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Theory and Engineering Practice of Intermittent Heat Injection-Enhanced Coalbed Methane Extraction

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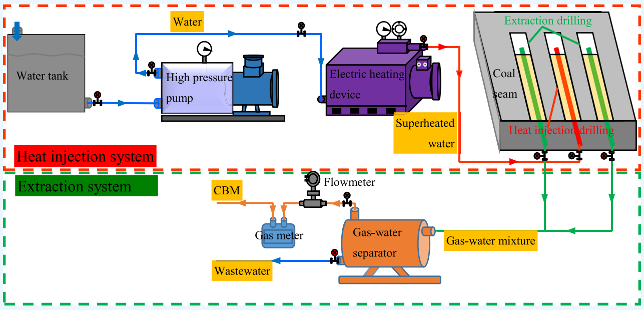

ABSTRACT: Because of the strong adsorption characteristics of methane and the low permeability of coal seams, the extraction efficiency of coalbed methane (CBM) is very low. Here, based on the energy conservation equation, we propose the theory of heat injection-enhanced CBM extraction. We developed a device for heat injection-enhanced CBM extraction and performed an on-site heat injection test in the Chengzhuang coal mine. The results showed that when the water injection rate was 0.5 m^3/h, the heat injection temperature was 145 °C, with two heat injections, yielding the best CBM extraction effect. This could fully utilize the heat injection equipment and achieve a fast, safe, and efficient extraction. The gas production law of the intermittent heat injection-enhanced CBM extraction method had obvious stages; the CBM concentration and daily gas production were very low during the heat injection stage but were greatly improved during the extraction stage after heat injection. The highest CBM concentration reached 100%, and the maximum daily gas production of CBM increased by 1269 times. The variation law of the cumulative gas production with time was fitted using Wang's empirical formula. Comparative analysis showed that, compared to traditional extraction, intermittent heat injection shortened the extraction time by 6.6 years. Compared with other enhanced CBM extraction methods, the intermittent heat injection method had obvious technical advantages and greater improvements in concentration and CBM extraction speed. Therefore, the results are of great significance for improving the recovery rate of CBM and for reducing greenhouse gas emissions.

1. INTRODUCTION

As an important unconventional natural gas resource and strategic supplement to conventional energy, coalbed methane (CBM) is important in the global energy structure.[1] However, mine gas, as the main component of CBM, also threatens the safety of coal miners.[2−4] The effective exploitation of CBM resources has become a hot topic for coal safety exploration and energy utilization. Therefore, technological innovation is of great significance for improving the recovery rate of CBM and promoting resource utilization and safe coal mine production.[5−7]

The reservoir permeability has an important impact on the extraction of CBM. In general, the higher the reservoir permeability is, the shorter is the extraction time of CBM.[8,9] Therefore, some scholars have conducted permeability experiments under different conditions. For example, Cai et al.[10] discovered that the relationship between coal permeability and temperature is influenced by the relative relationship between effective and thermal stresses. Zhang et al.[11] investigated the permeability changes of raw coal samples before and after a temperature shock using a permeability experiment and concluded that temperature shock might improve coal permeability. Li et al.[12] investigated the seepage properties of raw coal at various temperatures using a triaxial servo seepage apparatus and discovered that coal permeability increased with the increase of temperature. Shao et al.[13] conducted experiments on the permeability characteristics of lignite and found that the permeability of lignite initially decreased with an increase in temperature, then increased sharply, and finally decreased. Braga and Kudasik[14] conducted experiments on the permeability of raw coal under various temperature conditions, which showed that the permeability of raw coal changes stagewise with temperature.

Numerous CBM development practices show that the current technology, mainly focusing on increasing permeability, cannot meet the needs of efficient CBM extraction.[15−17] External load stress technologies, such as hydraulic fracturing, high-energy gas fracturing, and detonation fractur-

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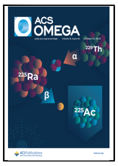

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ing, increase the permeability of coal seams and improve the CBM extraction efficiency.[18,19] However, these technologies also have certain disadvantages. Water will hinder the desorption and migration of CBM.[20,21] Therefore, the improvement effect of methods such as hydraulic fracturing on CBM extraction is not ideal. In addition, some scholars try to improve the extraction of CBM through gas phase-change fracturing[22] and gas displacement.[23] However, high-energy gas fracturing and detonation fracturing technologies will form stress concentration areas in coal seams and increase the possibility of accidents. Therefore, the extraction efficiency of CBM was not significantly improved.[24] Because gas displacement technology can be applied only to coal seams with high permeability, it is difficult to popularize this technology. Hence, the key technologies for CBM exploitation need urgent innovation. Heat injection mining can promote rapid methane desorption, increase the driving force of CBM extraction, and thereby increase the extraction rate of CBM.[25−27] Scholars such as Salmachi,[28] Goraya,[29] and Jebelli[30] believe that heat injection is an effective method to improve the recovery rate of CBM in the future and have conducted extensive experimental research in the laboratory.

As we all know, the higher the temperature of the coal seam is, the lower is the adsorption capacity of coal for CH4.[31,32] Therefore, some researchers have studied the adsorption and desorption laws of CBM under the influence of temperature.[33−35] For example, Ren et al.[36] discovered through intermittent heat injection experiments that the desorption of coal briquettes increases as the temperature increases. Yang et al.[37] discovered through adsorption and desorption experiments that adsorption is an exothermic process with increasing temperature, whereas desorption is an endothermic process with decreasing temperature. Zhao et al.[38] discovered through a coal desorption experiment with heating and water injection that the desorption capacity of coal samples increased rapidly as the temperature increased. It is worth noting that desorption is an endothermic process, and energy is the key factor of desorption efficiency.[39,40] Therefore, the CBM recovery rate can be increased by energy injection. Heat injection, as a way of directly injecting energy, is gradually becoming the most important method to strengthen CBM extraction.[23,41,42] Therefore, many scholars worldwide have conducted laboratory and numerical simulation research on the recovery rate of CBM after heat injection. For example, Shahtalebi et al.[43] conducted a study on increasing CBM production by thermal stimulation and found that increasing the temperature of coal seams is beneficial to the desorption and migration of methane. Lan et al.[24] proposed the microwave heating technology and conducted absorption experiments in the laboratory. The experimental results showed that the microwave heating method could significantly improve the desorption capacity of methane. Multiple numerical simulation results have shown that the heat-injection method can improve the CBM recovery rate.[44,45] Xie and Zhao[46] developed a thermal-fluid−solid coupling mathematical model suitable for low-permeability coalbed methane mining. The results showed that the temperature of the coal seam directly affects the CBM output. Teng et al.[47] also established a heat-moisture-fluid−solid fully coupled mathematical model, which showed that the heat injection method can effectively promote the desorption of CH4. To sum up, the previous research on heat injection mainly focused on the desorption law and numerical simulation of CBM. However, the principles and field application of heat injection-enhanced CBM extraction technology are rarely discussed.

