR 32, and the $T_2$ cutoff value is an important parameter to divide movable space from immovable space. On this basis, the NMR $T_2$ spectrum is divided into two parts: the immovable pore volume (IPV) on the left side represents micropores and poor connectivity, while the movable pore volume (MPV) on the right side represents seepage pores and fractures with good connectivity. Therefore, the $C_f$ of fracture and seepage pore can be further calculated according to the variation of movable space wave spectrum under different confining pressures. The calculation method is consistent with eq 5.

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Figure 10. $T_2$ spectrum distribution after desorption for 480 min of four groups.
production; meanwhile, the performance of uniform depressurization desorption was the worst. Desorption efficiency of the four schemes from high to low was FSTF depressurization (94%), one-stop desorption (85%), FFTS desorption (79%), and uniform depressurization desorption (61%).

To further explore the difference of desorption behavior under different pressure drop schemes, the desorption rate was calculated and fitted, as shown in Figure 12. Relationship between the desorption rate and time of the water-saturated coal sample in the presence of confining pressure can be expressed as follows

\[ A(t) = a(t - b)^m \]  

where \( A(t) \) is the desorption rate expressed by the LF-NMR spectrum at time \( t \), p.u./min; \( a \) is the initial desorption rate, p.u./min; \( b \) is the node time corresponding to the depressurization stage, mins, such as 0, 60, 120, 180, and 240 min in scheme 3; and \( m \) is the attenuation coefficient of the desorption rate, dimensionless.

The fitting results show that the initial desorption rate and attenuation coefficient of the one-stop desorption scheme were the largest (Figure 12a), and the \( T_2 \) spectral area decreased rapidly from 0 to 60 min during the desorption process. Besides, the large pressure difference in the initial stage promoted rapid migration and production of methane, making it the most effective desorption before 360 min. However, a larger attenuation coefficient led to slow desorption in the later stage.

The uniform depressurization scheme (Figure 12d) held a uniform pressure reduction rate of 1 MPa/h, while different desorption rates showed in different desorption stages. For example, gas pressure reduced from 8 to 4 MPa kept the same depressurization value as from 4 to 0.1 MPa, and the desorption rate in the low-pressure stage from 4 to 0.1 MPa (240 to 480 min) was twice that in the high-pressure stage from 8 to 4 MPa (0–240 min); this was mainly due to the characteristics of nonlinear desorption of methane. Comparing the experimental results of FFTS (Scheme 2) and FSTF (Scheme 3) (Figure 12b,c), it can be seen that the desorption efficiency was significantly different because of the change in time node appearing because of rapid depressurization. When rapid depressurization was applied in the low-pressure stage, the desorption rate was relatively large, and the contribution to the cumulative gas production is the largest. Besides, combined with the four physical desorption schemes, the desorption rate of the FSTF scheme was the highest in the low-pressure stage, which was also the reason for the best overall desorption efficiency.

The abovementioned results show that the most effective desorption method is not the scheme of maximum pressure difference (one-stop depressurization) but the specific desorption stage in which with the large pressure difference has a greater impact on the final cumulative desorption volume. Meanwhile, the difference between the initial desorption rate and attenuation coefficient of four schemes is the reason for these variations.

Therefore, methane desorption efficiency can be improved by different pressure drop settings, and the first slow and then...
fast desorption mode is the most conducive to methane desorption. Although physical experiments are small scale, the conclusions can guide the development of a reasonable production system. Meanwhile, numerical simulation methods will be used to expand the experimental results from the laboratory scale to field scale.

4.2. Determination of Compressibility and Permeability. Accurate measurements and calculations of reservoir compressibility were crucial for CBM numerical simulation with different depressurization schemes. Based on this, a dynamic permeability model reflecting field production was established. LF-NMR can accurately calculate the compressibility of movable space by applying confining pressure in a saturated water sample, according to the method described in Subsection 3.1.2, and $T_2$ spectrum distribution (Figure 13) and $T_2$ cutoff value under saturated and centrifugal conditions were obtained.

