Low-Yield Genesis of Coalbed Methane Stripper Wells in China and Key Technologies for Increasing Gas Production

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ABSTRACT: For the problem where numerous coalbed methane (CBM) stripper wells exist in China, this paper analyzes the genesis of the stripper wells from the aspects of geological conditions and development technologies combined with the CBM development of some typical blocks. A series of key secondary stimulation technologies for CBM stripper wells are put forward, including low-damage fracturing fluid for preventing reservoir damages, proppants with multigraded sizes for supporting multilevel fractures, large-scale fracture network stimulation (FNS) for improving reservoir permeability, and coal measure gas development for increasing the exploitable resources within a single well scope, as well as coordinated stimulation of parent–child wells for the overall production improvement of low-yield blocks. Also, it is pointed out that all types of stripper wells could adopt the low-damage fracturing fluid and multigraded proppant and optimize the drainage schedule to inhibit reservoir damage and promote the maintenance of fracture conductivity. For resource-controlled stripper wells, large-scale FNS of coal seams, coal measure gas development, and coordinated stimulation of parent–child wells could be adopted according to the differences in resource abundance and coal seam distribution. For the stripper wells controlled by the coal structure and ground stress, FNS of the surrounding rock could be conducted to construct stable and efficient channels for CBM migration. In addition, by conducting large-scale FNS, the stimulation effect of fracturing-controlled stripper wells improves, while after unblocking and reopening the existing reservoir fractures of the drainage-controlled stripper wells, an optimized drainage schedule could be adopted to prevent reservoir damages and promote the maintenance of fracture conductivity.

1. INTRODUCTION

Coal has been dominant in the energy mix of China for a long time. However, coal mining and combustion have caused increasingly severe pollution in recent years.4−6 According to the work report of the Chinese government in 2021, the CO2 emissions need to be reduced by 18% during the 14th Five-Year Plan period and strive to achieve the peak CO2 emission by 2030 and the carbon neutrality by 2060, indicating the urgency of clean energy development and utilization. Also, China issued the 2020 Guideline on Energy Work, which emphasized the requirement for yield increase of natural gas, indicating that natural gas is becoming an important growth point of modern clean energy.

China has abundant unconventional natural gas resources with higher reserves than that of conventional natural gas. According to the difference in the occurrence state and reservoir characteristics, unconventional natural gas mainly includes four types, i.e., coalbed methane (CBM), shale gas, tight gas, and natural gas hydrate. As the conventional natural gas production cannot meet the increasing demand, all types of the unconventional natural gas are gradually entering the regional commercial development stage (i.e., CBM, shale gas, and tight gas) or pilot testing stage (i.e., natural gas hydrate).4−6 Among them, the in situ CBM resources with the burial depth of less than 2000 m are 29.8 × 1012 m³ in China, showing a high development value. However, the CBM development in China is faced with complex geological conditions and the coal seams are generally featured with low reservoir pressure, low permeability, and low gas saturation.7−9 Also, CBM resources in coal seams with high ground stress, low permeability, and well-developed tectonic coal account for more than 75% of the total resources. Meanwhile, the CBM resources in the soft coal (i.e., granulated and mylonitic coals) account for 29%.10,11

Under the complex geological conditions, the CBM development industrialization progress in China is slow, and the total annual CBM production in 2020 was only 63.7 × 108 m³, which was far lower than what was expected in the 13th Five-Year Plan of China (i.e., 100 × 108 m³). The existence of numerous CBM stripper wells is an important reason for the situation. The so-called CBM stripper wells refer to the wells that have failed to

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achieve the lowest gas production for commercial development, which is generally set as 1000 m³/day according to the current economic and technical conditions in China. However, as the main CBM production regions in China, only 25% of the CBM wells in the Qinshui Basin and Ordos Basin possess the gas production rate higher than 1000 m³/day, while 56% of the wells have the gas production rate of less than 500 m³/day.²

Compared with the previous successful cases of CBM commercial development in different regions, the lack of targeted development technology might be the crux of the low production of numerous CBM wells. Specifically, the United States, Australia, Canada, and China have successively achieved CBM commercial development in Black Warrior Basin, San Juan Basin, Surat Basin, Alberta Basin, Qinshui Basin, etc. Different development technologies have been adopted in these areas according to the different CBM geological characteristics, such as open-hole completion, nitrogen fracturing, and coal measure gas (CMG) development, and high gas production has been achieved (Table 1). These cases show that CBM should be developed with targeted technologies based on the specific geological conditions.

Recently, new development technologies have been continuously put into tests, such as fracture network stimulation (FNS), horizontal well high-density cutting, pseudo-reservoir stimulation, and CMG development.⁶ All these have provided strong support for the CBM commercial production. However, there is still a lack of synthetic discussion on the genesis mechanism of CBM stripper wells and the establishment of a development technology system in China. Therefore, this study aims to analyze the genesis of CBM stripper wells comprehensively and propose targeted technologies for the secondary stimulation based on different genesis so as to provide a theoretical basis for the secondary stimulation implementations of CBM stripper wells and the CBM development in new blocks in the future.

2. RESULTS AND DISCUSSION

2.1. Genesis of CBM Stripper Wells. The genesis of CBM stripper wells could be generally classified into two aspects, i.e., geological conditions and development technologies, and some CBM development cases are analyzed in this section to demonstrate this issue.

2.1.1. Geological Conditions. 2.1.1.1. Resource Condition. Resource condition is the material basis that determines the commercial value of CBM. According to the current economic and technological conditions in China, the CBM resource abundance should be higher than 1.0 × 10⁸ m³/km² to meet the demand of CBM commercial development.⁵ An insufficient CBM resource has a significant impact on well production, for example, in the Xishan Block and the Zhaozhuang Block, Shanxi Province.