Therefore, on the basis of the principle of energy conservation, the desorption and migration of CBM were theoretically analyzed in this study, and the theory of heat injection-enhanced CBM extraction was perfected. Then, a field test was carried out in the Chengzhuang coal mine to verify the proposed heat injection theory and method. This work will provide technical parameters and experience for the application of heat injection-enhanced CBM extraction in coal mines.

2. THEORY AND PARAMETERS

2.1. Theory of Intermittent Heat Injection-Enhanced CBM Extraction.

2.1.1. Effect of Energy Stimulation. Any system in nature maintains a state of energy balance before being disturbed by outside forces. The system changes only when the original energy balance breaks. For example, when a coal seam is disturbed, a large amount of CBM in the coal seam begins to desorb. Therefore, to obtain more CBM, it is necessary to break the energy balance of the coal seam and inject additional energy.[48−50]

It is well-known that methane molecules always move from a higher-energy state to a lower-energy state, which undoubtedly requires energy consumption. In the process of extraction, the more energy is injected from the outside, the more methane is produced.[23,51,52] This process can be expressed by the energy conservation equation, and this energy conservation can be represented by eq 1.[53] The heat injection method is a direct energy injection method for strengthening CBM extraction. Therefore, it can break the energy balance of the coal seam, provide continuous energy injection for the coal seam, and significantly improve the production of CBM.

$$E_{\mathrm{pr}} = E_{\mathrm{in}} + E_{\mathrm{or}} - E_{\mathrm{co}} \tag{1}$$

where E_{pr} is the net new energy generated after injection; E_{in} is the energy injected into the coal seam; E_{or} is the original energy of coal and CBM in the system; and E_{co} is the energy consumed by the coal, injection medium, and CBM.

2.1.2. Effect of Promoting CBM Desorption. The methane in coal seams can be divided into adsorbed and free methane.[32] In an actual coal seam, >90% of the methane is adsorbed on the surface of the coal matrix. Therefore, CBM mining transforms adsorbed methane to free methane. Notably, the desorption of methane is an energy-consuming process; therefore, sufficient energy must be provided to the coal seam to obtain more free methane.[40]

According to the improved Langmuir equation, increasing the reservoir temperature and reducing the reservoir pressure can promote CBM desorption, as expressed in eq 2.[47] However, as a method of strengthening CBM extraction, heat injection can heat a coal seam through heat conduction and thermal convection. After injection of the superheated water, the desorption rate and the desorption speed of the CBM increase rapidly. Therefore, heat injection can provide energy to coal seams in the form of thermal energy and promote CBM desorption.

$$V_{\mathrm{sg}} = \frac{V_{\mathrm{L}}p}{P_{\mathrm{L}} + p}\exp\left[-\frac{c_2(T - T_{\mathrm{ref}})}{1 + c_1 p}\right] \tag{2}$$

where V_{sg} is the methane adsorption content (m^3/kg), P_{L} and V_{L} are the Langmuir pressure constant and volume constant

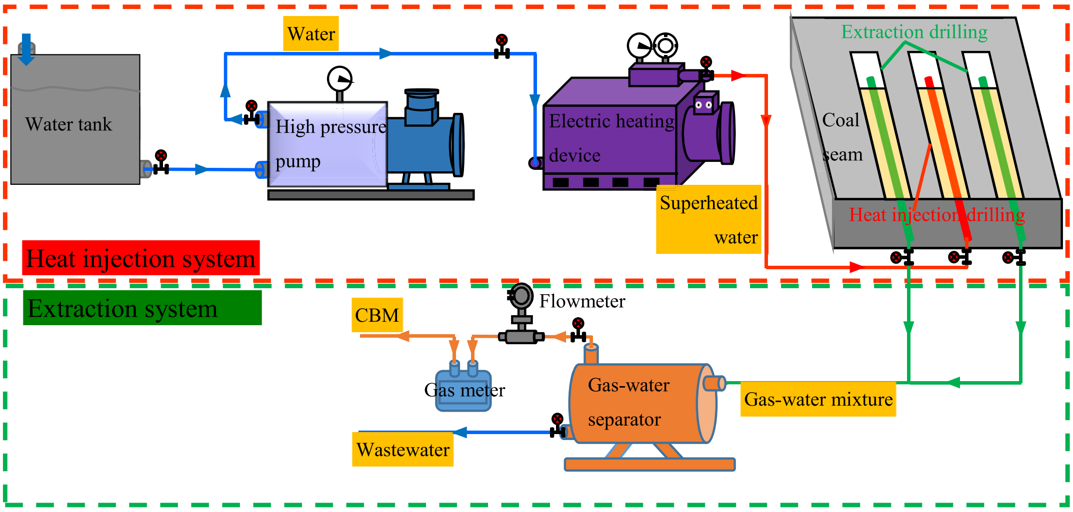

Figure 1. System connection.

(Pa and m^3/kg, respectively), T_{ref} is the reference temperature for methane adsorption (K), and c_1 and c_2 are the pressure and temperature coefficients (Pa^{-1} and K^{-1}, respectively).

