Study on the Differences between Various Gas Injection Sources in the Process of Coal Seam Methane Replacement by Gas Injection

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ABSTRACT: To study the differences between various gas injection sources in the process of coal seam methane replacement, experimental research was conducted to study the influences of different gas injection sources and gas injection ratios on coal seam methane replacement by considering the strong adsorption gas CO$_2$ and the weak adsorption gas N$_2$. The experimental results show that the temperature rise effect of the CO$_2$ injection gas is greater and lasts longer than that of the N$_2$ injection gas in the process of coal seam methane replacement by gas injection, and the temperature rise can promote the desorption of adsorbed methane well. However, due to the different effects of gas compressibility, the increase in gas pressure caused by injecting N$_2$ under the same conditions is higher than that of CO$_2$; due to the strong adsorption of CO$_2$, the gas pressure after injecting CO$_2$ continues to decrease slowly. From the displacement effect, the adsorbability of the injection source gas has a significant effect on the displacement rate and injection-placement ratio, while the injection ratio has a significant effect on CO$_2$ displacement but not on N$_2$ injection. From the experimental results, for N$_2$ injection, the effects of coal seam methane replacement by gas injection can be enhanced by improving the gas injection method and process; for CO$_2$ injection, the effects of coal seam methane replacement by gas injection can be improved by the following two aspects: gas injection volume and gas injection time.

1. INTRODUCTION

Displacement coalbed methane technology involving gas injection is a technique that involves forcibly injecting N$_2$/CO$_2$ and other injection source gases into the coal seam to improve the exploitation efficiency of coalbed methane and reduce greenhouse gas emissions during coal mining. At the end of the 20th century, the United States injected CO$_2$ into coal seams in the San Juan Basin to improve coalbed methane recovery and achieved success, which displayed the feasibility of utilizing coal seam gas injection to displace methane.$^1$ Afterward, some scholars attempted to apply this technology underground and use it to enhance the drainage of coal seam gas, which also achieved good results.$^2$−$^6$ The occurrence state of gas in coal can be divided into two states: the adsorption state and the free state. The purpose of injecting gas to displace methane in coal seams is to achieve the desorption of adsorbed methane. The mechanism behind gas injection is quite different from that of “water flooding” and “gas flooding” in petroleum systems. To solve this problem, domestic and foreign scholars have carried out much research work. Mazumder$^7$ and Pone$^8$ used CO$_2$, N$_2$, and mixed gas to replace methane in coal, and the influences of the three gases on methane replacement were compared. It was found that pure CO$_2$ gas was better than both mixed gas and N$_2$ gas. Yu$^9$ used eight models, including Langmuir, Freundlich, Langmuir Freundlich, TOTH, extended Langmuir, Brunauer–Emmett–Teller (BET), D-R, D-A, and three curve regression equations to fit the experimental data on CH$_4$ adsorption found by Jincheng and Lu’an in coal. It was found that the more parameters that existed in the model or equation, the higher the fitting degree and the stronger the fitting effect of the D-A model coal adsorption isotherm. Luo$^{10}$ used nuclear magnetic resonance (NMR) to carry out an experiment of replacing methane in coal with strongly and weakly adsorbed gases and found that gas in large pores is easier to replace than in small pores. Liang$^{11}$ performed infiltration and displacement experiments under different stress and temperature conditions using self-developed experimental equipment and found that coal has a strong adsorption capacity for supercritical CO$_2$. Yang$^9$ conducted a simulation experiment involving the use of N$_2$ injections to promote gas drainage in coal seams under the conditions of uniaxial stress and layered precompression. The experimental results showed that the displacement and displacement effects continued throughout the gas injection process, and the gas in the coal body was discharged by the combined effect of
the displacement and N$_2$ injections. To study the adsorption characteristics of coalbed gas containing heavy hydrocarbons, Wang used a self-developed mixed gas adsorption/desorption experimental device to conduct isothermal adsorption tests on CH$_4$−C$_2$H$_6$ binary gases with different composition ratios and found that at the same equilibrium pressure, the adsorption capacities of single component C$_2$H$_6$ coal samples are significantly greater than those of single component CH$_4$ coal samples.