After the $T_2$ cutoff value was obtained, the $T_2$ spectrum distribution under 0, 5, 10, 15, and 20 MPa confining pressure was acquired according to the experimental method in Subsection 2.2.2 (Figure 14). Then, $T_2$ spectra under different confining pressures were further divided into MPV and IPV according to the $T_2$ cutoff value (Figure 14), and $C_f$ is calculated according to the method described in Subsection 3.1.2 (Figure 15).

The results show that the cutoff value of $T_2$ obtained by the saturation—centrifugation method was significantly smaller than that obtained by the spectral morphology method (Figure 13), with a $T_{2C1}$ value of 0.8 ms and $T_{2C2}$ value of 3.2 ms. It can be seen that MPV obtained by the saturation—centrifugation method was 1.4 times that determined by the spectral morphology method. Compression tests and data processing results under different confining pressures indicate that the $T_2$ spectrum area showed a decreasing trend with increasing confining pressure (Figure 14), indicating that the pore space was deformed by effective stress. Meanwhile, $C_f$ of different pore types from high to low were MPV, total pores, and IPV, and seepage pores represented by movable water show greater stress sensitivity, which was consistent with the conclusion of Zhang et al.\textsuperscript{45} experiments.

Generally, reservoir permeability is only closely related to the MPV.\textsuperscript{39} According to the exponential relationship of eq 1, the dynamic permeability change of the reservoir was calculated, as shown in Figure 16. Also, two additional $C_f$ values (0 and 0.075 MPa$^{-1}$) were added for comparison. Moreover, production history data were used for fitting through numerical simulation, and results under the four compression ratios are shown in Figure 17.

$C_f$ was a key parameter reflecting the difficulty of compressive deformation of fractures and the permeability sensitivity of stress. The permeability changed under different pore compression ratios and indicated that with the increase in effective stress, reservoir permeability decreased exponentially, and the greater the compression ratio, the more obvious the decrease in permeability (Figure 16). Correspondingly, the higher the compression rate, the lower the peak gas production of CBM wells and the shorter the stable production time (Figure 17).

Comparing the historical fitting results of the production data with different compression ratios, it can be seen that $C_f$ of MPV (0.039 and 0.050 MPa$^{-1}$) characterized by LF-NMR can be well fitted with production data, indicating that LF-NMR can accurately characterize MPV and compression deformation of coal reservoirs. The $T_2$ cutoff value and compression ratio obtained by the spectral morphology method showed a higher fitting degree compared with the saturation—centrifugation method, and gas production of rising and falling stages could be well fitted to the historical data.

In general, many factors are affecting the $T_2$ cutoff value, such as coal rank, pore structure, and so forth.\textsuperscript{41} The $T_2$ cutoff value determined by the saturation—centrifugation method may be more suitable for coal reservoirs with better pore connectivity.\textsuperscript{42,43} In this paper, the immovable water peak and the movable water peak of the sample have obvious trough (Figure 13), and each peak represents a kind of pore system. Therefore, $C_f$ determined by the spectral morphology method (0.050 MPa$^{-1}$) can express the dynamic process of permeability and improve the calculation accuracy of numerical simulation of different depressurization schemes.

4.3. Numerical Simulation of CBM Wells with Different Depressurization Schemes. Based on the accurate expression of dynamic permeability, simulation of CBM production with different depressurization schemes was carried out according to the method described in Subsection 2.5. The daily and cumulative gas production curves of 1200 d of five schemes are shown in Figure 18.