2.1.3. Effect of Promoting CBM Migration. The migration of CBM in coal seams is the basic movement of natural substances. The migration path of CBM is composed of the pore system and fracture system.[7] Therefore, diffusion and seepage constitute the migration of CBM.[54−56]

It is well-known that the diffusion and seepage of CBM in pores and fractures consume energy. When the resistance and driving force of CBM migration reach a balance, the CBM migration stops. Therefore, it is necessary to inject energy into coal seams to provide the power for CBM migration. As a way of directly injecting energy, heat injection can not only promote methane desorption and increase the diffusion and seepage rates of CBM but also cause thermal damage to the coal body and increase the migration channel of CBM.[41]

2.2. Parameters of Intermittent Heat Injection-Enhanced CBM Extraction.

$$Q_{CH_4} = \frac{C_{CH_4} \times Q_{mix}}{L} \tag{3}$$

where Q_{CH4} is the daily gas production of a 100 m borehole (m^3/day), Q_{mix} is the mixed flow in the heat injection test area (m^3/day), C_{CH4} is the concentration of CBM (%), and L is the 100 m length of the extraction borehole (100 m).

$$Q = \sum_{i=1}^{t} Q_{(CH_4)_i} \times L \tag{4}$$

where Q is the cumulative extraction volume of CBM (m^3) and t is the total time of extraction (days).

$$\eta = \frac{Q_1}{Q_2} \tag{5}$$

where η is the ratio of the total extraction of CBM to the total water injection, Q_1 is the cumulative extraction volume of CBM during the heat injection stage and its extraction stage (m^3), and Q_2 is the cumulative water injection volume in the heat injection stage (m^3).

3. FIELD TEST

3.1. Technological Process. The heat injection process involved six steps: drilling construction and sealing, system connection, system sealing inspection, heat injection, CBM extraction, and data monitoring and collection.

(1) Borehole construction and sealing

Boreholes were constructed according to the requirements of the experimental design, and it is required that all boreholes can be used as heat injection holes or extraction holes. The boreholes were sealed with cement to prevent leakage.

(2) System connection

The system connection mainly includes three parts: the heat injection system connection, the extraction system connection, and the data monitoring and collection system connection. The system connection is shown in Figure 1.

(a) Heat injection system connection

The heat injection system was mainly composed of a mine water supply pipeline, a water injection pump, an electric heating boiler, a heat transfer pipeline, and a heat injection pipeline. Normal-temperature and high-pressure water was used between the mine water supply pipeline and electric heating boiler, which were connected by a high-pressure rubber hose. However, superheated water was used between the electric heating boiler and the heat injection pipeline, which were connected by seamless steel pipes (Figure 1).

(b) Extraction system connection

The extraction system consisted of an extraction pipe, a gas−water separator, an orifice flowmeter, and mine gas negative pressure extraction pipes (Figure 1).

(c) Data monitoring and collection system connection

This part is mainly used for monitoring the coal seam temperature and pressure and collecting CBM and water.

(3) System sealing inspection

Before the heat injection was started, all pipelines and valves were checked, and it was ensured that the pipelines were smooth and did not leak.

(4) Heat injection

After the water injection pump and electric heating boiler were opened, the normal temperature water was heated to superheated water and then injected into the coal seam.

(5) CBM extraction

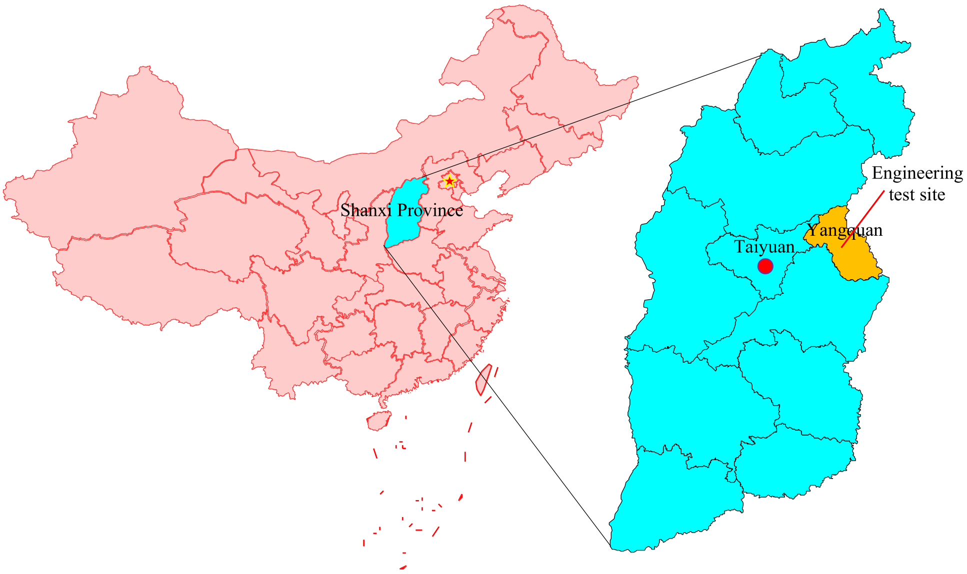

Figure 2. Location of the in situ test.

After the completion of the heat injection, the CBM extraction was performed. When the extraction speed dropped to the minimum required by the test, CBM extraction was stopped, and then the next stage of heat injection was performed by repeating step 4.

(6) Data monitoring and collection

Pressure gauges and temperature sensors were used to monitor the temperature and pressure of the coal seams. When the temperature and pressure of the adjacent borehole met the requirements of the test, heat injection was stopped.

3.2. Overview of the Test Site.

As shown in Figure 2, we chose the 15# coal seam of Chengzhuang Coal Mine as the test site. The buried depth of the coal seam is 200−440 m. The direct roof and floor are sandy mudstone, which plays the role of a water-resisting layer. The average CBM content of the 15# coal seam is 6.87 m^3/t, and the average firmness coefficient of the coal is 0.86. The thickness of the coal seam varies in the range of 5 to 7 m, and the average gas pressure is 0.61 MPa. The industrial analysis of the 15# coal seam is given in Table 1.

