A Study on Three-Phase Gas Content in Coal Reservoirs and Coalbed Methane-Water Differential Distribution in the Western Fukang Mining Area, Xinjiang, China

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ABSTRACT: The daily gas production of a single well (coalbed methane (CBM) vertical well) in the western Fukang mining area in the southern margin of the Junggar Basin, Xinjiang, China is relatively high. However, there are significant differences between gas and water production of CBM wells at different locations in the area, and the reason has not been adequately explained. To explore the distribution characteristic of coalbed methane and water in the Fukang mining area, the three-phase CBM gas (adsorption gas, free gas, and water-soluble gas) content was determined based on theoretical analysis and simulation. Combining the calculation results and the basis of geological data, the CBM-water differential distribution in the study area was discussed. The results show that the average daily water production and average daily gas production of CBM wells show a negative correlation in the study area. The CBM wells with high daily gas production are mainly located in the high areas of the structure, and these wells commonly begin to produce gas within a short period. The calculation of three-phase CBM gas content and the test results of gas composition show that the gas content (especially the free gas) is relatively high in the high areas of the structure, while the concentration of C2H6 is relatively low. Meanwhile, the concentration of C2H6 shows a positive correlation with buried depth, which indicates that CBM migrates from the deep areas to the higher areas. The calculation of equivalent water level elevation and hydraulic head shows that the groundwater mainly flows from the central part to the east and the west within the CBM well areas, and the groundwater flows downward along the coal seam controlled by gravity, which results in the CBM-water differential distribution. The CBM-water differential distribution in the western Fukang mining area is the result of coupling control of tectonic and hydrological geology factors. Multistage tectonic movements formed large-scale folds and faults in the area, which controlled the migration direction of CBM and groundwater. The dip angle of the stratum in the study area is commonly greater than 45°, and the gravity effect is greater in the process of groundwater flow, which promotes the CBM-water differential distribution. Free gas migrates to the high area of the structure, and groundwater accumulates in the axial part of the syncline. The results in this study provide a basis for the large-dip angle CBM exploration and development in the Fukang mining area.

1. INTRODUCTION

Xinjiang is an area rich in coalbed methane (CBM), accounting for about 26% of China’s CBM resources. The amount of CBM (burial depth is less than 2000 m) is 95,100 × 10⁸ m³.1−3 In the 13th five-year plan for coalbed methane development and utilization issued by the National Energy Administration of China in 2016, it is pointed out that the southern margin of the Junggar Basin will be taken as a new industrialization base for CBM development during the 13th five-year plan period.4 In recent years, CBM in Xinjiang has developed rapidly, among which the Fukang mining area can be a typical representative. The annual gas production in the Fukang mining area reaches 100 million m³ at present. The highest daily gas production of the well CSD01 was 17,125 m³, which was first put into production in 2012. Also, the average daily gas production for three consecutive years is approximately 10,000 m³ (the average daily gas production for a single well in China during the same period is 770 m³), which sets the highest gas production for the CBM vertical wells in China. At present, the daily gas production of this well is maintained at approximately 3000 m³. Moreover, the
The maximum daily gas production of another vertical well CS11-X1 is 21,852 m³, which was put into production in January 2015. The cumulative gas production in the first year of this well is approximately $163.2 \times 10^4$ m³, and the average daily gas production after three years can still reach approximately 6000 m³. The excellent gas production of wells shows the development potential of CBM in the Fukang mining area. With the development of CBM, scholars have carried out a number of relevant studies in recent years focusing on four aspects in the Fukang mining area, including geological background, reservoir characteristics, accumulation mode, and engineering development. For example, Fu et al. (2017) discussed the controlling effect of tectonics, deposition, and hydrogeology on CBM accumulation in the Xishanyao Formation in the south of the Junggar Basin and believed that the axial part of the syncline with stress concentration was the main CBM enrichment area. Li et al. (2017) put forward four models of CBM accumulation in the west of the Fukang mining area based on factors such as the depth of a coal seam, hydrogeology, and origin of CBM. Hou et al. (2020) quantitatively characterized the pore characteristics of coal reservoirs in the south of the Junggar Basin based on the results of high-pressure mercury injection, low-temperature liquid nitrogen adsorption, scanning electron microscopy, and low-field nuclear magnetic resonance. They also discussed the control effect of coal quality on pore structure by combining the results of proximate analysis and other tests. However, research on CBM in the Fukang mining area is still in the development stage, and several scientific problems still need to be clarified. For example, some scholars found that the water and gas productions of CBM wells at different locations in the western Fukang mining area have significant differences, and there were obvious areas with high gas production-low water production and low gas production-high water production. At present, such differences have not been adequately explained.

CBM accumulation is a macroscopic dynamic geological process, and the migration of CBM controlled by geological conditions runs through the whole process. Due to the great difference in physical properties between natural gas and water, as well as the influence of geological conditions, the migration rate and direction of gas and water may be greatly different in the process of fluid migration, which leads to gas-water differential distribution. It is believed that gas-water differential distribution in reservoirs is controlled by two mechanisms. The first mechanism is gravity. The gas floats...
above water because the density of natural gas is less than that of water, eventually forming “the upper part is gas and the lower part is water”. The second mechanism is the opposite, which is commonly found in the deep basin or central basin gas reservoirs. The mechanism is that during the formation of a tight reservoir, the reservoir is adjacent to the hydrocarbon source rock. In the process of hydrocarbon generation, a large amount of natural gas discharged from the source rock pushes up the movable water in the reservoir like a piston and finally forms the macroscopic inversion of “the upper part is water and the lower part is gas”. 17,18 On the other hand, controlled by multistage tectonic movements, the dip angle of coal reservoirs in the Junggar Basin is commonly between 50 and 90°. 10,19,20 The reservoir conditions, preservation conditions, and fluid distribution characteristics of large-dip angle coal seams are different from those of low-angle or horizontal coal seams. He et al. (2018) believed that the gas-water differential distribution was more obvious in the vertical direction of large-dip angle coal reservoirs. The closer to the upper part of the coal reservoirs is, the higher the free gas content is. 21 Therefore, one of the possible reasons for the difference between CBM and water production at different locations in the west of the Fukang mining area is the difference between CBM and water migration direction, which leads to the difference between the enrichment areas of gas and water. It is of great significance to deeply discuss the gas-water differential distribution and its mechanism in the study area.