The target layers for CBM development in the Xishan Block are the no. 2 coal seam of the Lower Permian Shanxi Formation and the no. 8 and no. 9 coal seams of the Taiyuan Formation. The block was put into development in 2011, and there are nearly 600 CBM wells in operation, which are mainly vertical wells.⁶ The total gas production rate was 15 × 10³ to 20 × 10³ m³/day from 2014 to 2019, and the average production rate per well was less than 300 m³/day. Among them, the wells with the gas production rate higher than 1000 m³/day accounted for only 1.41%, while stripper wells with the production of 500–1000 m³/day and 300–500 m³/day and less than 300 m³/day accounted for 9.28, 18.21, and 46.06%, respectively. Also,

| Table 1. CBM Geological Features and Development Methods of the CBM Wells with High Gas Production in Different Regions of the World |
|---|---|---|---|---|---|
| Region | Target Coal Seam | Geological Features | Stimulation Methods | Production Rate |
| Black Warrior Basin, US | Lower Ordovician | Multiple coal seams with thin thicknesses | Improved large-scale horizontal completions for joint production | CMG production rate of approximately 20,000 m³/day per well |
| San Juan Basin, US | Fruitland Formation in the northern US | Thick coal seams with high original permeability and pressure coefficients | Open-hole cased completion and elimination of drilling and completion damage in near borehole zones | Stable production rate of above 6000 m³/day of a U-type well |
| Powder River Basin, US | Cowan Formation in Alberta, Canada | Lignite coal with low gas content (i.e., less than 2 m³/t), large thickness, and extremely low permeability | Large-scale nitrogen fracturing and blocking near borehole zones | CMG production rate of 10,000–30,000 m³/day per well |
| Middle Jurassic, Wallan Basin, US | Dunham Formation in the Surat Basin, Australia | Large number of thin coal seams with high gas saturation and extremely low permeability | Full borehole evaluation before horizontal well drilling, infilling, and blocking near borehole zones | CMG production rate of 10,000–30,000 m³/day per well |
| Upper Jurassic, Hengshui Formation in Inner Mongolia, China | Large number of thick coal seams with high gas saturation and extremely low permeability | Full borehole evaluation before horizontal well drilling, infilling, and blocking near borehole zones | CMG production rate of 10,000–30,000 m³/day per well |
| Zhongnantai Coalmine of the Jiaozuo mining area, China | Large number of thin coal seams with high gas saturation and extremely low permeability | Full borehole evaluation before horizontal well drilling, infilling, and blocking near borehole zones | CMG production rate of 10,000–30,000 m³/day per well |
25.04% of the wells had no gas production (Figure 1). The average total thickness of the no. 2, no. 8, and no. 9 coal seams is 7.31 m, and their gas contents are 3.36–13.4 m³/t (avg. 7.49 m³/t), 3.18–15.14 m³/t (avg. 8.64 m³/t), and 2.77–15.45 m³/t (avg. 8.24 m³/t), with the average resource abundance of only 0.19 × 10⁸, 0.36 × 10⁸, and 0.26 × 10⁸ m³/km², respectively, which are rather low (Table A1). The gas production rate of CBM wells in the block has a strong correlation with the gas content of coal seams, showing that wells with the gas production rate higher than 500 m³/day are generally distributed in areas with the gas content higher than 8 m³/t and the average resource abundance of 1.12 × 10⁸ m³/km². However, in most areas, the average resource abundance is only 0.43 × 10⁸ to 0.88 × 10⁸ m³/km², and the gas production rate of CBM wells is generally lower than 500 m³/day, indicating that a low CBM resource abundance is the main reason causing low gas production in the block (Figure 1).

In addition, the main coal seam in the Zhaozhuang Block is the no. 3 coal seam of the Lower Permian Shanxi Formation. The gas productions of 47 CBM wells showed that only 5 and 7 wells had gas production rates higher than 500 m³/day and of 300–500 m³/day, respectively, while that of the other 35 wells was below 300 m³/day. Note that the no. 3 coal seam is 0–6.35 m thick (avg. 4.69 m) and has a gas content of 0.23–18.79 m³/t (avg. 10.3 m³/t) with the average CBM resource abundance of only 0.69 × 10⁸ m³/km² (Table A1). Even though the gas content of the coal seam is higher than that in the Xishan Block, its thin thickness still results in low CBM resource abundance, which is the main factor affecting the production of CBM wells.

2.1.1.2. Coal Structure. Tectonic coal is widely developed in China under the influence of multistage tectonic movements, and the low gas production from the soft coal has been a bottleneck restricting the CBM industrialization in China. The low production of CBM wells in the Shoushan Coalmine, Henan Province, is mainly caused by the coal structure.

Shoushan Coalmine was mainly engaged in the joint CBM development of the no. 21 coal seam of the Shanxi Formation and the no. 39 coal seam of the Xiashihezi Formation. The no. 21 coal seam has gas contents of 11.15–11.35 cm³/g (avg. 11.71 cm³/g) and 10.26–15.45 cm³/g (avg. 11.65 cm³/g), respectively. The CBM resource abundance and pressure gradient are 1.49 × 10⁸ m³/km² and 0.95 MPa/100 m, respectively, showing a good resource condition (Table A1). In 2011, five vertical wells were constructed in the area and subjected to layered fracturing and joint drainage. During 420 days of drainage, the peak and average gas production rates of the five wells were only 205–886 m³/day (avg. 406.2 m³/day) and 41–350 m³/day (avg. 157.6 m³/day), respectively.

The main coal seams in the Shoushan Coalmine are mainly composed of soft coal, which belongs to a plastomer and cannot be fractured. However, the stimulation method adopted in the area was coal seam hydrofracturing, which only squeezes and punctures the coal body and can hardly form stable fluid migration channels. Therefore, CBM is mainly produced in the form of diffusion, resulting in the low gas production of the wells.

2.1.1.3. Ground Stress. The intensity and direction of ground stress not only control the shape of hydraulic fractures but also affect the reservoir permeability greatly in the drainage process. The gas production of CBM wells in the Zhengzhuang Block, southern Qinshui Basin, is mainly affected by ground stress.

The main CBM development target in this block is the no. 3 coal seam of the Shanxi Formation with a burial depth of 350–1300 m (Figure 2). The thickness of the coal seam is 2.15–7.70 m (avg. 6.11 m), and it is dominated by the primary undeformed and cataclastic coal. The gas content of the coal seam ranges from 0.83 to 31.44 m³/t (avg. 19.10 m³/t), and the resource abundance is approximately 1.71 × 10⁸ m³/km². Also, the gas saturation and the ratio of critical desorption pressure to reservoir pressure (C_e) are relatively high, which are 69.19% and 0.56, respectively.

These conditions are conducive to the CBM development (Table A1). Since 2011, the block has had more than 1000 production wells put into operation with an average gas production rate of 560 m³/day, and nearly two-thirds of the wells have the gas production of less than 500 m³/day. Among them, high-yield wells are mainly distributed in the southwestern area with a low burial depth (i.e., <600 m), and the average production rate is approximately 1000 m³/day. Meanwhile, stripper wells are mainly distributed in the central and northern areas with a high burial depth (i.e., >600 m), and the gas production rate is generally less than 600 m³/day.

Figure 1. Diagram showing the proportion and CBM resource abundance of the wells with different gas production rates in the Xishan Block.

