Different adsorbed gas effects on the reservoir parameters and production in coalbed methane extraction by multibranch horizontal wells

Qixian Li¹,² | Jiang Xu¹,² | Shoujian Peng¹,² | Fazhi Yan¹,² | Chaolin Zhang³ | Ende Han¹,²

¹State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing, China
²State and Local Joint Engineering Laboratory of Methane Drainage in Complex Coal Gas Seam, Chongqing University, Chongqing, China
³Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou, China

Correspondence
Shoujian Peng and Fazhi Yan, State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400030, China. Emails: sjpeng@cqu.edu.cn (S. P.); yfzcumt163.com (F. Y.)

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Abstract
Coalbed methane (CBM) is an efficient energy source that mainly contains CH₄ and CO₂. Multibranch horizontal wells (MBHWs) are widely used in CBM extraction. In the study, CH₄ and CO₂ were employed to perform CBM extraction experiments by MBHWs. Based on the experiments, a phenomenon occurs wherein gas from the high-pressure production layer enters the low-pressure production layer during the initial stage. Reservoir pressure, temperature, permeability, and instantaneous flow rate exhibit similar evolution laws. Specifically, they initially increase sharply, then declining rapidly, and finally level off in the production layer with the minimum initial pressure. Increase in the adsorption capacity lowers the increase in reservoir pressure, although the phenomenon persists longer from appearance to disappearance. The moment of permeability recovery is related to the adsorption capacity, and the moment of permeability recovery under CO₂ conditions occurs after that under CH₄ conditions. The instantaneous flow rate curve is divided into three categories, namely steep flow rate increase curve, flow rate inhibition curve, and backflow curve. The results are useful for CBM extraction of multiple coal seams.

Keywords
coalbed methane, multibranch horizontal wells, multiple coal seams, physical simulation, production, reservoir parameters
Coalbed methane (CBM; also known as coalbed natural gas and coal seam gas) is a type of efficient and clean unconventional natural gas generated and stored in coalbeds. The projected global consumption of natural gas in 2035 will have increased by 25% compared with that of 2010, and natural gas exhibits good consumption prospects. China has the third largest CBM deposits in the world, and its CBM resources buried shallower than 2000 m correspond to 29.8 trillion cubic meters. Therefore, the Chinese government initiated a major superimposed gas systems are formed in the vertical direction. In many coal-bearing basins in China, the gas production from vertical wells is typically poor, and multibranch horizontal wells (MBHWs) are potentially an effective method to achieve high CBM production. For coal-bearing basins with multiple close coal seams, MBHWs are typically used to improve CBM production. In 1999, MBHW technology was first applied in the United States to the development of low-permeability CBM fields. In 2004, after introduction the introduction of MBHW technology in China, many companies, such as the China National Petroleum Corporation and China United Coalbed Methane Corporation, performed experiments in the Qinshui Basin and Hancheng and Baode regions, and a high drilling success rate was attained mainly in the southern part of the Qinshui Basin. Compared with traditional vertical wells, MBHW technology can play an important role in the development of CBM fields by maintaining relatively higher gas production rates, high reserve recoveries, and high economic benefits. Several studies focused on MBHW technology, mainly via numerical simulations and field tests. Ren et al. used field pilot data and indicated that the performance levels of MBHWs are relatively stable when compared with those of most fractured vertical wells. Zhang et al. considered main factors affecting the CBM yield as gas content, drilling footage length, branch distribution, and continuity of the extraction process based on field data from the Fanzhuang region of the Huabei oilfield. Liu et al. constructed a model to predict the pressure decline and the production levels of MBHWs. Fan et al. established a hydraulic-mechanical-thermal coupled model of MBHW extraction. However, many influencing factors were not explored using the approach due to the limitations of numerical simulations such as the simplifications and assumptions in numerical models. Given the limitations of field conditions, field tests typically fail to capture many key parameters and are not always convenient. As a common occurrence in coal resources, CBM mainly consists of a mixture of CH₄ and CBM is a general term for a mixed gas. Specifically, CO₂ is one of the components of CBM, and it is an adsorption gas. Additionally, the adsorption and desorption characteristics of CH₄ and CO₂ are different. Knowledge of the different gas transport properties in coal is important for CBM gas production, and the gas flowing in coal plays an important role in gas production. It is extremely important to investigate gas transport characteristics of different gases for CBM production. Hence, several studies intensively focused on the effects of different adsorptive gases on coal in three aspects: strain, permeability, and temperature. Coal swells with increases in gas adsorption and shrinks with increases in gas desorption, and the strain caused by adsorption or desorption depends on the amount of adsorbed gas or desorbed gas and the sorbed gas composition. The adsorption energy of CO₂ exceeds that of CH₄ and results in a higher adsorption capacity for CO₂ when compared with that of CH₄. The coal strain induced by CO₂ sorption is more severe than that induced by CH₄ sorption, and the strain induced by CO₂ adsorption exceeds that induced by CH₄ adsorption under the same adsorption equilibrium pressure conditions. Coalbeds are generally considered dual-porosity-type reservoirs, and the permeability of a CBM reservoir is a key gas production parameter. Coal swells with increasing adsorption and shrinks with increasing desorption, thereby changing the widths of fractures, and thus, the permeability also changes. The permeability of CH₄ in coal exceeds that of CO₂ at a constant effective stress. The desorption process is an endothermic process, and coal absorbs heat when gas is desorbed and the temperature drops. Conversely, the adsorption process is a heat release process, and the adsorption of different gases onto coal releases different amounts of heat. The heat release in coal during CO₂ adsorption exceeds that during CH₄ adsorption. In the study, we developed a set of physical simulation experimental research methods for CBM extraction of multiple coal seams. Physical simulation tests of CBM extraction of multiple coal seams by two different adsorptive gases (CO₂ and CH₄) were performed. The investigated indexes in the experiments included reservoir pressure, reservoir temperature, permeability, reservoir deformation, wellbore pressure,
and instantaneous flow rate. We examined fluid and reservoir characteristics in the reservoir and fluid characteristics in the branched horizontal wells via two different adsorptive gases in the extraction process.