In this study, based on the basic geological data and CBM well production data in the west of the Fukang mining area, the three-phase gas content of the coal reservoirs was determined by combining experiments and numerical simulation. Combined with the results of gas composition, the distribution characteristic of CBM and water in the study area were analyzed. The gas-water differential distribution and its control mechanism were discussed to provide a basis for the exploration and development of CBM for the large-dip angle coal reservoirs in the study area.

2. GEOLOGICAL BACKGROUND

The Fukang mining area is located in the west of the Junggar Basin in China, at the northern foot of the eastern Tianshan mountains. Due to the nappe action of the Bogda anticline in the south, the structure in the study area is relatively complex, and regional folds and faults are developed. The dip angle of the two flanks of the fold varies greatly. The length of the axial part is more than 10 km, and the width is 2–3 km. The anticline and syncline at the top of the arc are often reversed, and the axial part is often damaged by faults. The representative folds in the area are the Fukang syncline, the south Fukang syncline, and the south Fukang anticline. The Fukang syncline is an asymmetrical syncline that opens to the west and plunges, and the eastern part is the rising end; the dip angle in some areas is up to 60°. The faults are mostly high-angle thrust faults and small interlayer faults. For example, the Shuimohe-Lijiazhuang fault is a long-term active reverse fault with a northerly convex arc on the plane. The south Chigang fault is located in the south of the mining area (Figure 1a).

The coal-bearing strata in the study area are mainly the Xishanyao Formation of middle Jurassic (J2x) and the Badaowan Formation of lower Jurassic (J1b). The average thickness of the Badaowan Formation is approximately 940.54 m. There are 45 coal seams with a thickness greater than 0.30 m in the formation, among which the 14-15 coal is the main target seam for CBM production, and the average total thickness of coal seams is about 68.48 m (Figure 1c). There are several rivers with large extensions in the area, such as the Shuimo river, the Sangong river, and the Sigong river. The CBM wells are mainly located within the Fukang syncline. From the axial part of the Fukang syncline to the flanks, there are six well groups, which are CS5, CS16, CS8, CS15, CS13, and CS11 (Figure 1b). The depth of the coal seam decreases gradually from the axial part to the flanks due to the influence of the rising end.

3. METHODS

3.1. Experiments. In this study, the coal samples in the study area were tested for gas content and coal quality, and the water samples were tested for salinity. The gas content was tested by the United States Bureau of Mine (USBM) method. The coal core was taken out and put into the desorption tank, and the volume of desorbed gas was recorded. Meanwhile, the desorption gas was collected using cylinders (the gas components were tested by gas chromatography according to the national standard of China GB/T 13610-2003). When the average daily gas desorption volume was no more than five cm³ for three consecutive days, the desorption measurement was completed. After desorption, the coal sample was taken out to determine the volume of residual gas. Three groups of the desorption samples with a mass of not less than 100 g were selected and placed into a grinding tank. Then, the samples were crushed by a grinding machine, and the grinding time was no less than five minutes. The grinding tank was connected to the gas metering device, and the gas volume was recorded periodically. The residual gas content is obtained by the average value of the results of three groups of samples. The lost gas was estimated by the direct method. In the initial stage of desorption, the gas volume correlates positively with the square root of time. Therefore, the cumulative gas volume under the standard state is used as the ordinate and the square root of the sum of the lost time and desorption time is the abscissa. The desorption data measured within 1 h were fitted linearly, and the intercept of the fitted line in the vertical axis was the lost gas content. The gas content was finally obtained by adding the lost gas, desorption gas, and residual gas. After gas content testing, the coal cores were sealed with a plastic wrap and brought back to the laboratory after being taken from the mining site; then, relevant experiments were carried out. According to the standard ISO 7404-5:2009, the maceral composition was measured. Proximate analysis was conducted according to the standard ISO 17246-2010. The density was tested according to the standard of China GB/T 23561.2-2009. The samples were crushed into centimeter-sized pieces, and the final density was the average of three tests. Isothermal adsorption was carried out according to the standard of China GB/T 19560-2008. The test was conducted with 60–80 mesh powder samples. The test gas was methane, and the maximum pressure was 8 MPa. The maximum adsorption capacity (Vₐ) and Langmuir pressure (pₐ) were calculated by the Langmuir model. The salinity of water collected from CBM wells was tested according to the standard of China SY/T5523-2006.

3.2. Numerical Simulation.

(1) Calculation of free gas
The test results of free gas content have a large error due to the lack of pressure-retaining coring in the study area. Therefore, numerical simulation was used to characterize the free gas content in this study. At present, the calculation model of free gas content in CBM is reliable. In this study, the free gas content was first calculated based on the gas state equation. When the gas density is obtained under different temperature and pressure conditions, the free gas volume at the standard state can be calculated by formula 1.

\[
V_{\text{free}} = 22.4 \times 10^3 \frac{\rho_{\text{CH}_4} (\phi_{\text{f}})}{M_{\text{CH}_4}}
\]

where \(V_{\text{free}}\) is the free gas content (\(\text{cm}^3/\text{g}\)), \(\rho_{\text{CH}_4}\) is the density of methane (\(\text{t}/\text{m}^3\)), \(\phi_{\text{f}}\) is the porosity not occupied by water (%), \(M_{\text{CH}_4}\) is the molecular weight of methane (\(\text{g}/\text{mol}\)), and \(\rho_{\text{coal}}\) is the density of coal (\(\text{t}/\text{m}^3\)).

The methane density can be calculated based on formula 2.

\[
P V = nRT
\]

where \(P\) is the gas pressure (MPa), \(V\) is the volume of gas (\(\text{cm}^3\)), \(n\) is the amount of the substance (mol), \(R\) is the gas constant (\(\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}\)), and \(T\) is the reservoir temperature (K).