Figure 2. Structural contour map of the top of the no. 3 coal seam in the Zhengzhuang Block. Reprinted with permission from ref 33. Copyright 2018 Elsevier B.V.
According to the well test results, the no. 3 coal seam in the depth range of 519.33−1272.8 m has a vertical stress (σ_v) of 14.02−34.37 MPa, and the maximum horizontal principal stress (σ_h) and the minimum horizontal principal stress (σ_h) are 14.02−34.37 MPa and 10.51−29.09 MPa, respectively.37 The σ_h of the coal seams in the 62.5% area in the block ranges from 10 to 18 MPa, and in the 34.4% area, it is 18−30 MPa.32 According to the evaluation criteria of Kang et al.,38 the Zhengzhuang Block is dominated by medium-high stress areas, while the saturated compressive strength of the no. 3 coal seam is only 1.46−25.09 MPa (avg. 7.68 MPa).39 During the drainage stage, the proppants tend to embed into the fracture surface when the effective stress (σ_eff) is higher than the coal compressive strength (S_c), causing the fracture aperture to decrease and leading to stress sensitivity damage (Figure 3a,b). The coal seams in the central and northern Zhengzhuang Block are buried deep, and the σ_h far exceeds the S_c of the coal seams. Therefore, the intensive stress sensitivity damage in the drainage stage is the main reason for the low production in the deep area in the block.

With the continuous expansion of CBM exploration and development in China, the development scope has gradually shifted from shallow parts to deep parts with the burial depth deeper than 1000 m, e.g., the Yanchuannan CBM field in the southeast of the Ordos Basin and the Cainan area in the eastern part of the Junggar Basin. The impact of ground stress on CBM development will be increasingly significant.

2.1.1.4. Hydrodynamics. Hydrodynamics not only controls the CBM migration and accumulation but also has a great impact on the development process. When the coal seam is close to aquifers and links up with the aquifers through hydraulic fractures, faults, or collapse columns, it is easy to cause excessively high water production of the CBM wells, hindering gas desorption and production severely. The low gas production of some wells in the Liulin Block, eastern Ordos Basin, is mainly controlled by the hydrodynamics.

The targets for CBM development in the Liulin Block are the no. 3, no. 4, and no. 5 coal seams of the Shanxi Formation as well as the no. 8 and no. 9 coal seams of the Taiyuan Formation. The single layer thickness of the coal seams is generally 2−5 m, and the coal structure is dominated by a primary undeformed structure. The no. 3 and no. 4 coal seams possess a relatively high gas content, which is 10.98 m³/t on average, while the gas content of the no. 5, no. 8, and no. 9 coal seams is generally 8.64−8.96 m³/t (Table A1).40,41 The block is mainly engaged in the joint development of multiple coal seams with the average CBM resource abundance of 1.44×10⁸ m³/km², showing good CBM resource conditions. However, as of 2018, the gas production rate of 193 vertical wells in the Liulin Block was generally 300−500 m³/day, far lower than the predicted result of numerical simulation (i.e., 1500−2000 m³/day per well), and the wells differed greatly in the water production rate.41,42 Note that all the wells with the no. 8 coal seam in the development interval had a high water production rate of generally 50−150 m³/day, which seriously restricted the gas production process.43

The direct roof of the no. 8 coal seam in the block is the limestone karst-fissured aquifer of the Taiyuan Formation (Figure 4a), which is recharged by atmospheric precipitation. The surface water in the northern part of the block flows into the aquifer through faults (Figure 4b), while that in other areas flows to the deep from the outcrop in the eastern block through limestone fissures (Figure 4c).43 Most areas in the block are in the groundwater runoff zone and the salinity of the underground water in the aquifer is 1190−3210 mg/L. Previous development results showed that the water produced from the CBM wells

Figure 3. Diagrams showing the reservoir damage and pressure drop of a CBM well during the drainage process: (a) fracture configuration in different stages, (b) reservoir permeability variation mechanisms, and (c) pressure drop curves under different drainage strengths.
with the no. 8 coal seam in the development interval had salinity close to that of water in the limestone, indicating that the high water production in the central area is caused by the limestone aquifer. For example, the FL-EP2 well in the block had cumulative water and gas productions of 62,557.2 and 7892.26 m$^3$, respectively, in the period of more than 600 days of drainage. Also, the maximum water production rate reached 256.91 m$^3$/day. According to the fracture monitoring results during hydrofracturing, the height of the hydraulic fractures reached 19.3 m, which is far higher than the coal seam thickness, indicating that the fracture linked up with the aquifer, making it difficult to form a pressure drop funnel in the coal seam to desorb CBM effectively. Therefore, the aquifer development is an important cause for the low production of partial wells in the block.

### Table 2. First and Secondary Hydrofracturing Parameters of Well HN-01

| Stimulation Interval | Stimulation Object | Fracturing Fluid Type | Fluid Volume (m$^3$) | Displacement (m$^3$/min) | Adding Sand Type | Sand Volume (m$^3$) |
|----------------------|--------------------|-----------------------|----------------------|--------------------------|-----------------|-------------------|
| First Hydrofracturing | No. 8 and no. 9 coal measure | Coal seam | Active water fracturing fluid | 884.8 | 7.0–8.0 | Continuously adding | 83.0 |
|                      | No. 6 coal measure | Coal seam | Active water fracturing fluid | 778.0 | 7.0–8.0 | Continuously adding | 69.0 |
| Secondary Hydrofracturing | No. 8 and no. 9 coal measure | Coal seam and the surrounding rocks | Low-damage fracturing fluid | 1750.0 | 5.0–10.0 | Intermittently adding | 71.5 |
|                      | No. 6 coal measure | Coal seam and the surrounding rocks | Low-damage fracturing fluid | 1962.0 | 5.0–10.0 | Intermittently adding | 76.0 |

2.1.2. Development Technologies. Apart from the geological conditions, development technologies such as hydrofracturing and drainage control also affect the production of gas wells.

2.1.2.1. Hydrofracturing. The situation of a CBM well (i.e., Well HN-01) in the Sunan Syncline Block, Huaibei Coalfield, is detailed in this section to demonstrate the relationship of hydrofracturing and gas production. The well had a poor gas production effect after the first hydrofracturing, but its gas production rate increased significantly after the secondary hydrofracturing, indicating that hydrofracturing can be an important factor affecting the production.

The main target for the CBM development in the Sunan Syncline Block is the no. 6, no. 7, no. 8, and no. 9 coal seams of the Middle Permian Xiaoshihezi Formation, which are 8.09–11.22 m thick in total. The coal structure is dominated by...
primary undeformed and cataclastic structures, and the gas content of the coal seams ranges from 7.16 to 11.86 m³/t (avg. 9.40 m³/t) with the average CBM resource abundance of 1.83 × 10³ m³/km². Also, both the gas saturation and Cₚ are high, i.e., 85–93% and 0.57–0.71, respectively, which are conducive to the CBM development (Table A1). After the first hydrofracturing, Well HN-01 had its gas production rate raised briefly to 940 m³/day but then dropped below 440 m³/day in the drainage stage. It was finally shut down and the development failed. However, after the secondary hydrofracturing, the gas production rate was stabilized at approximately 1100 m³/day and realized commercial production. By comparing the parameters between the first and secondary hydrofracturing (Table 2), the reasons for the failure of the first try can be summarized as three aspects, i.e., improper stimulation object, fracturing fluid type, and pumping procedure.