The simulation results displaced obvious differences in drainage efficiency of rapid depressurization (50 kPa/d), medium rate depressurization (15 kPa/d), and slow depressurization (8 kPa/d) (Figure 18). The higher the depressurization rate was, the earlier the critical desorption pressure will be reached, and the gas desorption went ahead greatly. However, cumulative gas production was the lowest because of the larger
decay rate. In contrast, the slow depressurization rate delayed gas desorption time, and the daily gas production rate declined relatively slowly. The medium depressurization rate avoided the abovementioned shortcomings, such as fast attenuation of the gas production rate or late gas desorption time, and a cumulative gas production of 1200 d was better than the abovementioned two schemes.

The other two schemes were the nonuniform step-down method, which represented the production history (FFTS) and the best physical desorption experiment scheme (FSTF). Numerical simulation showed that FSTF was the more appropriate production method, and compared with the rapid pressure drop scheme (50 kPa/d), the peak gas production and cumulative gas production were increased by 1.3 times and 1.2 times, respectively.

To explore the influence mechanism of different pressure-drop schemes on gas production of CBM wells, dynamic distribution of pressure propagation and reservoir permeability were analyzed after numerical simulation. The central horizontal line in Figure 7 was selected as a reference section, and the characteristics of the transient depressurization funnel were drawn (Figures 19 and 20). The dotted box area in Figure 7 was selected to draw the dynamic permeability distribution, as shown in Figure 21.

The results show that the stress sensitivity phenomenon of permeability occurred because of rapidly reducing the BHP (Figures 19 and 21a), the pressure distribution funnel cannot be fully expanded in this case, and gas supply was severely restricted. Meanwhile, simulation results of rapid depressurization were verified in the historical production data, that is, the

![Graph](https://example.com/graph1.png)

**Figure 15.** Calculation of $C_2$ of movable pore space (a,b) characterized by $T_{2C1}$ and $T_{2C2}$, respectively.

![Graph](https://example.com/graph2.png)

**Figure 16.** Dynamic change in permeability with different compressibilities.

![Graph](https://example.com/graph3.png)

**Figure 17.** Comparison of historical production matching of different compression ratio models.

![Graph](https://example.com/graph4.png)

**Figure 18.** Prediction of 1200 d gas production (a,b) under different pressure drop schemes.

![Graph](https://example.com/graph5.png)
larger daily gas production decay rate occurred after reaching the production peak.

A slow pressure drop rate was conducive to the transmission of the pressure drop wave (Figures 19 and 21), and the larger influence range of the pressure drop delayed the decline rate after peak gas production. The medium depressurization rate (15 kPa/d) and FSTF depressurization scheme (8 then 50 kPa/d) were more sufficient to expand the depressurization funnel for 1200 days. The overall depressurization time and reservoir pressure drop scale of the medium drawdown rate were relatively appropriate, so the corresponding productivity performance was excellent (Figure 18).

It can also be seen from Figure 21 that stress sensitivity was an inherent property of the coal reservoir, and no matter what depressurization scheme was adopted, permeability always changed with reservoir effective stress. The low permeability area had the characteristic distribution of the “O” ring around the wellbore, corresponding to the high permeability area after fracturing in the “O” ring, the stress-sensitive area around the “O” ring, and the low permeability change area at the far end. Therefore, for a coalbed methane reservoir with strong stress sensitivity, pressure drop expansion and production efficiency can be improved by controlling the changing pattern of BHP.

From the perspective of avoiding coal fine blockage or stress sensitivity, previous researchers proposed optimization design of the depressurization scheme for the single drainage depressurization stage, and the stage difference of desorption and seepage was neglected in the whole life cycle of CBM production. The dynamic process of CBM reservoir

Figure 19. Distribution of the depressurization funnel during initial desorption of different pressure drop schemes.

Figure 20. Distribution of the depressurization funnel for 1200th day.