In formula 1, the reservoir temperature is calculated based on well testing in the study area (injection-pressure drop method) (Table 1). The well testing results of six CBM wells show that the coal reservoir temperature correlates positively with the buried depth, and the correlation coefficient of the linear fitting is 0.8936 (Figure 2a). For different CBM wells, the reservoir temperature is calculated based on the fitting formula using the buried depth at the midpoint of the 14-15 coal. Similarly, the measured gas pressure (Table 2) in the study area shows that the gas pressure is positively correlated with the buried depth, and the correlation coefficient of the linear fitting is 0.9577 (Figure 2b). The gas pressure is calculated based on the fitting formula using the buried depth at the midpoint of the 14-15 coal. When \(n = 1 \text{ mol}\), the methane volume can be calculated from the temperature and pressure, and the corresponding methane density can be obtained from formula 3.

\[
\rho_{\text{CH}_4} = \frac{M_{\text{CH}_4}}{V}
\]

Moreover, to verify the reliability of the calculation results, the free gas content is also calculated based on the Mariotte law, which is more commonly used for calculation. The Mariotte law reduces the large errors caused by the fact that the volume of gas molecules and the forces between molecules are not taken into account in the ideal gas state equation, which can be expressed as follows

\[
V_s = \frac{\phi_{\text{f}} P T_0}{P_0 T Z}
\]

where \(V_s\) is the free gas content (\(\text{m}^3/\text{t}\)), \(\phi_{\text{f}}\) is the residual pore volume (\(\text{m}^3/\text{t}\)), \(P_s\) is the pressure (MPa), \(Z\) is the compression factor (dimensionless), \(T\) is the reservoir temperature (K), and \(P_0\) and \(T_0\) are the pressure and temperature under standard conditions (MPa and K). The residual pore volume is calculated using formula 5.

\[
\phi = (\phi - \phi_w) \times (1 - \varepsilon_v)/\rho_{\text{coal}}
\]

where \(\phi\) is the measured porosity (%), \(\phi_w\) is the porosity occupied by water (%), \(\varepsilon_v\) is the cumulative volumetric strain (dimensionless), and \(\rho_{\text{coal}}\) is the density of coal (\(\text{t}/\text{m}^3\)).

The measured porosity of coal is calculated by using the measured actual density and apparent density ((actual density – apparent density)/actual density \(\times 100\)). The test results of mechanical properties of coal in the west of the Fukang mining area show that the volume strain of coal buried (depth between 400 and 2000 m) is from 0.0024 to 0.0050, which is relatively small and has little influence on the calculation.22,23 Moreover,

Table 2. Measured CBM (Gas) Pressure in the Study Area

| depth /m | gas pressure/MPa | average gas pressure/MPa | depth /m | gas pressure/MPa | average gas pressure/MPa |
|---------|-----------------|--------------------------|---------|-----------------|--------------------------|
| 450     | 0.12            | 0.50                     | 676     | 0.50            |                          |
| 450     | 0.40            | 0.82                     | 676     | 0.82            |                          |
| 450     | 0.50            | 0.59                     | 676     | 0.59            | 0.71                     |
| 632     | 1.10            | 0.80                     | 694     | 0.80            |                          |
| 632     | 1.05            | 0.62                     | 694     | 0.61            | 0.85                     |
| 632     | 0.97            | 0.85                     | 694     | 0.84            |                          |
| 632     | 1.15            | 0.8                      | 694     | 0.8             |                          |
| 632     | 1.15            |                          |         |                 |                          |

Figure 2. (a) Relationship between coal reservoir temperature and buried depth. (b) Relationship between CBM pressure and buried depth.
the CBM wells in this study lack the measured mechanical properties of coal. The volumetric strain does not need to be considered, and formula 5 can be simplified as

$$q_i = (\phi_w - \phi_{c_0}) / \rho_{coal}$$  \hspace{1cm} (6)

The porosity occupied by water is calculated by formula 7.

$$q_{we} = M_e \times \rho_{coal} / \rho_w$$  \hspace{1cm} (7)

where $\rho_w$ is the density of water (t/m$^3$), $\rho_{coal}$ is the density of coal (t/m$^3$), and $M_e$ is the moisture content (%).

The moisture content is also the average measured value from the proximate analysis experiment. The water density is taken as 1.0 t/m$^3$. The values of gas pressure and reservoir temperature in formula 6 are the same as the calculation method based on the gas state equation. The compression factor is obtained based on the corresponding reservoir temperature and gas pressure using REFPROP 8.0 software.

(2) Calculation of water-soluble gas

The water-soluble gas content (in the standard state) is also calculated by a numerical simulation method, and the formula is as follows

$$V_s = 22.4 \times S \times M_e / \rho_w$$  \hspace{1cm} (8)

where $V_s$ is the water-soluble gas content (m$^3$/t), $S$ is the solubility (m$^3$ methane/m$^3$ water), $M_e$ is the moisture content (%), and $\rho_w$ is the density of water (t/m$^3$).

The moisture content is also the average measured value from the proximate analysis experiment. There are a number of studies focusing on the solubility model of methane in water. It is believed that the solubility of methane in water is mainly affected by temperature, pressure, and salinity. Shen et al. (2015) established a methane solubility model (temperature less than 353.13 K) based on the measured solubility of 104 groups of methane in water with different salinities. The error of the model is less than 6% after verification, and the accuracy is high. In this study, the above model is used to calculate the methane solubility, and the formula is as follows

$$V_{sol} = \phi S_m 0.55S_{fl}0.051-0.020P^{0.57}$$  \hspace{1cm} (9)

where $V_{sol}$ is the methane solubility (m$^3$ methane/m$^3$ water), $S_m$ is the water saturation (%), $\phi$ is the measured porosity (%), $S_{fl}$ is the salinity, $T$ is the reservoir temperature (K), $P$ is the gas pressure (MPa), and $\rho_{coal}$ is the density of coal (t/m$^3$).

The measured porosity of coal is also calculated by using the measured actual density and apparent density. The values of temperature and pressure are the same as those used in the calculation of free gas content. The measured salinity in the west of the Fukang mining area was statistically analyzed (Table 3). The results show that the salinity ranges from 0.85 to 12.96 g/L with an average of 5.99 g/L. The salinity gradually increases from the axial part of the Fukang syncline to the flanks. Due to the limited number of measured salinity in the study area, the salinity value of the well CS03 is taken to be 7.23 g/L. The salinity of the other three CBM wells is taken as the measured data of the well CS05 (similar buried depth of coal), which is 12.96 g/L.