First, the reservoir fracability is an important factor affecting the reservoir stimulation effect. Generally, it can be evaluated by reservoir brittleness and fracability indexes calculated from Young’s modulus and Poisson’s ratio, showing that the higher the two indexes, the better the reservoir fracability. However, the objects of the first hydrofracturing were only coal seams, while those of the secondary hydrofracturing were coal seams and the surrounding rocks. Compared with surrounding rocks, the coal seam possesses lower mechanical strength, brittleness index, and fracability index, indicating that the fracturing effect of coal seams is far inferior to that of surrounding rocks. Meanwhile, coal seam fractures are prone to proppant embedment in the drainage stage, leading to fracture closure, which is not conducive to the gas production.

Second, the fracturing fluids used in the first and secondary hydrofracturing were the active water fracturing fluid of 1.0% KCl + 0.05% fungicide and the low-damage fracturing fluid of 1.5% KCl + 0.05% AN (hydrophilic surfactant), respectively. According to the previous laboratory experiments, the active water fracturing fluid has high surface tension and causes high capillary pressure in pores, which can easily trigger serious water blocking damage to the reservoir. Thus, the matrix pores in the filtrate loss zones tend to be sealed by water, leading to the failure in CBM desorption (Figure 3a), while the low-damage fracturing fluid can significantly mitigate the water blocking damage. In the drainage stage after the first hydrofracturing, the cumulative water production and flowback rate of the fracturing fluid were only 526.02 m³ and 31.6% (the cumulative volume of the pumped fracturing fluid was 1662.8 m³), respectively, when the gas production rate reached the peak. However, after the secondary hydrofracturing, it showed a better flowback effect of the fracturing fluid. On the 166th day of the drainage stage, the gas production stage had not begun by then, while the 1831.64 m³ fracturing fluid was drained cumulatively and the flowback rate reached approximately 50% (the cumulative volume of the pumped fracturing fluid was about 3700 m³). This indicates that a large amount of active water fracturing fluid was retained in the reservoir after the first hydrofracturing, which increased the irreducible water saturation in the coal seams. The resulting water blocking damage is an important factor restricting the gas production.

In addition, fracturing fluid and proppant sand were pumped continuously with a displacement of 5.0–6.0 m³/min and a sand ratio of 5–20% in the first hydrofracturing. With such methods, only radial tensile fractures were formed in the direction of the maximum principal stress of the reservoir (Figure 5a). On the contrary, coal seams and surrounding rocks were subjected to integrated FNS in the secondary stimulation, which increased the reservoir permeability by a stimulated reservoir volume (SRV), rather than the conductivity of a group of fractures (Figure 5b). According to the calculation results of the reservoir permeability in the single-phase water stage during the drainage process, the reservoir permeability was only 0.339 mD after the first hydrofracturing and increased by 2.4 times to 1.162 mD after the secondary hydrofracturing. This indicates the poor fracturing effect in the coal seams during the first hydrofracturing, which was not conducive to the CBM development.

Numerous CBM wells in China had adopted a reservoir stimulation method similar to the first hydrofracturing of Well HN-01. This easily leads to a poor stimulation effect and serious reservoir damages and is an important factor hindering the CBM commercial development.

2.1.2.2. Drainage Control. Improper drainage control is another factor that causes the low production of CBM wells, including high-intensity, discontinuous and unstable drainage, etc.

An important reason for high-intensity drainage is the limited capability of equipment. Tubular pumps and pumping units have been combined for the drainage for more than 95% of CBM wells in China. However, this combination does not have a frequency conversion control function in the early days. For...
some CBM wells with low water production, it is difficult for the equipment to operate at low strokes, resulting in the fast drop of bottom hole pressure (BHP). In addition, some CBM wells were expected to obtain gas production as soon as possible after drainage was started, also resulting in the high intensity and fast drop of BHP. However, the fast drop of BHP can result in excessive reservoir pressure drop in near-wellbore zones, while it is difficult to replenish the fluid from the reservoir far from the wellbore in time and the effective stress increases rapidly, leading to serious stress sensitivity damage to the reservoir and reducing fracture conductivity (Figure 3). Meanwhile, the high flow velocity of fluid can easily cause particles in fractures to migrate and block fracture throats, thus causing velocity sensitivity damage and further hindering gas production (Figure 3).

There are many reasons for the discontinuous drainage of CBM wells, such as power outage at the well site, gas lock, and pump blocking in the wellbore. After drainage is restarted, it is often difficult to recover the gas production to the level before the interruption, indicating that irreversible damage has been caused to the reservoir. Note that to restore the BHP to the state before the pump stopping and promote the gas production recovery, the drainage intensity of many wells increased. However, this may cause serious stress sensitivity or velocity sensitivity damages to the reservoirs, which in turn lead to a decrease in gas production. In addition, unstable drainage means that the drainage intensity fluctuates. However, high-intensity drainage will cause severe stress sensitivity and velocity sensitivity damages to the reservoir, and such impacts can hardly be reversed even if the intensity is reduced, leading to the decrease in gas production.

2.2. Key Technologies for Promoting the Gas Production of CBM Stripper Wells. The successful experience of the United States, Canada, Australia, and some regions in China in CBM development shows that different development techniques should be adopted under different geological conditions. The complex CBM geological conditions and the simplistic development techniques in China are the main reasons for the ubiquity of stripper wells. Therefore, developing targeted technologies based on different geological conditions is necessary for promoting the gas production of the stripper wells.

2.2.1. Secondary Stimulation Technologies. Based on the genesis types of stripper wells, secondary stimulation technologies are proposed by changing active water fracturing fluid to low-damage fracturing fluid, double-graded proppants to multigraded proppants, CBM development to CMG development, and conventional hydrofracturing to large-scale FNS. In addition, coordinated development of child−parent wells can be adopted to increase production regionally for the low-yield blocks (Figure 6).