Table 1. Industrial Analysis of the Test Coal Seam[a]

number	proximate analysis (%)				R^0_{max} (%)	coal rank and type	
	M_{ad}	A_d	V_{daf}	$S_{t,d}$		rank	type
15#	0.81	9.39	12.44	1.90	2.47	high-grade bitumite	lean coal

[a] Note: M_{ad} is the moisture content, A_d is the ash yield, V_{daf} is the volatile matter, $S_{t,d}$ is the sulfur content, and R^0_{max} is the coal body's maximum vitrinite reflectance.

3.3. Borehole Arrangement and Test Scheme.

The spacing of the boreholes in the heat injection test was 5 m. The borehole arrangement is shown in Figure 3. The horizontal design depth of the boreholes was 100 m, and the sealing depth was 30 m. Before the intermittent heat injection test, the traditional CBM extraction test was carried out, and the CBM was extracted by means of negative pressure. This stage is termed the original extraction stage. Subsequently, an intermittent heat injection test was performed. This stage is termed the heat injection and extraction stage. The process flow of intermittent heat injection-enhanced CBM extraction can be simplified to heat injection, extraction, secondary heat injection, extraction, tertiary heat injection, and extraction.

4. TEST RESULTS

The 4# borehole was a heat injection borehole. The 1#, 2#, 3#, 5#, 6#, and 7# boreholes were extraction boreholes. The details of the intermittent heat-injection tests are listed in Table 2.

According to eqs 3 and 4, the average daily gas production of a 100 m borehole (Q_{CH4}) and cumulative extraction volume (Q) in each stage of the intermittent heat injection test area were obtained, as shown in Figures 4 and 5.

It can be seen from Figure 4 that after three heat injections, the total extraction volume (Q) of CBM was 2206 m^3. The cumulative heat injection and extraction times were 44 and 129 days, respectively. As shown in Figure 4, the cumulative extraction volume increased in stages with time. The curves of the cumulative extraction volume during the original extraction stage and the heat injection stages were almost parallel, whereas the cumulative extraction volume during the extraction stages after intermittent heat injection increased significantly. This shows that the time period to produce a large amount of CBM was the extraction stage after heat injection.

As shown in Figure 5, the average daily gas productions (Q_{CH4}'s) are 0.16 m^3/day in the original extraction stage; 0.05 1.65, and 1.23 m^3/day in the three heat injection stages; and 34.9 34.73, and 20.78 m^3/day during the extraction stages after intermittent heat injection. This showed that, compared with the original extraction stage, the daily gas production during three heat injection stages did not change but increased by more than 100 times during the extraction stages after intermittent heat injection. The daily gas productions in the extraction stage after intermittent heat injection (34.9, 34.73, and 20.78 m^3/day) were 218, 217, and 130 times, respectively, of the original extraction stage (0.16 m^3/day). Therefore, heat injection could promote CBM desorption, improve the extraction speed of CBM, and achieve the purpose of efficient extraction.

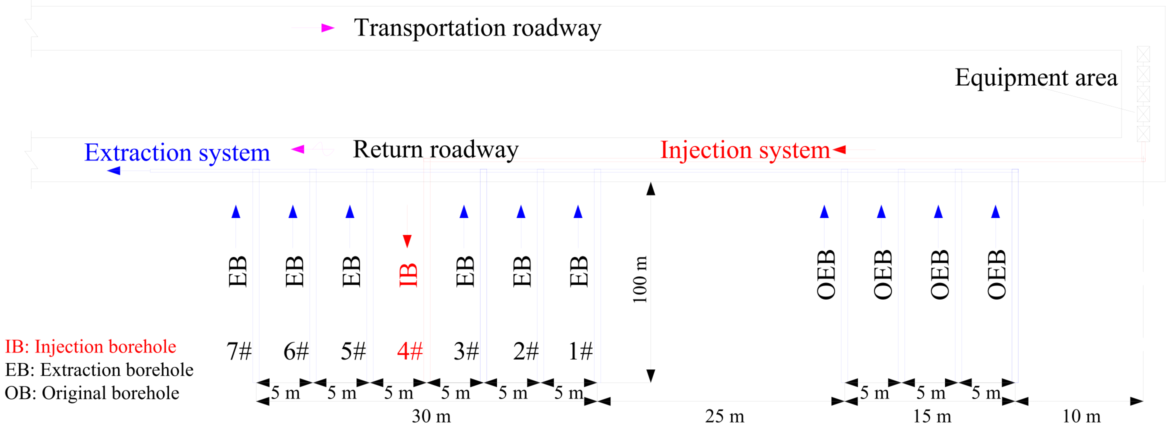

Figure 3. Schematic diagram of the borehole layout.

Table 2. Intermittent Heat Injection Parameter

stage	water injection pressure/MPa	water injection temperature/°C	heat injection/ extraction time/day	cumulative water injection volume/m^3	cumulative extraction volume of CBM/m^3
original extraction stage			29		24.7
first heat injection stage	8	145	23	254.7	4.2
extraction stage after first heat injection			26		675.3
second heat injection stage	8	145	8	85.2	2.8
extraction stage after second heat injection			43		1045.5
third heat injection stage	8	145	13	100.6	4.5
extraction stage after third heat injection			24		449.0

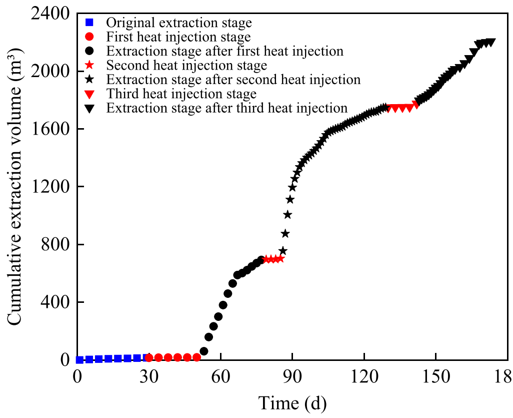

Figure 4. Cumulative extraction volume in the intermittent heat injection test area.