### 4. RESULTS AND DISCUSSION

#### 4.1. Gas-Water Differential Distribution Indicated by CBM Production

The gas and water productions of twenty-four CBM wells (more than 300 production days) at different locations in the west of the Fukang mining area are summarized (only the first 300 days of CBM production data were counted to ensure the comparability). The results show that the average daily water production and average daily gas production show a negative correlation (Figure 3). The average daily gas production is between 228.67 and 11680.66 m$^3$, and the average daily water production is from 4.13 to 25.16 m$^3$ (Table 4). The average daily gas production has a large range of variation. The highest average daily gas production is 51.08 times that of the lowest average daily gas production. However, the maximum average daily water production is only 6.09 times that of the minimum average daily water production, which reflects the difference of gas and water production of CBM wells at different locations in the study area. The average daily gas production of the CS11 well group at the rising end of the Fukang syncline is significantly higher in both a single well and well groups. The average daily gas production of the CS11 well group is approximately 5 times that of other well groups, and the average daily gas and water productions of other well groups are relatively close (Table 4). For the CBM wells located in the same flanks of the Fukang syncline, the average daily gas production first decreases slightly and then increases rapidly from the tectonic height to the lower part, while the average daily water production first increases slightly and then decreases (Figure 3b). The difference in gas and water production at different locations indicates the existence of gas-water differential distribution in the study area, and the enrichment area of gas and water is different.

On the other hand, the shape of CBM well production curves also indicates the gas-water differential distribution phenomenon in the western Fukang mining area. The CBM well production curves reflect that the CS11 well group shows the characteristics of rapid gas production. Several wells began to produce gas on the first day. On the contrary, the CBM production curves of the CS15 and CS16 well groups with a large buried depth show the characteristics of beginning to produce gas after a long time of drainage (Figure 4). Moreover, the beginning time for the gas production increases from the axial part to the flank of the Fukang syncline. The beginning time for the gas production of the CS11 well group is less than 30 days, with an average of 10.33 days, which is significantly earlier than other well groups. The difference between the beginning time for the gas production at different locations indicates that the free gas content may be higher at the axis of the Fukang syncline in the study area. Therefore, the migration characteristics of CBM in the study area are worth further exploring.

#### 4.2. Distribution and Migration Characteristics of CBM

**4.2.1. Evidence From Gas Content and Composition.** The gas content distribution characteristics in the west of the Fukang mining area were clarified in previous studies. Li et al. (2017) summarized the measured gas content of coal reservoirs at different locations in the study area. It is concluded that the distribution of gas content is obviously

### Table 3. Measured Salinity in the Study Area

| well   | salinity (g/L) | well   | salinity (g/L) |
|--------|----------------|--------|----------------|
| CS01   | 7.27           | CS02   | 0.85           |
| CS05   | 12.96          | CS04   | 1.65           |
| CS03   | 7.23           |        |                |
regional, and the rising end of the Fukang syncline is a high-value region of gas content. The distribution of gas content adequately indicates that CBM migrates toward the rising end of the Fukang syncline. The characteristics of gas content and composition within the CBM well areas will be mainly discussed in this study. The gas content of the 14-15 coal from four CBM wells varies widely, ranging from 7.71 to 16.64 m³/t (air-dried basis). The average gas content of the 14-15 coal of the wells CSD03, CS8-X4, CS13-1, and CS16-X1 is 12.17, 11.78, 12.64, and 12.80 m³/t, respectively (Table 5). The average gas content shows a small increasing trend from the axial part of the Fukang syncline to the flanks (Figure 5b). The maximum average gas content was only 1.09 times of the minimum average gas content. The difference between gas content at different locations is far less than that reflected by the CBM well production data. However, in the vertical direction, the gas content of the coal samples collected from the same well decreases first and then increases with the increasing buried depth. The main target coal (14-15) for CBM development has a higher gas content (Figure 5c, e), which may be caused by the free gas migration from the lower coal seam to the 14-15 coal. The change of gas composition can reflect the CBM migration. Compared with heavy hydrocarbons, methane is characterized by small molecular diameter, low density, and slightly lower adsorption capacity. Therefore, CH₄ migrates farther than C₂+ in the coalbed methane migration process. After the long-distance migration, CBM is rich in CH₄ and poor in C₂+ compared with the original state. The gas composition of the coal samples taken from the 14-15 coal in the study area shows that the CH₄ concentration is between 88.42 and 97.21%, and the C₂H₆ concentration is between 1.89 and 6.58% (Table 5). The gas composition at different locations is significantly different, and the C₂H₆ concentration of the coal samples collected from the tectonic height is lower. The C₂H₆ concentration shows a trend of decrease from the axial part of the Fukang syncline to the flanks (Figure 5b), which reflects that CBM migrates toward the tectonic height. Meanwhile, the gas composition of other coal seam samples collected from the Badaowan Formation shows that CBM migrates from the lower part to the upper part. Taking the 38 samples from six layers of coal in the well CS13-1 as an example, the CH₄ concentration is between 87.61 and 95.87%, and the C₂H₆ concentration ranges from 0.14 to 8.52%. The C₂H₆ concentration varies in a wide range with the maximum value being approximately 80 times of the minimum. The C₂H₆ concentration shows increases with the increasing buried depth (Figure 5d, e), which reflects that CBM migrates from the lower part to the upper part.

4.2.2. Evidence from Three-Phase Gas Content. CBM commonly occurs in adsorption, free, and water-soluble states. Analyzing the three-phase content of CBM at different locations in the study area is of great significance to clarify the characteristics of gas-water migration. In this study, four CBM wells with complete test data in the study area were selected to quantitatively characterize the difference of three-phase content at different locations by physical and numerical simulation.