2.2.1.1. Changing Active Water Fracturing Fluid to Low-Damage Fracturing Fluid. The active water fracturing fluid adopted in the conventional hydrofracturing can only mitigate reservoir water sensitivity damage; however, the prevention of water blocking and velocity sensitivity damages is ignored. During the secondary stimulation, it is necessary to use low-damage fracturing fluid with the properties of mitigating water sensitivity, water blocking, and velocity sensitivity damages (Figure 6a). These properties of the fluid depend on the clay stabilizer and hydrophilic surfactant (e.g., the fracturing fluid of 1.5% KCl + 0.05% AN shown in Section 2.1.2.1). Specifically, the hydrophilic surfactant can significantly reduce the surface tension of the fracturing fluid and the pore capillary pressure. Thus, the resistances of the capillary effect and Jamin effect to gas desorption and migration will be mitigated and the critical aperture for water blocking damage will be reduced (Figure 3a). Also, the hydrophilic surfactant can improve the wetting ability of fracturing fluid, which is conducive to promoting the
rapid sedimentation and agglomeration of particles in fractures. The liquid bridging force and cohesion between the particles are significantly increased after agglomeration, which improves the resistance of particles to fluid impingement and mitigates the velocity sensitivity damage of the reservoir.46

2.2.1.2. Changing Double-Graded Proppants to Multigraded Proppants. Double-graded quartz sand is generally adopted as the proppant in the conventional hydrofracturing, including medium sand and coarse sand with the particle sizes of 20–40 mesh (0.42–0.84 mm) and 16–20 mesh (0.84–1.18 mm), respectively. Multigraded quartz sand shall be used as the proppant in the secondary stimulation of stripper wells, which is generally a multigraded combination of silty sand (e.g., 70–100 mesh, 0.17–0.225 mm), fine sand (e.g., 40–70 mesh, 0.225–0.42 mm), and medium and coarse sands (Figure 6b). There is no clear standard for the division of proppant gradation, and the amounts of organic carbons in carbonaceous mudstone, dark mudstone, and sandy mudstone near coal seams, which are characterized by this mode.12 However, the high gas production of the wells in the Surat Basin proves that the difference in gas production characteristics of different reservoirs will not affect the overall development effect.

2.2.1.3. Changing CBM Development to CMG Development. The targets of CMG development include not only the CBM in the main coal seams but also the gas resources in the roof and floor shale, tight sandstone, and thin coal seams.21 Previous explorations show that there are generally certain amounts of organic carbons in carbonaceous mudstone, dark mudstone, and sandy mudstone near coal seams, which are capable of generating and storing hydrocarbons.50 Therefore, CMG in the surrounding rock can be treated as the supplement to CBM (Figure 6c).

In addition, the CMG development also possesses other technical advantages. First, the surrounding rocks of coal seams generally contain a certain amount of brittle minerals and are conducive to fracture initiation and propagation as well as the formation of a fracture network. Second, the surrounding rocks possess higher Young’s modulus and compressive strength, which are helpful to resist proppant embedment in fractures during the drainage stage. Finally, when channel fracturing is adopted during hydrofracturing, the fractures supported by board-and-pillar propping are more stable in the surrounding rocks, which is beneficial to maintain the fracture conductivity.52

It should be noted that interlayer interference generally occurs during the CMG development, which may adversely affect the gas production. During the hydrofracturing stage, the difference in reservoir properties (e.g., permeability and fracture pressure) can lead to uneven distribution of fracturing fluid and a poor stimulation effect in the partial reservoir. To this point, methods such as high displacement and temporary plugging by ball casting can be adopted to mitigate the interlayer interference effect.52 Also, the reservoirs with extremely high permeability or fracture pressure may not be included into the development scope. On the other hand, during the drainage stage, the pressure difference among the CMG reservoirs in different development intervals is not neglectable, which may cause the fluid of the high-pressure reservoir to flow into the reservoirs with relatively low pressure and hinder the gas production. In this case, it is possible to control the BHP to achieve staged drainage of the different intervals or conduct joint production with different drainage pressure systems by using multiple drainage pipelines and packers.53 Additionally, the gas occurrence characteristics of different types of reservoirs are different, which make each reservoir start to produce gas at different drainage stages. The CMG development in the Surat Basin in Australia is characterized by this mode.12 However, the high gas production of the wells in the Surat Basin proves that the difference in gas production characteristics of different reservoirs will not affect the overall development effect.

2.2.1.4. Changing Conventional Hydrofracturing to Large-Scale Fracture Network Stimulation. In general, fractures of single types formed by conventional hydrofracturing can hardly meet the requirements for the efficient production of CBM (Figure 5a). During the secondary stimulation of stripper wells, it is suggested to conduct large-scale FNS to increase the stimulation volume, especially along the direction of the minimum principal stress of reservoir, and to improve the reservoir permeability by SRV. For horizontal wells, the tubing plus packer technology is required in the secondary stimulation because of the segmented multicluster perforation in the first hydrofracturing. However, the displacement under the technology can hardly meet the requirements of FNS. Therefore, this study only focuses on the secondary stimulation of vertical wells, mainly including the selection of stimulation interval, as well as the optimizations of perforation mode and pumping procedures (Figure 6e).

(1) Selection of stimulation intervals: For the selection of stimulation intervals, comprehensive consideration should be given to the CMG resource quantity within the well control range, the fracability, fracture pressure, and permeability of the reservoirs, and the hydrodynamics.59 The coal seam can be stimulated alone in the case of abundant CBM resources. Otherwise, it is necessary to incorporate the surrounding rocks with high gas-bearing possibility into the stimulation interval for CMG development.

(2) Optimization of perforation mode: During the secondary stimulation of vertical wells, multilayer uneven perforation should be adopted for the perforation of new intervals. Thus, under the stress field interference generated by fracture propagation in each layer, the original stress direction is changed and the fractures are forced to re-orient, which is conducive to linking up with more natural fractures and forming a fracture network.54 The reservoirs that cannot be fractured (e.g., soft coal) or possess abnormally high permeability or fracture pressure should not be perforated. In addition, there should be not too many perforations in the same stimulation interval so to avoid a low flow rate of fluid in blast holes due to the limited displacement, which makes it difficult to form fractures and transport proppants.

(3) Optimization of pumping procedures: The optimization of pumping procedures includes the technologies such as variable displacement, large displacement, large fluid
volume, variable sand ratio, and limited-entry fracturing. Among them, variable displacement fracturing and large displacement fracturing are conducive to forming a complex fracture network with multiple levels and types of fractures (Figure 5b). Fracturing with a large fluid volume is beneficial to increasing the volume of the fracture network. In fracturing with a variable sand ratio, proppant sand is pumped in the slug manner to form board-and-pillar propping in fractures. The channels between the support pillars are the gas and liquid production channels, which is conducive to the improvement and maintenance of fracture conductivity. Limited-entry fracturing includes temporary plugging by ball casting, tip screenout, and intrastratal temporary plugging. Temporary plugging by ball casting is the most commonly used method, but the number of the balls needs to be optimized. Tip screenout and intrastratal temporary plugging can seal the ends of fractures and promote fracture re-orientation, but it is easy to cause serious sand plugging, showing certain engineering risks.