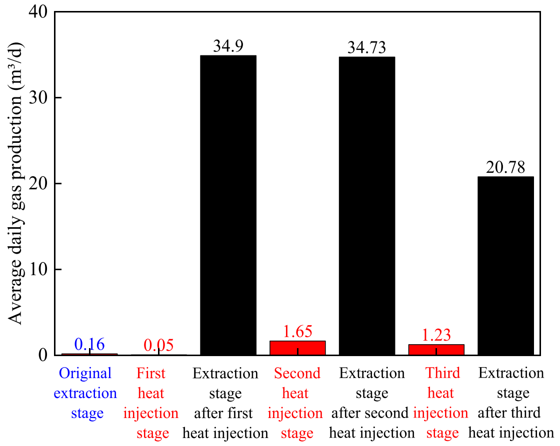

Figure 5. Average daily gas production at each stage in the intermittent heat injection test area.

5. LAW ANALYSIS AND EFFECT EVALUATION OF THE INTERMITTENT HEAT INJECTION METHOD

5.1. Analysis of the Gas Production Law. *5.1.1. Variation Law of the Daily Gas Production.* Figure 6 shows the variation curve of daily gas production with time in the intermittent heat injection test area.

As shown in Figure 6, the daily gas production exhibits the characteristics of periodic change. That is, the daily gas productions (Q_{CH4}'s) during the original extraction stage and three heat injection stages were very low and were no more than 1 m^3/day. However, Q_{CH4}'s during the extraction stages after intermittent heat injection were significantly increased and were >10 m^3/day. Therefore, the extraction stage was the period in which a large amount of CBM was produced. The following is an analysis of the gas production law during the extraction stages after intermittent heat injection.

During the extraction stage after the first heat injection, the peak value of Q_{CH4} was 113 m^3/day, which was 706 times that of the original extraction stage. As of the start of the second heat injection, Q_{CH4} was 6 m^3/day, which was 38 times that of the original extraction stage. During the extraction stage after the second heat injection, Q_{CH4} first rapidly increased to a peak value of 203 m^3/day, which was 1269 times that of the original extraction stage, and then gradually decreased. As of the start of the third heat injection, Q_{CH4} was 4 m^3/day, which was 25 times that of the original extraction stage. During the

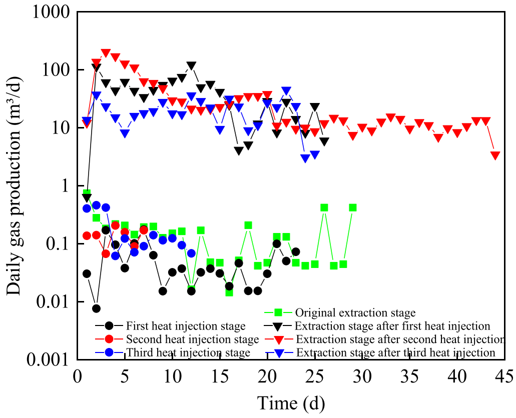

Figure 6. Variation in daily gas production with time in the intermittent heat injection test area.

extraction stage after the third heat injection, Q_{CH4} first increased to 37 m^3/day, which was 231 times that of the original extraction stage, and then fluctuated thereafter. By the end of the test, Q_{CH4} was 4 m^3/day, which was 25 times that of the original extraction stage. Notably, although Q_{CH4} during the extraction stages after intermittent heat injection fluctuated significantly, it was considerably larger than that during the original extraction stage. Therefore, Q_{CH4} during the heat injection stages almost did not increase; however, during the extraction stages after intermittent heat injection, it increased significantly with an average increase of more than 100 times.

According to the Langmuir adsorption equation (as shown in eq 2), increasing temperature and reducing pressure can promote the desorption of CBM. In the process of heat injection, the desorption rate of CBM is very low because the CBM is in the environment of high temperature and high pressure. But, during the extraction process after heat injection, the desorption rate of CBM is greatly improved because the CBM is in the environment of high temperature and low pressure. Therefore, the daily gas production of CBM during the heat injection stage is very low but is greatly increased during the extraction stage after heat injection. In summary, the heat injection theory can not only explain the gas production law well but also be used to guide the field heat injection test.

5.1.2. Variation Law of CBM Concentration. Figure 7 shows the variation curve of the CBM concentration over time in the intermittent heat injection test area. It can be seen from Figure 7 that the CBM concentration and daily gas production have similar change laws; that is, the CBM concentrations during three heat injection stages are very low; however, during the extraction stages after intermittent heat injection, they are greatly increased. The maximum CBM concentrations during the original extraction stage and three heat injection stages were <10%; however, the maximum values of CBM concentration during the extraction stages after intermittent heat injection were 100%, and the minimum values were also >20%.

During the extraction stage after the first heat injection, the CBM concentration increased and then decreased. On the 22nd day, the CBM concentration reached 100%, and the CBM concentration remained at 35% until the second heat injection. During the extraction stage after the second heat injection, the CBM concentration first increased rapidly and then gradually decreased. On the second day, the concentration of CBM reached 100% and remained at 100% for 7 days, and until the third heat injection, the CBM concentration remained at 59%. During the extraction stage after the third heat injection, the CBM concentration first increased rapidly and then gradually decreased. On the eighth day, the concentration of CBM peaked at 79%, and by the end of the test, the concentration of CBM remained at 60%.

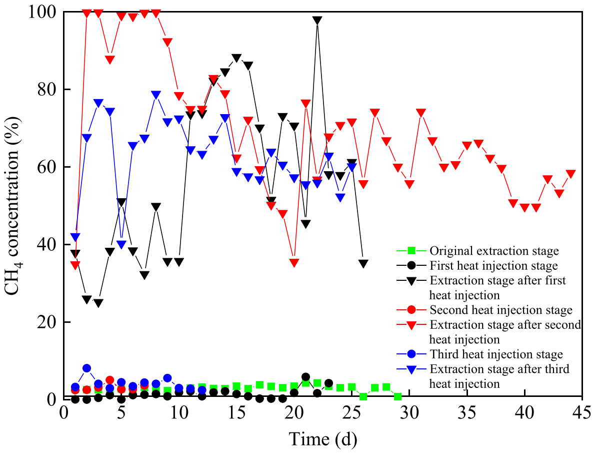

Figure 7. Variation in CBM concentration with time in the intermittent heat injection test area.