2 | EXPERIMENTAL METHODS

2.1 | Experimental apparatus

A novel large-scale multifunctional apparatus was adopted to conduct the CBM extraction experiments,35 and the apparatus mainly consisted of the following components: monitoring and control system, reservoir system, and extraction system, as shown in Figure 1. The main features of the apparatus were as follows: the apparatus realized simultaneous extraction or independent extraction experiments of multilayer reservoirs under true triaxial stress loading conditions. The internal dimensions of the coal specimen box corresponded to 1050 mm × 400 mm × 400 mm, which can contain large-scale specimens and avoid boundary effects. There were four loading plates in the vertical and lateral directions of the coal specimen box, and the oil pump provided a maximum force of 1000 kN to the loading plates. The back direction included a loading plate, and the oil pump can provide up to 2000 kN to the pressure plate. The extraction system was mainly composed of four horizontal wells, and the length and inner diameter of a horizontal well corresponded to 330 and 6.4 mm, respectively. The monitoring and control system mainly included a data acquisition system and a servo control system. The frequency of data acquisition is 1 Hz.

2.2 | Experimental scheme

As widely known, CBM is a gas mixture containing more than just CH4. The adsorption and desorption characteristics of coal for different gases are different, and thus, the characteristics of methane mixtures containing different components are not identical. Therefore, two gases (CH4 and CO2) with different adsorption capacities were selected to study their effects on the CBM extraction process. To examine the characteristics of multiple coal seams in the process of CBM extraction and considering the conditions of the equipment, four gas production layers were designed in the experiments. As shown in Figure 2, we designed two physical simulation experiments for multiple coal seams to better understand the CBM extraction process of multiple coal seams. The experimental scheme is summarized in Table 1.