In summary, scholars have performed much research on the modeling, mechanisms, and displacement effects of gas injection for coal seam methane displacement; however, there is little research on both the variation laws of the temperature field and pressure field in coal and the different displacement effects created by different gas injection sources during gas injection-based coal seam methane displacement. The occurrence of gas in coal is dynamic, and adsorption and desorption phenomena constantly exist in coal. From the classical thermodynamic theory, temperature and pressure are the most important factors affecting the occurrence of gas in coal. The increase in temperature and pressure leads to the intensification of the thermal movement of gas molecules, thus increasing the energy of gas molecules required to break free from the constraints of the coal surface. However, the increased movement of gas molecules increases the probability of collision between gas molecules and the coal surface, so the increase in temperature and gas pressure increases the speed of adsorption and desorption simultaneously. However, relatively speaking, the influence of temperature on desorption is far greater than its influence on adsorption, while the influence of pressure on adsorption is far greater than its influence on desorption. Similarly, with decreasing temperature and pressure, the kinetic energy of gas molecules decreases, and the adsorption and desorption rates slow down. Overall, the gas desorption amount increases with increasing temperature, and the gas adsorption amount increases with decreasing temperature. The increase in pressure will lead to an increase in gas adsorption capacity, while the decrease in pressure will lead to a decrease in gas adsorption capacity. Therefore, to study the mechanism of coal seam methane replacement by gas injection, we cannot ignore the change laws of the temperature field and pressure field in coal. Studying the temperature field and pressure field in the process of gas injection is of great significance to the mechanism research and engineering practice concerning the effects of gas injection-based coal seam methane replacement.

2. EXPERIMENTAL DEVICE AND METHOD

2.1. Experimental Device. The multicomponent gas replacement system for coal-containing gas consists of six subsystems: a high-pressure gas supply system, a constant-temperature adsorption and desorption system, a self-storage temperature and pressure sensor system, a gas component analysis system, a vacuum degassing system, and a data acquisition system. The experimental device is shown in Figure 1.

2.2. Experimental Samples. The coal samples in this experiment were taken from the Jiulishan Mine of Henan Energy and Chemical Industry Group Co., Ltd., and the newly exposed lump coal was sealed and brought to the laboratory. According to the measurement method of methane adsorption of coal (high-pressure capacity method) (MT-T 752-1997), industrial analysis method of coal (GB/T212-2008), determination method of true relative density of coal (GB/T217-2008), and determination method of apparent relative density of coal (GB/T 6949-2010), for samples, 60−80 mesh granular pulverized coal must be screened by a standard sieve to eliminate the influence of moisture on the experiment; then, the experimental coal sample is placed in a drying oven, dried at the ambient temperature of 105 °C for over 8 h, and then cooled for later use. The basic parameters of the experimental coal sample are shown in Table 1. Mad refers to the air drying base moisture of coal. Aad refers to the residue left after the coal is completely burned. Vad refers to the product of the liquid (vapor state) and gas

| Mad (%) | Aad (%) | Vad (%) | real density (kg/m$^3$) | apparent relative density (kg/m$^3$) | porosity (%) |
|--------|--------|--------|--------------------------|-------------------------------------|------------|
| 1.01   | 13.32  | 7.95   | 1760                     | 1691                                | 4.06       |

Figure 1. Schematic diagram of the experimental device.
decomposed from the coal after the coal is heated at 900 ± 10 °C for a certain period of time in a container isolated from the air minus its moisture; it is an important index for evaluating coal quality and an important basis for coal classification.

2.3. Experimental Methods. This experiment involves coal seam methane replacement by gas injection under the condition of a high-pressure injection. The experimental scheme is shown in Table 2.