Table 4. Statistics of the First 300 Days of CBM Well Production

| well group | well  | average daily gas production/m³ | average daily water production/m³ | beginning time for the gas production/day |
|------------|-------|---------------------------------|-----------------------------------|------------------------------------------|
| CS11       | CS11-X1 | 3718.84                         | 10.83                             | 25.00                                    |
|            | CSD03 | 3000.00                          | 9.56                              | 8.00                                     |
|            | CSD04 | 4197.87                          | 8.32                              | 1.00                                     |
|            | CSD05 | 4477.44                          | 9.05                              | 1.00                                     |
|            | CSP06-1V | 3477.08                         | 12.92                             | 19.00                                    |
|            | CSP-1H | 11680.66                         | 8.38                              | 8.00                                     |
|            | average | 5091.98                          | 9.84                              | 10.33                                    |
| CS13       | CS13-1 | 1149.07                          | 18.21                             | 46.00                                    |
|            | CS13-X1 | 1952.90                          | 17.60                             | 27.00                                    |
|            | CS13-X2 | 260.72                           | 18.04                             | 41.00                                    |
|            | CS13-X3 | 446.60                           | 13.26                             | 97.00                                    |
|            | average | 952.32                           | 16.78                             | 52.75                                    |
| CS15       | CS15-X1 | 228.67                           | 11.01                             | 73.00                                    |
|            | CS15-X2 | 1550.75                          | 10.52                             | 32.00                                    |
|            | CS15-X3 | 1691.44                          | 11.40                             | 96.00                                    |
|            | CS15-X4 | 361.55                           | 16.03                             | 92.00                                    |
|            | average | 958.10                           | 12.24                             | 73.25                                    |
| CS18       | CS18-1 | 1165.00                          | 4.13                              | 132.00                                   |
|            | CS18-X1 | 1158.00                          | 6.86                              | 92.00                                    |
|            | CS18-X2 | 1652.00                          | 5.09                              | 24.00                                    |
|            | CS18-X3 | 2984.00                          | 6.73                              | 13.00                                    |
|            | CS18-X4 | 1672.00                          | 11.00                             | 65.00                                    |
|            | average | 1726.2                           | 6.76                              | 65.20                                    |
| CS16       | CS16-X1 | 1180.00                          | 11.80                             | 41.00                                    |
|            | CS16-X2 | 2033.00                          | 13.09                             | 40.00                                    |
|            | CS16-X4 | 706.00                           | 4.61                              | 61.00                                    |
|            | CS16-X5 | 503.00                           | 25.16                             | 59.00                                    |
|            | CS16-X6 | 2669.00                          | 6.75                              | 54.00                                    |
|            | average | 1418.2                           | 12.29                             | 51.00                                    |
Adsorbed gas characterization is based on the isothermal adsorption experiment of the eight coal samples collected from the 14-15 coal in the four CBM wells. The maximum adsorption capacity (air-dried basis) $V_{L,ad}$ is between 15.50 and 38.61 m$^3$/t. The coal adsorption capacity from the well CSD03 located at the tectonic height is much higher than that of other wells, which is 1.76–2.20 times that of the other three wells (Table 6). The higher adsorption capacity is the main reason for its long-term high CBM daily gas production. The adsorption capacity of coal shows a trend of decreasing from the axial part of the Fukang syncline to the flanks (Figure 5b). The different adsorption capacity of coal is due to the difference in pore structure influenced by the maceral composition. There is a weak positive correlation between the adsorption capacity and the vitrinite content and a weak negative correlation between the adsorption capacity and the inertinite content (Figure 6a,b). Similar conclusions have also been reported by Clarkson and Bustin (1999) and Zhao et al. (2019). The reason is that the pore structure of macerals is different. Tao et al. (2018) found that compared with lignite, the content and pore volume of low rank coal are relatively

Figure 4. CBM well production curves ((a) well CSD04, (b) well CSD05, (c) well CS13-1, (d) well CS13-X1, (e) well CS15-X2, (f) well CS15-X3, (g) well CS16-X2, and (h) well CS18-X1).
lower, but low rank coal has greater adsorption capacity.\textsuperscript{29} Moreover, Li et al. (2020) counted the test results of 498 different coal samples around the world. The results showed that the pore volume and specific surface area increase with the vitrinite content, while the specific surface area decreases with the inerter content.\textsuperscript{30} Therefore, compared with the inerter, the higher specific surface area of the vitrinite leads to a higher adsorption capacity. The isothermal adsorption experiment of nine samples from different coal seams in the well CS13-1 shows that the adsorption capacity was between 15.50 and 23.04 m\textsuperscript{3}/t, with an average of 17.91 m\textsuperscript{3}/t. The correlation between adsorption capacity and burial depth is relatively poor, showing a weak negative correlation (Figure 6c). The burial depth controls the adsorption capacity by changing the