2.3 | Experimental procedure

2.3.1 | Preparation

The briquette specimens used in these experiments are mainly based on two reasons. First, the briquette specimens are similar to raw coal specimens in terms of geomechanical properties and
permeability behavior. Second, the briquette specimens are convenient for laying sensors and extraction pipes, and the briquette specimens exhibit good homogeneity. The molding procedures for the specimens, including lump mud and coal preparation, crushing and sieving work, pulverized mud and coal preparation, drying work, mixing work, and specimen pressing work were conducted in accordance with the scheme shown in Figure 3. The raw coal samples were collected from the Jinjia coalmine (Figure 4), and the mud samples were collected from Gele Mountain, Chongqing, China. Table 2 lists the basic information of the coal samples. The reason that lump coal and lump mud were collected was to produce large-scale specimens containing four independent reservoirs and a mud layer between adjacent reservoirs. The raw coal and mud samples were crushed separately, and specific particle sizes were obtained via sieving (0.000-0.150, 0.150-0.180, 0.180-0.250, and 0.250-0.425 mm). The pulverized mud and coal were dried in a drying oven, and the cooled pulverized coal and mud were separately mixed based on the details listed in Tables 3 and 4, respectively. Subsequently, the mixed powdered coal was used to establish four reservoirs of the same size, and the mixed powdered clay was used to realize a gas and water barrier between adjacent reservoirs. Simultaneously, gas pressure sensors and extraction pipes were arranged at specific positions (Figure 5). Four horizontal wells, namely Nos. 1, 2, 3, and 4, were located in D1, D2, D3, and D4 sections, respectively (Figure 5). The mixed pulverized coal and mud were used to establish the reservoir and mud layers, respectively. The relevant sensors and
extraction pipes are buried based on Figure 5. A molding pressure of 7.5 MPa was applied for 1 hour using a 5000-kN molding machine.

When the briquette specimens were fabricated, the related equipment and piping were connected. The helium is a type of inert gas that cannot be absorbed by coal. After helium is injected into the coal specimen box, the leak detection method using soapy water was used to ensure seal tightness.

2.3.2 | Degassing and gas adsorption

The specimen was degassed to remove air and helium. Based on the geostress conditions, $\sigma_{11} = \sigma_{12} = \sigma_{13} = \sigma_{14}$ corresponding to 5.0 MPa, $\sigma_2$ corresponding to 4.0 MPa, and $\sigma_{31} = \sigma_{32} = \sigma_{33} = \sigma_{34}$ corresponding to 3.0 MPa are gradually loaded onto the loading planes. After degassing and stress loading, gas (CH$_4$ and CO$_2$) was injected into each of the four production layers to a pressure of 1.0 MPa ($P_I$), 1.4 MPa ($P_{II}$), 1.8 MPa ($P_{III}$), and 2.2 MPa ($P_{IV}$) to achieve the adsorption equilibrium state.

2.3.3 | CBM extraction

After the specimens reached the adsorption equilibrium state, the gas outlet control valves of the four gas production layers were simultaneously opened, and the relevant monitoring data were simultaneously recorded.
3.1 Dynamic evolution of the fluid parameters in the reservoirs

To analyze the fluid characteristics during CBM extraction, reservoir pressure and cumulative flow were measured in four production layers. The initial pressures in the first, second, third, and fourth production layers correspond to 1.0, 1.4, 1.8, and 2.2 MPa, respectively. To compare the changes in reservoir pressure over time at the same location in the different production layers, the monitoring points corresponding to P5, P15, P25, and P35 were selected for analysis. The changes in reservoir pressure and cumulative flow over time under adsorptive gas conditions are shown in Figure 6.

As shown in Figure 6A, the pressure decline curves of CH$_4$ and CO$_2$ in the first production layer exhibit a rising stage, and the maximum reservoir pressures of CH$_4$ and CO$_2$ correspond to 1.20 and 1.16 MPa, respectively. The cumulative flow curves of CH$_4$ and CO$_2$ experience periods of negative values, and the maximum negative cumulative flows of CH$_4$ and CO$_2$ correspond to −7.9 and −3.8 L, respectively. During the extraction process of multiple coal seams with the same main well, the pressure-holdup effect occurs in the main well and results in the gas from the high-pressure gas production layer entering the first production layer. The gas that enters the first production layer mainly results in two effects, namely a portion of the gas enters the reservoir fractures as free gas and the other portion of the gas is adsorbed on the coal matrix (adsorbed gas). The adsorption capacity of CH$_4$ is lower than that of CO$_2$, and thus, less CH$_4$ is adsorbed and a larger amount of free CH$_4$ gas occurs in the reservoir fractures. When compared with CO$_2$, the cumulative flow of CH$_4$ into the first production layer is higher. Therefore, the reservoir pressure rise due to CH$_4$ is higher.