### Table 2. Experimental Parameters of Coal Seam Methane Replacement by Gas Injection

| Name  | Gas injection ratio | CH4 equilibrium pressure (MPa) | CH4 injection quantity (cm^3/g) | Injection quantity of source gas (cm^3/g) | N2 | CO2 |
|-------|---------------------|--------------------------------|---------------------------------|-----------------------------------------|----|-----|
| 1/2   | 0.5                 | 13.38                          | 6.66                            | 6.72                                    |    |     |
| equal |                    |                                |                                 |                                         |    |     |
| 1/2   | 1.0                 | 23.97                          | 12.34                           | 11.65                                   |    |     |
| equal |                    |                                |                                 |                                         |    |     |
| 1/2   | 1.5                 | 29.27                          | 14.57                           | 14.49                                   |    |     |
| equal |                    |                                |                                 |                                         |    |     |

High-pressure injection refers to injecting a certain amount of source gas at a condition higher than the equilibrium pressure after CH4 adsorption equilibrium. The experimental process is shown in Figure 2. According to the experimental conditions in Table 2, first, a certain amount of methane gas is injected into a coal sample chamber filled with coal samples. After the methane adsorption is balanced (the change of gas pressure is less than 0.1 MPa within 8 h), a certain amount of displacement gas is injected into the coal sample chamber through a piston booster pump; after the displacement gas is fully diffused and balanced (the change of gas pressure is less than 0.1 MPa within 8 h), the sample gas is collected. Finally, the free phase volume fraction of each gas is obtained by a chromatographic analyzer, and real-time measurements of the internal temperature and pressure of the coal throughout the gas injection displacement process are monitored by a built-in self-storage temperature and pressure sensor. At the end of the experiment (for example, when the gas adsorption equilibrium is 0.5 MPa), the differences in the temperature field, pressure field, and replacement benefit in coal under different injection source conditions are analyzed.

3. RESULTS

3.1. Temperature Differences during Coal Seam Methane Replacement by Gas Injection. Figure 3 shows the changes in the internal temperature of coal with time during coal seam methane replacement by gas injection. The results from 300 min of N2 gas injection for coalbed methane replacement are displayed in Figure 3. Figure 3a shows that the change in the internal temperature of the coal sample tank underwent approximately three stages: a rapid temperature increase (40 min), a rapid temperature decrease (150 min), and a slow temperature balance (300 min).

At the stage of rapid temperature rise in the coal sample tank, the gas temperature under the #1, #2, #3, #4, #5, and #6 gas injection conditions quickly rose to the peak value over time, and the gas temperature under the #6 gas injection condition was the highest, reaching 31.6 °C, with a temperature change range of 6.6 °C. The #1 gas injection condition had the lowest gas temperature, with a temperature of 25.0 °C and a temperature variation of 4.0 °C. In this gas injection and replacement stage, with the injection of source gas, the pressure of gas entering the coal sample tank decreased sharply, resulting in the Joule–Thomson temperature rise effect. The temperature of the mixed gas in the container rose rapidly.

At the stage of rapid temperature drop in the coal sample tank, the temperature of the mixed gas under gas injection conditions #1, #2, #3, #4, #5, and #6 quickly dropped from the peak state to the range of 28–29 °C, among which the peak temperature of the #6 gas injection condition was the highest, with the largest drop rate reaching 3.1 °C. At this stage, after completing all of the injections of the source gas, the temperature rose to the highest point. Under the influence of the partial pressure effect and temperature rise effect, a large amount of the methane adsorbed in coal began to desorb. Because the desorption process needed to absorb heat, coupled with the heat transfer effect, the temperature began to drop rapidly.

In the slow equilibrium stage of temperature in the coal sample tank, the temperature of the mixed gas gradually recovered to approximately 27 °C under the gas injection conditions #1, #2, #3, #4, #5, and #6, among which the groups that experienced the #3 and #4 conditions had slightly higher
temperatures than the other four groups, which remained at 28 °C. As the system temperature gradually dropped to the ambient temperature, the heat transfer effect began to weaken gradually. At this time, the adsorption/desorption process of both methane and N$_2$ gradually reached a dynamic equilibrium, and the system temperature gradually approached the ambient temperature.