### Table 5. Gas Content and Composition Test Results

| Sample ID | Depth/m | Gas content (m\textsuperscript{3}/t) | CH\textsubscript{4}/% | C\textsubscript{2}H\textsubscript{6}/% |
|-----------|---------|----------------------------------|----------------|----------------|
| CSD03-A2-1| 888.60  | 12.98                            | 93.81           | 0.21           |
| CSD03-A2-2| 890.25  | 13.70                            | 95.88           | 0.17           |
| CSD03-A2-3| 890.85  | 12.44                            | 96.29           | 0.18           |
| CSD03-A2-4| 892.20  | 12.70                            | 95.99           | 0.17           |
| CSD03-A2-5| 893.35  | 12.68                            | 93.36           | 0.19           |
| CSD03-A2-6| 893.85  | 10.67                            | 96.04           | 0.18           |
| CSD03-A2-7| 894.90  | 11.29                            | 92.84           | 0.16           |
| CSD03-A2-8| 897.10  | 12.51                            | 92.07           | 0.14           |
| CSD03-A2-9| 898.35  | 13.80                            | 92.60           | 0.12           |
| CSD03-A2-10| 899.50 | 13.17                            | 92.66           | 0.01           |
| CSD03-A2-11| 900.65| 7.71                             | 93.01           | 0.14           |
| CSD03-A2-12| 901.70  | 14.61                            | 93.93           | 0.01           |
| CSD03-A2-13| 903.70  | 12.88                            | 92.97           | 0.22           |
| CSD03-A2-14| 905.00  | 10.04                            | 93.41           | 0.16           |
| CSD03-A2-15| 905.40  | 12.49                            | 95.56           | 0.26           |
| CSD03-A2-16| 907.30  | 10.11                            | 93.34           | 0.12           |
| CSD03-A2-17| 908.40  | 13.19                            | 93.77           | 0.16           |
| CSD03-A2-18| 908.90  | 9.74                             | 95.33           | 2.96           |
| CSD03-A2-19| 909.50  | 11.11                            | 95.24           | 3.19           |
| CSD03-A2-20| 909.80  | 11.57                            | 94.96           | 3.46           |
| CSD03-A2-21| 910.60  | 12.50                            | 93.80           | 3.52           |
| CSD03-A2-22| 911.10  | 12.21                            | 94.56           | 3.78           |
| CSD03-A2-23| 911.10  | 13.12                            | 94.90           | 3.32           |
| CSD03-A2-24| 912.20  | 12.50                            | 92.83           | 4.26           |
| CSD03-A2-25| 913.00  | 10.83                            | 93.94           | 3.89           |
| CSD03-A2-26| 913.45  | 10.75                            | 93.49           | 3.47           |
| CSD03-A2-27| 913.95  | 7.07                             | 94.95           | 3.57           |
| CSD03-A2-28| 914.10  | 13.33                            | 93.05           | 4.10           |
| CSD03-A2-29| 914.20  | 11.15                            | 93.69           | 4.40           |
| CSD03-A2-30| 915.65  | 7.42                             | 94.07           | 4.51           |
| CSD03-A2-31| 918.40  | 10.12                            | 92.02           | 6.07           |
| CSD03-A2-32| 918.80  | 6.30                             | 93.12           | 5.16           |
| CSD03-A2-33| 1165.45 | 10.86                            | 92.41           | 2.11           |
| CSD03-A2-34| 1165.85 | 7.15                             | 94.49           | 2.12           |
| CSD03-A2-35| 1166.45 | 11.47                            | 93.16           | 1.93           |
| CSD03-A2-36| 1169.85 | 12.86                            | 93.33           | 2.16           |
| CSD03-A2-37| 1171.00 | 11.70                            | 92.79           | 1.89           |
| CSD03-A2-38| 1172.15 | 13.68                            | 98.90           | 2.07           |
| CSD03-A2-39| 1173.45 | 8.47                             | 92.02           | 3.59           |
| CSD03-A2-40| 1174.45 | 13.21                            | 92.94           | 2.52           |
| CSD03-A2-41| 1175.45 | 12.27                            | 93.17           | 2.57           |
| CSD03-A2-42| 1186.12 | 8.84                             | 91.77           | 4.15           |
| CSD03-A2-43| 1188.82 | 14.51                            | 93.07           | 3.31           |
| CSD03-A2-44| 1193.77 | 16.64                            | 92.33           | 3.30           |
| CSD03-A2-45| 1200.40 | 16.12                            | 92.36           | 3.33           |
| CSD03-A2-46| 1206.90 | 15.55                            | 92.98           | 2.81           |
| CSD03-A2-47| 1207.90 | 14.32                            | 91.92           | 3.29           |
| CSD03-A2-48| 1208.97 | 13.86                            | 93.52           | 3.01           |
| CSD03-A2-49| 1209.97 | 11.51                            | 92.14           | 3.91           |
| CSD03-A2-50| 1213.99 | 13.17                            | 93.12           | 3.13           |
| CSD03-A2-51| 1216.94 | 12.63                            | 91.77           | 4.11           |
| CSD03-A2-52| 1216.95 | 12.20                            | 92.56           | 3.16           |
Figure 5. (a) Gas content distribution characteristics (Reprinted with permission from ref 10. Copyright 2017 Mete Oner http://www.ejge.com/2017/Ppr2017.0119ma.pdf). (b) Gas content at different locations. (c) Relationship between gas content and buried depth. (d) Relationship between C2H6 concentration and buried depth. (e) Gas content and C2H6 concentration distribution characteristics in the vertical direction in the well CS13-1.

Table 6. Results of Isothermal Adsorption and Maceral Composition

| sample ID | depth/m | temperature/K | \(V_{\text{sat}}\) (m³/t) | vitrinite/% | inertinite/% | exinite/% |
|-----------|---------|---------------|-----------------|-------------|-------------|-----------|
| CSD03-A2-1| 888.60  | 293.15        | 38.61           |             |             |           |
| CSD03-A2-9| 898.35  | 293.15        | 38.00           |             |             |           |
| CS8-X4-A2-1| 1165.45 | 303.15        | 17.10           | 89.2        | 9.0         | 1.8       |
| CS8-X4-A2-7| 1173.45 | 303.15        | 17.66           | 96.7        | 1.6         | 1.7       |
| CS13-1-A1-1| 988.83  | 303.15        | 16.58           | 85.7        | 11.5        | 2.8       |
| CS13-1-A1-5| 1024.15 | 303.15        | 23.04           | 95.2        | 2.4         | 2.4       |
| CS13-1-A1-17| 1036.38 | 303.15        | 18.99           | 96.8        | 3.0         | 0.2       |
| CS13-1-A1-1| 1076.35 | 303.15        | 14.03           | 98.8        | 1.0         | 0.2       |
| CS13-1-A9-1| 1122.75 | 303.15        | 19.81           | 93.7        | 2.2         | 4.1       |
| CS13-1-A9-1| 1127.31 | 303.15        | 17.33           | 87.7        | 5.6         | 6.7       |
| CS13-1-A9-7| 1132.06 | 303.15        | 15.50           | 68.9        | 29.7        | 1.4       |
| CS13-1-A9-3| 1158.65 | 303.15        | 19.06           | 89.3        | 9.2         | 1.5       |
| CS13-1-A9-7| 1162.55 | 303.15        | 16.89           | 95.4        | 0.8         | 3.8       |
| CS16-X1-A2-5| 1360.40 | 309.15        | 21.99           | 96.9        | 1.0         | 2.1       |
| CS16-X1-A2-17| 1377.34 | 309.15        | 21.50           | 93.2        | 5.9         | 0.9       |
| CS16-X1-A2-1| 1446.95 | 311.15        | 21.61           | 99.2        | 0.4         | 0.4       |
temperature and pressure. With the increase in burial depth, the increasing temperature leads to the decrease in adsorption capacity, while the increasing pressure results in the increase in adsorption capacity. The reason for the weak negative correlation between adsorption capacity and buried depth in the study area may be that the negative effect of temperature on adsorption capacity is more obvious within the corresponding depth range.