Figure 21. Transient analysis of permeability (a–e) during different pressure reduction schemes (29–43 row grid in Figure 7).
development is the coupling of matrix desorption and fracture seepage, and methane is first desorbed from the coal matrix and is strongly controlled by fracture permeability.46

According to the research of Zhang et al.,47 the depressurization desorption process was divided into the inefficiency desorption stage, slow desorption stage, rapid desorption stage, and sensitive desorption stage using the start pressure point, turning pressure point, and sensitive pressure point in the isothermal adsorption curve. The rapid and sensitive desorption stage has a great contribution to CBM well productivity, while the low efficiency and slow desorption stage are very small, and the desorption efficiency under unit pressure drop is gradually increasing with the decrease in equilibrium pressure (Figure 22a). Only single-phase water flow exists before gas desorption of the unsaturated coal reservoir, and permeability is affected by effective stress individually; hence, the relative permeability of the water phase keeps the maximum value. Subsequently, the adsorbed gas is continuously desorbed, and relative permeability of the gas phase begins to increase, while the relative permeability of the water phase continues to decrease (Figure 22b).

The differential control of depressurization in different drainage stages is the core of formulating a reasonable production system. Although the coal reservoir damage caused by stress is unavoidable, it can control the time of its occurrence and the purpose of depressurizing and expanding the desorption area in the early stage, and rapid production in the later stage can be achieved by matching the desorption stage and the seepage process (Figure 22). Xu et al. proposed a single-phase flow stage drainage optimization plan and suggested that a single-phase flow stage should ensure that the pressure-reducing range is expanded as much as possible before the arrival of two-phase flow. This paper believes that the slow pressure reduction scheme is not only suitable for the pressure reduction strategy of undersaturated reservoirs but also should be extended to the stage of ineffective desorption and slow desorption (Figure 22a) for saturated reservoirs because of small desorption contribution and large water phase permeability. The rapid pressure reduction production proposed by Su et al. also satisfies the abovementioned discussion; the maximum gas saturation pressure in the research was 2.5 MPa, which belongs to the stage of rapid and sensitive desorption (Figure 22a), and the rapid production method is also recommended in this work.

The abovementioned results indicate that the excessive pressure reduction in the early stage of drainage is not conducive to the expansion of pressure drop, and the limited amount of desorbable gas leads to unstable production capacity. Therefore, a small BHP reduction rate is recommended in a single water phase or ineffective and slow desorption stage. A large amount of desorption gas appeared in the subsequent stage, and it is appropriate to increase the pressure difference to achieve rapid production.

5. CONCLUSIONS

The effects of different depressurization schemes on methane desorption and production were simulated by physical and numerical simulation, and the conclusions are as follows.

First, the desorption rate characterized by the \( T_2 \) spectral area of the LF-NMR method satisfied the relationship of \( A_t = a(t - b)^m \). The difference between the initial desorption rate and the decay rate of four pressure drop schemes resulted in varied desorption efficiency. The desorption ratio from high to low was FSTF depressurization (94%), one-stop desorption (85%), FFTS desorption (79%), and uniform depressurization desorption (61%). Physical simulation desorption experiments show that the FSTF desorption method was the most conducive to methane desorption.

Second, the movable water pore (MPV) and immovable water pore (IPV) can be accurately distinguished using the LF-NMR spectrum morphology method. Fracture compressibility \( C_f \) calculated by LF-NMR under confining pressure was 0.05 MPa\(^{-1}\), and a high fitting degree was verified by production history fitting. Therefore, \( C_f \) of MPV by the spectral morphology method is suitable for the evaluation of permeability dynamic change in this paper.

Third, numerical simulation results show that a medium depressurization rate (15 kPa/d) and FSTF (8 then 50 kPa/d) showed better productivity. The expansion of the depressurization funnel in the single-phase water flow stage plays a decisive role in stable and high-yield production in the later stage. Besides, the distribution of low permeability areas in the process of drainage and production has an O-shape feature.
Finally, the FSTF depressurization strategy was recommended for field production based on the results of the desorption experiment and numerical simulation. The slow depressurization scheme should be continued until ineffective desorption and slow desorption stage for saturated coal seam or before gas desorption for unsaturated coal reservoir.

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Notes
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