Figure 3b shows the variation law of the internal temperature of coal with time in the process of coalbed methane replacement by CO$_2$ injection. It can be seen from the figure that, similar to the change trend of N$_2$, the change in the internal temperature of coal during CO$_2$ gas injection for 300 min underwent three stages: a rapid temperature increase, a rapid temperature decrease, and a slow temperature decrease until it was the same as the ambient temperature. Compared with N$_2$, when the equilibrium pressure of methane was the same and the injection amount was the same, the temperature increase in CO$_2$ was larger, and the second stage, that is, the rapid temperature drop stage, lasted longer.

Figure 4 shows the relationship between the injection amount of different injection sources and the temperature rise of coal. It can be seen from the figure that with the increase in the injection amount, the temperature rise of coal shows a trend of continuous growth, and the injection amount is in direct proportion to the temperature rise. Under the condition of the same methane equilibrium pressure and a nearly equal injection amount, the temperature rise of CO$_2$ is higher than that of N$_2$. When the methane equilibrium pressure was 0.5 MPa and the gas injection rate was 6.66 (N$_2$)/6.72 (CO$_2$) cm$^3$/g, the temperature rise from the N$_2$ injection was 4.00 °C and that of the CO$_2$ injection was 6.16 °C, indicating that the temperature increase from the CO$_2$ injection was 1.54 times that of the N$_2$ injection. When the methane equilibrium pressure was 1.0 MPa and the gas injection rate was 12.34 (N$_2$)/11.65 (CO$_2$) cm$^3$/g, the temperature rise from the N$_2$ injection was 5.39 °C and that of the CO$_2$ injection was 8.21 °C, indicating that the temperature increase from the CO$_2$ injection was 1.52 times that of the N$_2$ injection. When the methane equilibrium pressure was 1.5 MPa and the gas injection rate was 28.05 (N$_2$)/28.15 (CO$_2$) cm$^3$/g, the temperature rise of the N$_2$ injection was 6.69 °C and that of the CO$_2$ injection was 9.85 °C, indicating that the temperature increase from the CO$_2$ injection was 1.47 times that of the N$_2$ injection.

Figure 5 shows the duration of different stages in the process of replacing coal seam methane with N$_2$ and CO$_2$. It can be seen from the table that the duration of N$_2$ in stage I was longer than that of CO$_2$. Considering that the temperature rise of CO$_2$ was generally 1.4−1.5 times that of N$_2$, it can be inferred that the temperature rise rate of CO$_2$ was much higher than that of N$_2$ in the rapid temperature rise stage of coal seam methane replacement by gas injection. In stage II, that is, during the rapid cooling process, the duration of N$_2$ was shorter than that of CO$_2$ with differences of 44, 54, 52, 100, 52, and 118 min, which was proportional to the gas injection rate. The higher the gas
injection rate was, the longer the duration was generally. In stage III, the duration of $N_2$ was generally longer than that of $CO_2$. From the comparative analysis of the duration of each stage, it can be found that the duration of $N_2$ in stages I and III was longer than that of $CO_2$, but the duration in stage II was shorter than that of $CO_2$. Considering that the temperature of $CO_2$ was generally higher than that of $N_2$ throughout coal seam methane replacement by gas injection, the temperature rise effect of the $CO_2$ injections had a greater impact on the replacement than that of the $N_2$ injections.

According to the temperature change law of coal seam methane replacement by gas injection, $N_2$ and $CO_2$ injections generally experienced three stages: a temperature rapid rise, a temperature rapid drop, and a temperature slow drop until the temperature was the same as the ambient temperature. However, there were two differences between them. First, the temperature rise range was different. Under the same methane equilibrium pressure and the same gas injection rate, the temperature rise resulting from the $CO_2$ injections was obviously higher than that of the $N_2$ injections. The main reason is that the compression coefficient of $CO_2$ is obviously smaller than that of $N_2$, indicating that $CO_2$ is more easily compressed than $N_2$, and gas compression is an exothermic process, so the temperature resulting from $CO_2$ injections is higher than that of $N_2$ injections. Second, $CO_2$ lasts longer in the temperature rapid drop stage than $N_2$. In addition, because the
temperature rise of CO$_2$ is higher than that of N$_2$, it lasts longer when the temperature drop rate is similar, and because CO$_2$ is a strong adsorption gas than N$_2$, its adsorption capacity is larger during gas injection. According to previous research, the adsorption heat of CO$_2$ is higher than that of N$_2$. Because gas adsorption is an exothermic process, stronger adsorption and higher adsorption heat are also some of the reasons for the longer duration of CO$_2$ gas temperature drop. From the experimental results, CO$_2$ injection had a higher temperature rise range and a longer duration than N$_2$ injection, that is, CO$_2$ injection had a more obvious temperature rise effect than N$_2$ injection under the same conditions. Previous studies concluded that CO$_2$ injection had a higher displacement efficiency than N$_2$ injection because the CO$_2$ adsorption was stronger than N$_2$ adsorption. In addition, the higher temperature rise effect of CO$_2$ injection was another contributing factor. As the temperature increases, methane desorption is promoted. Therefore, from the displacement mechanism, the temperature rise effect is one of the reasons why CO$_2$ injection is more efficient than N$_2$ injection.