(2) Free gas

The free gas content (based on the gas state equation) in four CBM wells is between 0.0049 and 0.4151 m³/t, and the free gas content (Mariotte law) is between 0.0072 and 0.5010 m³/t (Table 7). The calculation difference between the two models is between 20.7 and 45.7%. The strain of coal is not considered in the calculation process based on the Mariotte law, which is part of the reason for the error. However, the free gas content calculated by both the two models tends to decrease from the axial part of the Fukang syncline to the flank (Figure 5b), which indicates the reliability of the results. The free gas content in the well CSD03 located at the tectonic height is 70–85 times that of the well CS16-X1. The free gas content difference at different locations is obvious, which reflects that free gas migrates toward the tectonic height. Meanwhile, although the depth of coal in the well CS8-X4 is lower than that in the well CSD03, the free gas content of coal in the well CS8-X4 is higher. The reason is that several NE reverse faults with a large scale developed near the well CS8-X4, which formed a closure and was not conducive to the migration of free gas. The higher free gas content adequately explains that the adsorption capacity of coal in the well CSD8-X4 is lower than that in the wells CS16-X1 and CS13-1, but the gas content of coal in the three wells is similar.

(3) Water-soluble gas

Table 7. Free Gas Content Calculation* 

| well   | average depth of the 14-15 coal/m | average actual density (t/m³) | average apparent density (t/m³) | average porosity /% | average moisture content/% | free gas content (m³/t) based on the gas state equation | free gas content (m³/t) based on the Mariotte’s law |
|--------|----------------------------------|------------------------------|--------------------------------|---------------------|--------------------------|--------------------------------------------------------|-------------------------------------------------|
| CSD03  | 898.65                           | 1.18(2)                      | 1.11(2)                         | 5.93(2)             | 0.87(17)                 | 0.4151                                                 | 0.5010                                           |
| CS8-X4 | 1171.40                          | 1.32(2)                      | 1.23(2)                         | 6.82(2)             | 2.15(6)                  | 0.4008                                                 | 0.5584                                           |
| CS13-1 | 1028.93                          | 1.33(2)                      | 1.28(2)                         | 3.76(2)             | 1.93(9)                  | 0.0970                                                 | 0.1388                                           |
| CS16-X1| 1370.77                          | 1.28(2)                      | 1.25(2)                         | 2.34(2)             | 1.84(11)                 | 0.0049                                                 | 0.0072                                           |

*The number of samples is shown in parentheses.

Table 8. Water-Soluble Gas Content Calculation 

| well   | average depth of the 14-15 coal /m | gas pressure/ MPa | reservoir temperature /K | solubility of methane (m³ methane/m³ water) | water-soluble gas content (m³/t) |
|--------|-----------------------------------|-------------------|-------------------------|--------------------------------------------|--------------------------------|
| CSD03  | 898.65                            | 1.14              | 297.37                  | 0.011                                      | 0.0022                          |
| CS8-X4 | 1171.40                           | 1.63              | 301.85                  | 0.034                                      | 0.0162                          |
| CS13-1 | 1028.93                           | 1.37              | 299.51                  | 0.027                                      | 0.0118                          |
| CS16-X1| 1370.77                           | 1.99              | 305.12                  | 0.033                                      | 0.0134                          |

*The number of samples is shown in parentheses.
The calculated water-soluble gas in four CBM wells is between 0.0022 and 0.0162 m$^3$/t, with an average of 0.01089 m$^3$/t (Table 8). Compared with free gas and adsorbed gas, the contribution of water-soluble gas to the gas content is limited. The water-soluble gas content shows an increasing trend from the axial part of the Fukang syncline to the flank (Figure 5b). The water-soluble gas content of coal in the well CSD03 is relatively small, which is approximately 13.5 to 18.6% of that in the other three wells. The main reason is that the moisture content of coal in the well CSD03 is lower, which is approximately 40 to 50% of that in the other three wells. Moreover, the salinity of the water in the well CSD03 is also low. The water-soluble gas content of coal in the other three wells is similar.

4.3. Distribution and Migration Characteristics of Groundwater. Groundwater commonly flows from the high potential energy zone to the low potential energy zone along a hydraulic slope from the bedding layer of the shallow buried replenishment zone. Li et al. (2017) and Kang et al. (2018) calculated the equivalent water level elevation of the Badaowan Formation and the hydraulic head based on borehole exploration data and CBM well data in the west of the Fukang mining area. The results show that the water level elevation is higher in the northwest and southeast in the study area, while that in other parts is low. In particular, the rising end of the Fukang syncline forms the groundwater stagnation area. As for the vertical direction, the Badaowan Formation is a weak aquifer, which can be further divided into two aquifers and two impermeable layers. The coal seam has a poor hydraulic connection with the overlying strata, so it can be regarded as an independent aquifer. The stratigraphic histogram shows that siltstone and mudstone with poor permeability are usually developed in the coal overlying strata (Figure 1). Therefore, the groundwater mainly flows down the coal seam controlled by water gravity.

4.4. Gas-Water Differential Distribution Characteristics. Based on the superposition results of CBM and groundwater distribution in the west of the Fukang mining area, the migration direction of CBM and water can be inferred. The gas-water differential distribution occurs in the area to different degrees both in the plane and in the vertical direction (Figure 8). The measured gas content and the three-phase gas content show that CBM mainly migrates toward the tectonic height. The buried depth of coal located at the rising end of the Fukang syncline is shallow, and the free gas content is relatively high. However, groundwater flows from the northwest and southeast to the east and the west of the Fukang mining area. Also, groundwater flows from the central part to the east and west within the CBM well area. The difference in gas-water migration direction leads to gas-water differential distribution in the study area. The measured C$_2$H$_6$ concentration decreases with the increasing buried depth, which indicates that CBM migrates from the lower part to the upper part. The groundwater flows downward the coal seam controlled by water gravity, which results in the gas-water differential distribution in the vertical direction. Only local gas-water differential distribution occurs in the plane of the study area, and gas-water differential distribution is more obvious in the vertical direction.