2.2.1.5. Coordinated Stimulation of Child−Parent Wells. Secondary stimulation is infeasible for the wells with a severely damaged wellbore. However, the coordinated stimulation of child−parent wells can be used to increase the production regionally for the low-yield blocks. Adopting this technology, new wells are drilled between the stripper wells and large-scale FNS is conducted to improve the CBM exploitation efficiency in the block. The original stripper wells are the parent wells and the newly deployed wells are the child wells. Both parent and child wells can be a vertical well (cluster well) or horizontal well, showing four combination types (Figure 6d). The parent wells generally possess a small single-well stimulation scope and low resource exploitation efficiency. However, a certain range of pressure drop funnel has been formed around the parent well, and both the reservoir pressure and ground stress within the funnel have been reduced. Hydraulic fractures are prone to extend toward the parent wells during the stimulation of the child wells. The fracture network centered on the child wells and hydraulic fractures near the parent wells are thus interlaced with each other, and the stimulation scope in the region is greatly expanded, resulting in a larger scope of the pressure drop funnel during the drainage.
process. Therefore, both the CBM desorption area and resource exploitation efficiency increase, which promotes the gas production regionally in the block.

Note that for a horizontal well, it is recommended to deploy it in the stable surrounding rock of coal seam and conduct pseudo-reservoir stimulation. In the staged fracturing of horizontal wells, a segment length of less than 50 m and a cluster spacing of 3–5 m are recommended to ensure the extension length of fractures and strengthen the stress field interference to promote the formation of a complex fracture network. In addition, segments and clusters of horizontal wells should be arranged as evenly as possible to facilitate uniform FNS of the reservoir.

The coordinated stimulation of child–parent wells has been successfully applied in some blocks. For example, a group of child–parent wells has been constructed in the northern part of the Zhaozhuang Block (see Figure 7 for well locations). The child well is a U-type well and its horizontal section is located in a stable rock stratum on the roof of the coal seam. In the drainage stage, the child well showed high gas production with the maximum gas production rate of up to 11,000 m³/day and the gas production rate remaining stable at about 4500 m³/day after more than 300 days of drainage (Figure 8a). Limited by the stimulation scale, fractures of the child well failed to link up with those of the parent wells, which was manifested by the lack of pressure disturbance in the parent wells during the hydrofracturing of the child well. However, the higher gas production of the child well indicates that the CBM resources in the area that were not exploited by the parent wells had been successfully developed and the production has been increased regionally. Meanwhile, in the Zhengzhuang Block, horizontal wells were deployed in the coal seam as child wells. After the hydrofracturing, the gas production of six parent wells (vertical wells) increased significantly (Figure 8b) and the average gas production rate reached 2400 m³/day per well, which was 3.6 times higher than that of other vertical wells in the block. In addition, the gas production rate of the child wells was 3655–11,301 m³/day, with an average of 5436 m³/day, which was 4.2 times higher than that of other horizontal wells.

2.2.2. Drainage Control Technology. The drainage process of CBM wells can be affected by many factors. Among them, stress sensitivity and velocity sensitivity effects as well as slug flow in the two-phase flow stage may cause the decrease in reservoir permeability, which belongs to negative permeability effects. On the contrary, the matrix shrinkage and brittle deformation of the coal body caused by CBM desorption can improve the fracture conductivity, which are the positive permeability effects beneficial to the CBM production. Therefore, the drainage control should weaken the negative effect but enhance the positive effect to maintain the fracture conductivity and promote CBM production effectively.

2.2.2.1. Prevention of Stress Sensitivity Damage. A pressure drop funnel centered on the wellbore is formed in the reservoir as the reservoir fluids are gradually drained during the drainage process. High-intensity drainage makes the pressure drop funnel steep and has great pressure drop in the near-wellbore zone. This can easily cause serious stress sensitivity damage and the reduction of fracture aperture in the zone, which is not conducive to fluid production. Meanwhile, the pressure drop range is small along the reservoir direction, accompanied by a small CBM desorption area and limited gas supply range (as shown by the type I curve in Figure 3b,c). Note that the stress sensitivity damage to the reservoir caused by pressure drop is inevitable. However, the matrix shrinkage caused by CBM desorption promotes the increase in fracture aperture, which can offset part of the impact of stress sensitivity damage. When the matrix shrinkage effect is enhanced, the permeability variation trend changes from curve I to curve II in Figure 3b, and the drop in permeability is effectively reduced and is easier to recover. Additionally, when fractures are supported by board-and-pillar propping, the displacement of the coal body between the support pillars will produce tensile and shearing fractures on the fracture surfaces (Figure 9a). Furthermore, uneven matrix shrinkage will also form tensile and shearing fractures, which are conducive to the increase in reservoir permeability (Figure 9b). Accordingly, it is an important objective for the drainage control to achieve a smooth transition from the negative permeability effect to the positive permeability effect for minimizing the reservoir damages.

Specifically, the pressure drop rate should be reduced in the single-phase water stage during the preliminary drainage process to keep the pressure drop funnel as smooth as possible and maximize the pressure drop range along the reservoir directions. This can effectively reduce the intensity of stress sensitivity damage in the near-wellbore zone and create conditions for the increase in CBM desorption area in the next stage. Meanwhile, as the water phase permeability of the reservoir is relatively high in the single-phase water stage, a smooth pressure drop funnel can greatly promote the water drainage before CBM desorption, which is conducive to mitigate the liquid retention caused by the decrease in water phase permeability in the two-phase flow stage. In addition, the pressure drop rate should also be kept low in the early stage of gas production to make the pressure drop funnel further extend to the far-wellbore area. This can realize even pressure drop in the near- and far-wellboere zones, maximizing the CBM desorption area and increasing the coal volume experienced with matrix shrinkage and brittle deformation. Therefore, the positive permeability effect can be maximized, while the stress sensitivity damage can be mitigated.

Concerning the large differences in geological conditions, fluid migration capacity, and drainage capacity of different areas, it is difficult to set a fixed quantitative criterion for drainage
control. However, according to the previous practical experience, the drop rate of BHP can be controlled below 0.05 MPa/day in the single-phase water stage. After the BHP is reduced to the CBM critical desorption pressure, the BHP could be stabilized for more than 1 month to maximize the range of the pressure drop funnel. Then, the BHP drop rate of 0.05–0.1 MPa/day can be adopted to gradually increase the gas production rate. However, the specific drainage schedule needs to be adjusted according to the actual drainage situation of the well, e.g., the production of pulverized coal or the formation of slug flow.