3.2. Gas Pressure Difference in the Process of Gas Injection Replacing Coal Seam Methane. Figure 6 shows the variation in gas pressure with time during gas injection. It can be seen from the figure that during the 300-min CO$_2$ injection process to replace coalbed methane, the change in gas pressure in coal can be roughly divided into the following three stages: the first stage (corresponding to I in Figure 6) is the rapid rise in gas pressure. In the initial stage of coalbed methane replacement by gas injection, the pressure of the mixed gas in the coalbed rises sharply with a large amount of injected source gas injected into the closed space, which lasts for a short time and ends approximately at the time of the completion of the injection of the source gas. The second stage (corresponding to II in Figure 6) is the rapid drop in gas pressure. As CO$_2$ enters the closed space, a large amount of CO$_2$ starts to compete for the adsorption vacancy in the coal and changes from the free state to the adsorption state, so the gas pressure inside the coal starts to drop rapidly. The third stage (corresponding to III in Figure 6) is the slow drop in gas pressure. As a large amount of CO$_2$ changes from the free state to the adsorbed state, the CO$_2$ component in the mixed gas begins to decline, and the desorption of some of the methane also offsets the pressure drop caused by CO$_2$ adsorption to some extent, so the pressure drop rate of coal gas begins to slow, but the adsorption capacity of CO$_2$ is stronger than that of methane. Therefore, the desorption of methane in a short period of time cannot completely offset the pressure change caused by the adsorption of CO$_2$, so the gas pressure in coal has shown a slow downward trend. Compared with CO$_2$, N$_2$ is not obvious in the rapid decline stage and slow decline stage, with the exception of during the rapid rise stage. In contrast, in the middle and late stages of the process of replacing coal seam methane with N$_2$ under the same conditions, there is a trend of gas pressure rising slowly, as shown in Figure 6b,c, which shows the above characteristics. The main reason for this trend is that N$_2$ is a weaker adsorption gas than methane. Therefore, the adsorption or displacement effect is not obvious, so there is no rapid or slow drop in gas pressure in the late stage of N$_2$ injection.

Figure 7 shows the comparison of the highest pressures of different gas injection sources under the same conditions and the pressures at the end of the 300-min experiment in the process of gas injection-based coal seam methane replacement. It can be seen from the figure that both the maximum pressure during the gas injection and the final pressure after the gas injection of N$_2$ injection are higher than those after CO$_2$ injection. At the same temperature and gas injection rate, the compression coefficient of CO$_2$ is generally smaller than that of N$_2$. This results in the pressure of N$_2$ mixed gas injection being higher than that of CO$_2$. At the end of gas injection, the pressure of N$_2$ mixed gas injection is higher than that of CO$_2$ injection, which is related to the adsorption capacity of different gases in coal. Under the same conditions, the adsorbability of CO$_2$ is much higher than that of N$_2$. At the end of gas injection, coal can absorb more CO$_2$ gas, resulting in a higher pressure of mixed gas injected with N$_2$ than that injected with CO$_2$.