4.5. Gas-Water Differential Distribution Mechanism. Geological conditions directly or indirectly affect the migration and preservation of CBM. Meanwhile, groundwater flows from a high water level to a low water level driven by gravity. Geological conditions control the location of the high potential energy zone, thus affecting groundwater migration. Therefore, CBM and water migration direction may be different due to the control of geological conditions, which results in gas-water differential distribution. On the whole, gas-water differential distribution in the western Fukang mining area is mainly controlled by tectonic and hydrogeological conditions. The main coal seam for CBM development in the study area is the Badaowan Formation of lower Jurassic. The coal seam mainly experienced the Yanshan and Himalayan movements. In the early stage of the Yanshan movement, the stratum in the area was uplifted by vertical movement. Later, the late Yanshan movement dominated by horizontal movement had a strong effect on the reconstruction of the study area. The stratum settled down substantially, and the depth of coal increased. The strong tectonic compression effect caused the strata to be deformed and then formed folds of different scales in the area, such as the Fukang syncline and the
Yanshan movement. On the other hand, the strong tectonic faults were formed in the study area in the process of the paleogeothermal temperature reached approximately 80 °C. As organic matter matures, hydrocarbon generation begins, and part of the gas migrated to the tectonic height in a free state. Compared with low-angle or horizontal coal seams, the free gas migrated more easily due to the large dip angle. Then, the Himalayan movement showed strong compressing and twisting action, which results in the stratum in the area rising greatly. Consequently, the coal seam was exposed to the surface in several areas. Tectonic uplifting causes the release of coal reservoir stress and the continuous migration of free gas to the tectonic height. Meanwhile, the Himalayan movement intensified the Bogda nappe structure and formed a number of EW-trending thrust faults at the rising end of the Fukang syncline, which provided an excellent sealing condition for the free gas enrichment in the later period. Moreover, the movement changed the groundwater migration direction, which resulted in the deterioration of the hydraulic connection between the two sides of the fault.

Hydrogeological conditions also control gas-water differential distribution in the study area. In the north and east of the Fukang syncline, the Badaowan Formation is exposed to the surface, and several rivers are developed in the area (Figure 1). Groundwater mainly receives lateral replenishment from the surface, and it is difficult to replenish from the southwest due to the water-nonconducting faults. Several normal faults are developed in the southeast, which enhances the hydraulic connection and leads to the high hydraulic head in the southeast due to the lateral replenishment. Therefore, the groundwater flows from the central part to the east and the west. The groundwater flow direction in several areas (mainly in the central part of the Fukang syncline) is different from the direction of CBM migration. The stagnation area formed in the rising end of the syncline provided blocking for CBM. Moreover, the gas content especially free gas content at the tectonic height is high due to the sealing property of the reverse faults. However, gas-water differential distribution in the central part of the Fukang syncline, which has relatively low gas content due to the migration of free gas and the gas production of the CBM wells is low. In the vertical direction, the coal seam in the Badaowan Formation is overlaid with siltstone and mudstone, and the vertical groundwater replenishment is weak. The groundwater flows down the coal seam controlled by water gravity. The dip angle of the stratum in the southeastern flank of the Fukang syncline is larger due to the tectonic movements. The gravity effect on groundwater flow is more obvious, which promotes the downward migration of groundwater. CBM mainly migrates from the lower part to the upper part of the Fukang syncline. The migration direction of CBM is opposite to that of groundwater, which leads to the gas-water differential distribution in the vertical direction. The superposition of gas-water differential distribution in different directions results in the great difference between gas and water production at different locations.

5. CONCLUSIONS

CBM well gas and water production at different locations in the western Fukang mining area, China is significantly different. The three-phase gas content of the coal reservoirs was determined based on the basic geological data and CBM well production data combined with experiments and numerical simulation. Combined with the results of gas composition, the distribution characteristics of CBM and water in the study area were analyzed. Based on the results, the following conclusions are obtained.

The average daily water production and average daily gas production of CBM wells in the study area are negatively correlated. The high gas production zones are mainly concentrated at the tectonic height. Meanwhile, the CBM wells at the tectonic height commonly begin to produce gas in a short period. The difference in gas and water production at different locations indicates the difference in CBM and groundwater migration direction. The gas content and composition test results show that the gas content is relatively high at the height of the structure. Meanwhile, the C2H6 concentration at the height of the structure is lower. The C2H6 concentration shows a positive correlation with the buried depth, which indicates that CBM migrates from the lower part to the upper part. The calculation of three-phase gas content shows that the free gas content at the tectonic height is relatively high, which can reach approximately 70% that of free gas content in the low part of the structure. The equivalent water level elevation and the hydraulic head calculation results show that the groundwater flows from the central part to the

![Figure 8. CBM and groundwater migration direction sketch map.](https://dx.doi.org/10.1021/acsomega.0c05930)
east and west within the CBM well areas. Groundwater is accumulated at the rising end of the Fukang syncline and forms the groundwater stagnation area. Meanwhile, groundwater flows down the coal seam in the vertical direction controlled by water gravity. The difference between CBM and groundwater migration leads to differential distribution both in the plane and vertical direction.

Gas-water differential distribution in the western Fukang mining area is mainly controlled by tectonic and hydrogeological conditions. The Yanshan movement caused the stratum to be deformed and faulted, forming a series of folds and faults of different scales. The stratum in several areas shows a high dip angle characteristic. The coal seam is heated to generate hydrocarbons due to the tectonic compression, and the free gas continuously migrates to the higher part of the structure. The Himalayan movement intensified the Bogda nappe structure and formed a number of EW-trending thrust faults at the rising end of the Fukang syncline, which not only provides excellent sealing conditions for CBM but also changes the groundwater migration direction. Groundwater is accumulated at the rising end of the Fukang syncline, which forms a great hydraulic blocking for the free gas enriched at the tectonic height. The large dip angle of the stratum leads to a more obvious gravity effect on groundwater migration, which promotes gas-water differential distribution in the vertical direction.

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Notes
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