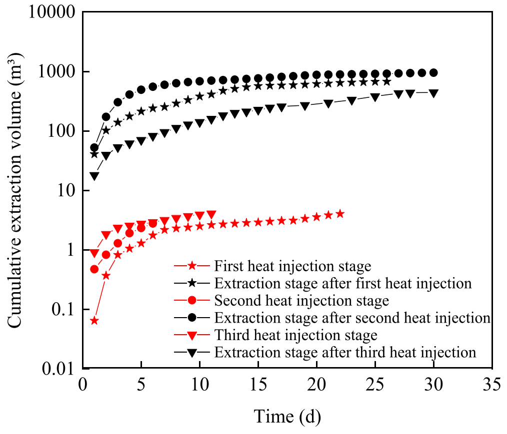

Figure 8. Variation in cumulative extraction volume with time in the intermittent heat injection test area.

5.1.3. Variation Law of Cumulative Extraction Volume. Figure 8 shows the change curve of the cumulative extraction volume (Q) with time at different stages. As mentioned in the previous section, Q had the characteristics of periodic change with time; that is, Q increased slowly during the intermittent heat injection stages, whereas it increased significantly during the extraction stages after intermittent heat injection. Among them, Q did not exceed 4.5 m^3 during the intermittent heat injection stages; however, the values were 675.3, 1045.5, and 449.0 m^3 during the extraction stages after intermittent heat injection. This indicated that the intermittent heat injection stage was the time period when the coal was heated by superheated water and a large amount of CBM was desorbed and that the extraction stage was the time period when a large amount of CBM was produced.

Figure 8 shows that regardless of the heat injection stages or the extraction stages after intermittent heat injection, the cumulative extraction volume increases significantly in the early stage and slowly in the late stage. Many scholars have also obtained the same experimental results.[23,24,57,58] Therefore, many researchers have conducted extensive studies in the laboratory and field on the variation law of CBM production with time in an attempt to identify an empirical formula for the cumulative extraction volume with time that applies to most situations.

By studying the adsorption of various gases by natural zeolite, Barrer[59] obtained the following empirical formula:

$$Q_t = K_1\sqrt{t} \tag{6}$$

where Q_t is the total desorption amount of gas at time t (cm^3/g) and K_1 is the cumulative desorption amount of the exposed coal sample within 1 min ($cm^3/(g{\cdot}min^{0.5})$).

Wang and Yang[60] measured the desorption rate of CBM in coal using a gravimetric adsorption device and obtained the following relationship:

$$Q_t = \frac{ABt}{1 + Bt} \tag{7}$$

where A is the limit desorption amount of CBM (cm^3/g) and B is a constant that reflects the change in coal quality (min^{-1}).

Qin et al.[61] proposed the following empirical formula when studying the desorption law of CH4:

$$Q_t = \frac{AB_1\sqrt{t}}{1 + B_1\sqrt{t}} \tag{8}$$

where B_1 is a constant characterizing the gas desorption rate ($1/s^{0.5}$).

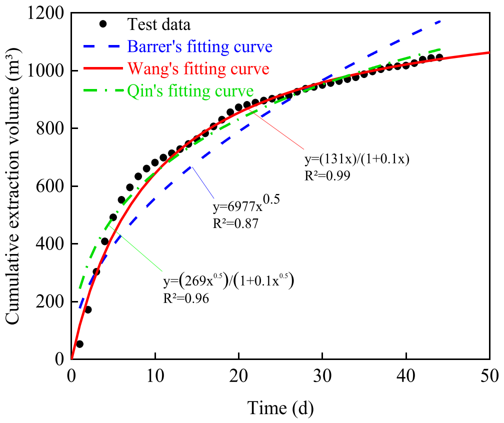

Figure 9. Variation law of the cumulative extraction volume with time.

Taking the test data of the extraction stage after the second heat injection as an example, the fitting situation of the empirical formula above was obtained, as shown in Figure 9.

Through the fitting results, it was found that the correlation coefficient of Wang's formula was the highest at 0.99, whereas the correlation coefficients of Barrer's and Qin's formulas were 0.56 and 0.96, respectively, suggesting that, compared with other empirical formulas, Wang's formula can more accurately characterize the variation law of CBM extraction volume with time in the CBM extraction process after heat injection.

5.2. Effect Evaluation of the Intermittent Heat Injection Method.

Heat injection-enhanced CBM extraction is a systematic project that integrates multiple factors, including the cost of heat injection, economic benefits, and safety of construction.[62] In coal seam heat injection engineering, scientific evaluation of the efficiency of the heat injection-enhanced CBM extraction method is the main foundation for process and technical optimization. Therefore, the ratio of CBM production to heat injection, as well as the average daily gas production, was utilized as an evaluation indicator in this study to comprehensively evaluate the CBM production speed and energy efficiency of the intermittent heat injection method.

5.2.1. Relationship between Times of Heat Injection and Efficiency.

After sorting the data of the water injection volume and cumulative extraction volume, the ratio of CBM production to heat injection (η) and the average daily gas production (Q_{CH4}) can be obtained according to eqs 4 and 5, as shown in Figures 10 and 11. The average daily gas production was the average of the daily gas production in the heat injection stage and that in the extraction stage after heat injection.

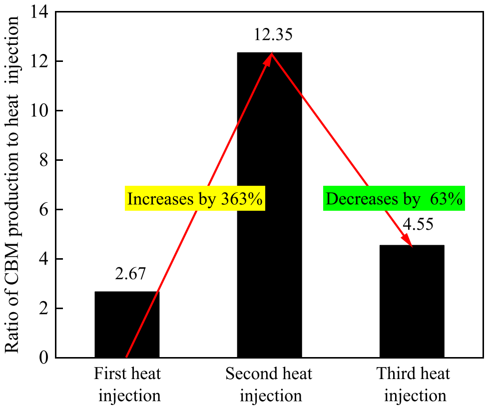

Figure 10. Relationship between the ratio and the numbers of heat injection.