According to the pressure change law in the process of coal seam methane replacement by gas injection, there are two differences between N$_2$ injection and CO$_2$ injection. First, the pressure of N$_2$ injection is higher than that of CO$_2$ injection, and the main reason is the same as the first reason for the temperature rise effect because CO$_2$ is more easily compressed, so the pressure of mixed gas is lower than that of N$_2$ injection. The second difference is that CO$_2$ injection has a stage of rapid pressure decrease and a stage of slow pressure decrease after the pressure increase, while N$_2$ injection does not have these two obvious stages. From the change trend of gas pressure, it can be
seen that CO₂ is more adsorbable than N₂ and the duration of methane replacement is longer. In future research and engineering practice, properly prolonging the duration of CO₂ injection will also help to improve the replacement effect.

4. DISCUSSION

To study the difference in the coal seam methane replacement effect by different gas injection sources, two indices, replacement rates and injection-placement ratios, were selected to measure the replacement effect of gas injection sources. The replacement rate refers to the ratio of methane displaced during gas injection to methane adsorbed in coal before gas injection, which represents the change rate of methane adsorbed in unit volume coal. The injection-placement ratio refers to the ratio of methane gas replacement and injection of source gas after gas injection, which represents the efficiency of methane replacement in coal by source gas per unit volume. The specific calculation formula is as follows:

(1) The volume of methane in the free phase after gas injection \( Q_{f,CH_4} \) is as follows

\[
Q_{f,CH_4} = V_i \times C_{CH_4} = \frac{273.2 \times V_i \times P}{Z \times (273.2 + t) \times 0.101325} \times C_{CH_4}
\]

where \( Q_{f,CH_4} \) is the volume of a component in the free phase at standard temperature and pressure after gas injection, \( cm^3 \); \( V_i \) is the volume of mixed gas under standard temperature and pressure after gas injection, \( cm^3 \); \( C \) is the volume fraction of a component in the free phase after gas injection, \( \% \); \( V_i \) is the standard volume of the remaining space in the coal sample room, \( cm^3 \); \( P \) is the absolute pressure of the coal sample room after gas injection, \( MPa \); \( Z \) is the compression factor of free gas \( i \) under pressure; and \( t \) is the system temperature, \( °C \).

(2) After gas injection, the adsorption amount of methane in coal \( Q_{s,CH_4} \) is as follows

\[
Q_{s,CH_4} = Q_{CH_4} - Q_{f,CH_4}
\]

where \( Q_{s,CH_4} \) is the adsorption amount of methane in coal after replacement, \( cm^3 \); \( Q_{CH_4} \) is the total amount of methane injected, \( cm^3 \).

(3) After gas injection, the displacement of methane \( Q_z \) in coal is as follows

\[
Q_z = Q_{x,0,CH_4} - Q_{s,CH_4}
\]

where \( Q_z \) is the displacement of methane in coal after gas injection, \( cm^3 \); \( Q_{x,0,CH_4} \) is the adsorption amount of methane in coal before gas injection, \( cm^3 \).

(4) The replacement rate \( R_{CH_4} \) is as follows

\[
R_{CH_4} = \frac{Q_z}{Q_{x,0,CH_4}}
\]

(5) The injection-placement ratio \( Q_I \) is as follows

\[
Q_I = Q_z \quad (5)
\]

where \( Q_I \) is the injection gas amount, \( cm^3 \).

Table 3 shows the data of methane displacement, displacement rate, and injection-placement ratio calculated by the above formula.

| Table 3. Table of Gas Displacement Effect of Different Injection Sources |
|----------------|----------------|----------------|----------------|
| condition  | methane displacement (cm³/g) | replacement rate (%) | injection-placement ratio (%) |
| #1  | 1224.8 | 1705.2 | 2.6 | 6.6 | 3.3 | 4.6 |
| #2  | 806.4 | 1920.7 | 3.1 | 6.1 | 4.0 | 8.8 |
| #3  | 1143.0 | 1854.8 | 2.0 | 4.2 | 2.4 | 3.0 |
| #4  | 333.9 | 2928 | 3.7 | 8.6 | 2.7 | 6.1 |
| #5  | 594.2 | 2008.3 | 2.2 | 5.3 | 2.4 | 8.2 |
| #6  | 974.3 | 3388 | 4.0 | 12.5 | 0.9 | 9.2 |