As shown in Figure 6B, the reservoir pressure rapidly declined in the initial stage but slowed over time, and the pressure decline rate of CH$_4$ significantly exceeded that of CO$_2$. After 240 minutes, the pressure decline values of CH$_4$ and CO$_2$ correspond to 1.21 and 1.07 MPa, respectively. The change behavior of the cumulative flow curve is similar to that of the reservoir pressure decline curve, and the cumulative flow increase rate of CO$_2$ significantly exceeds that of CH$_4$. After 240 minutes, the cumulative flows of CO$_2$ and CH$_4$ correspond to 235.1 and 153.5 L, respectively.

In Figure 6C,D (1.8 and 2.2 MPa, respectively), the reservoir pressure and cumulative flow curves are similar to the curves in Figure 6B. In the initial stage, a large amount of stored free gas in the pore-fracture system is extracted, and the change in the values of the reservoir pressure and cumulative flow are significant. Over time, the extracted gases are mainly composed of free gases converted from adsorbed gases. The adsorbed gas flow to the producing well requires the following three steps: desorption from the coal matrix surface, diffusion from the pores through the coal matrix to the fracture system, and finally flow to the producing well. When compared with the free gas flowing to the producing well, more steps are required to adsorb gas, thereby resulting in low change rates of the reservoir pressure and cumulative flow in the later stage. In the study, the difference between CH$_4$ and CO$_2$ is that the adsorption capacity of CO$_2$ exceeds that of CH$_4$. The desorption of CO$_2$ from the surface of the coal matrix requires more energy. Under the same coal volume and adsorption equilibrium pressure conditions, the amount of CO$_2$ adsorbed exceeds that of CH$_4$. Therefore, the pressure decline rate of CO$_2$ is lower than that of CH$_4$, and more CO$_2$ is extracted at the same time.

To more vividly display the migration laws of the different adsorptive gases in the reservoir, the data measured in sections D1, D2, D3, and D4 are selected for the four production layers, and the quiver function in MATLAB is used to draw gas migration maps. Zhang et al. fully described the specific calculation methods and interpolation principle, and it is used to draw the gas pressure field. The different colors along the graduated color contours denote the reservoir pressure classification ranges in isobars, and the directions of the arrows denote gas migration directions while the lengths of the arrows denote relative gas migration velocities.
Figure 7A,C show the gas migration maps of CO₂ and CH₄, respectively, in the first production layer at 1 minute. The directions of the arrows are toward the reservoir boundaries, and the lengths of the arrows near the extraction pipes exceed those in the other zones, thereby indicating that gas migrates from the extraction pipe to the reservoir near the extraction pipe. Increases in the gas migration velocity cause gas flow from the high-pressure production layer to increase and enter the first production layer. The shapes of the isobars near the extraction pipe are elliptical. As the isobars come closer to the extraction pipe, they exhibit higher density. The results indicate that the reservoir pressure field is symmetrically distributed and that the reservoir pressure gradient is high close to the extraction pipe. The length of the extraction pipe (160 mm) is not equal to its inner diameter (6.4 mm), and thus, the shape of the isobaric line is elliptical as opposed to circular.¹⁵

Figure 7B,D show the gas migration maps of CO₂ and CH₄, respectively, in the first production layer at 3 minutes. As shown in Figure 7D, the arrows are directed toward the extraction pipe as opposed to toward the reservoir boundaries, thereby indicating that gas migrates from the reservoir to the extraction pipe. The difference between the CO₂ and CH₄ conditions is that the arrow directions are different at 3 minutes. The result indicates that the time required in the CO₂ and CH₄ experiments for the gas migration direction to change from flowing toward the reservoir boundaries to flowing toward the extraction pipe exceed 3 minutes (in both cases). The adsorption capacity of CH₄ is lower than that of CO₂, and thus, less energy is required for CH₄ desorption.