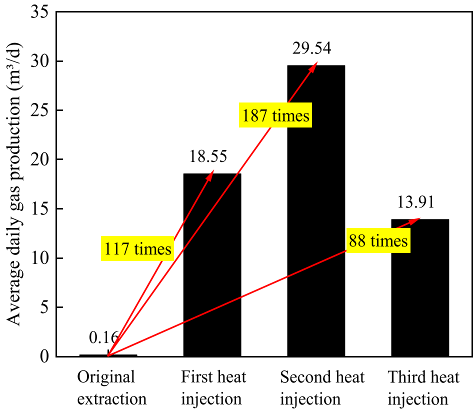

Figure 11. Relationship between the average daily gas production and the number of heat injection.

Figure 10 shows that the ratios (η's) of the three heat injections are all greater >1, which show that for every 1 m^3 of superheated water injected, 2.67, 12.35, and 4.55 m^3 of CBM can be obtained after the first, second, and third heat injections, respectively. Compared with that of the first heat injection, the ratio of the second heat injection was increased by 363%, which showed that heat had a "superposition effect", and the second heat injection could increase the utilization efficiency of heat and save the cost of heat injection. Compared with that of the second heat injection, the ratio of the third heat injection was reduced by 63%, which showed that after the third heat injection, although the heat could be superimposed, it increased the ineffective heating area, lengthened the seepage path of CBM, and ultimately led to a reduction in the ratio of CBM production to heat injection.

Figure 11 shows that the average daily gas productions (Q_{CH4}'s) in the original extraction stage and the three heat injection stages are 0.16, 18.55, 29.54, and 13.91 m^3, respectively. Compared with the original extraction stage, the average daily gas productions in the three heat injection stages increased by 117, 187, and 88 times, respectively, which showed that intermittent heat injection promoted CBM desorption, increased the CBM pressure of reservoir, and greatly improved the migration speed of CBM.

According to the previous analysis, the relationship between the heat injection efficiency and number of heat injections was not linear, and there was an optimal number of heat injections. The relationship of the ratio (η) and the daily gas production (Q_{CH4}) to the number of heat injections is shown in Figure 12.

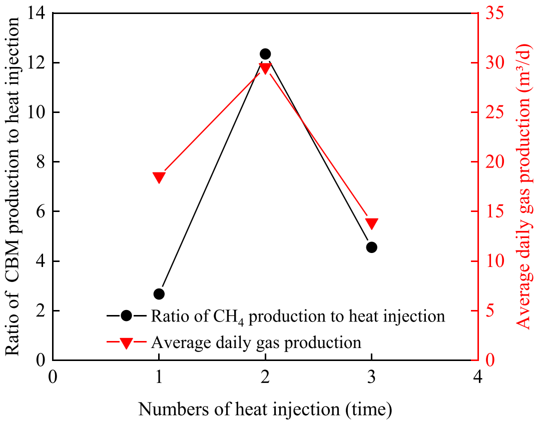

Figure 12. Change curve of the ratio and average daily gas production over time.

Figure 12 shows that with an increase in the number of heat injections, both the ratio (η) and the daily gas production (Q_{CH4}) increase first and then decrease. This was consistent with the results of previous studies; that is, after two heat injections, the CBM extraction speed and utilization rate of heat were increased. After the third heat injection, the ratio and the daily gas production decreased to varying degrees. This was because excessive rounds of cyclic heat injection not only increased the permeability path of CBM, resulting in a decrease in daily gas production, but also enlarged the ineffective heating zone of the coalbed, reducing the efficiency of heat utilization.

5.2.2. Comparison of the Traditional Extraction Method and Intermittent Heat Injection Method. The intermittent heat injection-enhanced CBM extraction test was the first field test. Therefore, it was necessary to discuss the effects of intermittent heat injection and traditional extraction methods, as shown in Figure 13.

The calculation formula for the shortened time after adopting the intermittent heat injection method is

$$t = \frac{Q}{Q_{CH4} \times L \times 365} - t_0 \tag{9}$$

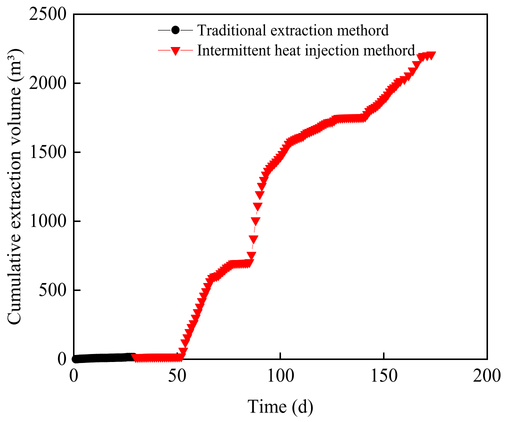

Figure 13. Comparison of intermittent heat injection and traditional extraction methods.

where Q is the total amount of CBM extraction after heat injection (m^3), t_0 is the extraction time required by the intermittent heat injection method (days), and Q_{CH4} is the average daily gas production of a 100 m borehole when the traditional extraction method is adopted ($m^3 \cdot d^{-1} \cdot 100m^{-1}$).

The cumulative CBM extraction volume in the heat injection test area was 1733 m^3, the extraction time of the heat injection method was 144 days, and the average daily gas production of the traditional extraction method was 0.16 m^3. Therefore, according to eq 7, the shortened extraction time after adopting the heat injection method was 6.6 years.

The cumulative extraction volume hardly increased when the traditional extraction method was used, as shown in Figure 13. However, it was considerably improved when the intermittent heat injection method was used. The intermittent heat injection method produced 1733 m^3 of CBM. Compared to that of the traditional extraction method, the extraction time was shortened by 6.6 years. In conclusion, when compared with traditional extraction methods, the intermittent heat injection method promotes the desorption of adsorbed methane, increases the extraction volume of CBM, reduces the extraction time, and achieves efficient extraction of CBM.