### 2.2.2.2. Prevention of Velocity Sensitivity Damage and Slug Flow

Coal, rock, and proppant particles in fractures are in a balanced and static state before the drainage. However, the drag force on the particles and the rising force caused by the pressure difference between the top and bottom of the fractures will increase as the water velocity increases after the start of drainage. When the water velocity increases to a critical value, the force balance of the particles is disrupted and they will migrate with the fluid, which undoubtedly increases the risk of velocity sensitivity damage to the reservoir. Therefore, it is necessary to control the drainage intensity strictly and keep the pressure drop funnel as smooth as possible. Thus, it will be much easier to keep the fluid velocity lower than the critical value for particle migration and prevent the velocity sensitivity damage.

In addition, the formation of slug flow in the gas-water two-phase flow stage is also not conducive to gas production. Slug flow evolves from two-phase stratified flow. Its existence in unconventional reservoirs has been demonstrated by previous laboratory experiments and engineering practices of underground coal mine gas extraction and CBM development. The fluid velocity in fractures and the reservoir pressure drop fluctuate violently in the stage of slug flow. On the one hand, it tends to destroy the balanced and static state of the particles in the fractures and cause serious velocity sensitivity damage. On the other hand, strong disturbance is caused to the drainage system, which is not conducive to the stable operation of equipment. Therefore, the prevention of slug flow is also an important target of drainage control.

Note that slug flow can only be formed when there is a certain liquid level in the fracture and the gas flow velocity is higher than the critical flow velocity. Therefore, the key to the prevention of slug flow is to control the gas and liquid flow velocity. Specifically, the drainage rate should be reduced to achieve a smooth pressure drop funnel in the single-phase water stage, and as much reservoir water as possible should be drained before the formation of two-phase flow. Thus, the liquid level in the fracture will be relatively low in the two-phase flow stage, which is conducive to restraining slug flow. In addition, gas production shall be kept continuous and slow in the two-phase flow stage so as to control the two-phase flow pattern in the stratified flow stage, promote the further production of reservoir water, and further restrain the formation of slug flow.

In summary, the continuous, slow, and stable drainage should be adhered to in the drainage process after the secondary stimulation of the stripper wells. Continuous operation at a low pressure drop rate is required in the single-phase water stage during preliminary drainage so as to drain the reservoir liquid to the greatest extent. The BHP should be stabilized after the critical desorption pressure is reached to induce a stable and slow transition from single-phase water flow to gas-water two-phase flow. In the two-phase flow stage, the flow rate should be controlled strictly to prevent slug flow and velocity sensitivity damage.

### 2.2.3. Secondary Stimulation Technology for Different Types of Stripper Wells

The genesis types of CBM stripper wells can be divided into geological genesis and engineering genesis. The former includes resource-controlled, coal structure-controlled, ground stress-controlled, and hydrodynamics-controlled types, and the latter includes hydrofracturing-controlled and drainage-controlled types (Table 3).

To mitigate the reservoir damages, strengthen the support of the fractures by proppants, and promote the maintenance of the fracture conductivity, all types of the stripper wells can adopt low-damage fracturing fluid and multigraded proppants, as well as the “continuous, slow, and stable” drainage. In addition, there are certain differences in the stimulation technology adopted by each type of stripper well.

#### 2.2.3.1. Resource-Controlled Type

Resource-controlled stripper wells generally possess low CBM content or coal seam thickness, with the CBM resource abundance of less than $1 \times 10^8$ m$^3$/km$^2$. For the wells with slightly lower CBM resources (i.e., $0.8 \times 10^8$ to $1.0 \times 10^8$ m$^3$/km$^2$), large-scale FNS can be conducted for the coal seam to increase the stimulation volume and the quantity of recoverable CBM resources (Figure 5). However, for those with an extremely low quantity of CBM resources (i.e., $<0.8 \times 10^8$ m$^3$/km$^2$), blindly expanding the stimulation scale of coal seam can hardly meet the resource demand for commercial development. Therefore, it is required to conduct CMG development and incorporate the gas

| geological genesis | resource-controlled | CBM resource abundance lower than $1 \times 10^8$ m$^3$/km$^2$ | CMG development | coal seam large-scale FNS coordinated stimulation of child–parent wells | Xishan, Sijiazhuan, and Zhaozhuan Blocks of the Qinshui Basin and Jiaoping Block of the Ordos Basin |
|-------------------|---------------------|------------------------------------------------|-----------------|------------------------------------------------|------------------------------------------------|
| coal structure-controlled | development of granulated coal and mylonitic coal | surrounding-rock large-scale fracture network stimulation | Shoushan and Gushan Blocks in the Henan Province, as well as Luling Block of the Huabei Coalfield |
| ground stress-controlled | the minimum principal stress higher than the compressive strength of coal | integrated FNS of coal seams and surrounding rocks | Zhenghuang Block of the Qinshui Basin and Yanchuan Block of the Ordos Basin |
| hydrodynamics-controlled | coal seams connecting with an aquifer through hydraulic fractures | abandon | Lidin and Daning Jixian Blocks of the Ordos Block and Machang Block in the Henan Province |
| engineering genesis | hydrofracturing-controlled | conventional hydrofracturing | large-scale FNS | Well HN-01 in the Sunan Syncline Block of the Huabei Coalfield and Tunlan Block of the Qinshui Basin |
| drainage-controlled | too fast or discontinuous drainage | continuous, slow, and stable drainage | |

### Table 3. Genesis Types of the Stripper Wells and the Targeted Secondary Stimulation Technologies

Findings from the table are consistent with the text.
Table A1. Physical Properties of the Main Coal Seams in Different Blocks