Figure 8A,B,C,D show the gas migration maps of CO₂ and CH₄ in the fourth production layer at 1 and 3 minutes. Irrespective of the type of gas or the time, the directions of all arrows are toward the extraction pipe. The difference between the first and fourth production layers corresponds to the gas migration direction. The result demonstrates that gas does not migrate from the low-pressure production layer into the fourth production layer (high-pressure production layer). The minimum pressure decreases in the fourth production layer at 1 and 3 minutes for CO₂ corresponding to 0.15 and 0.40 MPa, respectively, and those for CH₄ correspond to 0.40 and 0.80 MPa, respectively. The results indicate that the pressure decline rate of CO₂ is lower than that of CH₄. The amount of CH₄ adsorbed is lower under the same reservoir pressure and reservoir volume conditions. Conversely, the desorption of CH₄ requires less energy than that of CO₂. Therefore, the pressure decline rate of CH₄ exceeds that of CO₂ at the same time.

### 3.2 Dynamic evolution of the reservoir parameters in reservoirs

To analyze the dynamic evolution laws of the reservoir temperature of the two different adsorptive gases during CBM extraction of multiple coal seams, the reservoir temperature and pressure were measured in the four production layers. To compare the changes in reservoir temperature over time in the different production layers, the

#### TABLE 4 Proportioning scheme of the pulverized mud

| Particle size (mm) | 0-0.425 mm | Plaster | Emulsion |
|-------------------|------------|---------|----------|
| Mass ratio (%)    | 90.2       | 6.8     | 3.0      |

![FIGURE 5 Internal layout of the coal specimen box: (A) Production and mud layer arrangement; (B) The spatial distribution of the sensors](image-url)
monitoring points corresponding to T1, T2, T3, and T4 were selected for analysis, and ΔT1, ΔT2, ΔT3, and ΔT4 correspond to the temperature changes of T1, T2, T3, and T4, respectively.

Figure 9A clearly shows that the temperature change curves of CH4 and CO2 exhibit upward trends in the initial stage, and the maximum change values of CH4 and CO2 correspond to 0.50 and 0.41°C, respectively. The reason for the phenomenon is that the high-pressure gas from the high-pressure production layer enters the low-pressure production layer (first production layer). When high-pressure gas enters a reservoir, the gas in the reservoir undergoes compression. The expansion process is an exothermic process, and thus, the reservoir temperature increases in this stage. Another reason is that the free gas from the high-pressure reservoir begins to be adsorbed, which releases heat.

As shown in Figure 9D, the temperature decline rate of CO2 significantly exceeds that of CH4, and the final decline values of CO2 and CH4 correspond to −6.58 and −3.36°C, respectively. Figure 9B,C exhibit the same behaviors as that of Figure 9D, and the discussion is not repeated. The reason for the phenomenon is that the desorption process of adsorbed gas is an endothermic process, which causes the temperature of the coalbed to decrease, and CH4 desorption requires less energy than CO2 desorption.25 The law of the temperature drop is similar to that of the reservoir pressure decline. Over time, the rate of temperature decrease slows down. In the initial stage, a large amount of free gas is rapidly produced from the reservoir, and the gas that remains in the reservoir is considered to undergo expansion.44 It is commonly accepted that the expansion process is an endothermic process, and thus, the reservoir temperature decreases rapidly in this stage. With the declining rate of the reservoir pressure slowing down, the adsorbed gas begins to be desorbed. The main reason for the drop in reservoir temperature is also the desorption effect although the rate of temperature decrease

**FIGURE 6** Changes in the reservoir pressure and cumulative flow with time for the different adsorptive gases (during 240 min): (A) 1.0 MPa initial pressure in the first production layer; (B) 1.4 MPa initial pressure in the second production layer; (C) 1.8 MPa initial pressure in the third production layer; and (D) 2.2 MPa initial pressure in the fourth production layer.
caused by the gas expansion effect exceeds that caused by the desorption effect. With decreases in the gas desorption rate, the rate of temperature decrease also decreases.