Figure 8 shows the replacement ratio and injection-placement ratio of different injection source gases under 1/2 proportion injection and equal proportion injection. As seen from Figure 8a, the replacement rate shows an overall upward trend with increasing methane adsorption equilibrium pressure. From the comparative analysis of the injection source gas, the replacement rate of the strong adsorption gas CO₂ is obviously higher than that of the weak adsorption gas N₂. The higher the methane adsorption equilibrium pressure, the greater the difference between CO₂ and N₂ in the replacement rate. From the analysis of different injection rates, the replacement rate of the equal injection ratio is obviously higher than that of the 1/2 injection rate when the injection source gas is the same, which indicates that the injection rate of the injection source gas has a great influence on the replacement rate. It can be seen from Figure 8b that, unlike the replacement rate, the injection-placement ratio shows a downward trend with increasing methane adsorption equilibrium pressure; however, with increasing equilibrium pressure, the decline rate gradually slows. From the comparative analysis of the injection source gas, the injection-placement ratio of strong adsorption gas CO₂ is obviously higher than that of weak adsorption gas N₂. According to the analysis of different injection rates, the injection ratio of equal injection rate is higher than that of 1/2 injection rate when the injection source gas is the same, but the two gases are slightly different. The strong adsorbent gas CO₂ is sensitive to the injection volume and injection ratio, and the difference between equal injection rate and 1/2 injection rate is large under the same equilibrium pressure, while the injection volume or injection ratio has little effect on the injection-placement ratio of N₂, which is between equal injection rate and 1/2 injection rate.

The adsorption capacity has a significant effect on the replacement ratio and injection-placement ratio, and the gas injection ratio has a significant effect on the replacement ratio and injection-placement ratio of CO₂ but has little effect on the replacement ratio and injection-placement ratio of N₂. Therefore, considering the engineering practice of injecting gas to displace coalbed methane, when CO₂ is used as the gas injection source, the appropriate increase in the gas injection will have a significant impact on the gas injection displacement effect. However, due to the prominent danger of CO₂ itself, it can also lead to coalbed methane misfire and explosion, so reasonable gas injection rate will be an important research direction in the future. However, when N₂ is used as the gas injection source, because the replacement ratio and injection-placement ratio are not sensitive to the gas injection rate, it will be an important
research topic in the future to improve the gas injection effect by intermittent gas injection and dynamic gas injection.

5. CONCLUSIONS

Through an experimental study, this paper compares and analyzes the differences in the temperature fields, pressure fields, and displacement effects between the strong adsorption gas CO$_2$ and the weak adsorption gas N$_2$ in the process of coal seam methane replacement by gas injection and draws the following conclusions:

(1) Under the same conditions, the temperature rise effect caused by CO$_2$ injection is generally higher than that caused by N$_2$ injection in the process of coalbed methane replacement; the temperature rise lasts longer and can promote methane desorption, so to some extent, the temperature rise effect is one of the mechanisms of coalbed methane replacement by gas injection.

(2) Because different gases have different compressibility values, the pressure of N$_2$ injection is higher than that of CO$_2$ injection under the same gas injection volume. Because CO$_2$ has stronger adsorption capabilities and a longer adsorption duration, there is a long-term gas pressure drop stage in the process of gas injection, which is obviously different from the pressure drop stage of the N$_2$ injection.

(3) From the analysis of the displacement effects, the gas adsorption capacity has a significant influence on the displacement ratio and injection-placement ratio, while the gas injection ratio has a great influence on the displacement effects of CO$_2$ injection but not on the displacement effects of N$_2$ injection.

(4) This paper mainly compares and analyzes the differences between using different gas injection sources for gas injection replacement and discusses the mechanism, effect, and technology of gas injection replacement of coal seam methane.

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K.Z. conceived the experiment, analyzed the results, and drafted the manuscript; H.Y., J.G., and Z.S. coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

Notes
The authors declare no competing financial interest.

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Figure 8. Replacement ratio and injection-placement ratio of different injection source gases under the conditions of 0.5 ratio and equal ratio. (a) Replacement ratio; (b) injection-placement ratio.
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