| blocks       | coal seams | thickness (m) | $R_o$ (%) | gas content (m$^3$/t) | reservoir pressure gradient (MPa/100 m) | gas saturation (%) | critical desorption pressure (MPa) | $C_R$ | permeability (mD) | resource abundance ($10^8$ m$^3$/km$^2$) | hydrodynamics |
|--------------|------------|---------------|-----------|----------------------|-----------------------------------------|-------------------|------------------------------------|-------|------------------|-----------------------------------------|--------------|
| Xishan       | no. 2      | 0.40–4.50, 1.83 | 1.25–2.08, 1.66 | 3.36–13.34, 7.49 | 0.31–0.63 | 36.00–89.00, 64.65 | 0.36–0.98, 0.13–0.22 | 0.026–0.044 | 0.19 | relatively simple |
|              | no. 8      | 0.90–5.00, 3.15 | 1.14–2.30, 1.67 | 3.18–15.14, 8.64 | 0.30–0.63 | 28.00–83.00, 56.70 | 0.87–1.12, 0.024–0.060 | 0.36 | stagnant and weak run off zones |
|              | no. 9      | 0.35–4.30, 2.33 | 1.39–2.26, 1.90 | 2.77–15.45, 8.24 | 0.62–0.63 | 20.00–99.00, 55.20 | 0.016–0.042 | 0.26 |                  |
| Zhaozhuang   | no. 3      | 0–6.35, 4.69   | 2.23–2.83, 2.41 | 0.23–18.79, 10.3 | 0.46–0.86, 0.66 | 33.63–66.97, 52.28 | 0.48–1.63, 0.0056–2.31 | 0.69 |                  |
| Shoushan     | no. 3, 10  | 0.90–5.15, 2.64 | 1.32–1.34, 1.33 | 10.26–13.35, 11.65 | 0.92–0.95, 0.94 | 65 | 0.25–4.00, 1.82 | 0.28 | 0.074 | 0.45 | simple |
|              | no. 2      | 1.20–10.70, 6.15 | 1.41–1.73, 1.56 | 11.15–13.19, 11.71 | 0.86–1.05, 0.95 | 1.16–1.69 | 0.04–0.094, 0.069 | 1.04 |                  |
| Zhengzhuang  | no. 3      | 2.15–7.70, 6.11 | 3.59–3.98, 3.76 | 0.83–31.44, 19.10 | 0.50–1.71, 0.85 | 2.97–98.78, 69.19 | 0.85–9.21, 3.91, 0.14–1.00, 0.56 | 0.012–1.13, 0.16 | 1.71 | relatively simple |
| Luolin       | no. 3 and 4 | 0.04–6.05, 2.81 | 1.38–1.69, 1.33 | 4.87–15.36, 10.98 | 0.46–1.10, 0.82 | 4.79–93.79, 67.28 | 1.01–2.53, 1.66, 0.2–0.87, 0.47 | 0.02–3.44, 0.82 | 0.44 | coal seam near aquifer |
|              | no. 5      | 0–5.04, 2.07   | 2.11–9.93, 8.64 | 32.75–87.91, 60.99 | 0.60–1.09, 0.84 | 32.75–87.91, 60.99 | 0.4–1.97, 1.14, 0.08–0.44, 0.25 | 0.01–2.26, 0.95 | 0.34 |                  |
|              | no. 8 and 9 | 0.79–10.66, 5.11 | 1.34–10.98, 8.96 | 37.74–84.90, 59.20 | 0.52–1.05, 0.82 | 37.74–84.90, 59.20 | 0.62–1.62, 1.31, 0.13–0.68, 0.33 | 0.02–24.8, 0.90 | 0.66 |                  |
| Sunan Syncline| nos. 6, 7, 8, 9 | 8.09–11.22, 0.89 | 0.73–1.05, 0.89 | 7.16–11.86, 9.40 | 0.64–1.11, 0.95 | 85–93 | 0.74–6.48, 0.57–0.71 | 0.01–5.0, 1.07 | 1.83 | simple |

$C_R$ is the ratio of critical desorption pressure to reservoir pressure.
resources in the surrounding rocks and thin coal seams into the development intervals during the secondary stimulation so as to increase the amount of recoverable gas resources within the well control range. In addition, for the stripper wells with a severely damaged wellbore, the coordinated stimulation of child—parent wells can be adopted to increase the exploitation efficiency of the CBM resources in the area to achieve a regional production increase. When a single coal seam is developed, a horizontal well can be drilled as a child well, while when multiple coal seams are developed, vertical wells can be adopted as a child well for carrying out CMG development (Figure 6).

2.2.3.2. Coal Structure-Controlled Type. For this type of stripper well, the coal seams are mainly composed of granulated coal and mylonitic coal, which possess extremely poor fracability. Large-scale FNS of the surrounding rocks is suggested to be conducted during the secondary stimulation of these wells. During the stimulation of the surrounding rocks, hydraulic fractures will link up with coal seams. Thus, CBM can diffuse to the fracture network of the surrounding rocks at a short distance (less than the coal seam thickness) after desorption and then flow to the wellbore by means of seepage flow,23 which is conducive to the increase in the gas production. In addition, the formation of the surrounding rock fracture network also provides channels for the production of shale gas and tight gas in the surrounding rocks, realizing the integrated development of CMG.

2.2.3.3. Ground Stress-Controlled Type. Coal seams in this type of stripper well generally possess a large burial depth and high ground stress but low compressive strength. Proppants are prone to embed into the coal body in the drainage stage, causing reservoir stress sensitivity damage (Figure 3). For such wells, large-scale FNS should be conducted to both coal seams and its surrounding rocks during the secondary stimulation. By this, an interlinked fracture network will be formed in the coal seams and surrounding rocks, providing more stable channels for CBM production and realizing the integrated development of CMG.

2.2.3.4. Hydrodynamics-Controlled Type. During the first hydrofracturing of this type of well, hydraulic fractures linked up with the aquifer near the coal seams, causing the gas well to become a water well. However, it is not recommended to carry out secondary stimulation for such wells when it is impossible to plug the fractures linking up with the aquifer under actual technical conditions.

2.2.3.5. Hydrofracturing-Controlled Type. The first hydrofracturing of this type of stripper well has problems such as small stimulation volume and serious reservoir damages. During the secondary stimulation, large-scale FNS is suggested to be conducted for the coal seams. By adopting supplementary perforation, large fluid displacement and volume, variable displacement and sand ratio, etc., the formation of the fracture network can be promoted and the stimulation volume can be increased, thereby promoting the production of CBM.

2.2.3.6. Drainage-Controlled Type. Due to the improper drainage control of such wells, fracture closure and blockage occur in the drainage stage after the first hydrofracturing, resulting in low gas production. During the secondary stimulation, low-damage fracturing fluid and multigraded proppants are suggested to be pumped continuously into the coal seam with relatively low displacement to unblock and reopen the fractures. Also, “continuous, slow, and stable” drainage is needed to promote the maintenance of fracture conductivity and the efficient production of CBM.

3. CONCLUSIONS

According to the geological conditions and the development technologies, the coalbed methane stripper wells in China can be generally divided into six genesis types. During the secondary stimulation, large-scale fracture network stimulation of coal seam, coal measure gas development, and child—parent well coordinated stimulation can be adopted for the resource-controlled stripper wells to increase the recoverable resource within the well control range. For the coal structure- and ground stress-controlled wells, the fracture network stimulation of surrounding rocks and the integrated fracture network stimulation of coal seams and surrounding rocks can be adopted, respectively, to provide stable coalbed methane migration channels. The hydrofracturing-controlled wells can adopt large-scale fracture network stimulation of coal seam to improve the stimulation effect, while the drainage-controlled wells need to realize the unblocking and reopening of the fractures in the coal seam through relatively low fluid displacement. In addition, each type of stripper well can adopt the low-damage fracturing fluid and multigraded proppants, as well as adhere to the “continuous, slow, and stable” drainage schedule to mitigate the reservoir damages and promote the maintenance of fracture conductivity. The physical properties of the main coal seams in different blocks are presented in Table A1.

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Notes

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