Coal permeability plays a decisive role in CBM drainage. During CBM drainage, the desorption effect is considered to enlarge the fractures and pores in the coal, thereby resulting in an increase in the permeability, and the desorption process is an endothermic process. The permeability decreases due to the closure of cleats and pores under the effect of the effective stress, and the strain increases. Therefore, the laws of reservoir deformation and temperature change can characterize the changes in permeability. Deformation values were obtained from the displacement sensors, and the volumetric strain is calculated as being equal to the sum of the strains in the X, Y, and Z directions (Figure 1). The dimensionless permeability $k/k_0$ is calculated using Equation 1, and the aforementioned parameters are listed in Table 5. Equation 1 is applied to analyze the evolution law of reconstructed coal permeability, and this proves the model's effectiveness for reconstructed coal specimen.

$$
\frac{k}{k_0} = \exp \left\{ -3C_f \left( 1 - \frac{p}{p_0} \right) + f \left( \frac{E}{3(1-2v)} \right) \left( \frac{\epsilon_{\text{max}}^m}{p} \right) \right\}
$$

where $k$ denotes the permeability; $C_f$ denotes the fracture compressibility, MPa$^{-1}$; $\sigma$ denotes the mean stress; $\sigma_0$ denotes the initial mean stress; $p$ denotes the reservoir pressure; $f$ denotes the internal swelling (shrinking) partition, which ranges from 0 to 1; $E$ is Young's modulus, MPa; $v$ is Poisson's ratio; $\epsilon_{\text{max}}^m$ denotes the maximum matrix sorption-induced

**Figure 7** Gas migration maps at different points in time: (A) first production layer under CO$_2$ conditions at 1 min; (B) first production layer under CO$_2$ conditions at 9 min; (C) first production layer under CH$_4$ conditions at 1 min; and (D) first production layer under CH$_4$ conditions at 3 min
strain; \( p_e \) denotes the Langmuir-type matrix sorption strain constant; and subscript 0 refers to the initial parameter values. The aforementioned parameters that are shown in Table 5 are obtained from basic experiments.

Figure 10 shows the evolution laws of the dimensionless permeability, temperature, and volumetric strain with time. As shown in Figure 10A,B, dimensionless permeability rapidly increases at the moment of extraction, and the maximum values of the dimensionless permeability of \( \text{CO}_2 \) and \( \text{CH}_4 \) correspond to 1.039 and 1.029, respectively. The main reason for the rapid increase in the dimensionless permeability is that the coal of the first production layer is compressed by the high-pressure gas from the high-pressure production layer. In the initial stage, the dimensionless permeability of \( \text{CO}_2 \) and \( \text{CH}_4 \) decreased rapidly and those of \( \text{CO}_2 \) and \( \text{CH}_4 \) decreased to approximately 0.942 at 140 and 45 minutes, respectively. The main reason for the rapid decrease in dimensionless permeability in the initial stage is the rapid increase in the effective stress caused by the rapid extraction of gas, and the rapid increase in effective stress causes a rapid increase in the reservoir volumetric strain as verified by the curves of the volumetric strain in Figure 10A,B. The rapid drop in temperature is caused by the gas expansion effect. Subsequently, the dimensionless permeability began to recover, and those of \( \text{CO}_2 \) and \( \text{CH}_4 \) increased to approximately 0.943 and 0.948 at 240 minutes, respectively. The phenomenon occurs because the matrix shrinkage effect caused by the desorption effect plays a leading role in changing the permeability. A comparison of the time points when the dimensionless permeability of

FIGURE 8  Gas migration maps at different points in time: (A) fourth production layer under \( \text{CO}_2 \) conditions at 1 min; (B) fourth production layer under \( \text{CO}_2 \) conditions at 3 min; (C) fourth production layer under \( \text{CH}_4 \) conditions at 1 min; and (D) fourth production layer under \( \text{CH}_4 \) conditions at 3 min
CO\textsubscript{2} and CH\textsubscript{4} began to recover indicates that the time point of CH\textsubscript{4} occurred much earlier than that of CO\textsubscript{2}. The adsorption capacity of CH\textsubscript{4} is lower, and methane is more easily desorbed when compared with carbon dioxide. Therefore, the phenomenon of permeability recovery is caused by the matrix shrinkage effect of CH\textsubscript{4} that occurs earlier.