6. DISCUSSION

To further analyze the effect of the intermittent heat injection method, the results of other field tests were sorted out. Wei et al.[63] conducted a test on liquid CO_2 displacing CBM in the Huainan and Hancheng mining areas, and the results showed that liquid CO_2 displacing could improve the production of CBM by 2 times and significantly shorten the extraction time. Yang et al.[64] conducted an exploratory test of N_2 displacing CBM, and the results showed that the CBM flow increased significantly after nitrogen injection. Zhang et al.[65] conducted a hydraulic flushing-enhanced CBM extraction test in the Yangquan mining area. The results showed that after adopting the hydraulic flushing method, the concentration and flow of CBM in the working face increased by 10 and 6 times, respectively.

By normalizing the CBM flow and concentration data obtained from the above field test, the change curve of the increase multiples of CBM concentration and flow rate of different extraction methods can be obtained, as shown in Figures 14 and 15.

Figure 14 shows the change curve of increase multiples of the CBM concentration. Figure 14 shows that, except for the

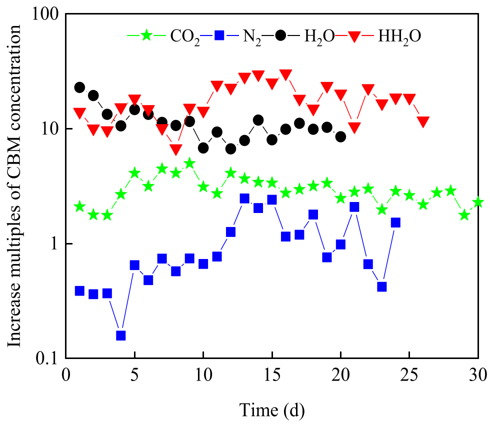

Figure 14. Change curve of the increased multiples of CBM concentration with time.

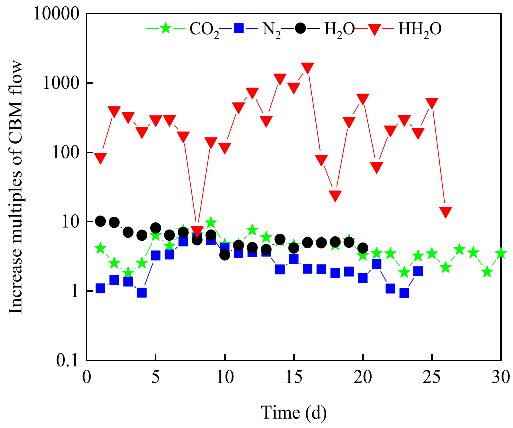

Figure 15. Change curve of the increased multiples of CBM flow rate with time. Note: LCO_2: enhanced CBM extraction method by injecting liquid CO_2; N_2: enhanced CBM extraction method by injecting N_2; H_2O: enhanced CBM extraction method by hydraulic punching; HH_2O: enhanced CBM extraction method by injecting superheated water.

N_2 injection method, the increase multiples of concentration of the other three methods were >1. Moreover, the heat injection method could increase the CBM concentration by more than 10 times. This shows that the heat injection method has the best effect on improving the CBM concentration. Figure 15 shows the change curve of increase multiples of CBM flow. It is obvious that the heat injection method can increase the flow of CBM by 100 times, and the maximum increase multiple is 1716 times. However, the maximum increase multiples of the other three methods were all <10 times. This shows that the heat injection method has the best effect on improving the CBM flow.

According to the principle of heat injection, the heat injection method can not only provide energy for coal seams and promote CBM desorption but also increase the migration speed of CBM and shorten the extraction time of CBM. In summary, by comparing the field test results of different methods, the CBM extraction effect of the heat injection method is the best. The pressure water during the heat injection process will enter the pores and fractures within the coal seam, obstructing the migration channel of CBM and increasing the resistance to CBM migration, thereby inhibiting methane desorption. However, heat injection can enhance methane desorption and alleviate the inhibitory effect of water on methane, thereby increasing the recovery rate of CBM. Therefore, the heat injection method can be the first choice to improve the desorption rate of CBM. Notably, the comparison of different extraction methods is a comparison of extraction effects and should also be comprehensively evaluated from the aspects of economic cost, test safety, and applicability. However, because of the lack of data and the length of the article, there is no comprehensive analysis here, and this is also the focus of the authors' future research to identify a more accurate method for evaluating extraction methods.

7. CONCLUSIONS

According to the geological conditions and characteristics of CBM in the Chengzhuang coal mine in the Yangquan mining area, boreholes were arranged in the 15# coal seam, and a field test was conducted using a self-developed heat injection device to verify the effect of the heat injection method. The main conclusions are as follows:

(1) The theory of heat injection was perfected, and the system and equipment for intermittent heat injection-enhanced CBM extraction were developed. The research results show that when the water injection speed is 0.5 m^3/h, the heat injection temperature is 145 °C, and the number of heat injections is two, which can give full play to the capacity of the heat injection equipment and achieve the goal of rapid, safe, and efficient extraction of CBM.

(2) Field tests have proven that the intermittent heat injection method can improve the desorption rate of CBM and substantially shorten the extraction time. After three cycles of heat injection, the concentration and extraction speed of CBM have been greatly improved; among them, the highest concentration of CBM was 100%, and the maximum daily gas production was increased by 1269 times.

(3) The gas production law of the intermittent heat injection method had obvious stages; that is, the concentration and daily gas production of CBM during the heat injection stage were relatively low; however, during the extraction stage after heat injection, they could be increased by more than 10 and 100 times, respectively. The variation law of cumulative gas production over time can be fitted using Wang's empirical formula.

(4) Compared with the traditional extraction method, the intermittent heat injection method can shorten the extraction time by 6.6 years. Compared with other methods of enhanced CBM extraction, the intermittent heat injection method had obvious technical advantages, and the increased multiples of concentration and flow of CBM were considerably greater than those of other methods.

■ ASSOCIATED CONTENT

Data Availability Statement

Research data are not shared. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Notes

The authors declare no competing financial interest.

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