Figure 10A,C show that the minimum dimensionless permeability of the first production layer (1.0 MPa) and fourth production layer (2.2 MPa) correspond to 0.942 and 0.685, respectively. In the initial stage, the increase in the initial reservoir pressure makes the effective stress more distinct, thereby leading to a more significant decrease in permeability. This situation implies that increases in the initial reservoir pressure further decreases permeability.

### 3.3 Dynamic evolution of the fluid parameters in the branched horizontal wells

The gas pressure in branched horizontal well No. 1 (i.e., No. 2, No. 3, No. 4, and No. 5) is shown in Figure 11. The gas produced in the four production layers converges into the main well through the MBHWs, and the pressure in each branch horizontal well increases.

Figure 11A shows the pressures in the No. 1 branched horizontal well for the two gases. For the two gases, it is observed that the pressure exhibits a rise phase. The pressure in the No. 2 branched horizontal wells does not exhibit

| Parameters                          | Value | Table 5 | Experimental parameters\textsuperscript{22} |
|-------------------------------------|-------|---------|---------------------------------------------|
| Young’s modulus ($E$) (MPa)         | 292   |         |                                             |
| Poisson’s ratio ($\nu$)             | 0.158 |         |                                             |
| Fracture compressibility ($C_f$) (MPa$^{-1}$) | 0.19126 |         |                                             |
| Maximum matrix sorption-induced strain ($\varepsilon_{\text{max}}$) | 0.05187 |         |                                             |
| Langmuir-type matrix sorption strain constant ($\mu$) (MPa) | 2.913 |         |                                             |
| Internal swelling partition ($f$)   | 0.5   |         |                                             |
FIGURE 10  Changes in the dimensionless permeability, volumetric strain, and temperature with time for the different adsorptive gases (during 240 min): (A) First production layer under CH$_4$ conditions; (B) First production layer under CO$_2$ conditions; (C) Fourth production layer under CH$_4$ conditions; and (D) Fourth production layer under CO$_2$ conditions
an evident rise phase as shown in Figure 11B. Under CH$_4$ conditions, the pressures in the No. 1 and No. 2 branched horizontal wells increase to their maximum values at 0.03 minute and correspond to 1.45 MPa. Under CO$_2$ conditions, pressures in the No. 1 and No. 2 branched horizontal wells increase to their maximum values at 0.05 minute and correspond to 1.45 MPa. Figure 11C, D show the gas pressures in the No. 3 and No. 4 branched horizontal wells, respectively, and both appear to exhibit a rapid decline in the gas pressure. Under CH$_4$ conditions, the No. 3 and No. 4 branched horizontal well gas pressures decrease to 1.45 MPa at 0.03 minute. Under CO$_2$ conditions, the No. 3 and No. 4 branched horizontal well gas pressures decrease to 1.45 MPa at 0.03 minute.

The gas flows produced in all production layers are unable to rapidly pass through the main well, and the pressure-holdup effect occurs. The phenomena indicate that the maximum pressure of CO$_2$ and CH$_4$ in the main well is
approximately 1.45 MPa in the main wellbore at 0.03 and 0.05 minute, respectively, under the gas confluence conditions of the four multibranched horizontal wells. Therefore, the reason for the pressure rises observed in the No. 1 and No. 2 branched horizontal wells is that the high-pressure gas from the high-production layer enters the No. 1 and No. 2 branched horizontal wells. However, the pressure increase observed in the No. 2 branched horizontal well is lower than the initial pressure (1.40 MP) of the second production layer. The main reason is the inhibition of gas production from the high-pressure production to the low-pressure production layer. When the pressures of No. 3 and No. 4 branched horizontal wells decrease to the maximum pressure in the main well, the pressure-holdup effect disappeared, and the gas pressure begins to drop rapidly.

Figure 12A shows that the instantaneous flow rate of the No. 1 branched horizontal well increases from a negative value. Thus, the phenomenon of high-pressure gas from the high-pressure production layer entering the first production layer occurs. Under CO₂ and CH₄ conditions, the maximum instantaneous flow rate of the gas entering the first production layer corresponds to 3.9 and 12.8 L/min, respectively. Thereafter, the instantaneous flow rate of the gas entering the first production layer gradually decreases and reaches 0 L/min at 3.6 and 3.4 minutes, respectively. The result also indicates that the phenomenon of gas entering the first production layer has ended and No. 1 branched horizontal well begins to produce gas. The instantaneous flow rate of CO₂ and CH₄ reaches 1.9 and 1.8 L/min, respectively, at 18.2 and 10.9 minutes, respectively, and then slowly decreases.

As shown in Figure 12B, under CH₄ conditions, the phenomenon of gas entering the second production layer also occurs for the No. 2 branched horizontal well, maximum instantaneous flow rate of the gas entering the second production layer corresponds to 2.3 L/min, and gas production begins at 0.20 minute. Under CO₂ conditions, the phenomenon of gas entering the second production layer does not occur. Conversely, under CO₂ and CH₄ conditions, the instantaneous flow rates reach their maximum values at 0.4 and 0.8 minute, respectively, and correspond to 3.5 and 5.9 L/min, respectively. However, the time when the gas enters the second production layer occurs later and the instantaneous flow rate is relatively low, which is mainly manifested in the inhibition of the initial instantaneous flow rate. The result indicates that decreases in the initial gas pressure of the production layer increase the maximum instantaneous flow rate of the gas entering the low-pressure production layer. Figure 12C,D show that the instantaneous flow rate evolution laws of the No. 3 and No. 4 branched horizontal wells, respectively, are essentially identical. Thus, the instantaneous flow rate corresponds to the highest at the moment of extraction and then decreases slowly. Under CO₂ and CH₄ conditions, the maximum instantaneous flow rates of the No. 3 branched horizontal well correspond to 10.7 and 19.1 L/min, respectively, while those of the No. 4 branched horizontal wells correspond to 21.9 and 43.0 L/min, respectively. The results indicate that increase in the initial gas pressure of the production layer increase the maximum instantaneous flow rate of the production layer. The instantaneous flow rate curve is divided into three categories, namely steep gas flow rate increase curve (eg, curves No. 4-CO₂ and No. 4-CH₄), gas flow rate inhibition curve (eg, curves No. 2-CO₂ and No. 2-CH₄), and gas backflow curve (eg, curves No. 1-CO₂ and No. 1-CH₄).

4 | CONCLUSIONS

In the study, large-scale physical CBM extraction experiments were conducted to examine the dynamic evolution of fluid and reservoir parameters. Experiments with two adsorptive gases are conducted. Based on the results of the study, the following conclusions are obtained:

1. In the initial stage of CBM extraction, gas from the high-pressure production layer enters the low-pressure production layer, thereby rapidly increasing the reservoir pressure in the production layer with minimum initial reservoir pressure within a short time. Increases in the adsorption capacity lower the increase in reservoir pressure albeit increasing the duration that the phenomenon persists from appearance to disappearance. During CBM extraction, the pressure decline rate of CO₂ is significantly lower than that of CH₄.

2. The evolution laws of the reservoir temperature and permeability are similar to that of the reservoir pressure, which tend to increase in the initial stage. Increases in the initial reservoir lead to higher decreases in reservoir temperature and increases in reservoir deformation. The largest differences in the reservoir parameters between CO₂ and CH₄ adsorption correspond to the magnitude of the temperature drop and moment of permeability recovery. Under CO₂ conditions, the rates of the reservoir temperature decrease and the reservoir deformation increase exceed those under CH₄ conditions. The moment of permeability recovery is related to the adsorption capacity, and the moment of permeability recovery under CO₂ conditions occurs later than under CH₄ conditions.

3. The pressure-holdup effect occurs in the initial stage of CBM extraction. The gas pressure laws in the branched horizontal wells are similar to that of the reservoir pressure although the branched horizontal well with the second lowest initial pressure also experiences a small pressure increase. The instantaneous flow rate curve is divided into three categories: a steep gas flow rate increase curve, a gas flow rate inhibition curve, and a gas backflow curve. Decreases in the initial reservoir pressure of the production layer increase the maximum
instantaneous flow rate of the gas entering the low-pressure production layer.

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ORCID
Qixian Li https://orcid.org/0000-0002-9046-1593
Shoujian Peng https://orcid.org/0000-0002-1801-4246

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